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MODELING OF RESHAPING THE BOTTOM OF LARGE RESERVOIRS

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Abstract. The Kuibyshev reservoir was formed on the Volga river and is the largest in Eurasia. The length of the reservoir along the Volga is 510 km with its maximum depth of 41 m and average depth of 8 m; the area of water mirror is 6,450 km2. Conditions of runoff formation in catchment area, as well as seasonal and daily regulation are the reasons for unsteady regime of the reservoir. Specificity of flow control in the Kuibyshev reservoir pre-determines water masses motion, flow speed pattern, as well as degree of water saturation with suspended sediments and, therefore, reservoir bed siltation intensity. The lowest flow velocity in the reservoir is observed in summer-autumn period of year; at this time, the reservoir bottom is reshaped least actively. During spring filling, flow velocity in the reservoir is at maximum, hence, favorable conditions to transfer small and large fractions of suspended sediments are created. Most of them enter the reservoir during its spring time filling, although sometimes, sediments maximum was observed earlier, before reaching the peak of flood wave in the reservoir. Flow pattern unsteadiness leads to increase or decrease in flow transfer capacity and, hence, changes in bottom levels. Complex configuration of banks, large depth gradients and basin morphology's particulars pre-determine instability of sedimentation processes in water area. 3D hydrodynamic model of the reservoir (A. Rakhuba) forms the basis for calculating bottom level motions of the Kuibyshev reservoir. This model is supplemented with analytical formula for sediment consumption (M. Shmakova) and hydraulic ratios to calculate erosion and sediments accumulation (M. Shmakova). Four ice-free months runoff simulation of the Kuibyshev reservoir includes the following main water content phases: low water period and periods of snow flood and rain floods. The study of spatial and temporal patterns of bottom reshaping has shown that greatest intensity of such reshaping occurs during the period of large level gradients, i.e. high water. Flood swelling is featured by intensive bottom erosion. When flood recesses, transfer capacity decreases that leads to sedimentation. The greatest motions in bottom reshaping occurs in the places of channel contraction, which is explained by sharp changes in channel capacity.

Keywords: modeling, reservoir, bottom, sediment, erosion, accumulation.

1 INTRODUCTUON

Silting of reservoirs means changes in bottom level accompanied by decrease in water volume. The main reasons of silting are: silts coming with stream runoff and from the catchment area, wind-driven drift sands passage from onshore, chemicals setting-out, aquatic biomass formation and shores abrasion. The impact of each factor onto reservoirs silting process is pre-defined by reservoir type and its hydraulic profile, drainage basin and climatic conditions.

Currently existing methods of reservoir silting calculations, generally, enables acquiring common evaluation of its conditionally uniform filling with river sediments. These methods do not consider complicated reservoir morphometry, distribution of solids entered with stream runoff across the whole water area and its dynamics pre-defined by water content fluctuations within a year, low-flow water regulation, wind and icing impacts, shores subsidence, organic settlement formation, etc.

Therefore, the dynamics of the underwater topography of the reservoirs shall be based on hydrodynamical equations of suspensions-contained water masses and consider basic factors, which pre-define this process. Mathematical simulation of reservoirs silting enables not only evaluation of bottom levels behavior in current hydrodynamical conditions, but also forecasting changes on conditions of liquid and solids flow from the catchment as well, as initiated by different anthropogenic activities. It is important to stress that mathematical simulation assumes continuous interaction between changes in morphometric profile of reservoir and change the conditions of water masses.

For deformable alluvial channels with expressed channel levels and shores configuration movements, it's reasonable to include channel level into the system of equations describing stream flow movement, as one of arguments. Such statement of problem differs from typical hydrodynamic tasks, when boundary conditions are considered as constant values (Lubimova et al., 2020). All this enables considering stream flow counter reaction to changes in channel morphometry and performing interrelated and interdependent hydraulic and geomorphological calculations. Such model is classified as mobil bed model (Berger et al., 2015; Delft3D-FLOW, 2011; Reference Manual, 2016).

