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Shallow zones and their role in the ecosystem of the Sheksna Reach of the Rybinsk Reservoir

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Abstract. Based on the materials of monitoring of bottom sediments and a special voyage of the RV Akademik Topchiev in 2016–2018 in the Sheksna Reach of the Rybinsk Reservoir which is a recipient of semi-purified waste waters from chemical and metallurgical enterprises of the city of Cherepovets, the role of the littoral zone in dilution of pollutants in water and their accumulation in bottom sediments in the profundal zone of the flooded channel of the Sheksna River to the settlement of Gayutino has been estimated. The results indicate that runoff and wind-induced currents promote intensive horizontal transfer and dilution of sewages in a shallow zone, and hydrodynamic conditions in a deep-water zone promote vertical sedimentation and irretrievable deposition of pollutants in bottom sediments at depths of more than 6 m. Chemical and biological processes leading to self-purification of industrial and domestic wastewaters and contributing to the maintenance of optimal water quality take place along with the physical processes.

1. Introduction

Littoral is the most important element of water reservoir's ecosystem functioning. First of all, it is characterized by the instability of the water level associated with the value of yearly drainage volume (being low, medium or high in different years) and the operating mode, which leads to a change in the abiotic and biotic parameters of the environment. The connection of the littoral with the catchment area strengthens the influence of the anthropogenic factor on the ecosystem of the reservoir. On the other hand, the activation of hydrodynamic processes leads to the dilution and utilization of industrial and domestic wastewaters and self-purification of water from harmful pollutants.

Main aim of the study was to assess the multifactorial influence of the littoral zone of the Sheksna reach affected by the Cherepovets industrial complex (CIC) and find its effectiveness for the Rybinsk reservoir.

2. Materials and methods

Materials obtained during complex hydrological surveys of the Sheksna reach (table 1) which allowed finding the spatial-temporal transformation of the bottom complex and the intensity of sedimentation processes [1] were used in this work.

The figure represents a bathymetric map built using GIS-technologies, with standard sampling sites and sections according to K.K. Bakulin [2].

Table 1. Materials of bottom surveys.

Years	Number of sampling sites	Number of samples	The source of data
1955–1957	216	25	[3]
1960–1962	130	30	[3]
1965	144	38	[3]
1978	190	116	[1]
1992–1994	157	120	[1]
2000–2009	85	20	[1]
2016–2018	50	30	[1]

