Formation of bottom sediments in valley reservoirs and its research methods

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Abstract. The paper presents a review of studies by Russian and foreign scientists on the formation of bottom sediments in valley reservoirs. The typing of the main factors according to the time of occurrence and the source of income was carried out. Methods for studying the processes of bottom sediments formation are identified. This is an assessment of the material collapsed volume at coastal stations, the calculation of the solid flow in the main tributaries, sampling of bottom soil, repeated depth measurements. The organization of comprehensive studies of the input and expenditure components of the sedimentation balance and modelling of spatial and temporal changes in the bottom relief using GIS-technologies is important for predicting the siltation of reservoirs.

1. Introduction
Reservoirs are water bodies of slow water exchange. This contributes to accumulation of bottom sediments in it. The duration of the reservoir exploitation depends on the intensity of the sedimentation in the reservoir.

Bottom sediments – solid particles formed and deposited as a result of physicochemical and biochemical processes inside reservoirs occurring with substances of natural and man-made origin [1].

The papers N.A. Ziminov and V.P. Kurdin [2], Y.M. Matarzin [3], I.A. Pecherkin [4], S.L. Vendrov [5], V.V. Zakonov [6] etc. are devoted to study the formation and accumulation of bottom sediments processes, changes in composition of the soil complex in reservoirs.

The purpose of investigation is analysis of bottom sediments formation processes in reservoirs and methods for studying it.

All factors influencing the processes of sedimentation and redistribution of sediments can be classified according to two criteria:
- by time of development;
- by source of income.

The factors of formation of bottom sediments are divided into two periods by the time of development: the first – immediately after the creation of the reservoir, when all processes proceed most intensively, and the second – when the intensity of the processes decreases and the underwater relief stabilizes [3].

The reservoirs are characterized by the discrepancy between the shape of the reservoir and the new hydro-meteorological conditions. As a result of filling the reservoir the properties of the rocks composing the reservoir significantly change in the initial period of its existence. This leads to rapid changes in the underwater relief and sedimentation [5].
The composition of the soil complex changes all the time. The replacement of soils with silty sand or sandy silt is observed. Also there was replacement the peaty and transitional silts to gray silt [7].

The advancement of sandy sediments to great depths occurs together with the evolution of the composition of silty sediments. Evolution is caused by a change in the ratio of allochthonous and autochthonous substances in reservoirs. The inflow of allochthonous suspensions has small variations, since the existing annual changes in solid runoff, determined by fluctuations in river runoff, are small. Inflow of autochthonous soil-forming material often changes. The depletion of soil-forming material with organic matter occurs during self-cleaning of reservoirs from flooded land vegetation, as well as erosion the peat. At the same time, the formation of shallow waters and a decrease the intensity of coastal processing leads to a decrease in the content of mineral suspensions. These changes cause a significant reorganization of bottom soils [2].

The main sources of sediment inflow are: solid runoff of tributaries; shore abrasion products; organic residues. Soils and various bedrock and friable rocks (outcrops of clay, loam, limestone, dolomite, etc.) are submerged when the reservoir is filled. Also alluvial channel sediments, silt sediments of lakes and oxbows take part in structure of bottom soils. These soil-forming materials (primary soils) are the basis of formation and evolution (transformed soils) of bottom sediments (secondary soils) [8].

The formation of a soil complex is closely dependent on turbidity. The small dust particles formed as a result of a coast processing and brought by the main tributaries determine the character of the water suspensions. Its quantity, composition and annual and seasonal dynamics are determined by the lithology of rocks of the catchment and the coast, the morphological features of the reservoir, the direction, speed and duration of the prevailing winds, waves, the development of permanent and temporary currents [9].

Besides to materials of terrigenous origin, coming from shores and catchment area, various organic residues play a significant role in bottom sediments formation [10]. Additional sources of suspended matter in the reservoirs are the process of phytoplankton production and the development of higher aquatic vegetation [3]. Specificity of the sedimentation process is sharp differentiation of its rates by areas and depths of water bodies in accordance with the type and degree of the water mass hydrodynamic activity [3].

2. Materials and methods

The main methods for investigating the dynamics of bottom sediments are described in papers by N.A. Ziminova and V.P. Kurdin [2], I.A. Pecherkin [4], L.A. Kuznetsova [11], R.B. Tarverdiev [12], N.N. Nazarov [13], V.G. Kalinin and D.N. Gainullina [14], M.V. Shmakova [15] et al.

Analysis of publications by Russian and foreign scientists devoted to study of bottom sediments formation processes in reservoirs, allowed us to identify the following methods for studying it:

- estimation of collapsed material volume at coastal stations;
- calculation of sediment inflow with solid runoff along tributaries;
- sampling of bottom soil;
- development of statistical models based on regression analysis;
- repeated depths measurements.