This study is focused on interconnected calculation of unstable and uneven stream motions, as well as bottom transformations in different water content states for flowing Kuybishev reservoir, the biggest in Europe.

2 OBJECT OF STUDY

Kuybishev reservoir is founded in 1955 when regulating the river near the Zhigulevsk city. The reservoir was filled within three phases. In 1957, water level has reached design level of 53.0 m of Baltic Sea level datum. Upon constructing of Cheboksary and Nizhnekamsk HPP, water surface area has amounted to 5900 km^2. and its total capacity at normal water level (NWL) has reached 58.0 km^3. Total length along submerged channel way in Volga River is 510 km and the biggest width is 27 km. Kuybishev reservoir is generally fed from above-located Cheboksary and Nizhnekamsk reservoirs. Kuybishev reservoir has the shape extended from north to south and enough complicated morphology, wherein the places of channel's narrows alternate with deep extensions and have non-uniform morphometry; wide shallow-watered sections stand in contrast with deep-watered channel section and the deepest part of the reservoir, appurtenance pool of Zhigulevsk HPP (Fig. 1). Relief of submerged terrain, intense channel part, big drawdown level amplitude and headwater conditions pre-define shore configuration parameters, basin shape, channel shape varieties and water exchange intensity and trends in different parts of the reservoir.

The most typical channel formations are numerous deeps and intense longitudinal channel profile. Depending on origin, the deeps (headwater estuarial afflux area, low water area and direct headwater area before the Zhigulevsk dam) differ in morphometry, as well as water exchange intensity and trends. Meantime, longitudinal channel profile is relatively uniform in the middle and lower parts of the reservoir with differences in Kama and Volzhsk regions of variable headwater and in places of their junction.

From hydrodynamic viewpoint, the most active are Kama and Volzhsk regions of variable headwater and places of channel narrows of the reservoir. For shallow-watered Cheremshansk and Usinsk bays (average depth is 5 m), the impact of high water, as well as seasonal and daily transitional waves on HPP create oscillatory differently-directed water flows, which pre-define intensity of bottom transformation processes. In deep-watered locations of the reservoir (max. depth amount to 40 m), same as in bays, the impact of unstable conditions is insignificant and expressed intensively in the places of channel narrows of the reservoir.

For Volga and Kama flows of Kuybishev reservoir, located in the area of evident headwater from Zhigulevsk dam, bottom transformation processes are pre-defined by hydrodynamical regime from the above-located Cheboksary and Nizhnekamsk reservoirs. These reservoirs, among other things, act as desilting basins for river sediments. This way, the flow of sediment, is carried by Volga and Kama on the sections under consideration, are predominantly formed as a result of channel deformations and erosion activity, in the catchments of these flows. Thereat, stable bed erosion is observed, generally, in the section of Volzhsk branch of the reservoir (below the city of Kazan up to junction with Kama), while for Kama branch (below Vyatlka outlet up to Vyatka and Kama junction), accumulation and scour are typical for different water content phases (Kyubishev, 1983).

Thereat, according to (Shirokov, 1965), for Kuybishev reservoir in the first years of its life, considering shores erosion and islands score, average silting level amounted to approx. 8 mm. Current investigations in sedimentation processes and intensity have shown that average organic and mineral sedimentation for Kuybishev reservoir is 4.4 mm/year (Zakonnov, 2007).

