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Review

Structure of the Rybinsk Reservoir bottom and its transformation

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Abstract. The analysis of a database on comprehensive and specialized studies of the Rybinsk Reservoir for the period from its filling to 2022 is presented. Hydrological surveys of the reservoir in 10–15 years after its construction served the basis for a modern map of the soil complex of the ecosystem's bottom layer. The map was created with the use of morphometric characteristics and GIS-technologies. The data on this unique reservoir, distinguished by its complex external and internal processes, will help unveil the specifics of synecological cooperativity in functioning the ecosystem under interaction of abiotic/biotic factors in the conjugated environments.

Keywords: monitoring, water masses, bottom sediments, hydrodynamics, transformation of bottom layer, Rybinsk Reservoir ecosystem

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Научный обзор

Структура дна Рыбинского водохранилища и его трансформация

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Аннотация. В работе выполнен анализ базы данных комплексных и специальных исследований Рыбинского водохранилища с момента заполнения по 2022 год. На основе гидрологических съемок водохранилища через 10–15 лет после его создания с использованием морфометрических характеристик и ГИС-технологий, была создана современная карта площадей грунтового комплекса (нижнего яруса экосистемы). Информация об этом уникальном водохранилище, в котором проявляются сложные внешние и внутриводоемные процессы, поможет раскрыть особенности синэкологической кооперативности функционирования экосистемы при взаимодействии абиотических и биотических факторов в сопряженных средах.

Ключевые слова: мониторинг, водные массы, донные отложения, гидродинамика, трансформация нижнего яруса, экосистема Рыбинского водохранилища

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"What doesn't exist today will exist tomorrow;
science holds many directions within
and a power that is still unknown to science itself..."
V.V. Veresaev (p. 218)[1]

Introduction

The Rybinsk Reservoir is the most thoroughly studied reservoir in the Volga Cascade. A wide range of the reservoir research is represented by 5000 publications. Every year, new directions appear and reveal the science potential in utilizing the data on monitoring the aquatic environment and its inhabitants in combination with geo-digitalization of processes unveiling the diversity of freshwater ecosystem functioning.

Data on the reservoir's abiotic/biotic parameters were first summarized in the Collective of Articles edited by A.G. Poddubny (Ekologicheskoe raionirovanie..., 1990). However, this research area was not further developed despite its relevance.

Twenty years later, on the initiative of A.P. Levich (Bikbulatov et al., 2011, 2014), an attempt was made to return to this topic with the focus on ecological norms for finding the correlations between biotic/abiotic characteristics of the ecosystem in case of unfeasibility to use standard analytical tools. This work contains the data on biological and physicochemical parameters obtained during five expeditions to the Rybinsk Reservoir in summer of 2010–2011. The authors collected the data on the bioindicative potential of fluorescence parameters and made its comparison with other plankton characteristics and physicochemical indicators of water quality. Unfortunately, the bottom layer of the ecosystem is not represented in the paper that makes the comprehensive analysis of the state of the Rybinsk Reservoir incomplete.

Finally, a fundamental monograph (edited by V.I. Lazareva) describes in detail the transformations of the upper and low layers of the ecosystem, including hydrological regime, water chemistry, bottom sediments, genetic classification of soils, phytoplankton, primary production, microbial community, zooplankton, and ichthyofauna (Struktura i funktsionirovanie..., 2018).

Long-term data on the reservoir characterized by its complex hydrodynamic and biochemical processes will contribute to understanding the synecological cooperativity of two or more factors in the conjugated environments for self-maintenance of the aquatic ecosystem stability (Ostroumov, 2005).

The aim of this review is to recommend the quantitative basis of sedimentation characteristics for solving the problems of functioning the Rybinsk Reservoir ecosystem with due regard for the triadic approach: water-bottom sediments-biota.

Materials and methods

The Rybinsk Reservoir, filled to 101.81 m BS (1941–1947), became a testing ground for hydrological and biological-chemical (geoecological) monitoring research. This article summarizes the materials of several published studies (Butorin et al., 1975; Zakonnov, 2007; Zakonnov and Poddubny, 2002; Zakonnov et al., 2015, 2019).

Since the reservoir's construction, 6–10 surveys (including winter) have been conducted annually at standard stations: 1 – Koprino, 2 – Mologa, 3 – Sredny Dvor, 4 – Navolok, 5 – Izmailovo, 6 – Breitovo. Since 2010, a complete series of observations have been implemented in four reaches: I – Volzhsky, II – Molozhsky, III – Sheksninsky, IV – Glavny (up to 40 stations) with constant coordinates (Struktura.., 2018).

