Modeling and analysis of changes in the channel regime of the Kama river within the boundaries of 1639,0-1644,5 km during the development of the channel part of the Sidorovskoye occurrence

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Abstract. The problem studied in the framework of this work is devoted to issues related to the projected excavation of soil from the channel part of the Sidorovskoye sand and gravel deposit on the river. Kama. The channel part of the deposit is located at 1639.0-1644.5 km of the Nizhnekamsk sluice–mouth of the river. Vyatka, which is the upper part of the Kuibyshev reservoir. The paper presents the results of the analysis of channel reformations of the studied section of the river according to field data and hydraulic calculations performed to model the channel process in the section of the river. Kama, is located in the downstream of the N. Kamskaya HPP, taking into account the planned engineering measures related to the extraction of river alluvium from the channel open pit.

1 Introduction

The section 1639.0-1644.5 km studied of the Kama River is located in the zone of unsteady hydrological regime, caused by daily regulation of the flow of N. Kamskaya hydroelectric power station. Starting from the HPP site, the river is underflow from the Kuibyshev reservoir in a certain range of levels. The boundary of the seepage zone at this section changes as the reservoir fills and draws down. For the same reason the hydrological regime of the Kama river is particularly complicated. The level regime of Kama river differs in particular complexity, the level regime at the studied site depends on filling of Kuibyshev reservoir and water releases through N. Kamskaya HPP (Fig.1).

Nizhne-Kamskaya HPP operates in a daily regulation mode during summer and winter low-water periods and does not introduce significant changes in the passage of floods on the river. As a result, the flow in the lower reach of the HPP is characterized by two significantly different regimes: the flow similar to natural flow during the flood and unsteady flow during winter and summer low water periods, when daily and weekly flow regulation is carried out. Intense channel reshaping, occurring in the studied area, is caused by peculiarities of hydrological regime.

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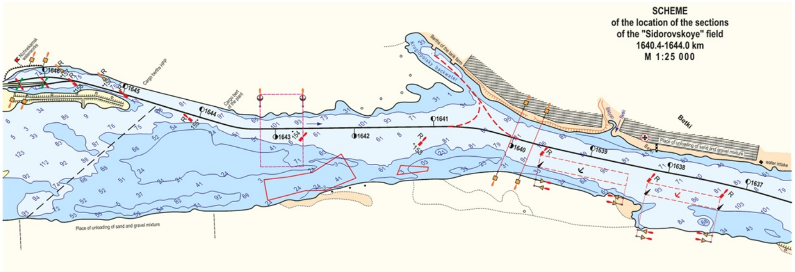

Fig. 1. Scheme of the section 1639.0-1644.5 km of the Kama river.

It is known that the removal of large volumes of sand and gravel from river channels leads to a significant impact on the development and intensity of the channel process, to a decrease in the free water surface elevations and, as a consequence, to the restructuring of the flow velocity field.

Decrease of low-water levels, which can be traced as a result of quarrying, in turn, can cause difficulties with maintaining the necessary navigable depths, lowering of the ground water level in the floodplain, deterioration of water intakes, irreversible channel deformations. Thus, in rivers with developed infrastructure (settlements, power plants, industrial activities) on their banks, it is extremely undesirable to change the height of low-water levels as a result of engineering activities. On the basis of the above, quarrying should not lead to a noticeable lowering of water level in the river, accordingly, the permissible level reduction is currently estimated by the value of the average error of depth measurements, which is about 10 cm.

2 Methods and materials

To study the level regime and to establish the estimated water discharge at the 1639.0-1644.5 km section of the Kama River, the data from hydrological dailies 1979-1986 and 1988 were used. The data from hydrological dailies for 1979-1986, 1988 and information on the operation of N. Kamskaya HEPP for 1979-1991. These data were supplemented with the materials of the production and technical department of N. Kamskaya HEPP for the period of 1993-2003.