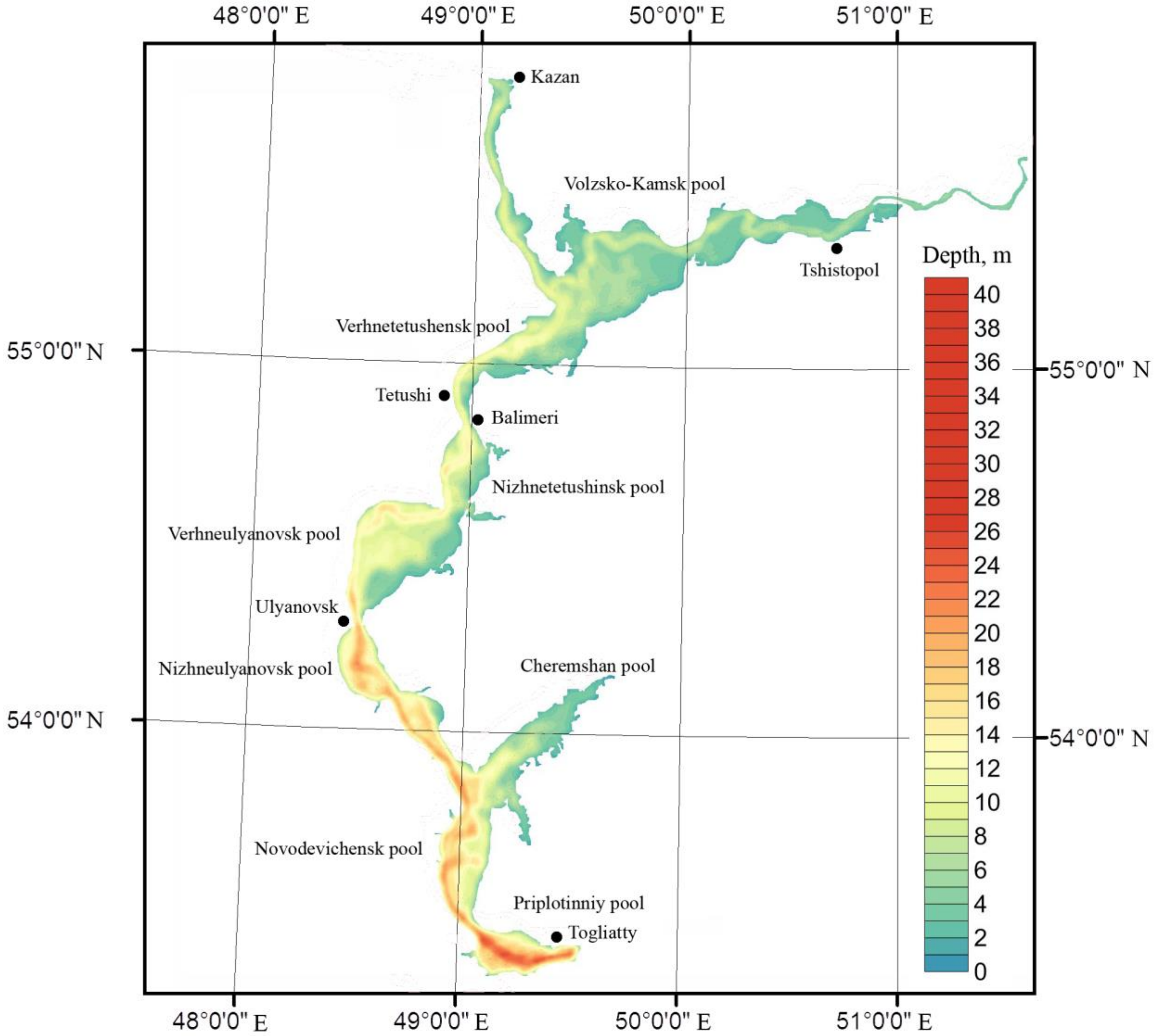

Figure 1. Map of the depth of the Kuibyshev reservoir (m)

3 METHODS

Volna 3-D hydrodynamic model, as developed by RAN Volzhsk Basin Ecology Institute (Rakhuba, 2007), represents shallow-water set of equations. The model is supplemented with solid flow calculation algorithms (analytical formula of sediment transport (Shmakova, 2018)), changes in flow transport capacity and, as a consequence of the latter, changes in bottom level (Shmakova, 2018). In this case, bottom level is considered in consequent calculations and serves as one of the model's arguments. Thermal and mechanical shores abrasion and wind fluctuations are not considered in the calculations and bottom transformation is calculated as scour function for the design section and river sediments coming from upstream cross-sections (accumulation). The model does not consider organic sedimentation, too.

