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NUMERICAL STUDY OF ICE AND CHANNEL PROCESSES ON THE BRIDGE SUPPORTS ACROSS THE KUIBYSHEV RESERVOIR (KAZAN)

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Abstract: Numerical hydrodynamic modeling of water movement at discharges of 1% and 10% supply is considered in order to study the effect of ice effects and bottom deformations on the bridge supports across the reservoir of the Kuibyshev hydroelectric complex, and to predict the general erosion of the channel. The calculations use two-dimensional shallow water and sediment transport equations implemented in the STREAM 2D CUDA software package.

Keywords: numerical modeling, shallow water equations, bridge crossing, general erosion, ice effects

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ДЕФОРМАЦИЙ ДНА И ЛЕДОВЫХ ЯВЛЕНИЙ НА ОПОРЫ СТРОЯЩЕГОСЯ МОСТА ЧЕРЕЗ КУЙБЫШЕВСКОЕ ВОДОХРАНИЛИЩЕ У Г. КАЗАНИ

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Аннотация: Рассматривается численное гидродинамическое моделирование движения воды при расходах 1%-ной и 10%-ной обеспеченности с целью исследования влияния ледовых воздействий и деформаций дна на опоры моста через Куйбышевское водохранилище, прогнозирование общих размывов русла. В расчетах применяются двумерные уравнения мелкой воды и транспорта наносов, реализованные в программном комплексе STREAM 2DCUDA.

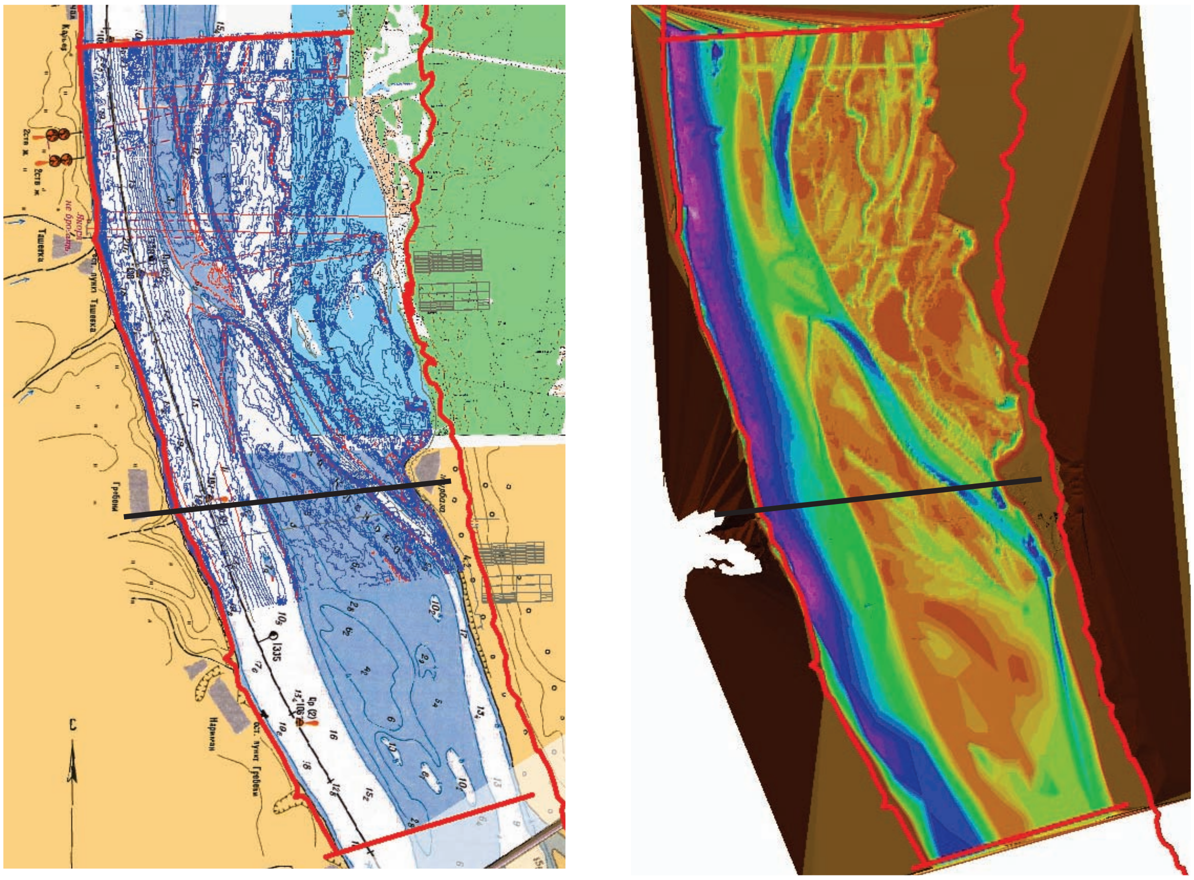
Ключевые слова: численное моделирование, уравнения мелкой воды, мостовой переход, общий размыв, ледовые воздействия

INTRODUCTION

The projected bridge across the Kuibyshev reservoir is a part of the Moscow-Nizhny Novgorod-Kazan highway and is located in the Republic of Tatarstan, 17 km to the south from Kazan. Complex natural and anthropogenic processes take place at this site, which require a comprehensive study, including engineering surveys and scientific research.

The main objective of the numerical simulation is to calculate the possible complex impact on the bridge during construction and operation under various hydrological conditions. Among natural factors, special attention was paid to hydraulic flow characteristics in spring period considering ice phenomena, reservoir bottom deformations at maximum water discharges, which can be observed during the bridge construction and operation period. The technogenic impact on the studied area from the temporary bridge, as well as from the permanently operating quarry was also assessed.

Large-scale cartographic materials [1, 2] and engineering-hydrographic plan were used to build a digital relief model (Figure 1, a). The data were reduced to a unified system of coordinates and heights. At the next stage a continuous surface was built by the Delaunay triangulation method, edited by semi-automatic method. The resulting digital relief model (hereinafter DRM) (Figure 1, b) was used as the initial relief data for the numerical hydrodynamic model. The data on the hydrological regime in the construction area were obtained from observations at the nearest hydrological stations in Uslon settlement. Verkhniy Uslon (upstream of the projected bridge) and the village of Kirelskoye (downstream of the projected bridge, below the confluence of the Volga and Kama rivers). In accordance with them, water discharges (1% and 10% probability) and levels typical for the flood period were selected for modeling. During the winter period of 2021 observations of ice conditions in the construction area were performed and based on their results ice parameters were specified in the model.



a b

Figure 1. The stages of building a digital relief model: a - data source; b - final result (black line - bridge span).