The methodological aspect is discussed in the above-mentioned works, in R.R. Khasanov et al. (2012), and in most detail in the monograph "Geographical methods for studying inland water ecosystems" edited by S.A. Poddubny (2024).

Data processing was performed using MS Excel 2010 and Statistica 10.

Stations were referenced to vessel conditions and coastal landmarks, covering the reservoir bed uniformly. Twenty stations (not less) were operated in the following depth intervals: 0–4, 4–6, 6–8, 8–10, 10–14, and >14 m.

[1] Veresaev, V.V., 2021. Uncknown notes of a doctor. AST, Moscow, Russia, 350 p.

Hydromorphometric characteristics of the reservoir (Bakulin, 1968), determined from the large-scale map compiled by Volgostroy, are the basis for estimating the areas of all types of bottom sediments (BS), sedimentation rates, and spatiotemporal dynamics of the bottom structure both for the reservoir itself, its reaches, and all 20 sections, depending on the bathymetry (Zakonnov, 2007).

The published maps of the soil complex are built with a high degree of generalization being, in fact, the schematic maps (Zakonnov, 2007). Advent of new technologies tested on the Volga-Kama cascade of reservoirs (the Kuibyshev Reservoir) made it possible at maximum to approximate to actual distribution of sediment types with an error of less than 5% from the topographic base (Khasanov et al., 2012).

Based on the digital bottom elevation model (DEM), independent estimations for the Uglich, Gorky, and Volgograd reservoirs (Zemlyanov et al., 2011) yielded similar results. A forecast for the reservoir's 100th anniversary (2041) was made using the trend of actual distribution of areas, volumes, masses of different-type soils and bottom sediments in the series of long-term investigations taking into account the linear coefficient of determination.

Results, discussion, implementation

In quantitative geoecology, the measured parameters are not as important as their dynamics related to natural and anthropogenic factors. In the river-reservoir system, the tail water or upstream areas with a variable backwater corresponding to river conditions (flow velocity > 1 m/s) are regulated by hydraulic structures. Lake-like with specific dynamic processes (near dam) middle and low reaches become "traps" for fine sediments. Each of 20 selected sections of the Rybinsk Reservoir is a part of this system having the same zones (shallow water or littoral up to 4 m, sublittoral from 4 to 10 m, and profundal > 10 m) and similar processes occurring throughout the reservoir (Zakonnov, 2007).

Main sediment-forming sources of the reservoir are given in Table 1.

According to I.A. Lifanov (1946), the reservoir filling resulted in inundation of 56.2% of forests and shrubs, including about 18% of swamps, 40.3% of agricultural lands, 3.5% of residential areas, numerous river valleys, and floodplain lakes of the Mologo-Sheksna Lowland. Reservoir bed flooding (lasted for 7 years) brought to soil swelling, erosion, emerge on the surface and transport of peat islands and suspended sediments driven by wind-wave and runoff currents. The areas of main soil types and bottom sediments were formed just at that time.

The conducted hydrological surveys revealed multidirectional changes (10–15 years after the reservoir's construction) in the structural areas of its bed under new aquatic conditions (Table 2). The analysis of the current situation suggests that:

- at $R^2 > 0.60$ (0.75–0.89), a trend towards the increasing area of sand (including with gravel), the formation of new bog soils and deposits of dead macrophytes, a reduction in the area of waterlogged soils, their transition to the category of meadow and bog soils, as well as decreasing water and peaty silt areas is recorded;
- at R^2 close to 0.50 (0.45–0.60), a stabilization of the area of exposed (eroded) soils and rocks, sand with peat particles, clayey and peaty silts occurs;
- at $R^2 < 0.40$ (0.21–0.40), uncertainty is noted in distribution of flooded bog areas, including relict coastal floating peat mats and those from variable-level zones, as well as surfaced ones depending on hydrometeorological factors. For instance, sediments cover peat deposits that hampers their appearance on the surface, and floating mats are exposed to wave-induced erosion.

Later, a gradual transition of bed transformation to stabilization takes place. Forecasts for 2010 and 2022 have been virtually confirmed. Because of natural and anthropogenic factors, some soils differ owing to a water content of the year, water level regimes, a flow regulation in the Cascade, and hydrological (environmental) risks (Zakonnov and Litvinov, 2015). Water balance and water level during the growing season between soil surveys serve as a direct evidence here (Table 3).