To analyze the condition of the channel process in the near-drainage area, the materials of channel surveys performed by N. Kamsky Waterways District from 1979-2021 were processed. To ensure the comparability of the channel surveys, a unified methodology for processing hydrographic materials was selected. In particular, channel morphometric characteristics: - cross-sectional area W, channel width B and average depth H were calculated for a number of fixed design cross-sections at channel filling corresponding to the normal water retaining level with the mark Z=53.0 m. The results of the calculations are shown graphically in Fig. 2 in the form of the combined graphs of changes in the cross-sectional area of the channel along the length of the river.

Proceeding from the data obtained, it can be assumed that in the immediate vicinity of the hydropower plant, erosion processes will continue to occur, but their intensity over time will fade. In turn, the erosion base will subsequently move downstream of the river.

Analysis of the obtained materials shows that the dynamics of changes in the morphometric characteristics of the channel in this section appears to be quite complex. This is due to the fact that, along with natural alterations associated with the development of the scour funnel, the impact of aggregates extraction from the river channel, which was carried out here in previous years, manifested itself in this section. In this regard, the data obtained characterize the intensity of the channel process development at this site against the background of engineering activities in the river channel. Given that there is no specific information on the volumes of aggregates extraction in the studied area, we can speak only about the trend of changes in the channel morphometry to date without distinguishing the contribution of the components that caused these changes [1].

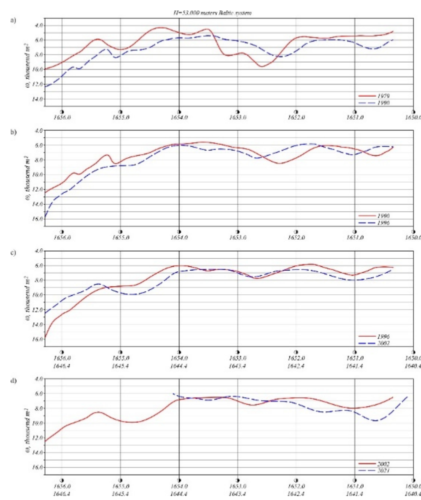

Fig. 2. Plotted cross-sectional area change graphs of the Kama river channel at the site of 1640.4-1646.6 km for the periods: a) 1979-1990; b) 1990-1996; c) 1996-2002; d) 2002-2021.

In the present work to assess the influence of open-cut mining on the level regime and deformations of the channel and the right bank of the Kama River, the software package "FLOOD" was used to calculate the distribution of average flow velocities across the width of the channel and calculate the initial deformations of the bed in the plan formulation [2].

The software package has been extensively tested in solving similar problems at other sites and allows us to obtain reliable predictions [3].

When performing hydraulic calculations, channel survey performed by N. Kamsky region of waterways and navigation in navigation 2021. In this case the length of the calculated section was set in the boundaries from 1639.0 km to 1644.5 km, covering the aggregates quarries planned for development. Preparation of initial data for modeling consisted in compiling an array of the values xi, yi and zi, characterizing the relief of the bottom and the outlines of the coastal strip both in the natural state, and taking into account the projected measures. On this basis, as a result of the hydraulic calculations performed in the work, an assessment of the impact of the projected quarry on the flow kinematics and channel deformations in the immediate vicinity of its location is given. The analysis of a field of speeds of a current in a zone of influence of the quarry has allowed to receive an estimation of its influence on navigable conditions and deformations of the right coast [4, 5, 6].

Hydraulic calculations in gauging the mathematical model were performed to obtain free surface elevations along the length of the river. Calculations were performed at two water levels (discharges).

The first level, at which the calculations were carried out, corresponds to the average annual water discharge in the flood, the value of which, according to the data of the study is Q=6700 m3/s. Water levels Z=55.75 m for Nizhnekamsk HPP and Z=55.5 m for Elabuga correspond to this discharge respectively.

The second level, at which the calculations were carried out, corresponds to the design water discharge Q=650 m3/s. Water levels Z=50.0 m for Nizhnekamsk HPP and Z=49.5 m for Yelabuga meet this discharge.

When passing from the mean annual flood level (Z=55.75 m) to the design water level (Z=50.0 m) slopes of free surface increase and connection between average velocities of flow and value of Shezi coefficient becomes unambiguous [7].

