Sedimentation in the Volga Cascade reservoirs in the 21st century

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Abstract. The complex surveys of sediments in the Volga River reservoir has begun in the 20th century and continued in the 21st century providing the basis for a modern quantitative assessment of the impact of bottom sediments on functioning of freshwater ecosystems. The results may be used in modelling of the multi-factor components in the water-bottom sediments-biota system, prediction, creating of object-oriented, special and thematic maps as well as for making decisions on elimination the negative consequences associated with water quality.

1. Introduction
In the 20th century, the construction of hydroelectric power plants proceeded at a faster pace than the studies of large plain reservoirs. Technical problems related to the resettlement of people, alienation of lands, energy production and transfer, navigation, water consumption, recreation, etc. were solved promptly, but hydroecological problems were not predictable still being relevant [1; 2]. The Volga reservoirs are the most studied ones in Russia, where the issues of sedimentation (formation, distribution and accumulation of bottom sediments) were given priority attention long before their design. The study of the bed of future reservoirs was of utmost importance, since it was the primary link in soil erosion and the place of formation of secondary soils - bottom sediments (BS) [3; 4].

Bottom sediments are multicomponent mineral-organic natural formations, reflecting all the diversity of intra-water basin, basin and planetary, hydrophysical and biogeochemical processes in their heterodispersity and chemogenic composition that affect the functioning of freshwater ecosystems through the interaction between water, sediments and biota.

The process of sedimentation – the deposition of suspended sediment (80–90%), biological substance and chemical deposition of salts, including pollutants in the sediment (10–20%) is not just a manifestation of the physical laws of hydrodynamics, but a complex formation of a new substance in nature, where, pollutants from various sources dissolved in water participate in the process along with suspended particles (seston) [5; 6].

The purpose of the article is to assess the specificity and direction of sedimentation processes at the beginning of the 21st century to use the information obtained in further hydrobiogeochemical studies.

2. Materials and methods
The paper summarizes the materials of monitoring studies of sedimentation in the Volga reservoirs from the middle of the 20th century, performed according to unified methods [3; 4]. Since 2001, the
second stage of water reservoirs’ existence began when the sedimentary processes became stable and predictable, which makes it possible to make situational forecasts to the 100th anniversary of the operation of technogenic reservoirs. As before, all complex hydrological surveys were carried out within a the standard grid of sampling stations. The error in determining the intensity of sedimentation is 10-20%, which is quite acceptable for this kind of calculations. The area covered by various types of BS was determined using bathymetric maps and project morphometric documentation, which characterizes the littoral, sublittoral and profundal zones of water bodies, taking into account their probabilistic distribution. Method error is about 5% and depends on the number of stations in the specified depth intervals.

3. Analysis of the results

The processes of sedimentation have their own peculiarities in each reservoir. However, the dynamics of the distribution of various types of soils and bottom alluvia in the Volga reservoirs with a 10-year ranking to the 100th anniversary of their operation, revealed general patterns of transformation of the bottom complex (drawing):

- Reduction of the areas occupied by soils, their transition to the category of transformed soils and newly formed hydromorphic soils - swamps and swamp-meadow;
- an increase in the areas of sandy alluvia;
- an increase in the ranges of clayey silts, and then their reduction.

The diagrams of the total magnitude of the latter (secondary sediments) demonstrate a gradual increase lasting for 30-40 years, and then a decrease and stabilization of areas.

![Figure 1](image)

**Figure 1.** Distribution of the area of the bottom complex in the Volga reservoirs. 1 – transformed soils, 2 – sandy alluvia, 3 – silty sediments, 4 – secondary sediments.

The morphological and hydrodynamic features of the reservoirs determine the specifics of the distribution and features of its bed formation [7] (table 1).