To calculate the deformations of the reservoir bottom, the results of engineering-geological surveys were used [1, 2]. Forty-four wells were analyzed in the channel part of the bridge crossing. In the span of the bridge there are predominantly sandy sediments, which in the upper part are covered with loam and silt. The cohesive soils had a small thickness in the section and are mostly withdrawn in the process of construction, losing their resistance to scouring. Therefore, they were not considered in the calculations. Among sandy sediments, medium and fine sands occupy the largest volume. Since the fine and medium sands are unevenly distributed along the depth and alternate with each other, the mathematical modeling assumed that the deformable soil consists of two

fractions of different sizes at a 50%:50% ratio. Cumulative curves were drawn for these sediments based on their grain size distribution, from which d50 and d90 values were derived to calculate deformation.
Fraction 1 (fine) d_{50}=0.13 mm, d_{90}= 0.28 mm.
Fraction 2(medium) d_{50}=0.25 mm, d_{90}=0.55 mm.
On the top border of limestone deposits the non-degradable surface has been appointed.
In the process of modeling, it was also necessary to consider man-made factors arising during the construction and operation of the structure. During the construction period the working (temporary) bridge will be operated. It consists of spans of 110 x 21.4 m on one-row and two-row pile piers of 1.02 m diameter pipes with the ice-breakers device. The permanent bridge crosses the active quarry with a length of almost 6km and a width of 80 to 540 m. Extraction of soil is expected on a constant basis for a long time under low-water conditions. The minimum level of the quarry bottom was assumed to be 26 m.

CALCULATION OF POSSIBLE COMPLEX IMPACT DURING SPRING ICE DRIFT ON TEMPORARY STRUCTURES (WORKING BRIDGE)

The objective of this part of the study is to assess the ice impact on temporary structures (temporary bridge) during the construction period (without the supports of the main bridge). The work was conducted in two stages. On the first stage there was an ice flood modeling to determine the dependence of discharge, levels, speed and gradients in the investigated area. At the second stage ice load on the temporary bridge piers was calculated using the results of previous calculations as initial data.

Simulation of river flow to assess water flow velocities and water surface gradients, including ice jam conditions
For numerical modeling in the computational domain, a hybrid mesh of triangular quadrangular structure (variant 1), with the number of cells about 63 thousand, was constructed. As boundary conditions on the inlet boundary (in the upper part of the computational domain) the water discharge in the river with 10% probability was set equal to 30 000 m3/s. On the outlet boundary (in the lower part) the water level was set. Because of ambiguity of the level modes (among other reasons because of distribution of the head from the downstream hydraulic facility) the calculation was made for two variants of the water level marks on the outlet boundary, which were 53.0 m and 54.0 m.
The roughness coefficient of the river bottom in Manning's formula was accepted to be 0.025, the additional roughness coefficient of the bottom surface of fixed solid ice in the ice jam was also taken to be 0.025, i.e., the total reduced roughness coefficient in the ice jam section was taken to be 0.05.
It was assumed that a temporary bridge as a disturbance in the channel would provoke ice jam upstream. Therefore, ice cover was modeled in the upstream part of the bridge structure, and the water surface downstream was set as ice-free. The ice thickness was assumed to be 10% probability and equal to 0.73 m according to the design data. The close average value was obtained from the data of full-scale measurements in the beginning of March, 2021.
Numerical studies were performed using the widely tested [3-9] Russian software package for hydrodynamic modeling STREAM 2D CUDA developed at the NPP "Aquarius Analytic" Ltd. [10]. High-precision original algorithms [11-15] used in the calculations allow accounting for the complex orography of the underlying surface [16-18], sediment transport and bottom deformations, taking into account soil heterogeneity and self-bedding phenomena [19-20], as well as the presence of ice phenomena.
Comparative calculations showed that water gradients above the bridge increase more than doubled from 3 cm/km to 6.7 cm/km in the presence of ice jam (Figure 2). Other parameters showed insignificant changes.

The calculation variant with the boundary condition at the outlet of 54 m showed the closest value with the in-situ measurements at the given roughness coefficients, which was accepted for the further modeling.