3 Results and discussion

According to the initial data development procedure, a rectangular coordinate grid with X and Y axes (in the conventional coordinate system) was laid out on the site plan. Further on the plan the calculated area was selected, for which lateral (impermeable) boundaries were the lines passing along the shallow water bars, the inlet boundary was a cross-section at 1644.5 km, and the outlet boundary was a cross-section at 1639.0 km of the Kama river.

Fig. 3 shows the constructed finite-element triangular grid. Number of triangular elements of the grid is taken equal to 18490 pcs. This value is the main characteristic of the grid, which indicates the number of points within the area in question, where the bottom and water surface depths marks, flow velocities and bottom deformations were further determined.

After constructing the grid, preparation and input of the initial data for description of the bottom topography was carried out. The bottom relief was set in the form of a triad of numbers: plan coordinates X, Y and bottom marks Z, selected according to the method of arbitrary outline. Bottom relief data processing was performed according to the program of interpolation into the centers of triangular elements.

Fig. 4 shows the scheme of the considered area according to the data of machine processing and shows the bottom relief in the marks of the Baltic system of heights.

Further calibration of mathematical model was performed, which consisted in carrying out test calculations of free surface elevations at water discharge Q=650 m3/s at Nizhnekamsk HPS (Fig. 5).

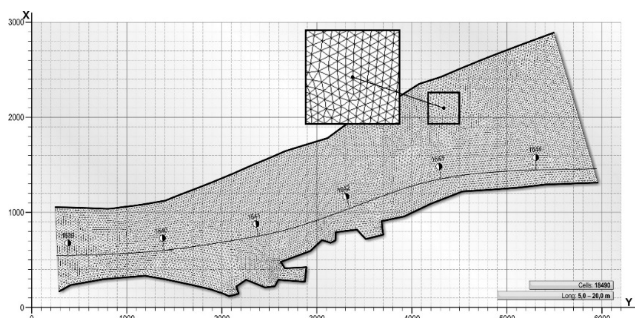

Fig. 3. Triangular finite element grid for current calculation at the section 1639.0-1644.5 km of the Kama river.

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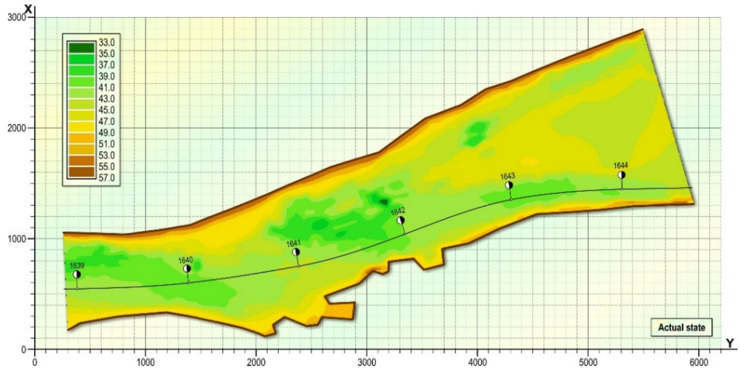

Fig. 4. Bottom relief at the section 1639.0-1644.5 km of the Kama river in domestic condition.

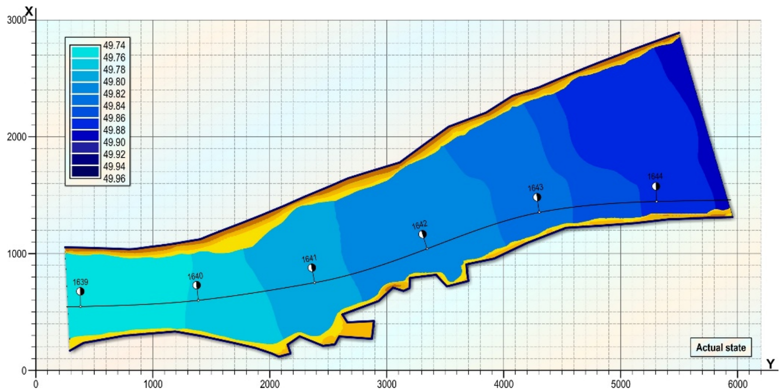

Fig. 5. Relief of free water surface at km 1639.0-1644.5 of the Kama river in domestic condition at the design level.