A water level, which is constantly under (1–2 m with maximum of 2.9 m) the normal affluent level (101.81 m) of the reservoir, creates the conditions for the area reduction up to 3600 km² and a water volume loss of 4.3 to 8.04 km³ (Bakulin, 1978). This triggers active dynamic processes in the shallow water zone leading to a coastal erosion, the formation of spits, shoals and coastal ridges, bed leveling, the appearance of the more complex bottom structure with a variety of bottom sediment types (from sand

Table 1. Transformation of balance characteristics of suspended sediments in the Rybinsk Reservoir, %.

Period (years)	Inflow			Discharge	
	abrasive activity	river sediments	production of aquatic organisms	sedimentation	discharge through a hydraulic structure
1947–1992	87	10	3	95	5
1993–2022	84	13	3	94	6
2023–2041	82	15	3	92	8

Table 2. Spatiotemporal transformation of the Rybinsk Reservoir soil complex area, %. * – projected data for the reservoir's 100th anniversary; R^2 – linear coefficient of determination.

Soil, ground, bottom sediments	Soil surveys, years							
	1955	1965	1978	1994	2010	2022	2041*	R^2
Reservoir's area, km^2	4550	4550	4550	4550	4480	4480	4460	
Waterlogged soils	0.2	0.7	0.9	1.3	2.1	1.6	2.0	0.86
Transformed soils								
Swampy soils	7.0	5.6	4.9	4.8	5.0	2.0	2.0	0.85
Exposed (eroded) soils	47.7	9.4	10.3	12.0	9.3	8.1	8.0	0.46
Flooded peat and peat floating	2.3	2.0	2.8	3.5	2.7	2.2	2.0	0.21
Sand sediments								
Sand with pebbles	0.3	0.4	0.5	1.8	2.0	2.0	2.0	0.81
Sand with peat particles	3.0	2.0	5.0	6.1	5.5	5.0	5.0	0.44
Sand	12.4	24.1	30.5	33.2	34.1	35.9	37.5	0.75
Silty sand	4.3	10.5	6.0	14.9	11.7	14.9	11.0	0.38
Silty sediments								
Sandy	5.7	29.5	7.5	4.3	7.0	3.7	4.5	0.23
Clayey (gray)	2.7	5.5	22.4	12.2	13.8	18.2	20.0	0.48
Peatogenic	1.8	2.2	2.0	1.5	1.4	1.4	1.5	0.58
Peaty	12.6	8.0	7.1	5.9	5.1	4.5	4.0	0.77
Macrophyte sediments								
	0.0	0.1	0.1	0.1	0.3	0.5	0.5	0.89

Table 3. Water balance (km³) and water level of the Rybinsk Reservoir (m BS) for the periods between surveys.

Parameter	Period, years						
	1947–1955	1956–1965	1966–1978	1979–1994	1995–2010	2011–2022	1947–2041
Inflow	34.88	33.88	28.21	35.94	31.52	35.40	33.15
Precipitation	1.78	2.29	2.18	2.52	2.35	2.58	2.31
Runoff	33.78	31.81	26.95	33.81	30.93	34.39	37.79
Evaporation	1.98	2.41	2.04	1.78	1.53	1.31	1.82
Average level for V–X	101.03	101.05	100.64	100.90	100.79	100.97	100.88

and gravel sediments to peat-macrophytic silts), including the emergence of swamps with hydromorphic soil formation. By 2041, such a reduction in the reservoir area will reach approximately 100 km² or 2% of the projected volume.

Materials of the Table 2 and the map of the bed structure of the upper layer (10 cm) of bottom sediments (Fig. 1) created using quantitative parameters of two methods (Bakulin, 1968; Khasanov et al. 2012) are bound to the bathymetry and results of the soil survey (2022).

Such a distribution of bottom sediments is caused by the interaction of hydrodynamic (wind-wave and runoff) processes when different-rhumb air masses are transporting over the water area (Fig. 2), as well as by a bottom topography of the shallow reservoir. The topography was formed under the influence of the Volga, Mologa, and Sheksna rivers in the Mologa-Sheksna Lowland, periodically flooded before the construction of the Rybinsk HPP dam. This is the first real example of interacted conjugated environments, namely, the atmosphere-water-bottom. Horizontal mixing is a result of the combined action of three main factors: wind stress on the water surface, inflow/outflow from the reservoir, and bottom topography. In the Main Reach of the reservoir, where wind-driven circulation prevails, all three factors are present (Poddubny and Sukhova, 2002). In river reaches, runoff currents play a significant role. Minimum flow velocities are observed in the eddy current zones, while the maximum in the sites of longshore water transport. Centers of eddy currents are located in deep-water areas of flooded channels and valleys of main rivers characterized by intensive silt accumulation with a vertical current component playing a significant role in suspended matter sedimentation and directly influencing the conditions for aquatic habitats formation.

