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Review

Dynamics of sedimentation processes in the Rybinsk Reservoir and their impact on bottom sediment productivity

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Abstract. This work is a continuation of the study of the bottom structure in the Rybinsk Reservoir and its transformation. Based on the results of monitoring the abiotic parameters of the reservoir, the transformation of its bottom sites, the dynamics of sedimentation processes (volume, mass, accumulation rates), the concentrations of organic matter and nutrients, as well as plant pigments present in a core thickness in the years of soil surveys have been determined. The materials are presented in the form of a matrix of 20 parameters that most fully reflect the interrelations in the water-bottom sediment system. The analyzed data are close to the long-term average and correspond to actual productivity of the ecosystem bottom. Both, positive and negative correlations are observed between individual components, indicating the need to continue the detailed research. We have established the uncertain relationship between hydrological characteristics, the content of organic matter and nutrients in bottom sediments at $R^2 < 40$, a trend towards increasing sedimentation areas at $R^2 > 50$, and a positive trend in sediment thickness, silt volume and mass, as well as the content of chlorophyll and pheopigments at $R^2 > 60$.

Keywords: monitoring, distribution, accumulation, sedimentation rates, nutrients, plant pigments

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Научный обзор

Динамика седиментационных процессов в Рыбинском водохранилище и их влияние на продуктивность донных осадков

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Аннотация. Работа служит продолжением исследования структуры дна Рыбинского водохранилища и его трансформации. По результатам мониторинга абиотических характеристик водоема определены: трансформация площадей структуры дна, динамика седиментационных процессов (объем, масса, темпы накопления), концентрации органического вещества и биогенных элементов, а также растительных пигментов по толщине кернов в годы грунтовых съемок. Материалы представлены в виде матрицы из 20 параметров, наиболее полно отражающих взаимосвязи в системе вода – донные отложения. Анализируемые данные близки к среднемноголетним и соответствуют реальной картине продуктивности дна экосистемы. Показано, что между отдельными компонентами наблюдаются как положительные, так и отрицательные корреляционные зависимости, что указывает на необходимость продолжения детальных исследований. При $R^2 < 40$ выявлена неопределенная связь гидрологических характеристик, содержания органического вещества и биогенных элементов в донных отложениях; при $R^2 > 50$ – тенденция увеличения площадей осадконакопления; при $R^2 > 60$ –положительный тренд толщины осадков, объема и массы илов, а также содержания хлорофилла и феопигментов.

Ключевые слова: мониторинг, распределение, накопление, темпы седиментации, биогенные элементы, растительные пигменты

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Introduction

The issues of systematization of factors and processes, involved in water self-purification, have been discussed by many authors (Ostroumov, 2005). However, the use of quantitative indicators in this area is limited that prevents assessing their role both within natural environments and at the interfaces.

When simulating processes and making forecasts, it is important to consider not only the areas of different-type bottom sediments, but also the indicators associated with their accumulation, i.e. a sedimentation rate and a substrate quality.

Materials and methods

This work continues the study of the Rybinsk Reservoir bottom structure and its transformation (Zakonnov et al., 2026). A database water-bottom sediment (BS) system of the Rybinsk Reservoir, allowing for the digital-based identification of quantitative relationships between characteristics, is proposed (Sigareva, 2012; Sigareva and Timofeeva, 2023; Zakonnov, 2007).

The research methods developed for the Rybinsk Reservoir can be applied to other water bodies, where advances in digitalization of abiotic parameters, modeling, forecasting, creation of thematic/soil maps of high-resolution, data on the composition and quality of natural waters, as well as bottom sediments and indigenous biotic components (bacteria, algae, zooplankton, macrophytes, and benthic-eating fish) are available (Geograficheskie metody..., 2024; Lazareva, 2010; Sigareva, 2012).

We consider sedimentation processes from three perspectives:

- 1) deposition within the reservoir at normal headwater level;
- 2) sedimentation in sites of coarse-grained (sands) and fine-grained sediments (silts) distribution, excluding the zones of bottom erosion and hydromorphic soil formation (swamps);
- 3) silt accumulation in sites of concentration of silt-clay, sand-clay, and peat sediments with high sorption capacity for deposition of organic matter, biogenic elements (C, N, P), and pollutants.