Changes in the morphometric characteristics of the reservoirs taking place in the result of their long-time functioning are caused by the alienation of areas of the reservoir due to formation of hydromorphic soil, accretion of quagmires with the bottom, the creation of new reservoirs (Cheboksary, Nizhnemanskoe), the cut-off and erosion of the coast (Volgograd), sand drifting of the bed. The provided table gives information on the zones of the erosion, which are mainly located in the lower reaches, river areas with high flow, as well as in shallow water reservoirs (Rybinsk) and lake-like stretches and extensions, which are dominated by the circulation of water caused by wind-wave processes for the first time. These areas are natural reactors saturating the water with oxygen and self-cleaning from harmful pollutants.
The results of the last bottom surveys at the junction of the centuries showed the stability of the structure of the bed and intensity of sedimentation by type:
- sedimentation - accumulation of all types of alluvia (coarse and finely dispersed) in the area of their distribution;
- sand drifts - on the area of the reservoir;
- Silt accumulation is the accumulation of aleuritic and perlitic fractions in their area (tables 2; 3).

**Table 1.** Structure of the bottom complex of Volga reservoirs in the beginning of 21st century.

| Bed structure          | Area | Average depth, cm | Volume, $10^6$m$^3$ | Mass, $10^6$t |
|------------------------|------|------------------|---------------------|--------------|
|                        | km$^2$|                  |                     |              |
| Ivankovo – 2012 [8]    |      |                  |                     |              |
| Hydromorphic bottoms   | 40   | –                | –                   | –            |
| Erosion zones          | 43   | –                | –                   | –            |
| Sandy alluvia          | 134  | 47               | 8.1                 | 109          |
| Silty alluvia          | 110  | 38               | 22.5                | 247          |
|                         |      |                  |                     |              |
| Uglich – 2012 [9]      |      |                  |                     |              |
| Hydromorphic bottoms   | 23   | –                | –                   | –            |
| Erosion zones          | 24   | –                | –                   | –            |
| Sandy alluvia          | 139  | 61               | 8.6                 | 120          |
| Silty alluvia          | 63   | 28               | 28.6                | 179          |
|                         |      |                  |                     |              |
| Rybinsk – 2010 [10]    |      |                  |                     |              |
| Hydromorphic bottoms   | 70   | –                | –                   | –            |
| Erosion zones          | 567  | 13               | –                   | –            |
| Sandy alluvia          | 2639 | 59               | 8.1                 | 2138         |
| Silty alluvia          | 1274 | 28               | 41.0                | 5223         |
|                         |      |                  |                     |              |
| Gorky – 2010 [11]      |      |                  |                     |              |
| Hydromorphic bottoms   | 82   | –                | –                   | –            |
| Erosion zones          | 202  | 13               | –                   | –            |
| Sandy alluvia          | 790  | 53               | 8.5                 | 670          |
| Silty alluvia          | 506  | 34               | 25.1                | 1270         |
|                         |      |                  |                     |              |
| Cheboksary – 2010 [12] |      |                  |                     |              |
| Erosion zones          | 208  | 17               | –                   | –            |
| Sandy alluvia          | 630  | 53               | 3.3                 | 208          |
| Silty alluvia          | 362  | 30               | 8.8                 | 319          |
|                         |      |                  |                     |              |
| Kuybyshiev – 2016 [13] |      |                  |                     |              |
| Hydromorphic bottoms   | 30   | –                | –                   | –            |
| Erosion zones          | 788  | 14               | –                   | –            |
| Sandy alluvia          | 2602 | 44               | 11.1                | 2888         |
| Silty alluvia          | 2480 | 42               | 43.2                | 10714        |
|                         |      |                  |                     |              |
| Saratov – 2017         |      |                  |                     |              |
| Erosion zones          | 465  | 25               | –                   | –            |
| Sandy alluvia          | 1056 | 57               | 11.3                | 1192         |
| Silty alluvia          | 312  | 18               | 45.0                | 1400         |
|                         |      |                  |                     |              |
| Volgograd – 2016       |      |                  |                     |              |
| Erosion zones          | 390  | 12               | –                   | –            |
| Sandy alluvia          | 1559 | 48               | 13.9                | 2167         |
| Silty alluvia          | 1299 | 40               | 46.5                | 6040         |
Table 2. Average annual intensity of sediment formation in Volga reservoirs in the end of 20th century.