Thus, the bottom relief and free surface marks obtained as a result of the calculation quite objectively reflect the state of the stream and channel at the study site. Consequently, this mathematical model can be used for computational justification of the designed measures.

After calibrating the model, a calculation of the flow plan for the domestic condition of the channel at the design level was performed. The field of average velocities at the site of the projected quarry location is shown in Fig. 6.

To estimate the influence of quarries on the level regime and flow kinematics without taking into account deformations, the hydraulic calculation of the free surface curve and flow plan for the design state of the channel at the design level of track works was performed. At the same time, the bottom topography was corrected within the limits of the open-pit mines. The bottom relief, free surface elevations and average velocity field of the section with channel excavation, obtained as a result of calculations, are shown in Figs. 7-9.

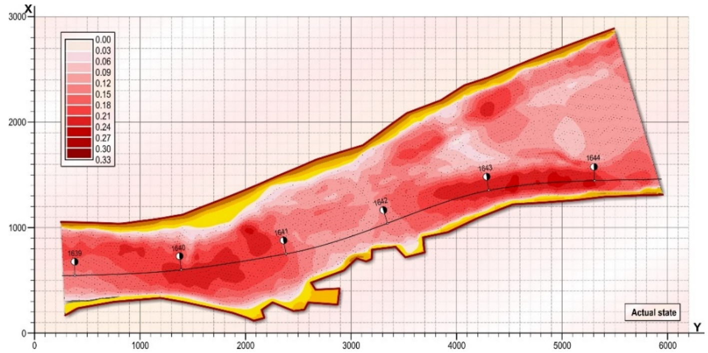

Fig. 6. Field of average bottom velocities at the section 1639.0-1644.5 km of the Kama river in the domestic state.

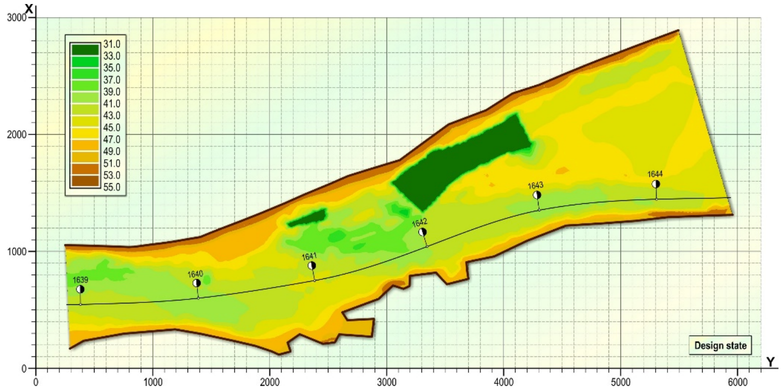

Fig. 7. Bottom relief at the section 1639.0-1644.5 km of the Kama river in the design condition.

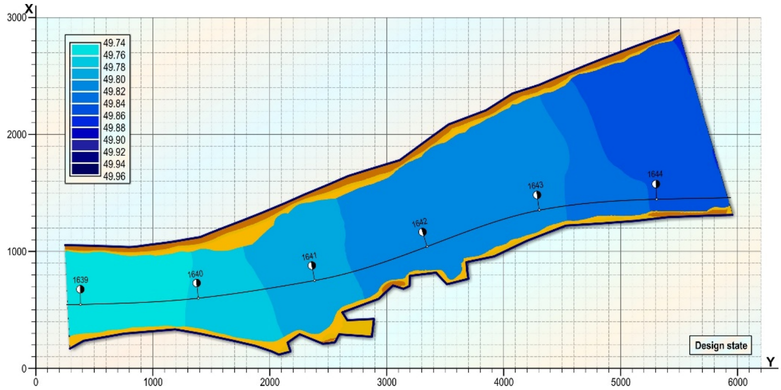

Fig. 8. Relief of free surface on the section 1639.0-1644.5 km.