Results and discussion

Sedimentation is a stochastic process that tends to become ordered. On the one hand, bottom sediments, are dynamic systems that alter over time and in space, being, on the other hand, relatively conservative formations. Occurrence of BS primarily depends on water balance characteristics, water level regime, wind and wave effects, operating conditions of hydraulic structures, sources and composition of soil-forming material (coastal abrasion, bottom erosion, catchment area, solid runoff of rivers, granulometry, lithology of sedimentary rocks of the basin, production of hydrobionts, anthropogenic pollution).

The sedimentation database for the bottom ecosystem of the Rybinsk Reservoir is presented in Tables 1–4, summarizing the results of hydrological monitoring from 1955 to 2022. Using this database, a matrix of numerous abiotic parameters (> 50) that characterize the synecological cooperativity of external and internal processes within the water body has been created. For further analysis, we selected 20 hydromorphometric, hydrodynamic, sedimentation and chemical parameters, characterizing the relationships within the conjugate spheres and influencing the bottom sediment productivity (Table 5).

Table 1. Distribution and accumulation of bottom sediments in Reaches of the Rybinsk Reservoir by 2022. A is the area; T_{ave} – the average thickness of BS; L – the layer, W – the volume; M – the air-dry mass.

Type of bottom sedimentation	F, km ²	h _{ave} , mm	W, mln m ³	M, mln t	Average annual accumulation			
					h, mm	W, mln m ³³	M, mln t	M, kg/m ²
Volzhsky								
Marsh soils	15	–	–	–	–	–	–	–
Transformed soils	102	–	–	–	–	–	–	–
Coarse-grained	260	72	18.7	26.2	0.9	230.9	323.5	1.2
Fine-grained	173	440	76.1	22.8	5.4	939.5	281.5	1.6
Sedimentation	433	219	94.8	49.0	2.7	1170.4	605.0	1.4
Molozhsky								
Marsh soils	7	–	–	–	–	–	–	–
Transformed soils	8	–	–	–	–	–	–	–
Coarse-grained	150	96	14.4	20.2	1.2	177.8	249.4	1.7
Fine-grained	45	224	10.1	3.3	2.8	124.7	40.7	0.9
Sedimentation	195	126	24.5	23.5	1.6	302.5	290.1	1.5
Sheksninsky								
Marsh soils	22	–	–	–	–	–	–	–
Transformed soils	75	–	–	–	–	–	–	–
Coarse-grained	420	96	40.3	56.5	1.2	497.5	697.5	1.7
Fine-grained	180	416	74.9	22.5	5.1	924.7	277.8	1.5
Sedimentation	600	192	115.2	79.0	2.4	1422.2	975.3	1.6
Glavny								
Marsh soils	28	–	–	–	–	–	–	–
Transformed soils	387	–	–	–	–	–	–	–
Coarse-grained	1800	80	144.0	201.6	1.4	1777.8	2488.9	1.4
Fine-grained	870	520	452.4	135.6	1.9	5585.2	1674.1	1.9
Sedimentation	2670	223	596.4	337.2	1.6	7363.0	4163.0	1.6

Table 2. Long-term sedimentation dynamics in the Rybinsk Reservoir. * – forecast for the reservoir's 100th anniversary.

Parameter	Year							
	1955	1965	1978	1994	2010	2022	2041*	
Average sand thickness, mm	56	154	104	61	31	83	80	
Average silt thickness, mm	192	123	171	339	408	484	580	
Average sediment thickness, mm	129	135	140	148	153	213	300	
Sedimentation rate, mm/year	average long-term	9.2	5.6	3.8	2.9	2.2	2.6	3.0
	by periods	9.2	6.0	3.8	5.7	2.8	5.0	4.0

Table 3. By-depth intensity of sedimentation (entry inflow) in the Rybinsk Reservoir by 2022. Notations as in Table 1.