In unstable calculation conditions in 2015 and the period of 150 days, for the whole area of Kuybishev reservoir, bottom transformation intensity was calculated for different water content phases and for the design period in a whole. Totally there are four water content phases of the design period: high water build-up period (30 days), high water period (40 days), high water fall period (30 days), and low water period (50 days).

4 RESULTS

Runoff control particulars in Kuybishev reservoir pre-define water masses behavior, currents velocity conditions, as well as level of water saturation with suspended sediments and, consequently, silting intensity of reservoir bed. Fig. 2 provides calculation results for Kuybishev reservoir bottom transformation in 30-days high water rise (a) and decline (b) periods, as well as total accumulation/scour for the whole 150-days calculation period (c).

Obtained results analysis testifies that erosion of the bottom is generally occurs during the rise of the water level and sedimentation occurs during the period of water level decline (Fig. 2). The highest scour values are reached in Volzhsk and Kama flows up to inflow into Volzhsk and Kama's part of reservoir and in the places of channel's narrows and reach 20 mm/month and above. In the main part of water reservoir, total erosion is 1 – 2 mm/month in average (based on simulation results).

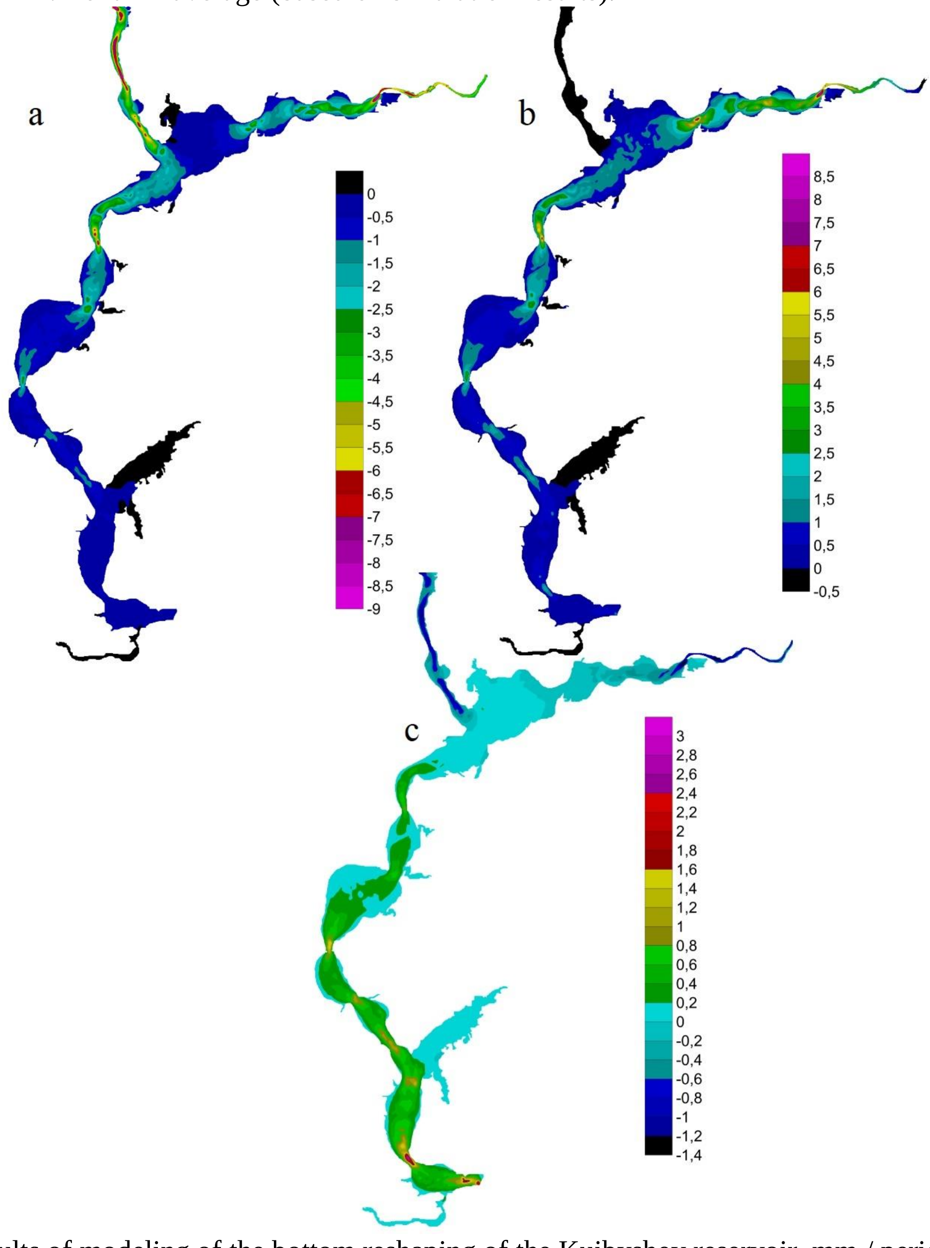

Figure 2. Results of modeling of the bottom reshaping of the Kuibyshev reservoir, mm / period: a – during the 30-day period of high water rise; b – during the 30-day period of high water fall; c – total accumulation (>0)/washout (<0) for the entire 150-day period of calculation

On high water decline, the most intensive accumulation processes are observed in Kama branch, particularly, in headwater area, as well in the places of channel's narrows, where max. values exceeded 20 mm/month. The area of Volga flow is distinguished by prolonged insignificant scour, max. values do not exceed 0.5 mm/month. In the main part of water reservoir area, on high water decline, flow transport capacity is lost that leads to sedimentation with intensity of 0.5 to 4.0 mm/month.