The Kama river in the design condition at the design level.

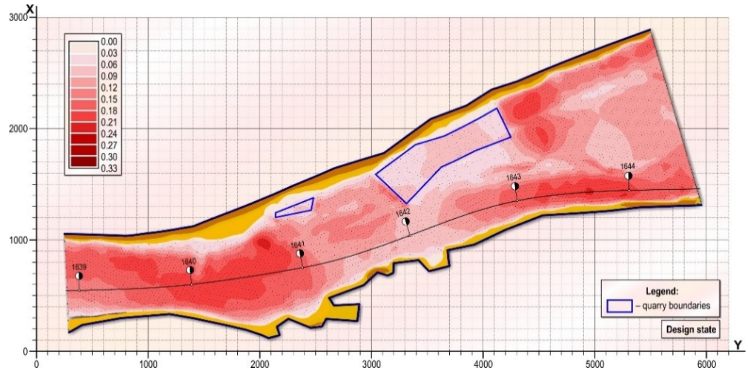

Fig. 9. Field of average bottom velocities at the section 1639.0-1644.5 km of the Kama river in the design condition.

Calculations of initial bottom deformations were performed at average flood discharge Q=6700 m3 /s for the time period of 80 days (average flood duration). Calculations were carried out both with and without taking into account the pit. The formula of R. Bagnold was chosen as the calculation formula for sediment flow rate (Fig. 10-11). [8]

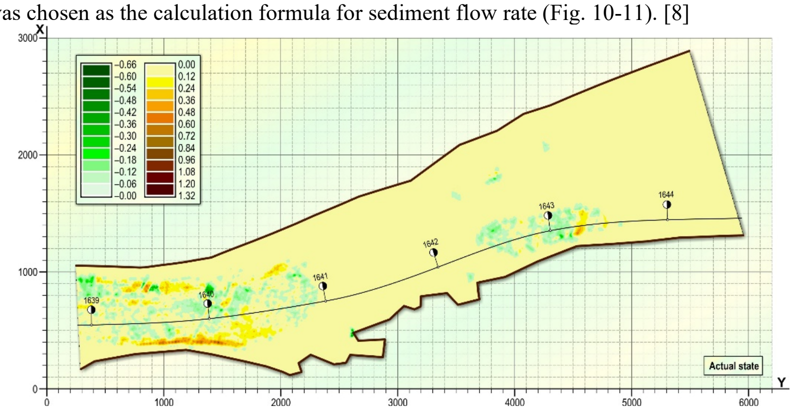

Fig. 10. Map of predicted bed deformations during the flood period duration of 80 days at the section 1639.0-1644.5 km of the Kama river in domestic condition at Q = 6700 m3 /s.

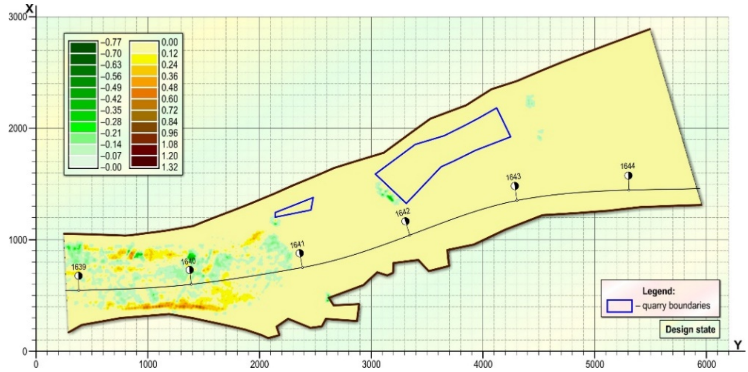

Fig. 11. Map of predicted bottom deformations for the flood period of 80 days at the section 1639.0-1644.5 km of the Kama river in the design condition at Q = 6700 m3 /s.