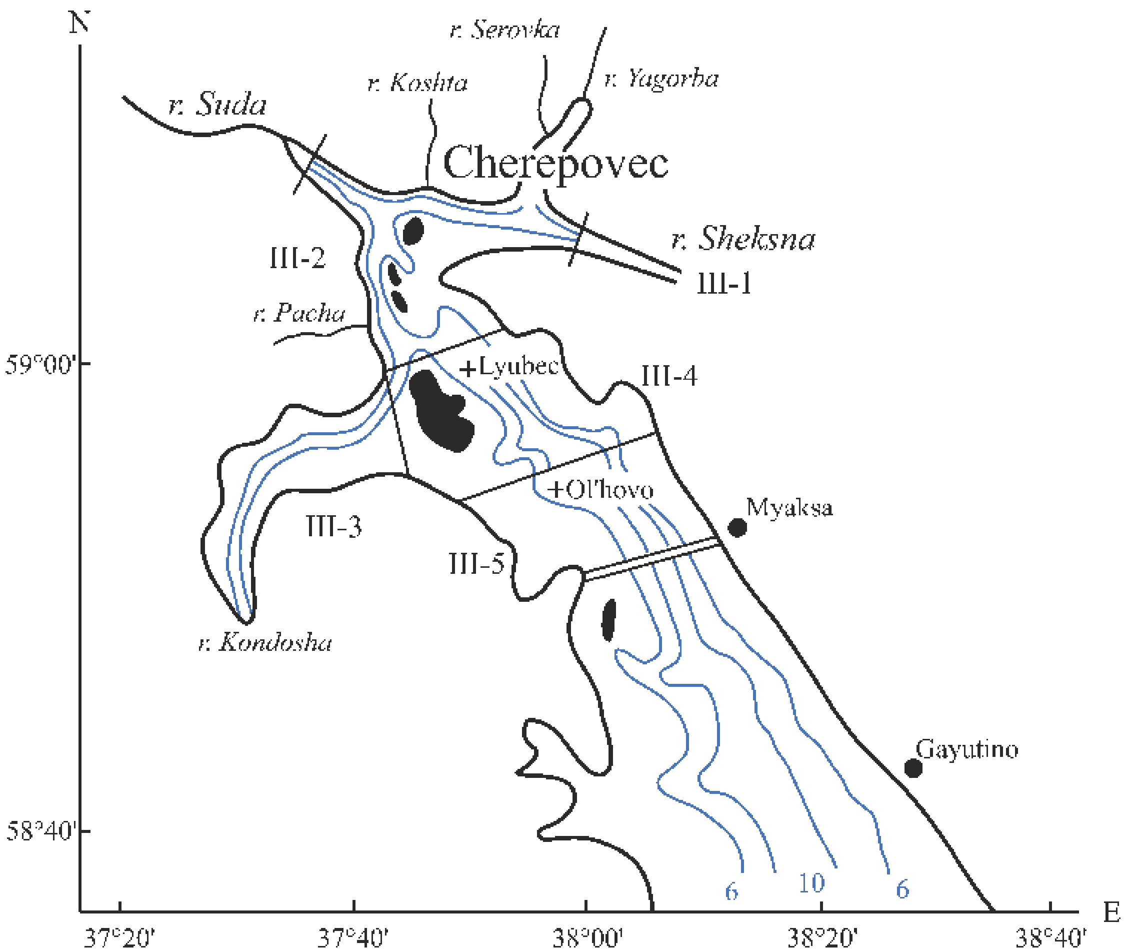

Figure 1. Schematic map of the Sheksna reach of the Rybinsk reservoir.

Morphometric characteristics calculated using maps drawn by “Volgostroy” utilizing the planimetric method, where section III-1 is the Sheksna dam lower pool down to the city of Cherepovets; III-2 – Cherepovets – Lyubets; III-3,4 – Lyubets – Olkhovo with river Kondosha bay and III-5 – Olkhovo – Myaksa sett. (Lyubets and Olkhovo – ruins of flooded churches).

Hydrophysical and chemical properties: depth, type of the bottom sediment, dry volumetric mass, average diameter of particles, average near-bottom current velocity, organic matter content were determined according to methodology [1; 3; 4]. The content of polychlorinated biphenyls (PCB, µg/kg) was estimated using gas liquid chromatography with electron capture detector in the laboratory of IEEP RAS. The accumulation of PCBs was calculated according to their concentration and mass of the bottom sediments [5]. Heavy metals in plants were estimated using atom-absorption spectrophotometer AAS-3.

3. Results and discussion

Rybinsk reservoir ecosystem is under the chronic influence of CIC wastewaters. Over the last decade their volume was 270·106 m^3/year on average, fluctuating from 343.1 in 2010 to 133.0·106 m^3/year 2017 [6]. Average long-term water drainage of river Sheksna is 4.9 km^3, river Suda 3.2 km^3. The presence of comparatively clear waters of northern tributaries running into the water reservoir, leads to the dilution of industrial-household wastewaters and their rapid neutralization. This is further facilitated by the morphometry of the Sheksna reach sections located consecutively and mainly being shallow, with depths 0-3 m constituting: III-2 – 45.2%, III-3,4 – 42.2% and III-5 – 36.2% of their overall area. Estimated average drainage and wind current velocities fluctuate from 0.2 to 1.0 m/s [2; 4]. The lower layer of bottom in these sections is formed from sand with 0.3–1.0 mm average diameter of particles. Bottom sediments on depths from 3 to 6 meters are built from a transitional type of alluvium – silty sand and sandy silt. Intensive accumulation of finely-dispersed particles along with formation of clayey sediments adsorbing pollutants takes place only in the profundal zone (>6 m, 25.8%) where there is almost no vertical transfer of water masses (V = 0.01–0.05 m/s).

Rates of sediment accumulation over 75 years of the Rybinsk reservoir existence have been calculated based on the previously performed studies (table 2).