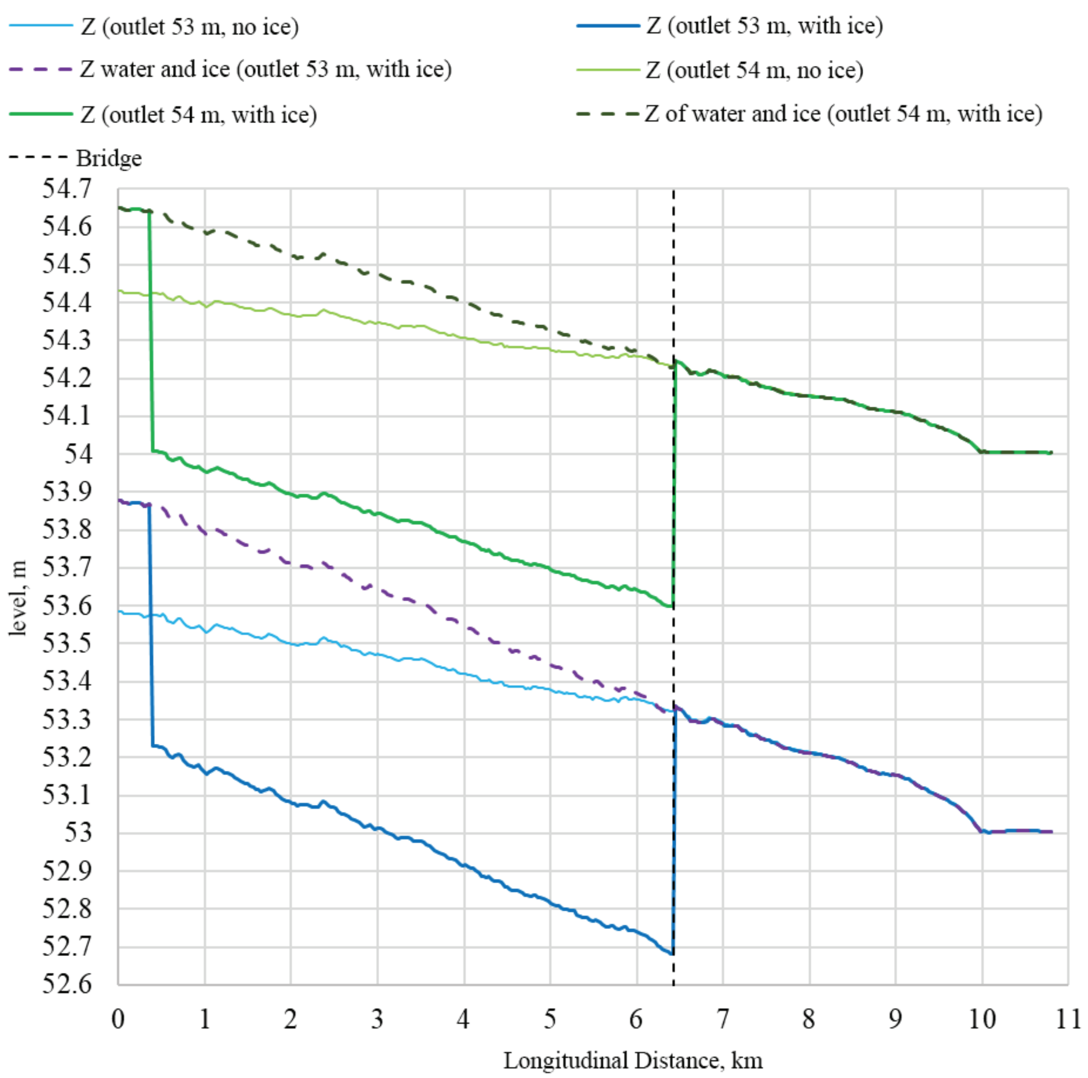


Figure 2.Longitudinal profiles of calculated water levels at Q=30000 m³/s.

Determination of ice forces on temporary technological structures (working bridge)

Based on the simulation results, the following values of the determining parameters and design features were adopted for the design conditions of the construction period during the ice drift to estimate the ice load on temporary structures:

- ice thickness is 0.73 m (10% probability, close to actual measured values for the 2021 flood);
- the depth average speed of stream flow in the deep-water part (in the area of the main fairway) for the conditions of 10% of the flood with the discharge of 30 000 m^3/s is 2 m/s (almost the same under ice, and without ice, as the results of modeling show);
- the depth-averaged flow velocity in the main shallow left bank water area is 1 m/s (practically the same under ice and without ice, as the simulation results show);
- for simplicity of calculations, the flow depth in the deep-water part under the right bank is assumed to be 20 m (will not actually be used in

the calculations), and in the shallow-water part it is 5 m;
- slope of water surface in the jam above the bridge is equal to 6.7 cm/km (I=0.000067);
- The temporary bridge is supposed to be built on the supports of relatively small diameter (1 m) with distance between supports 20 m, therefore it does not create essential additional resistance to water flow, however it is an obstacle for moving ice.

Two scenarios were considered to solve the set problems. According to the first scenario we considered the case of unfavorable natural conditions that could lead to a significant jam, i.e., provoke ultimate loads from ice pressure on the working bridge supports. The second scenario is based on the forecast of the spring flood of 2021, in which an insignificant ice jam is formed above the working bridge, and the main danger arises during the ice drift from the impact of floating ice floes.

According to **scenario 1**, based on calculations with ice (performed on the model with mesh variant 1), it can be assumed that an opening of 700 meters in width will let ice floes and ice fields through freely (current velocities reach 2 m/s in the deep-water part of the fairway bottom), but a jam of several kilometers in length and up to 2 km in width can arise on the left bank part above the temporary bridge.

The bridge supports (ice-cutters) will be impacted by the ice field approximately uniformly along the whole length of the temporary bridge, because the current velocity on the whole shallow-water part is equal to 1 m/s on average when the structure flow is passing through. The pressure force application point on the icebreaker will be at the middle of the ice field thickness, i.e., approximately 0.3 m below water level, or approximately at the mark of 54.0 m.

The total pressure of the ice field on one pier of the bridge (i.e., 20 linear meters) is composed of two components: the rolling force (projection of gravity force acting on the ice), equal to (in Newton)

$$F_1 = \rho_i g H_i IBL = 8.64xL\ н$$

and the friction force of the lower part of the ice against the water surface, that, assuming the above assumptions about the equality of the roughness coefficients of the channel bottom and the lower surface of the ice, is equal to half of the total friction resistance of the flow

$$F_2 = 0.5\rho_w g H_w IBL = 32.7xL\ н.$$

Thus, the resulting ice pressure on the support (ice cutter) of the temporary bridge is equal:

$$F = 41.3\ L.$$

Assuming that the length of the jam is 10 km (according to expert opinion, may be less, or maybe more), we get F=413,000 N, or about 40 Tf.

In the calculations of the "ice cutter-piles" system performed by the designers, the ice load is assumed to be equal to F ice = 29.6 Tf. Ice cutters will cut through the ice with a greater load, which will happen when the jam length is close to 7.5 km. When ice is weakened by temperature effects and its thickness decreases, ice breakup on the ice cutters can also start at shorter ice jam lengths.

However, if ice-cutting speed increases rapidly (such situations are possible), ice breaking speed may be insufficient, and then the actual loads on the temporary bridge supports may exceed the calculated ones. This question requires special research and observations. It should be reminded that all the above mentioned refers to the fully constructed temporary bridge.

On this basis, consider that ice jam is formed only at that width of the channel (in its shallow part), which is overlapped by the temporary bridge. Then the load on the outermost supports from static ice pressure will be about 2 times less than on the middle supports, but will not be able to exceed them in any way.

According to scenario 2, the length of ice jams was expertly estimated as 1 km in the situation existing at the beginning of April 2021 (with short sections of the built bridge). Thus, the load on the support will not exceed 4 Tf, there will be no danger of the support collapse.

However, there is a risk of impact load in this case (especially on the end supports of the bridge sections, and especially for the section in the central part). Due to increased flow velocities there (up to 2 m/s), a large impact load can arise with large sizes of ice floes.

The impact kinetic energy of a 100x100 m ice block of 0.73 m thickness at 2 m/sec velocity is $E=mV^2/2$ =1340 kilotons m, which is comparable to the collapse of a ship of 5000 T displacement on the footing at 2 m/s (tangentially to the footing).

The energy of a 10x10 m ice floe would be 100 times less, and would be 13.4 kilotonnes.

Modeling of bottom deformations for domestic conditions (before construction), during bridge crossing operation, and in the presence of an open pit

To estimate the effect on the reservoir bottom deformations in the area of the bridge piers, two design meshes were prepared by modifying the design mesh of variant 1: with all bridge piers highlighted (variant 2), and an identical mesh for domestic conditions (variant 3), so that the results of calculations with the bridge and in domestic conditions can be compared on these meshes by subtracting values in the cells. The mesh with cut-out bridge supports consists of 76556 cells, while the one without bridge supports consists of 76758 cells (Figure 3).

Modeling of currents and bottom deformations was performed for two constant water flows Q=30000 m3/s (10% flow rate) and Q=39400 m^3/s (1% flow rate) during 1 month (approximate time of high flood passage).