Depth, m	F		h _{ave} , mm	W, mln m ³	M, mln t	Average annual accumulation			
	km ²	%				h, mm	W, mln m ³	M, mln t	M, kg/m ²
0–4	1796.6	40	60	108	162	0.7	1.3	2.0	1.1
4–6	686.4	15	70	48	60	0.9	0.6	0.8	1.1
6–8	806.3	18	80	65	85	1.0	0.8	1.0	1.3
8–10	614.8	14	470	289	87	5.8	3.6	1.1	1.7
10–14	515.7	12	510	263	79	6.3	3.3	1.0	1.9
>14	60.2	1	960	58	16	11.9	0.7	0.2	3.3
Total	4480	100	185	831	489	2.3	10.3	6.1	1.3

Table 4. Long-term dynamics of silt accumulation in the Rybinsk Reservoir. Notations as in Table 1.

Year	F, km ²	h _{ave} , mm	W, mln m ³	M, mln t	Average annual accumulation			
					h, mm	W, mln m ³	M, mln t	M, kg/m ²
1955	1092	192	210	83	13.7	15.0	5.9	5.4
1965	2093	123	257	90	5.1	10.7	3.8	1.8
1978	1865	171	319	95	4.6	8.6	2.6	1.4
1994	1138	339	386	116	6.6	7.6	2.3	2.0
2010	1254	408	572	154	5.9	7.4	2.2	1.8
2022	1268	484	614	184	6.0	7.6	2.3	1.8
2041	1383	580	802	250	5.8	8.0	2.5	1.8

From values of the linear determination coefficient (R^2), the following trends towards changes (in time and space) of abiotic characteristics were identified:

- at $R^2 < 0.40$ (0.03–0.33), the uncertainty (chaos) was noted for 10 multidirectional parameters: natural rhythms of water content (W_1), including for the periods between soil surveys, runoff regulation (W_2) and, accordingly, water level regime (H), fluctuations in silt accumulation areas (A_{silt}), the average annual silt layer (L_{silt1}) and their mass per square meter (M_{silt2}), as well as the content of OM, C, N, P. The latter four enter the reservoir mainly because of hydrobionts production, partly with wastewater, and in minimal quantities owing to abrasion;

- at R^2 close to 0.50 (0.45–0.59), a tendency toward an increase in the sedimentation area (A_{sed}) was observed due to sites of coarse-grained sediments (sands) with minimal concentrations of OM, C, N, and P;

- at $R^2 > 0.60$ (0.65–0.98), the remaining 9 parameters demonstrated an increasing trend in sediment and silt thickness (L_{sed} and L_{silt}), silt volume and mass (W_{silt} and M_{silt}), accumulation rate by volume and mass (W_{silt1} and M_{silt1}), average diameter and number of pelitic particles (d_1 and d_2), as well as the content of chlorophyll and pheopigments (Chl + P) – the main easily assimilated OM of autochthonous origin.

Statistical methods of data processing make it possible to identify not only the previously established simple relationships and dependencies, but also more complex ones that directly or indirectly affect the bottom structure and the reservoir ecosystem as a whole. An analysis of the archive data (Table 6) has revealed that in addition to significant correlation coefficients, there are also others (0.30–0.80) determined by natural and man-made factors.

Inflow/outflow volumes, which influence the abiotic parameters responsible for the formation of the balanced natural-anthropogenic ecosystem, are the basis for the reservoir functioning. They primarily impact the human-controlled water level regime, silt thickness, average annual sedimentation rate, including concentrations of nutrients and Chl + Ph.

Sedimentation areas in the reservoir demonstrate negative correlations with many characteristics since sand and silt deposits accumulate unevenly over time and in space, influencing the concentrations of OM, C, N, and P. Therefore, the average thickness of BS directly correlates with volume and mass of silt, as well as concentrations of Chl + Ph (0.82–0.99), but it is negatively related to the accumulation rate of silt and average particle diameter. At the same time, a positive correlation is observed with the amount of pelitic particles—main sorbents of OM, nutrients, sedimentary pigments, and pollutants.

In the Rybinsk Reservoir, a grain size of sediments plays a significant role because it is determined by hydraulic coarseness of the structure-composing mineral-organic sediments (sand fractions) and the corresponding size fractions of macrophyte particles and peat debris (silt fraction).