Table 2. Sedimentation processes in the Sheksna reach over the period 1941-2016.

Sediment type	F, km^2	$h_{ср.}$, cm	V, $10^6 \cdot m^3$	$O_{мс}$, t/m^3	M, $10^6 \cdot t$	Average annual accumulation		
						mm	$10^3 \cdot t$	kg/m^2
Coarse-grained alluvia	420	9	378	1.4	53	1.2	707	1.7
Fine-grained alluvia	180	39	702	0.3	21	5.2	280	1.6
Sediment accumulation	600	18	1080	0.69	74	2.4	987	1.6

F, km^2 – area; $h_{ср.}$, cm – average thickness of alluvium; V, $10^6 \cdot m^3$ – volume of sediments; $O_{мс}$, t/m^3 – volumetric dry mass; M, $10^6 \cdot t$ – alluvium mass.

According to data over 1992-1994, the overall amount of PCBs accumulated in the upper 5 cm layer of deep-water zone (>6 м) sediments was 501.2 kg. Concentrations of PCB along the submerged channel of river Sheksna decreased rapidly from the sites of wastewaters discharge in the mouths of Serovka, Yagorba and Koshta rivers, correspondingly 580, 510, 430 µg/kg to Lyubets – 270 µg/kg and Gayutino 88 µg/kg [5].

Despite the efforts of nature conservation organizations on decreasing the CIC drainage, the main source of PCB polluting bottom sediments will remain for a long time [5].

Surveys of 2016-2018 have shown that PCB concentrations in the sand and silty sands was 3-7 µg/kg dry mass, 100-180 in sandy silts, 200–300 µg/kg in clayey silts. There is a gradual decrease of PCB content from the wastewater discharge down the reservoir reach and increase from the littoral to profundal zone as well as in the order: sand – silty sand – sandy silt – clayey silt (table 3).

This occurs due to hydrodynamic processes in the shallows and in the 0–3–6 m water column already in the northern part of the reach on sections III-2 with 0.4 km^3 water volume, then in III-3, 4 – 0.9 km^3 and in III-5 – 0.9 km^3. As the reach widens towards the central part of the reservoir (Main Reach – area of 3077 km^2 and volume 19.4 km^3) wind-wave impact penetrates to a depth of 10 m, which leads to an increase in the effect of dilution of industrial effluents.

Table 3. Main characteristics of bottom sediments in the Sheksna reach according to 2016-2018 surveys.

Sampling site	H, m	V_{av}, m/s	T_{bs}	Vo_{dw}, г/м^3	d_{av}, mm	OM, %	PCB, µg/kg
Serovka	2	0.10	C_s	0.48	0.10	16.4	1280.0
Yagorba	6	0.02	C_s	0.44	0.08	10.4	1075.0
Koshta	12	0.02	C_s	0.40	0.07	12.3	174.8
Lyubets	12	0.15	C_s	0.8	0.19	23.2	4.0
Gayutino	9	0.20	C_s	0.13	0.21	33.0	5.3

H – depth, m; Vav – average near-bottom current velocity, m/s; Tbs – bottom sediment type; Cs – clayey silt; Vodw , g/cm3 – volumetric dry weight; dav, mm – average diameter of particles; OM,% – organic matter, PCB, µg/kg

Thus, the presence of shallows facilitates quick mixing of diffuse industrial and domestic runoff of the city of Cherepovets with the waters of the tributaries – rivers Sheksna, Suda and smaller watercourses Pacha, Kondosha and others. Penetrating further into the Main Reach, these processes are amplified, nullifying the impact of CIC effluents on the ecosystem of the Rybinsk reservoir.

The main factors of water's self-purification are physical-chemical processes linked with dissolution and dilution of Cherepovets effluents, their transfer outside of the aquatic ecosystem into the lower sections and along the Volga's reservoir cascade, adsorption by suspended particles with simultaneous sedimentation.