Based on the conducted calculations it can be concluded that in the considered section of the Volga River channel near the projected bridge crossing in domestic conditions during high floods the bottom is on average in steady state of dynamic equilibrium, the balance between volumes of scour and bottom sediments is observed, there is no systematically expressed lowering or raising of erosion base.

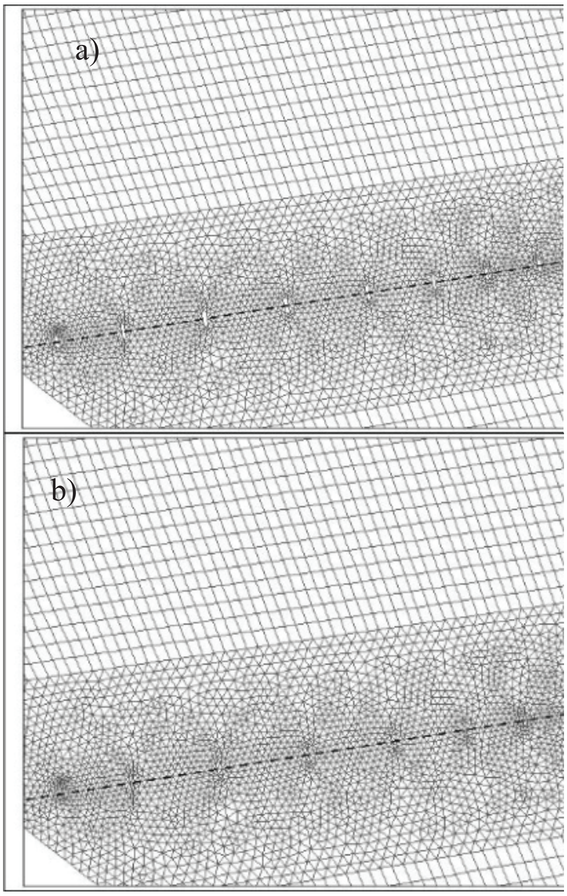


Figure 3. Calculation meshes with and without bridge supports cut out (fragment in the alignment of the bridge near the right bank). Dashed line - the bridge span

Next, the effect of bridge supports on water flow and bottom deformations was analyzed. Namely, channel deformations, flow rates and water levels obtained by calculation in the presence and absence of the bridge crossing were compared. For this purpose, the corresponding results obtained from the model with a bridge crossing (Variant 3) were subtracted from the mesh values of the results obtained from the model for domestic conditions (Variant 2). The results for the two design water flow rates are almost indistinguishable. Figure 4 shows the results for the 10% flow rate.

It should be noted that in the immediate vicinity of the bridge piers (about 10 m radius from the piers) the bottom deformations may not fully correspond to the real values because of the failure to consider in the applied mathematical model the three-dimensional helical flow near the piers, which leads to additional (local) scouring (should be considered separately, for example, by empirical dependencies).

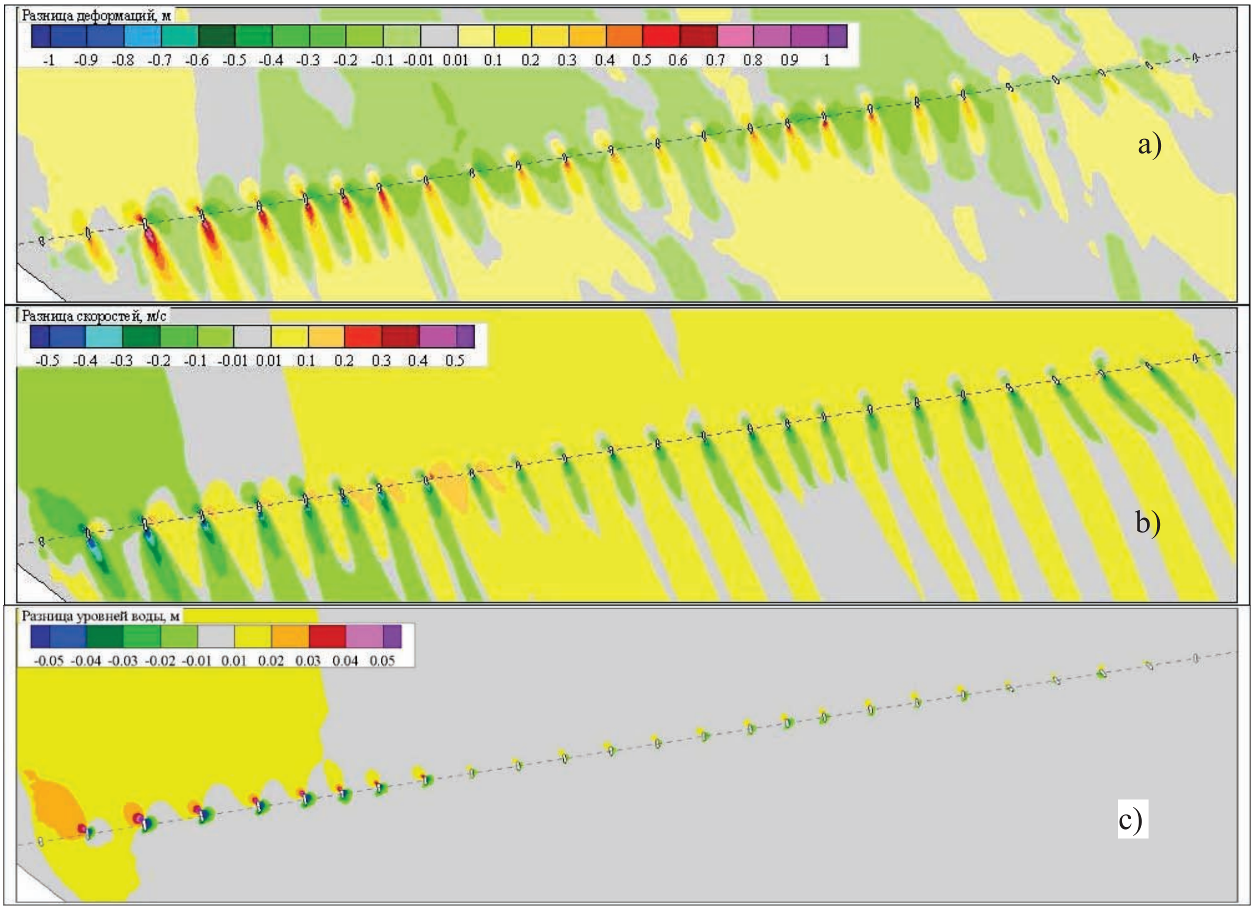


Figure 4. Difference in channel deformations, flow velocities and water levels in the calculation with Q=30000 m^3/s (10% flow, fragment near the bridge).