| Reservoir  | Sediment accumulation mm | Sediment accumulation kg/m² | Sand drifts mm | Sand drifts kg/m² | Silt accumulation mm | Silt accumulation kg/m² |
|------------|--------------------------|----------------------------|----------------|------------------|----------------------|-------------------------|
| Ivankovo   | 2.1                      | 1.8                        | 1.9            | 1.6              | 3.3                  | 1.8                     |
| Uglich     | 2.5                      | 1.9                        | 1.9            | 1.4              | 5.6                  | 1.9                     |
| Rybinsk    | 2.9                      | 1.8                        | 2.3            | 1.4              | 6.7                  | 2.0                     |
| Gorky      | 2.8                      | 2.1                        | 2.2            | 1.7              | 4.5                  | 2.3                     |
| Cheboksary | 2.3                      | 2.7                        | 1.8            | 2.2              | 3.6                  | 2.6                     |
| Kuybyshev  | 4.4                      | 2.9                        | 3.8            | 2.5              | 7.0                  | 3.8                     |
| Saratov    | 3.7                      | 4.3                        | 2.7            | 3.1              | 9.1                  | 6.0                     |
| Volgograd  | 5.4                      | 4.7                        | 4.6            | 4.0              | 8.0                  | 5.3                     |
| R²         | 0.70                     | 0.85                       | 0.59           | 0.84             | 0.50                 | 0.81                    |

Table 3. Average annual intensity of sediment formation in Volga reservoirs in the beginning of the 21st century.

| Reservoir  | Sediment accumulation mm | Sediment accumulation kg/m² | Sand drifts mm | Sand drifts kg/m² | Silt accumulation mm | Silt accumulation kg/m² |
|------------|--------------------------|----------------------------|----------------|------------------|----------------------|-------------------------|
| Ivankovo   | 1.9                      | 1.7                        | 1.7            | 1.4              | 3.0                  | 1.5                     |
| Uglich     | 2.1                      | 1.6                        | 1.8            | 1.4              | 4.0                  | 1.3                     |
| Rybinsk    | 2.7                      | 2.3                        | 2.4            | 2.0              | 5.9                  | 3.0                     |
| Gorky      | 2.7                      | 2.0                        | 2.2            | 1.7              | 4.6                  | 2.4                     |
| Cheboksary | 1.8                      | 2.0                        | 1.5            | 1.6              | 3.0                  | 1.9                     |
| Kuybyshev  | 4.4                      | 2.8                        | 3.8            | 2.4              | 7.1                  | 3.9                     |
| Saratov    | 3.8                      | 4.3                        | 2.8            | 3.2              | 9.0                  | 6.4                     |
| Volgograd  | 4.9                      | 4.4                        | 4.3            | 3.9              | 8.0                  | 5.3                     |
| R²         | 0.69                     | 0.78                       | 0.59           | 0.77             | 0.62                 | 0.73                    |

The geographic zoning of BS accumulation in the system of reservoirs of the Volga cascade is clearly traced despite the fluctuating character of sediment formation indices [14].

4. Conclusion
The study of sedimentation processes and conditions of sediment formation in limnic systems is very important, because in the first case, the characteristic of alluvia retention is given, which is necessary for calculating the operation time of a reservoir, and in others, hydroecological aspects are clarified related to: the peculiarities of the accumulation of bottom sediments, the bioproductivity of the bottom, the deposition of chemical elements, assessment of the risk of secondary water pollution, eutrophication of water bodies, operation, reconstruction, rehabilitation. This makes it possible to use an integrated geoecological approach in the study of bottom sediments:
- hydrological and geomorphological;
- sedimentological;
- hydrochemical;
- hydrobiological.

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