A positive correlation is found between the nutrient content and inflow/runoff volumes, including annual silt accumulation, while a negative correlation is observed with the sedimentation area. Among nutrients, phosphorus, positively correlates with inflow/runoff volumes, water levels during the navigation season, silt mass, and annual accumulation rates. It negatively correlates with the sedimentation area (particularly silt) and the amount of pelitic fraction. Phosphorus enters the reservoir with river runoff, coastal abrasion and industrial/agricultural wastewater. Other nutrients are produced by phytoplankton and macrophytes in the reservoir.

Chlorophyll and pheopigments positively correlate with many abiotic parameters, but negatively with the silt sedimentation rate, sediment thickness, and mean particle diameter since their deposition depend on indigenous sediment producers and faster sedimentation rates of mineral (compared to organic) particles. Owing to intensive mixing of water masses, organic particles irreversibly degrade in the water column.

The algological studies (Table 7) are evidenced of 1.5-fold increase in the average content of Chl + P of dry sediment (DS) in 2019 compared to 2009 at five standard stations. At the same time, the average content of pigments in the cores of Reach Glavny (Sredny Dvor, Breytovo) has increased by 1.6 and in the upper (river) sections (Koprino, Mologa, Cherepovets) by 1.2 times (Sigareva, 2012; Sigareva et al., 2013).

Table 5. Abiotic characteristics of the Rybinsk Reservoir ecosystem (average values). W_i – inflow volume, km³; W_r – runoff volume, km³; H – reservoir level during the open water period, m BS; A_{sed} – sedimentation area, km²; L_{sed} – sediment layer, mm; A_{silt} – silt accumulation area, km²; L_{silt} – silt layer, mm; L_{silt1} – annual silt accumulation layer, mm/year; W_{silt} – silt volume, million m³; W_{silt1} – annual silt accumulation, million m³/year; M_{silt} – silt mass, million t; M_{silt1} – annual silt accumulation, million t/year; M_{silt2} – annual silt accumulation, kg/m²; d_1 – average particle diameter, mm; d_2 – amount of pelitic (< 0.01 mm) particles, %; OM – organic matter, %; C – total carbon, %; N – total nitrogen, %; P – total phosphorus, %; Chl + P – chlorophyll + pheopigments, µg/g.

Parameter	Year						R ²
	1955	1965	1978	1994	2010	2022	
W_i	34.88	33.88	28.21	35.94	31.52	35.4	0.09
W_r	33.78	31.81	26.95	33.81	30.93	34.39	0.03
H	101.03	101.05	100.64	100.9	100.79	100.97	0.13
A_{sed}	2002	3776	3685	3646	3897	3898	0.45
L_{sed}	129	135	140	148	153	213	0.70
A_{silt}	1092	2093	1865	1138	1254	1268	0.13
L_{silt}	192	121	171	339	408	484	0.88
L_{silt1}	13.7	5.1	4.6	6.6	5.9	6.0	0.24
W_{silt}	210	257	319	386	512	614	0.98
W_{silt1}	15.0	10.7	8.6	7.6	7.4	7.6	0.69
M_{silt}	83	90	95	116	154	184	0.92
M_{silt1}	5.9	3.8	2.6	2.3	2.2	2.3	0.67
M_{silt2}	5.4	1.8	1.4	2	1.8	1.8	0.33
d_1	0.2	0.12	0.1	0.09	0.09	0.08	0.65
d_2	45	52	53	54	55	57	0.77
OM	21.2	19.7	19	10.6	19.6	20	0.03
C	8.7	6.0	4.7	4.9	4.9	6.0	0.30
N	0.54	0.4	0.35	0.36	0.37	0.45	0.12
P	0.15	0.14	0.07	0.12	0.14	0.15	0.02
Chl + P	87.6	98.4	97.3	99.8	106.7	146.9	0.68

Table 6. KCorrelation matrix of abiotic parameters of the Rybinsk Reservoir. Significant correlation coefficients are shown in bold. Notations as in Table 5.