The three-dimensional character of the flow has practically no effect on water surface levels and average flow velocities in depth, so these flow characteristics obtained by calculation, as well as general bottom deformations (scour) between the bridge piers can be considered quite reliable. It should also be noted that most of the piers, especially in deep water, have a small current slant. In the presence of a bridge, channel deformations are characterized by a stronger bottom washout in front of the supports themselves (by ≈10 cm) and between them (by ≈10-30 cm), which is associated with an increase in flow velocity in these places (by ≈0.1-0.2 m/s), and a more intensive scour (sedimentation) behind the bridge supports (by ≈ 10-80 cm), which is associated with a decrease in flow velocity behind them (by ≈0.1-0.5 m/s). Above the section closer to the right bank in front of the bridge there is an increase of the bottom washout (by ≈10 cm), which is associated with a decrease in flow velocity in this area (by ≈0.1 m/s). Water levels in the presence of the bridge crossing change mainly just in this area. Namely, they increase by about 1-3 cm (i.e., the pre-bridge backwater is practically absent), and also change locally at each pier. Before the pier they increase, behind the pier they decrease.

Modeling of the flows and deformations of the bottom in the presence of the bridge crossing and open pit was performed for the same boundary conditions. Calculation mesh with bridge supports (variant 3) was used, for which an additional DRM with the quarry was prepared.

Outside the quarry, the deformations, as in the previously presented calculation results for domestic conditions and with bridge supports, are not very intensive and mainly lie in the range from +1 m to -1 m. In front of the quarry, the bottom of the river is eroded, and the quarry itself is brought in from the upstream side (slightly at an angle, which is caused by the direction of the stream). The landslide of the slope of the quarry is observed. The similar picture of deformations and for the second flow Q=39400 m3/sec. Flow velocities almost do not change after erosion, levels also change in the process of calculation insignificantly, about 2 cm. It is interesting, that in the pit itself the average depth velocities of flow are less than in the fairway, and decrease in the transverse direction from the right side of the pit to the left.

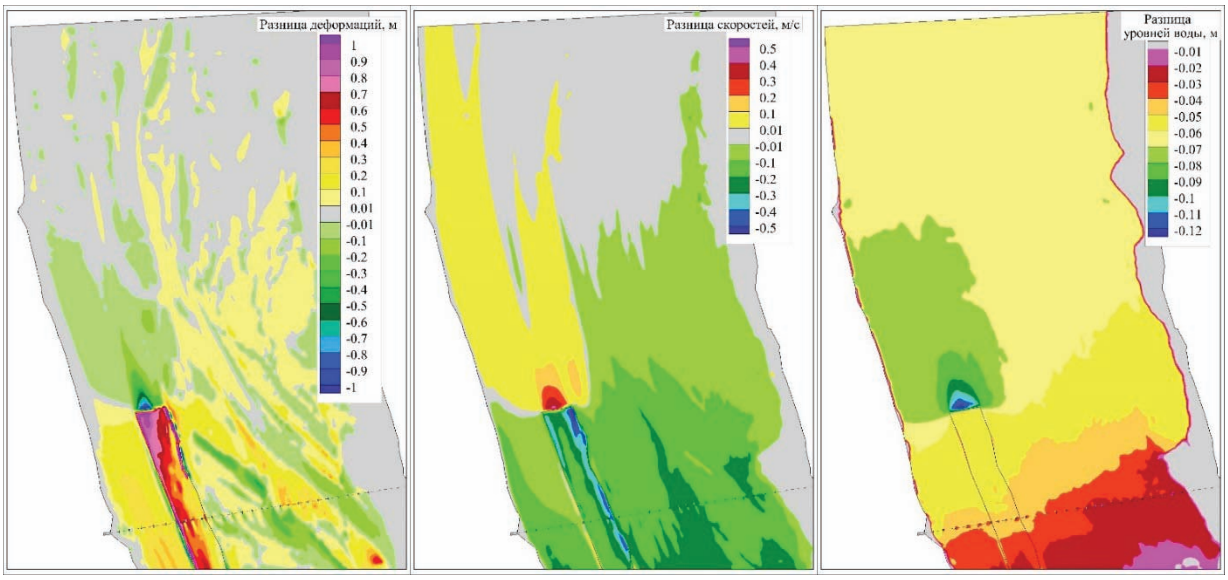


Figure 5. Difference in channel deformations, flow velocities and water levels at calculation with $Q=30000\ m^3/s$ (10% probability)

To analyze the influence of the quarry in detail, the corresponding results obtained from the model with bridge crossing and quarry were subtracted from the grid values of the results obtained from the model with bridge crossing only. Calculation results for the 10% flow rate are shown in Figure 5.

For both discharges the character of changes is the same. The difference of channel deformations showed that in the presence of the quarry we observe more intensive bottom erosion before the quarry (up to 90 cm) and on the approach to it (up to 10 cm), which is because of the flow speed increase before the quarry (up to 0.4 m/s) and on the approach to it (by ≈0.1 m/s), and further mostly more intensive washout in the quarry (up to 1m) and along the channel (up to 30 cm), which is connected with flow speed lowering. Water levels in the presence of the quarry decrease throughout the calculated area, in the vicinity of the bridge section water levels in the presence of the quarry are lower by 3 - 5 cm for the flow of 30000 m^3 /s in comparison with the model without the quarry, and for the flow 39400 m^3 /s - by 1 - 4 cm. Thus, the presence of the quarry leads to the landing of water levels in the alignment of the bridge up to 5 cm, and in the head of the quarry up to 10-12 cm.

Water levels in the crossing section after the construction of the quarry decrease by several centimeters, and to the greatest extent in the deep-water part and in the territory of the quarry itself. Current velocities decrease in the section of the bridge mainly by 0.1-0.3 m/s, but in some sections even more. Bottom deformations, on the contrary, are mainly positive, i.e., there is a kind of "general rewashing" of ground in the bridge alignment, except for local areas.