Vast Cheremshansk and Usinsk bays are distinguished by weak hydrodynamic activity with occurring phenomena of periodic currents sweep and water mass circulation due to unstable runoff conditions of Zhigulevsk HPP. Such circulation pre-defines short-term conditions for bottom erosion and silting for shallow-watered bays with total values not exceeding 0.5-1.0 mm/month.

For the period, including spring flood and summer runoff low, uneven sediments re-distribution is observed in water reservoir: erosion takes place in the upper part of the reservoir and sediments are accumulated in the middle and lower parts. Such trend in channel processes, pre-defined by decrease in water flow transport capacity from upper sections to lower ones, is typical for plain rivers (Alekseevskiy et al., 2012). Calculations show that max. bottom erosion in Kama flow within 150-days period is more than 1.5 mm; the scour in Volga flow reaches 1 mm for the period. There is the sedimentation to 0.5-2.5 mm for the period in main part of the reservoir. The areas with biggest sedimentation are Klimov narrow and the section before Zhigulevsk HPP. Sedimentation reaches 2 mm and above for the period here.

The longitudinal profile of bottom level change for the mentioned periods is presented on Fig. 3. Numbers of the graph show the points of longitudinal profile: 1 – the city of Chistopol (Kama River); 2 – Rechnoye settlement (Kama River); 3 – Laishevo settlement (Volzhsk and Kama deep); 4 – Kuybishev Pool settlement (Tetyushevo deep); 5 – Balymery settlement (channel's narrow, Tetyushevo deep); 6 – Undory settlement (Upper-Ulyanovsk deep); 7 – Ulyanovsk city (Upper-Ulyanovsk deep); 8 – Novo-Ulyanovsk city (Lower-Ulyanovsk deep); 9 – Sengiley city (Lower-Ulyanovsk deep); 10 – Novodevichye settlement (Novodevichye deep); 11– Aktushy settlement (appurtenance deep). The most intensive erosion/sedimentation processes on rise and decline are observed In the points 2, 5, 7, 9 and 11. These are pre-defined by big current velocity gradients in these sections. Deep extensions (points 1, 2, 4, 6, 8, 10), on the contrary, are characterized by low current velocities and weak intensity of channel processes.