Annual surveys of sites and detailed topographic surveys, supplemented by bottom soil sampling, are necessary for calculating the amount of material collapsed at coastal stations. The results allow to fix the dynamics of coastline retreat and calculate the collapsed material volume. Perennial research on the Kama and Votkinsk reservoirs are devoted to these issues [4; 16; 13].

I.A. Pecherkin developed a genetic classification of the Kama reservoir shores, and also identified the main factors determining the rate of shores destruction: strength of the component rocks, height of shores, total wave energy and level regime [4].

N.A. Ziminova and V.P. Kurdin [2] used the method of calculating the collapsed material volume from observations at coastal stations to assess the dynamics of bottom relief formation and coast in the
Rybinsk reservoir. They also used annual leveling, supplemented bottom soil sampling with subsequent determination of its particle size.

The next method for calculating the volume of shore-breaking materials is the analysis of aerial photographs in different years and regime observations of ravines dynamics on the banks of rivers and reservoirs [17].

The method of monitoring studies of exogenous geological processes on the Ust-Garevaya model landslide station in the central part of the Kama reservoir was proposed in [16]. The essence of the method was to conduct an annual large-scale topographic survey from the same reference points with the subsequent determination of the landslide displacement using GIS-technologies.

The calculation of the solid runoff of main tributaries is usually carried out based on hydrometric observations on the gauge stations [11]. R.B. Tarverdiev developed a method of accounting for sediment from gauge stations to river’s estuaries for the Mingechaur reservoir [12].

M.V. Shmakova created the method of sediment transport modeling in reservoirs for different phases of water regime. The model is based on the joint solution of the “shallow water” equations and the analytical formula for sediment discharge [15].

Statistical models based on multiple regression analysis are also used to study the bottom sediments formation processes in reservoirs depending on the main factors [18].

The method of sampling bottom soil consists of performing ground surveys using bottom samplers and ground pipes. This method allows to measure the height of the secondary sediments layer with a detailed description of the soil column and determine the physical and mechanical composition and volume weight of bottom sediments [10; 11].

The method of repeated depths measurements after a certain period of time allows to estimate the sedimentation dynamics in different parts of reservoirs. For the first time this method was applied by I.A. Pecherkin (1969) for the Kama reservoir [4].

V.G. Kalinin, D.N. Gainullina proposed a method of comparative evaluation of materials for repeated depths measurements in different years using GIS-technology. An important condition for the construction of correct DEM of the bottom is to ensure the comparability of the source data – an exact match of the quantity and spatial location of the measuring points [14].

3. Results

N.N. Nazarov [17] established the maximum growth of the ravines (up to 25 m) on the Kama reservoir based on the analysis of materials from different periods of aerial photography. Also he calculated erosion rates on several parts of the Votkinsk reservoir (from 1.0 to 3.0 km long). Average speed for shores, composed of red clay – 0.42–1.29 m per year, maximum – 1.41–3.97 m per year; for loams and sands – 1.5–2.5 m per year and 3.2–4.1 m per year, respectively [13].

I.A. Pecherkin calculated the rate of processing for different types of shores on the Kama reservoir. Maximum processing volumes were found for the shores composed of sand and loam, which amounted to 450-325 m³ per linear meter [4].

L.A. Kuznetsova [11] determined the 46 million tons of sediment entered into the Kama reservoir with a rivers solid runoff in 1956–1978.

M.V. Shimakova proposed a two-dimensional model of sediment transport in the Sestroretsky Spill reservoir for different phases of water regime and a sedimentation scheme was constructed for the period of flood recession. The analysis showed the highest values of sediment discharge and the maximum values of alluvium (6.0–9.0 mm per decade) indicated for the confluence of the main tributaries (the Sister and the Black rivers) and the drainage channel. Calculated sediment discharge values during the low-flow period did not exceed several grams per second [15].

N.V. Butorin et al. [7] compiled the sedimentation balance of the Kama reservoirs based on the observations of the coastal processing and the chemical composition of the water mass. The analysis of the main components of the balance showed that the greatest differences are registered in its coming part. So, if the flow of precipitation with solid runoff and from coastal destruction in the Kama reservoir is approximately equal parts (45.6% and 46.2%, respectively), but 84.2% of the incoming
balance sheet in the Votkinsk reservoir are the products of coastal destruction and only 4.5% come from a solid drain. Most of the suspended matter is deposited in the bottom of the Kama reservoir, which plays the storage place’s role in relation to the Votkinsk reservoir.

Analysis of geodynamic processes using the sampling method allowed I.A. Pecherkin [4] to make a scheme of genetic types of deposits. Studies performed by Y. M. Matarzin, I. K. Matskevich, N. B. Sorokina [9] showed that since the beginning of the existence of the Kama reservoirs and until 1968, the average value of the layer of silt deposits for the Kama reservoir was 8-12 cm, for the Votkinsky reservoir – 5-8 cm.