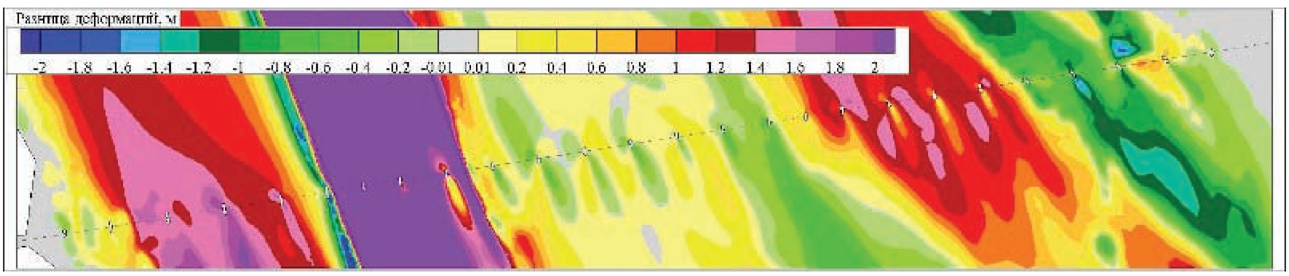
However, it should be noted that all these bottom changes will take place within the first tens of centimeters per one flood of rare recurrence, and in the vast majority of cases will be minimal, and cannot affect the choice of design solutions in any way. In this regard, an additional simulation of the situation for the period of 100 years (12 high floods) has been performed.

Deformations of the reservoir bottom, due to the uncertainty of the hydrological situation forecast and unpredictability of anthropogenic factors, it is impossible to forecast with high accuracy quantitatively, especially for a century period. However, the main tendencies of bottom deformation in the bridge area, predicted by numerical modeling, are quite clear and explainable from the point of view of reservoir bottom deformations development in time.

According to the results of calculations with the bridge without the quarry for the century period, it was obtained that flow velocities will change insignificantly, water levels will decrease insignificantly, up to 4-6 cm in the alignment of the bridge.

During modeling, considering the quarry, it was found that it influences bottom reshaping, including changing conditions of connection of the main (flooded channel of Volga River) and additional (flooded floodplain channel) fairways, as well as leading to sedimentation under the right bank in alignment of the bridge on the value up to 2-3 m. The quarry itself from the upstream side is subject to silting (sedimentation), but this process is quite long-term and can take hundreds of years. The matter is that the quarry is stretched along the channel (near the fairway), and its width is only about 10% of the river width. Therefore, it intercepts only a small portion of the river's solid flow. The velocity field is generally flattened while maintaining the same velocity values. Water levels drop by 8 cm on average (from 10 to 11 cm in the upper part to 6 to 7 cm in the lower part), which is largely due to the impact of the quarry, which has increased the area of the river cross-section.

The scour in the quarry itself can reach 5-7 m, and the total scour under the bridge in some sections will not exceed 1.5-2.0 m. It is interesting that the presence of the quarry reduces the intensity of deformation and scour depth in the side channel (the second fairway) compared with the variant without the quarry, which leads to some reduction in the size of scour at piers 19-22 (Figures 6,7). The quarry as if draws a part of the water flow to itself, reducing the share of the flow that enters the side channel. Current velocities with regard to the quarry will change within the range of plus 0.2 m/s - minus 0.1 m/s. Water levels in the bridge alignment will "sit" by 6-8 cm.



<u>Figure 6</u>. Difference in channel deformations over 100 years in the models with the bridge in the presence and absence of the quarry (fragment at the bridge)

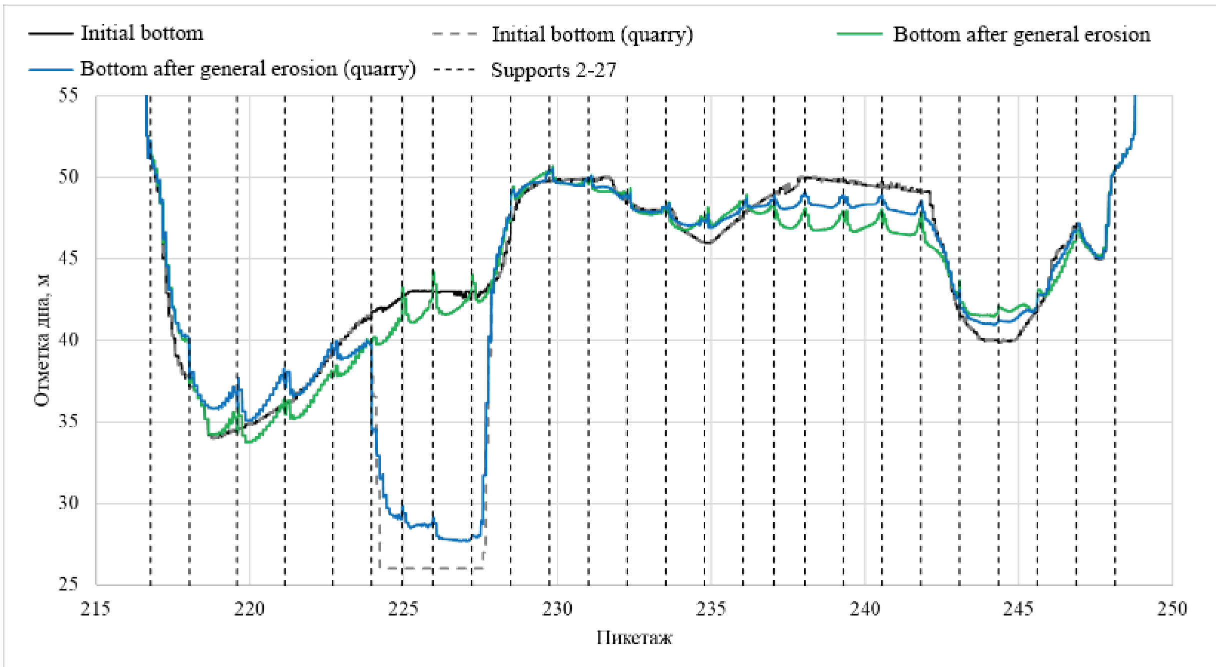


Figure 7. Profiles of the initial bottom and after 100 years in the bridge alignment with and without consideration of the quarry

CONCLUSIONS

In accordance with the stated objectives of the research work for the calculation of the possible complex impact during the spring ice drift on the temporary structures built for the construction of the bridge over the Volga River (ice loads, support, overflow). As well as modeling the deformation of the reservoir bottom near the bridge piers considering possible underwater sand pit development on the M-12 "Moscow-Nizhny Novgorod-Kazan highway under construction", the initial data for modeling were prepared and the scenarios for the modeling were developed.

The main conclusions are as follows:

1. ice phenomena, which may appear on the investigated section, do not pose a threat for the working bridge (which was confirmed in 2021) and for the designed bridge crossing.

2. the bridge piers have an insignificant influence on the hydrodynamic parameters and deformations of the reservoir bottom in the case of the high-water level (1% probability), in the spring period (10% probability) if ice phenomena occur, and in the long term (for 100 years).

3. At quarry excavations more intensive deformations of a reservoir bottom are observed, especially in the long time period. However, these phenomena are not dangerous for the bridge piers due to the actual location and configuration of the active quarry.