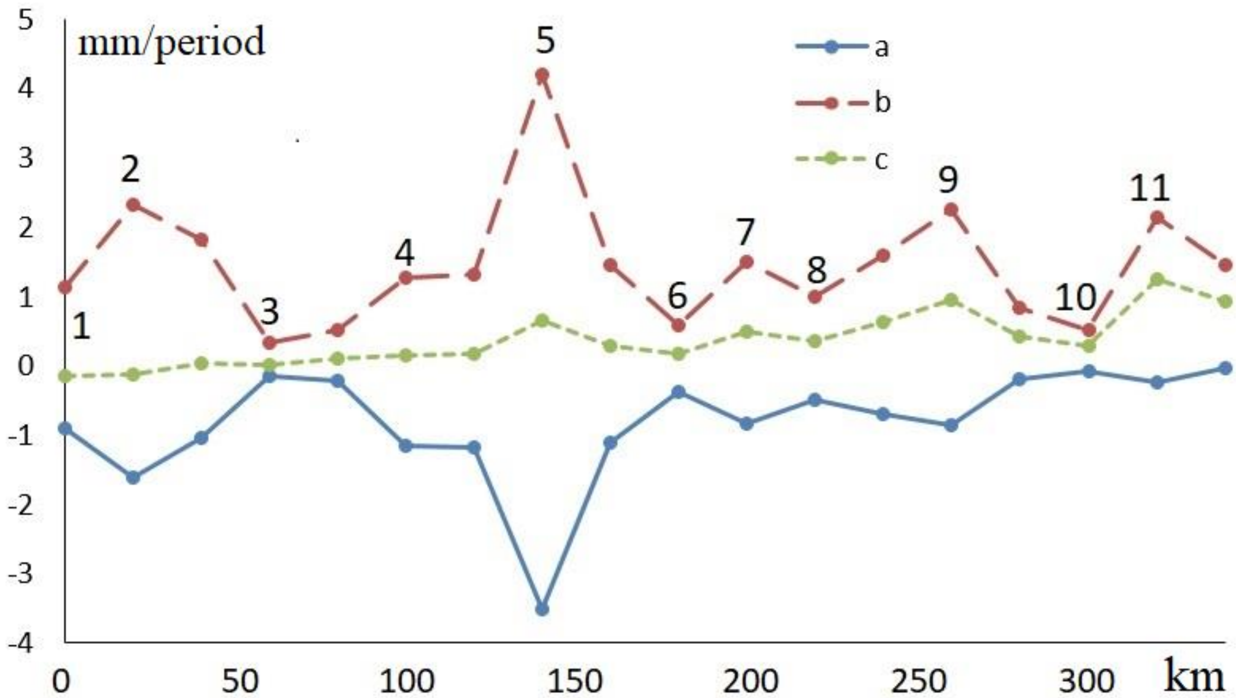

Figure 3. Longitudinal profile of changes in the bottom levels from Chistopol on the Kama river to Zhigulevskaya HPP, mm / period: a – for the 30-day period of high water rise; b – for the 30-day period of high water fall; c – total accumulation (>0)/washout (<0) for the entire 150-day period of calculation

The results of the bottom reshaping in channel cross-section for the most hydrodynamically active part of Kuybishev reservoir at Balymery station are presented on Fig. 4. The lesser intensity of bottom transformation falls to deepwater part of investigated section at the right shore (left part of Fig. 4), where the depths reach 25 m and above. On shallow-water from the left shore part (right part of Fig. 4), featured by the depths of approx. five meters, the biggest erosion and sedimentation values, up to 15 – 20 mm/month, are observed. However, for the whole 150-days simulation period, insignificant sediments accumulation within 1 – 2 mm for the period is here.