Conclusion

From the scheme of the reservoir zoning based on sedimentation conditions and the modern bottom structure map, the areas of soils and bottom sediments can be determined with high accuracy in all 20 sites that provides a statistical reliability in assessing the ecosystem functioning across the reservoir as a whole, its stretches (areas) and successive sections of the river-reservoir system.

Previous forecasts for 2010 and 2022 have been largely confirmed. However, there are differences in some soils depending on the nature and direction of hydrometeorological processes in the catchment area and the operating mode of the hydraulic structure. The forecast for the reservoir's 100th anniversary, made due to the analyzed dynamics, is supported by current data (2022) and can be employed in various areas of scientific research.

The recommended methods are suitable for applying to the Rybinsk Reservoir and other reservoirs where digitalization of abiotic/biotic processes with the use of geoinformation technologies is feasible.

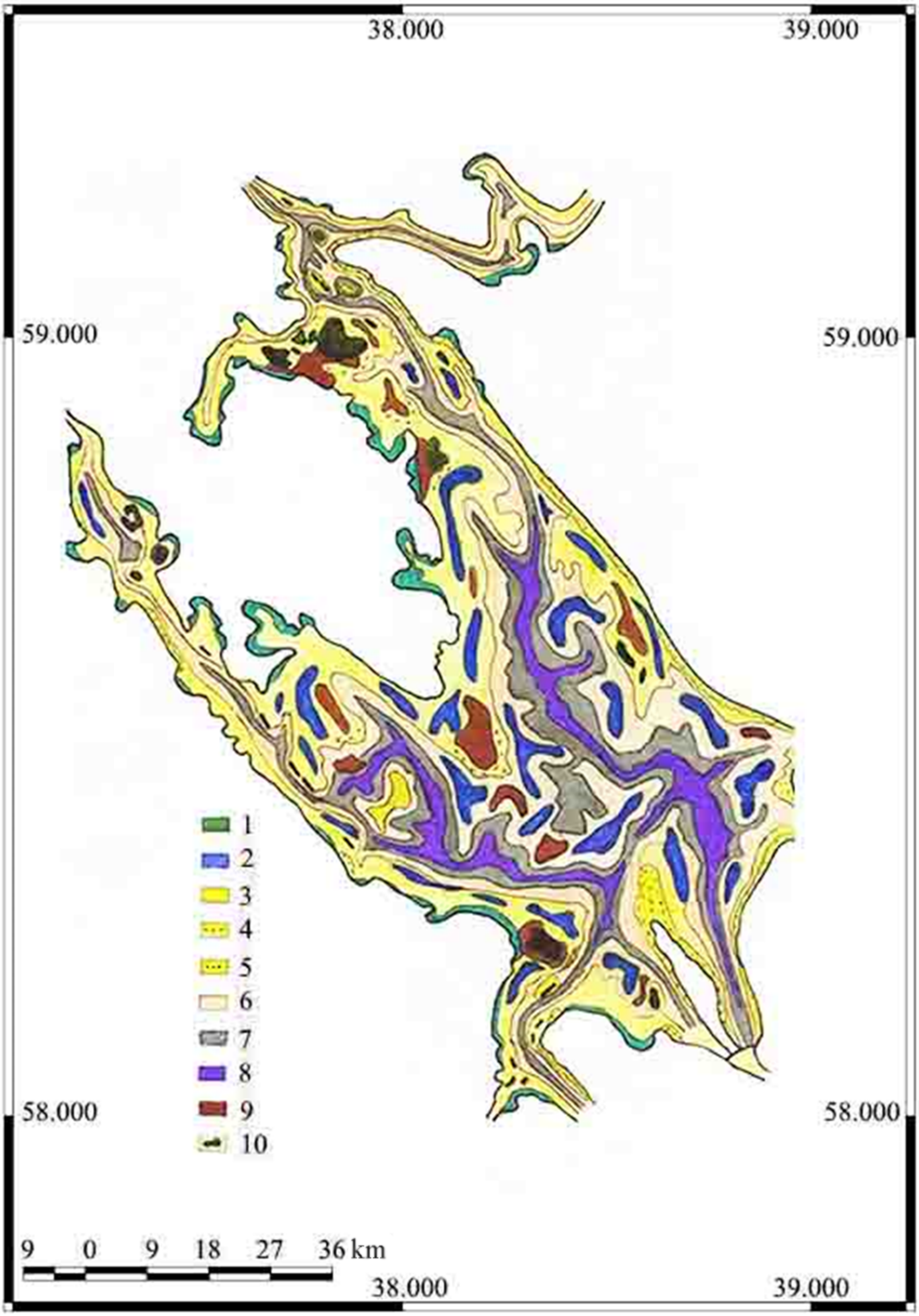

Fig. 1. Bottom Structure of the Rybinsk Reservoir by 2022 (Geograficheskie metody..., 2024). Transformed soils: 1 – swampy and waterlogged soils; 2 – eroded soils and rocks. Coarse-grained sediments: 3 – sand; 4 – sand with peat particles; 5 – sand with pebbles; 6 – silty sand. Fine sediments: 7 – sandy and clayey (gray) silt; 8 – peatogenic silt; 9 – flooded peat, peat-macrophytic floating mats and sediments; 10 – islands.

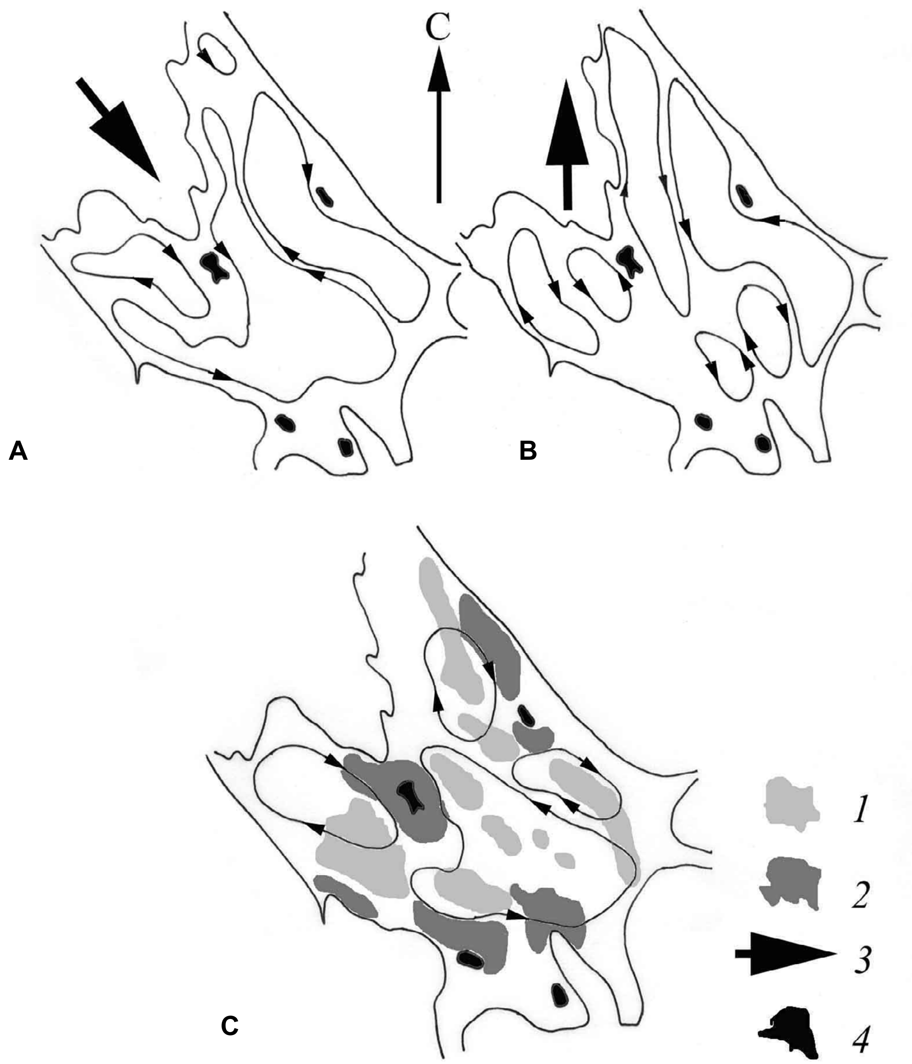

Fig. 2. Schematic diagram of integral water circulation in the Rybinsk Reservoir (Poddubny and Sukhova, 2002). **A** – with a northwesterly wind of 6 m/s; **B** – with a southerly wind of 6 m/s; **C** – with a summation action of wind taking into account two compass directions (315° and 180°); 1, 2 – zones of minimum and maximum integral transport velocities, respectively; 3 –wind direction; 4 – islands.

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