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мических процессов в водных объектах и их водосборных бассейнах, создание на основе разработанных моделей технологий поддержки решений в сфере водной безопасности для информационной модернизации водохозяйственной отрасли России”)

REFERENCES

1. Proektnaya dokumentaciya DSiR-2020-1163 Razdel 1. Poyasnitel`naya zapiska Podrazdel 2. Otchetnaya dokumentaciya po rezul`tatam inzhenerno-geologicheskix izy`skanij Chast` 1. Kniga 1. Poyasnitel`naya zapiska DSiR 2020-1163-P1-IGI-2.1.1 Tom 2.1.1 Moskva. 2020 (in Russian, unpublished).
2. Proektnaya dokumentaciya DSiR-2020-1163 Razdel 1. Poyasnitel`naya zapiska Podrazdel 2. Otchetnaya dokumentaciya po rezul`tatam inzhenerno-geologicheskix izy`skanij Chast` 1. Kniga 1. Poyasnitel`naya zapiska DSiR 2020-1163-P1-IGI-2.1.1 Tom 2.3.11 Moskva 2020(in Russian, unpublished).
3. **Belikov V.V., Aleksyuk A.I.** Modelimelkojvody` v zadachaxrechnojgidrodinamiki. Monografiya [Shallow water models in problems of river hydrodynamics. Monograph] M.: RAN, 2020. – 346 s. (in Russian)
4. **Vasil'eva E. S., Aleksyuk A. I., Belyakova P.A., Belikov V. V., Fedorova T.A.** (2019) Numerical Modeling of the Behavior of a Destructive Rain Flood on a Mountain River . Journal ofWater Resources,vol. 46, no. S1, pp. 43-55. doi:10.1134/S0097807819070169.
5. **Belikov V. V., Aleksyuk A. I., Borisova N.M., Fedorova T. A**. (2019) Use of Accumulation Basins to Reduce Silting of Reservoirs of Hydroelectric Power Plants Located on Mountain Rivers. Journal of Power Technology and Engineering, vol. 53, no. 4, pp. 429-439. doi:10.1007/s10749-019-01095-9.
6. **Fedorova T. A., Vasil'eva E. S., Belikov V.V.** (2020) Numerical Simulation of Triangular Dam Overflow. Journalof Power Technology and Engineering, vol. 54, no. 3,pp. 354-357. doi: 10.1007/s10749-020-01215-w.
7. **Belikov V.V., Aleksyuk A.I., Borisova N.M., Rumyantsev A.B., Glotko A.V.** (2022) Estimation of the Level of Floodplain Inundation in the Lower Don under the Effect of Economic Activity. Retrospective Hydrodynamic Modeling. Journalof Water Resources,vol. 49, no. 6,pp. 941-949. doi: 10.1134/S0097807822060021.
8. **Vasil`eva E.S., Belikov V.V., Glotko A.V.** (2022) Chislennoe modelirovanie kolichestvenny`x parametrov proxozhdeniya rasxodov vody` cherez Uspenskuyu plotinunu r. Klyaz`me. [Numerical modeling of the quantitative parameters of the passage of water flow through the Uspenskaya dam on the river. Klyazma]. Gidrotexnicheskoe stroitel`stvo, № 5,s. 30-35 (in Russian).
9. **Vasil`eva E.S., Belikov V.V., Glotko A.V.** (2022) Chislennoe modelirovanie volny` prory`va gidrouzla № 10 Belomorsko-Baltijskogokanala. [Numerical modeling of the breakthrough wave of the hydroelectric complex No. 10 of the White Sea-Baltic Canal].Gidrotexnicheskoestroitel`stvo, № 7,s. 25-29 (in Russian).
10. **Aleksyuk A.I., Belikov V.V.** Programmny`jkompleks STREAM 2D CUDA dlyaraschetatechenij, deformacijdnaiperenosazagryaznenij v otkry`ty`xpoto-kax s ispol`zovaniemtexnologij Compute Unified Device Architecture (nagraficheskixprocessorax NVIDIA). Svidetel`stvo o gosudarstvennojregi-straciiprogrammdlya E`VM № 2017660266 ot 20.09.2017 (in Russian).
11. **Aleksyuk A.I., Belikov V.V. (**2017) Modeli-rovanie techenijmelkoj vody` s obla-styamiobmeleniyairazry`vamidna. Vy`chislitel`naya matematika i matematicheskaya fizika, T. 57. № 2. S. 316-338 (in Russian).

12. **Aleksyuk A.I., Belikov V.V.**(2017) Simulation of shallow water flows with shoaling areas and bottom discontinuities. Journalof Comput. Math. Math. Phys., vol. 57, no.2, pp. 318–339.
doi:10.1134/S0965542517020026
13. **Aleksyuk A.I., Belikov V.V.** (2019) The uniqueness of the exact solution of the Riemann problem for the shallow water equations with discontinuous bottom. Journal of Computational Physics, vol. 390, pp. 232-248.doi:10.1016/j.jcp.2019.04.001
14. **Aleksyuk A.I., Malakhov M.A., Belikov V.V.**(2022) The exact Riemann solver for the shallow water equations with a discontinuous bottom. Journal of Computational Physics, 450, 110801.
doi: 10.1016/j.jcp.2021.110801.
15. **Aleksyuk A.I., Malaxov M.A., Belikov V.V.** Reshatel` zadachi Rimana dlya uravnenij melkojvody` s razry`vny`mdnom. Svidetel`stvo o gosudarstvennoj regi-stracii programmy` dlya E`VM №2020660617, 2020 (in Russian).
16. **Belikov V.V., Borisova N.M., Aleksyuk A.I., Rumyantsev A.B., Shurukhin L.A., Glotko A.V.** (2018) Hydraulic substantiation of the Bagaevskaya hydro complex project based on numerical hydrodynamic modeling.Journal of Power Technology and Engineering, vol. 52, no. 4, pp. 372-388.
doi:10.1007/s10749-018-0962-9.
17. **Rumyantsev A. B., Borisova N. M., Belikov V. V.**(2022) Assessing the Hazard Due to the Effect of Heat Discharges from the Novocherkasskaya SDPP on the Hydroecological Regime of the Lower Don Taking into Account the Future Bagaevskoe Reservoir. Journal of Power Technology and Engineering,vol. 49, no. 3,pp. 448-457.doi.org/10.1134/S0097807822030125.
18. **Belikov V.V., Borisova N.M., Glotko A.V.**(2021) Numerical Hydrodynamic 2D-Simulation of the Inundation of Tulun Town on the Iya R. during Flood 2019.Journal of Water Resources, vol. 48, no. 5,pp. 713-725.
doi 10.1134/S0097807821040023.
19. **Aleksyuk A. I., Belikov V. V., Borisova N. M., Fedorova T. A.** (2018) Numerical Modeling of Non-Uniform Sediment Transport in River Channels Journal of Water Resources,vol. 45, no. S1, pp. 11-17.
doi:10.1134/S0097807818050275.
20. **Belikov, V.V. Vasil'eva E.S.**(2020) Numerical Modeling of a Hydrodynamic Accident at an Earth-and-Rockfill Dam on the Dyurso River. Journal of Power Technology and Engineering, vol. 54, no. 3,pp. 326-331. doi:10.1007/s10749-020-01210-1