4 Conclusion

Analysis of the obtained results shows that at present in the Nizhnekamsk HEPP downstream pool scouring deformations are predominant. Their intensity at this stage is less than in the first years after commissioning of HPP. The erosion base is gradually shifting downstream. As shown by the channel forecasts made using the apparatus of mathematical modeling, these processes will develop further, although with less intensity.

Conducted researches and results of mathematical modeling of channel process at the studied site, located in the Nizhnekamsk HPP downstream pool, testify that engineering measures on river alluvium removal will not lead to intensification of channel process in the zone of influence of open-cut mining, and in some cases will have damping effect and promote prevention of uncontrolled deformations, connected with development of washout funnel. Deterioration of navigable conditions in this case does not occur.

The received results show that open-cutting of total excavation volume W=441.9 thousand m3 does not lead to change of the general character of channel deformations on a site. As a whole at the considered site, both in the household and in the design condition of the channel, sign-variable deformations of low intensity prevail, on the average less than 1 cm/day. After quarrying, due to the increase of channel capacity and some decrease of average flow velocities in the section, the intensity of channel deformations decreases [9, 10].

A set of additional scientific studies should be conducted when planning similar activities at this site, as well as when it is necessary to conduct quarrying in larger amounts than were evaluated in this work. Taking into account that the process of development of the scour funnel in the downstream of the HPP continues and the stabilization of the channel regime has not occurred so far, these studies should be preceded by special field observations at the studied site. This will allow continuous monitoring of the channel process development, and, if necessary, control the degree of permissible impact on it based on the interests of all water users, as well as in terms of protection of the natural environment.

Thus, the performed calculations showed that the factor of channel deformations has insignificant influence on the regime of water levels and navigable conditions at the considered site, and the development of the designed open pit in full volume will not lead to their deterioration.

References

1. V.V. Belikov, N.M. Borisova, T.A. Fedorova, O.A. Petrovskaya, V.M. Katolikov, Water Resources **46,** 20 – 28 (2019). DOI 10.1134/S0097807819070029.
2. T. Pilipenko, T. Mikhailova, D. Panov, J. of Phys.: Conf. Ser. **2131(3)** (2021). DOI 10.1088/1742-6596/2131/3/032070.
3. M.C.A. Clare, J.G. Wallwork, S.C. Kramer, C.J. Cotter, M.D. Piggott, GEM – Int. J. on Geomathem. **13(1)** (2022). DOI 10.1007/s13137-021-00191-1.
4. A.B. Rumyantsev, N.M. Borisova, V.V. Belikov, Water Resources **49(3),** 448 – 457 (2022). DOI 10.1134/S0097807822030125.
5. G.L. Gladkov, P.V. Belyakov, Vestnik Gosudarstvennogo universiteta morskogo i rechnogo flota imeni admirala S. O. Makarova (2021). DOI: 10.21821/2309-5180-2021-13-1-52-63.
6. G. Gladkov, M. Habel, Z. Babin´ski, P. Belyakov, Water (Switzerland), **13(15)** (2021). DOI 10.3390/w13152038.
7. X. Wan, J. Ding, N. Jiao, J. Q. Guo, J. of Performance of Constructed Facilit. **36(3)** (2022). DOI 10.1061/(ASCE)CF.1943-5509.0001725.
8. A.I. Aleksyuk, V.V. Belikov, N.M. Borisova, T.A. Fedorova, Springer Proceedings in Earth and Environmental Sciences, pp. 29 – 33 (2019). DOI 10.1007/978-3-030-03646-1_5.
9. S. Zheng, H. Cheng, M. Tang, Y. Jiang, Q. Zhou, J. of Oceanology and Limnology (2022). DOI 10.1007/s00343-021-1137-3.
10. G.L. Gladkov, M.V. Zhuravlev, Vestnik Gosudarstvennogo universiteta morskogo i rechnogo flota imeni admirala S. O. Makarova **11.6**, 1044–1055 (2019). DOI: 10.21821/2309-5180-2019-11-6-1044-1055.