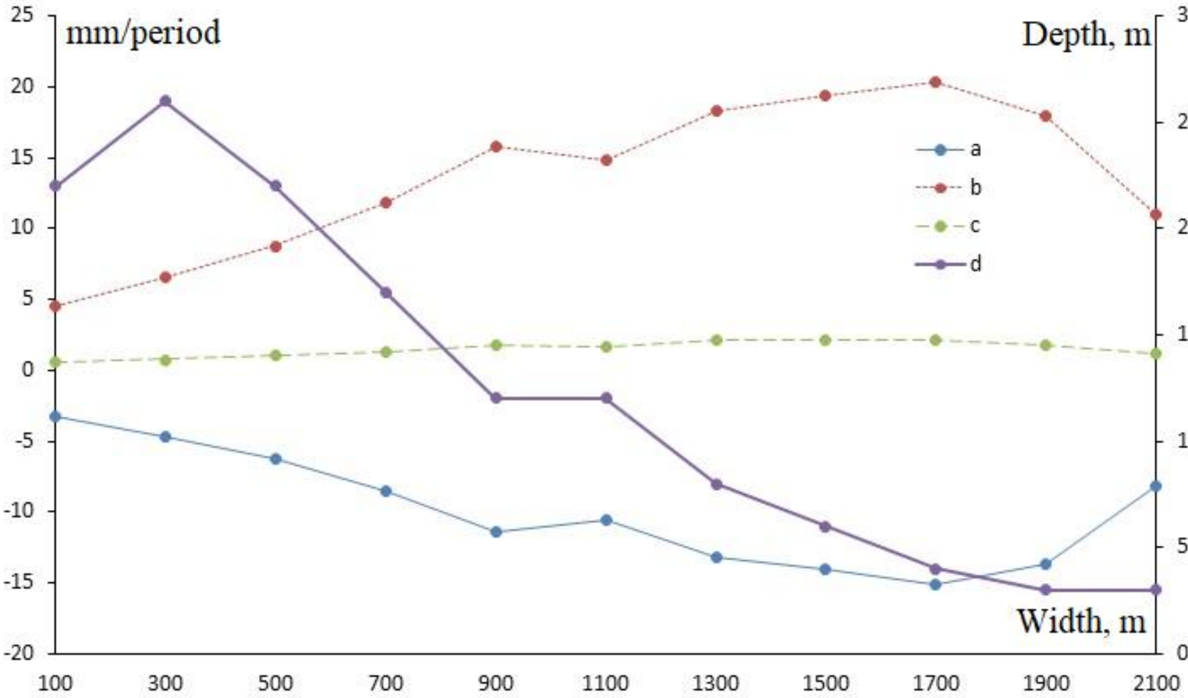

Figure 4. Cross-section profile of the Kuibyshev reservoir in the line of Balymera village: a – for the 30-day period of flood rise, mm / period; b – for the 30-day period of flood fall, mm/period; c – total accumulation (>0)/washout (<0) for the entire 150-day calculation period, mm / period; d – depth, m

Simulation result testify that the highest transverse profile transformation intensity falls to Volzhsk and Kama areas of variable headwater, as well as the whole Tetyushevo deep and the sections of channel's narrows between the deeps parts of reservoir. Obtained results closely match the data provided in (Kuybishev reservoir, 1983; Stupishin et al., 1981) and field data for Kuybishev reservoir sedimentation represented in the study (Zakonnov, 2007), which testify silting products runoff within spring fluctuations in current runoff velocity.

5 CONCLUSION

Following the simulation results, bottom reshaping maps for different water conditions were obtained, which illustrate trends in scour and accumulation processes for the whole area of Kuybishev reservoir. For the whole simulation period, average scour in water area reaches 0.5 mm; max. values confirm to deep narrows and amount to 2.5 mm and above; min. values confirm to deep extensions. Therein, deposition intensity in the reservoir is $6.45 \cdot 10^6$ m^3 per 150 days or $17 \cdot 10^6$ t per 150 days. Obtained results closely match with observation results (Kuybishev reservoir, 1983; Stupishin et al., 1981; Zakonnov, 2007).