Parameter	W_i	W_r	H	A_{sed}	L_{sed}	A_{silt}	L_{silt}	L_{silt1}	W_{silt}	W_{silt1}
W_i	1.00	0.98	0.67	-0.24	0.29	-0.51	0.32	0.41	0.11	0.20
W_r	0.98	1.00	0.61	-0.28	0.38	-0.62	0.44	0.48	0.21	0.20
H	0.67	0.61	1.00	-0.21	-0.06	0.18	-0.26	0.25	-0.30	0.47
A_{sed}	-0.24	-0.28	-0.21	1.00	0.46	0.39	0.39	-0.96	0.63	-0.91
L_{sed}	0.29	0.38	-0.06	0.46	1.00	-0.28	0.82	-0.30	0.89	-0.54
A_{silt}	-0.51	-0.62	0.18	0.39	-0.28	1.00	-0.64	-0.58	-0.35	-0.04
L_{silt}	0.32	0.44	-0.26	0.39	0.82	-0.64	1.00	-0.16	0.94	-0.62
L_{silt1}	0.41	0.48	0.25	-0.96	-0.30	-0.58	-0.16	1.00	-0.44	0.83
W_{silt}	0.11	0.21	-0.30	0.63	0.89	-0.35	0.94	-0.44	1.00	-0.77
W_{silt1}	0.20	0.20	0.47	-0.91	-0.54	-0.04	-0.62	0.83	-0.77	1.00
M_{silt}	0.19	0.31	-0.19	0.55	0.91	-0.39	0.95	-0.34	0.99	-0.67
M_{silt1}	0.24	0.25	0.50	-0.91	-0.53	-0.06	-0.59	0.85	-0.75	1.00
M_{silt2}	0.37	0.43	0.30	-0.98	-0.36	-0.48	-0.26	0.99	-0.51	0.89
d_1	0.18	0.20	-0.37	-0.96	-0.57	-0.15	-0.57	0.89	-0.75	0.99
d_2	-0.09	-0.09	-0.29	0.94	0.70	0.09	0.67	-0.84	0.84	-0.96
OM	-0.30	-0.18	0.16	-0.26	0.06	0.25	-0.18	0.23	-0.06	0.45
C	0.45	0.50	0.53	-0.89	-0.18	-0.30	-0.27	0.90	-0.45	0.91
N	0.50	0.58	0.47	-0.81	0.04	-0.41	-0.06	0.87	-0.24	0.80
P	0.76	0.83	0.70	-0.25	0.29	-0.44	0.36	0.45	0.21	0.30
Chl + P	0.26	0.34	0.01	0.52	0.99	-0.17	0.78	-0.36	0.88	-0.55

M_{silt}	M_{silt1}	M_{silt2}	d_1	d_2	OM	C	N	P	Chl + P
0.19	0.24	0.37	0.18	-0.09	-0.30	0.45	0.50	0.76	0.26
0.31	0.25	0.43	0.20	-0.09	-0.18	0.50	0.58	0.83	0.34
-0.19	0.50	0.30	0.37	-0.29	0.16	0.53	0.47	0.70	0.00
0.55	-0.91	-0.98	-0.96	0.94	-0.26	-0.89	-0.81	-0.25	0.52
0.91	-0.53	-0.36	-0.57	0.70	0.06	-0.18	0.04	0.29	0.99
-0.39	-0.06	-0.48	-0.15	0.09	0.25	-0.30	-0.41	-0.44	-0.17
0.95	-0.59	-0.26	-0.57	0.67	-0.18	-0.27	-0.06	0.36	0.78
-0.34	0.85	0.99	0.89	-0.84	0.23	0.90	0.87	0.45	-0.36
0.99	-0.75	-0.51	-0.75	0.84	-0.06	-0.45	-0.24	0.21	0.88
-0.67	1.00	0.89	0.99	-0.96	0.45	0.91	0.80	0.30	-0.55
1.00	-0.65	-0.41	-0.66	0.77	0.02	-0.33	-0.11	0.34	0.90
-0.65	1.00	0.90	0.99	-0.95	0.44	0.93	0.81	0.34	-0.53
-0.41	0.90	1.00	0.94	-0.89	0.29	0.93	0.88	0.43	-0.41
-0.66	0.99	0.94	1.00	-0.98	0.40	0.90	0.79	0.28	-0.59
0.77	-0.95	-0.89	-0.98	1.00	-0.29	-0.81	-0.67	-0.13	0.73
0.02	0.44	0.29	0.40	-0.29	100	0.48	0.51	0.26	0.12
-0.33	0.93	0.93	0.90	-0.81	0.48	1.00	0.97	0.57	-0.21
-0.11	0.81	0.88	0.79	-0.67	0.51	0.97	1.00	0.63	0.02
0.34	0.34	0.43	0.28	-0.13	0.26	0.57	0.63	1.00	0.30
0.90	-0.53	-0.41	-0.59	0.73	0.12	-0.21	0.02	0.30	1.00