The formation of bottom sediments is a long stage of impact on the bottom of the runoff and wind currents, sources of terrigenous material (erosion of shores and the bed), solids runoff of tributaries, transboundary transport, anthropogenic suspensions and dissolved chemicals of industrial and agricultural enterprises, as well as the impact of production processes taking place within the waterbody, associated with the development and death of macrophytes, phyto- and zooplankton, and the activity of benthic organisms as filter feeders. The content of PCB in fishes relative of the total mass of toxic substances is very insignificant (a fraction of percent) and located in the following series: bream > burbot > roach > zander > blue bream [5]. That is why it is advisable to carry out pollution mapping according to their concentrations in benthic sediments of various types.

Another inter-connectinf physical-biological factor – level regime and the overgrowth of shallows with macrophytes. The Rybinsk reservoir is characterized by deep seasonal and perennial regulation of drainage leading to level fluctuation amplitude of up to 3.1 m [7]. The dynamics of overgrowth, reservoir fill level vary in separate years and seasons, which led to a decrease of its area by 70 km^2, the area of Sheksna reach by 22 km^2 [8; 9]. Hydromorphic soils with bog-meadow vegetation are formed on the ground expropriated from the reservoir. Macrophyte quagmires connated with the bottom and macrophyte beds served as a buffer intercepting pollutants from the drainage area and sites of wastewaters discharge. According to T.F. Mikryakova the concentration of heavy metals in the fennel pondweed Potamogeton pectinatus L., which occurs in almost all sampling sites, gradually decreases with distance from the city of Cherepovets (table 4) [10].

Table 4. Concentrations of heavy metals in the fennel pondweed *Potamogeton pectinatus* L., µg/g of dry weight

Sampling site	Zn	Cu	Ni	Pb	Co	Cd
Koshta (mouth)	332.2	14.4	8.2	7.0	5.5	0.5
Sheksna, Suda (confluence)	193.1	7.4	5.2	6.1	3.0	1.3
Lyubets	40.0	5.0	7.1	3.4	2.0	0.1

The role of the natural process of self-purification of the aquatic ecosystem is great in the Sheksna reach. Many physical, chemical and biological processes take part in the formation of water quality, bottom sediments and biota, which are described in detail in the literature [11; 12; 13]. The systematization of factors and processes showed that they are interrelated and overlapping [14]. Their assessment indicates that gravitational sedimentation of mineral and organic particles (80-90%), chemical deposition of pollutants in combination with biological processes (10-20%) represent a complex energy-mass exchange in the system: water – bottom sediments – biota.

4. Conclusion

The impact of CIC effluents on the ecosystem of the Rybinsk reservoir after the accident at the end of December, 1986 at the metallurgical plant and emergency dumping of more than 103 m3 of sulfuric acid waste from the “Ammofos” production area on January 5, 1987, that led to an environmental disaster was carefully studied during a two-year period. The implemented program on various hydrochemical and hydrobiological aspects showed a rapid restoration of the ecosystem already on site III-2 directly adjacent to the city of Cherepovets [15].

Due to the low solubility and large specific gravity of PCBs, their migration is associated primarily with suspended particles [16]. The half-life of PCBs is 5 years. Subject to the cessation of the entry of toxic substances into the water body, the ecological risk for 25–30 years will be minimized [5]. The reduction of this period is significantly affected by the high rate of sedimentation of the fine-dispersed suspension, due to which a 5 cm surface layer, free from contamination, can be formed within 10 years.

The upper part of section III-2 is rather complex in hydrodynamic terms. Here counterflow runoff currents of the Sheksna and Suda rivers interact, on which wind water transfer is imposed, and favorable conditions are created for mixing and sedimentation of pure fine-dispersed particles. This pattern is observed in almost all mouth sites of Pacha, Kondosha and other rivers, as well as in open shallow waters, where coarse sediment forms.

Due to the continued flow of industrial wastewater of the city of Cherepovets into the waterbody, they are being actively self-purified by diluting with relatively clean waters of the rivers Sheksna and Suda already in the section Cherepovets – Lyubets. Further, mixing with the waters of the subsequent sections and the Main Reach, they undergo additional natural purification and do not degrade the quality of water in the downstream Volga reservoirs.

However, accumulated bottom sediments with a whole complex of harmful pollutants represent a real local hazard of secondary water pollution, especially when the level is reduced by 2.5 meters or more relative to the project horizon.

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