Plotted longitudinal profile for the whole reservoir and transverse profile for one the most hydrodynamically active part show the influence of unstable conditions the rising and falling high water on bottom relief formation. It is demonstrated that the biggest washout and alluviation values, up to 15 – 20 mm/month, fall to shallow waters area of the cross section of Balymery settlement from the left shore side. This cross section, together with Priplotinniy dub and Nizhneulyanovsk dub in the cross section of Sengiley settlement, are featured by greatest intensity of vertical channel deformations. Totally, river sediments contribution into silting of Kuybishev reservoir is insignificant. Low current velocities are not enough to initiate active channel transformations. Meanwhile, provided calculations did not consider shore abrasion processes following the results of different natural agents' impact, organic sedimentation, as well as bottom transformation due to wind impact onto the Kuybishev reservoir area. More water-rich years will lead to more intensive re-distribution of solid matter flow and bottom sediments coming from upstream.

Kuybyshev reservoir is of the great hydroeconomic importance for the region. Accordingly, operation of this water body by different branches of national economy has detected the necessity of detailed study of changes occurring in underwater relief. This is connected to the maintenance of artificial spawning grounds, ships route arrangement in different parts of the reservoir, different pipelines laying over the bottom and creation of different hydrotechnical facilities. Therefore, obtained results can be useful for rational water use planning for the water body under investigation.

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REFERENCES

Alekseevskij, N.I., Berkovich, K.M., Chalov, R.S., Chalov, S.R. (2012). Spatial and temporal variability of channel deformations on Russian rivers. *Geografiya i prirodny`e resursy`*, No 3, 13–21. (in Russian)

Berger, R.C., Tate, J.N., Brown, G.L., Savant, G. (2015). *Adaptive Hydraulics (AdH) Version 4.5. Hydrodynamic User Manual*. January.

Delft3D-FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments User Manual. (2011). Delft Deltares, 672 p.

Kuybishev reservoir. (1983). Leningrad, Nauka, 214 p. (in Russian)

Lyubimova, T., Parshakova, Y., Lepikhin, A., Lyakhin, Y., Tiunov, A. (2020). The effect of unsteady water discharge through dams of hydroelectric power plants on hydrodynamic regimes of the upper pools of waterworks. *Water (Switzerland),* Vol. 12, No 5, 1336.

Rakhuba, A.V. (2017). Experience in using the chiton-Volna measuring and computing system in hydroecological studies of the coastal waters, pp. 484-488. Tol`yatti. In vol.: *E`kologicheskie problemy` promy`shlenny`x gorodov*. Sbornik 8-j Mezhdunarodnoj nauchno-prakticheskoj konferencii. Saratov. (in Russian)

Reference Manual *RiverFlow2D Two-Dimensional River Dynamics Model.* (2016). Hydronia LLC, 229 p.

Shirokov, V.M. (1965). Formation of modern bottom sediments in the Kuibyshev reservoir. *Tr. Kujby`shev. gidromet. observatorii.* L., Vol. 5, 28 – 32. (in Russian)

Shmakova, M.V. (2018). *Raschety tverdogo stoka rek I zaileniya vodohranilisch* [*Calculations of solid river flow and siltation of reservoirs*]. SPb, Izdatel`stvo VVM, 149 p. (in Russian)

Stupishin, A.V., Trofimov, A.M., Shirokov, V.M. (1981). *Geographicheskie osobennosti formirovania beregov I dna Kuibyshevskogo vodohranilischa* [*Geographical features of the formation of the banks and bed of the Kuibyshev* reservoir]. Kazan`, Izd-vo Kazan. un-ta, 184 p. (in Russian)

Zakonnov, V.V. (2007). *Sedimentation in reservoirs of the Volga cascade.* Abstract for the academic degree of doctor of geographical Sciences. M., 52 p. (in Russian)