Index $E_{480/665}$ (an indicator of the physiological state of plant organisms) in soil cores is higher than the known values for phytoplankton and macrophytes. For instance, the index for planktonic algae ranges from 0.79 to 1.38 (Mineeva, 2004, 2021) and for macrophytes it is 0.68–0.99 (Sigareva and Timofeeva, 2023). The increase in $E_{480/665}$ value is explained by greater contribution of pheopigments, specific absorption of which is lower than in chlorophyll (Lorenzen, 1967), as well as by the elevated (compared to carotenoids) rate of chlorophyll degradation to colorless products.

Differences in intra-reservoir abiotic and biotic processes that influence the distribution and composition of the pigment complex, depending on the type of bottom sediments and the difficult-to-mineralize organic matter they contain, may be responsible for changes in correlations between the analyzed parameters. Oxygen consumption in sand sediments is lower than in silt because of the different number of bacterial populations on sediment particles and OM of the autochthonous (planktonic) and allochthonous (with a predominance of humus) origin (Brekovskikh et al., 2006; Romanenko and Zakonnov, 1990; Sorokin, 1959, 1967).

By chlorophyll content, the Rybinsk Reservoir during global warming is characterized as a mesotrophic water body. In terms of production of algae, bacteria, zooplankton, and benthic biomass it is the eutrophic reservoir (Struktura..., 2018). Change in its trophic status is confirmed by 1.0–1.5 °C rise in the average water temperature (a productivity factors) in summer of 2001–2019 (Zakonnova, 2021), as well as the data on the oxygen regime of the Volga and Kama reservoirs during this period (Lazareva et al., 2018).

Bottom sediments of the Rybinsk Reservoir are distinguished by elevated concentrations of organic matter and nutrients. Peat-rich silts are particularly prominent. They contain lignin-humic substances (difficult for aquatic organisms to digest), which make up 35–50% of silt mass and approximately 80% of total organic matter (Sorokin, 1959).

Conclusion

The Rybinsk Reservoir is distinguished by a highly diverse soil complex, where various types of sediments accumulate both beneficial (for aquatic life) components and harmful substances from precipitation, as well as from industrial, domestic, and agricultural runoff. The unique and complex processes occurring in water masses and the ecosystem bottom require the detailed study.

The average data, close to the average long-term ones, are quite informative and reflect the actual situation, allowing to reliably evaluate the ecosystem's bioproductivity as highly productive. Such investigations contribute to forecasting the transformations in freshwater bodies and estimating the production capacity of existing and projected reservoirs.

Table 7. Pigment characteristics of bottom sediments in cores of the Rybinsk Reservoir. $E_{480/665}$ is the ratio (carotenoids/chlorophyll) of extract's optical densities at 480 and 665 nm wavelengths (Sigareva and Timofeeva, 2023).

Station	Chl + P (2009)			Chl + P (2019)		
	µg/g d.s.	$E_{480/665}$	OM, %	µg/g d.s.	$E_{480/665}$	OM, %
Koprino	44.1 ± 2.9	3.3 ± 0.14	15.3	58.0 ± 3.1	3.3 ± 0.05	17.5
Mologa	90.0 ± 4.2	2.7 ± 0.04	21.2	109.1 ± 4.9	1.9 ± 0.04	13.0
Sredny Dvor	140.0 ± 5.4	2.0 ± 0.07	34.8	252.4 ± 4.0	2.0 ± 0.04	42.6
Breytovo	76.7 ± 3.0	2.4 ± 0.04	23.9	133.0 ± 6.8	2.2 ± 0.03	16.4
Cherepovets	48.7 ± 3.7	3.8 ± 0.06	9.8	55.7 ± 2.3	3.01 ± 0.04	10.8

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