V.G. Kalinin, D.N. Gainullina (2013) [14] carried out studies of the spatial and temporal dynamics of the bottom relief of the coastal shallow near the Chermoz town for the entire period of the Kama reservoir until 2010 based on the method of repeated depth measurements. Analysis of the results showed that the accumulation of bottom sediments ranged from 2 to 4 m.

Using the topography materials carried out before the creation of the Kama reservoir and the depth measurements 10 years later near the Visim village allowed I.A. Pecherkin [4] identify the following regularities: sediment deposition is observed in the lowerest parts of the bottom relief, while at the same time the positive bottom relief are destructed. This process often can be traced to a depth of 4-5 m from the normal reservoir level in areas with the wind activities. The islands are especially rapidly destroyed in the open parts of water bodies. The erosion rate of the islands depends on the lithology of rocks: 4.5 m / month for sands, 2.4–3.5 m / month for loams and 1.5–2.2 m / month for islands, composed of indigenous sandy-argillaceous deposits [4].

The method of repeated depth measurements was applied by us on the Kama reservoir. The initial data were topographic maps before the creation of the reservoir (1931), which were used to characterize the bottom relief at the time of its filling (1956) and depth measurements (1995, 2009, 2012) in the central part of the Kama reservoir.

The most characteristic changes for the period 1956–2009 were the accumulation of bottom sediments (6.0–8.0 m) along the old bed of the Kama River, which is associated with the transport of shore-breaking materials under the influence of waves, currents and fluctuations in water level. In 2009–2012 there was a slight erosion (1.0-2.0 m) in the zone of the old bed of the Kama River and the left-bank floodplain. A decrease in the volume of the study area was found by 18.2% for the entire study period.

Using the method of multiple regression analysis in the study of the processes of bottom sediments formation in Thailand’s reservoirs [18] showed the volume of sedimentation in different reservoirs varies from 0,0072 to 4,7718 million m³/year.

In paper [19] the assessment of transport capacity of the Aragon river and the influence of land-use on the processes of sedimentation is given, based on the differentiation of sediment size and composition (organic matter, carbonates) in the Yesa reservoir (Spain).

Japanese scientists obtained the dependences of the reservoirs existence duration on the average slope of the catchment, which determines the amount of incoming sediment. Pinping Luo, Bin He and Kaoru Takara [20] collected a database of the sedimentation rate of more than 400 Japanese reservoirs for the period 1994–2003. Calculations of the sediments spatial distribution are performed by GIS-technologies. An assessment of the sustainability and duration of the existence of reservoirs, which ranged from 335 to 5000 years, is given based on statistical analysis.

The average rate of reduction in volume of large reservoirs in the USA is different for reservoirs in the western and eastern parts of the country. The sedimentation rates of reservoirs vary from 0.2-0.5% per year for Pacific state reservoirs and up to 0.1% in northeast United States reservoirs. For comparison, the large reservoirs of China lose useful volume near 2.3% per year [21].

4. Discussion
The results of Russian and foreign experts show the study of the sediment formation in reservoirs is an important and actual question. A large number of different methods indicate the need to study a variety of factors which are determined the processes occurring in the reservoirs.
Accounting for additional sediment inflows from the gauge stations to river’s estuaries is very important to calculating solid runoff. Research by R.B. Tarverdiyev on the Mingechaur reservoir showed the increase in total sediment volume by 9.2% is due to additional inflows [12]. The highest values of solid runoff are observed in the confluence of the tributaries into the reservoir. The study of sediment transport in different phases of water regime is carried out using a two-dimensional model implemented by M.V. Shmakova for the Sestroretsky Spill reservoir [15].

An important result of foreign scientists is the creation of predictive models for reducing the volume of reservoirs based on using the multiple regression analysis and formation the dependencies between the reservoirs existence duration and the morphometric characteristics of its catchments.

At the same time, a comprehensive account of the main factors of the formation of bottom sediments and the compilation of sedimentation balance are necessary to highlight the prevailing processes occurring in a particular reservoir. The study of the spatial and temporal dynamics of the bottom relief in reservoir should be carried out by GIS-technologies using the methods of mathematical cartographic modeling.

5. Conclusion
1. Factors affecting the processes of sedimentation and redistribution of sediments are classified according to time of development and source of income.

2. The following methods are used to study the processes of formation of bottom sediments in reservoirs: an assessment the volume of the collapsed material on coastal stations; calculation of sediment runoff of main tributaries; sampling of bottom soil; development of statistical models based on regression analysis to predict siltation; repeated depth measurements.

3. The execution of comprehensive studies of income and spending components of the sedimentation balance and modeling of spatial-temporal bottom relief changes by GIS-technologies is necessary for a complete understanding of the bottom formation of a particular reservoir.

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