СПИСОК ЛИТЕРАТУРЫ

1. Проектная документация ДСиР-2020-1163 Раздел 1. Пояснительная записка Подраздел 2. Отчетная документация по результатам инженерно-геологических изысканий Часть 1. Книга 1. Пояснительная записка ДСиР2020-1163-П1-ИГИ-2.1.1 Том 2.1.1 Москва 2020 г.
2. Проектная документация ДСиР-2020-1163 Раздел 1. Пояснительная записка Подраздел 2. Отчетная документация по результатам инженерно-геологических изысканий Часть 1. Книга 1. Пояснительная записка ДСиР2020-1163-П1-ИГИ-2.1.1 Том 2.3.11 Москва 2020 г.
3. **Беликов В.В., Алексюк А.И.**Модели мелкой воды в задачах речной гидродинамики. Монография М.: РАН, 2020. – 346 с.
4. **Vasil'eva E. S., Aleksyuk A. I., Belyakova P.A., Belikov V. V., Fedorova T.A.** Numerical Modeling of the Behavior of a Destructive Rain Flood on a Mountain River //Water Resources. – 2019. – Vol. 46, No. S1. – P. 43-55. –
doi:10.1134/S0097807819070169.
5. **Belikov V. V., Aleksyuk A. I., Borisova N.M., Fedorova T. A**. Use of Accumulation Basins to Reduce Silting of Reservoirs of Hydroelectric Power Plants Located on

Mountain Rivers // PowerTechnology and Engineering. – 2019. – Vol. 53, No. 4. – P. 429-439. – doi:10.1007/s10749-019-01095-9.

6. **Fedorova T. A., Vasil'eva E. S., Belikov V.V.** Numerical Simulation of Triangular Dam Overflow // Power Technology and Engineering. – 2020. – Vol. 54, No. 3. – P. 354-357. – doi 10.1007/s10749-020-01215-w
7. **Belikov V.V., Aleksyuk A.I., Borisova N.M., Rumyantsev A.B., Glotko A.V.**Estimation of the Level of Floodplain Inundation in the Lower Don under the Effect of Economic Activity. Retrospective Hydrodynamic Modeling. // Water Resources. – 2022. – Vol. 49, No. 6. – P. 941-949. – doi 10.1134/S0097807822060021
8. **Васильева Е.С., Беликов В.В., Глотко А.В.**Численное моделирование количественных параметров прохождения расходов воды через Успенскую плотину на р. Клязьме. // Гидротехническое строительство. – 2022. – № 5. – С. 30-35
9. **Васильева Е.С., Беликов В.В., Глотко А.В.**Численное моделирование волны прорыва гидроузла № 10 Беломорско-Балтийского канала. // Гидротехническое строительство. – 2022. – № 7. – С. 25-29
10. **Алексюк А.И., Беликов В.В**. Программный комплекс STREAM 2DCUDA для расчета течений, деформаций дна и переноса загрязнений в открытых потоках с использованием технологий ComputeUnifiedDeviceArchitecture (на графических процессорах NVIDIA). // Свидетельство о государственной регистрации программ для ЭВМ № 2017660266 от 20.09.2017.
11. **Алексюк А.И., Беликов В.В.** Моделирование течений мелкой воды с областями обмеления и разрывами дна // Вычисл. матем. и матем. физ., 2017 г. Т. 57. № 2. С. 316-338.
12. **Aleksyuk A.I., Belikov V.V.** Simulation of shallow water flows with shoaling areas and bottom discontinuities. // Comput. Math. Math. Phys., 2017, Vol. 57, No.2, P. 318–339. doi:10.1134/S0965542517020026
13. **AleksyukA.I., Belikov V.V.**The uniqueness of the exact solution of the Riemann problem for the shallow water equations with discontinuous bottom // Journal of Computational Physics, vol. 390, pp. 232-248, Aug.2019. https://doi:10.1016/j.jcp.2019.04.001
14. **Aleksyuk A.I., Malakhov M.A., Belikov V.V.** The exact Riemann solver for the shallow water equations with a discontinuous bottom // Journal of Computational Physics. 2022, vol. 450, p. 110801, 2022, doi:10.1016/j.jcp.2021.110801
15. **Алексюк А.И., Малахов М.А., Беликов В.В.**Решатель задачи Римана для уравнений мелкой воды с разрывным дном // Свидетельство о государственной регистрации программы для ЭВМ №2020660617, 2020.
16. **Belikov V.V., Borisova N.M., Aleksyuk A.I., Rumyantsev A.B., Shurukhin L.A., Glotko A.V.** Hydraulic substantiation of the Bagaevskaya hydro complex project based on numerical hydrodynamic modeling.// Power Technology and Engineering. -2018. Vol. 52, No. 4. – P. 372-388. – doi:10.1007/s10749-018-0962-9.
17. **Rumyantsev A. B., Borisova N. M., Belikov V. V.** Assessing the Hazard Due to the Effect of Heat Discharges from the Novocherkasskaya SDPP on the Hydroecological Regime of the Lower Don Taking into Account the Future Bagaevskoe Reservoir. // Power Technology and Engineering – 2022. – Vol. 49, No. 3. – P. 448-457.doi.org/10.1134/S0097807822030125
18. **Belikov V.V., Borisova N.M., Glotko A.V.** Numerical Hydrodynamic 2D-Simulation of the Inundation of Tulun Town on the Iya R. during Flood 2019 //Water Resources. -2021. – Vol. 48, No. 5. – P. 713-725. – DOI 10.1134/S0097807821040023
19. **Aleksyuk A. I., Belikov V. V., Borisova N. M., Fedorova T. A.** Numerical Modeling of Non-Uniform Sediment Transport in

River Channels // Water Resources. – 2018. – Vol. 45, No. S1. – P. 11-17. – doi:10.1134/S0097807818050275.

20. **Belikov, V.V. Vasil'eva E.S.** Numerical Modeling of a Hydrodynamic Accident at an Earth-and-Rockfill Dam on the Dyurso River // Power Technology and Engineering. – 2020. – Vol. 54, No. 3. – P. 326-331. – doi:10.1007/s10749-020-01210-1

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