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OPTIMIZATION OF DESIGN OF THE FISH-SPAWNING PASS OF THE BAGAEVSKY HYDROELECTRIC COMPLEX USING NUMERICAL 2D MODELING

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Abstract: The paper addresses numerical hydrodynamic modeling of water and sediment transport through the fish passage and spawning channel of the Bagaevsky hydroelectric complex on the Don River. The calculations are based on two-dimensional equations of shallow water and sediment transport implemented in the STREAM 2DCUDA software package. The paper gives recommendations on changing the longitudinal profile and configuration of the inlet section, as well as on increasing the roughness coefficient of the bottom and sides of the channel to ensure fish protection requirements.

Keywords: numerical modeling, shallow water equations, fish-spawning pass, flow rate, siltation, design optimization

ОПТИМИЗАЦИЯ КОНСТРУКЦИИ ПРОЕКТИРУЕМОГО РЫБОХОДНО-НЕРЕСТОВОГО КАНАЛА БАГАЕВСКОГО ГИДРОУЗЛА С ПОМОЩЬЮ ЧИСЛЕННОГО 2D-МОДЕЛИРОВАНИЯ

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Аннотация: Рассматривается численное гидродинамическое моделирование пропуска воды и наносов через рыбоходно-нерестовый канал Багаевского гидроузла на р. Дон. В расчетах применяются двумерные уравнения мелкой воды и транспорта наносов, реализованные в программном комплексе STREAM 2DCUDA. Даются рекомендации по изменению продольного профилядна и конфигурации входного участка, а также по увеличению коэффициента шероховатости дна и бортов канала для обеспечения рыбоохранных требований.

Ключевыеслова: численное моделирование, уравнения мелкой воды, рыбоходно-нерестовый канал, скорость течения, заиление, оптимизация конструкции

INTRODUCTION

Bagayevsky hydroelectric power plant (BHPP) is a projected low-pressure hydroelectric power plant on the Don River in the Rostov region. The BHPP is located 4.4 km downstream of the inflow of the Manych River. The BHPP will ensure safe navigation conditions and the required track dimensions (80 m width, 4 m depth, 500 m radius of curvature) for unobstructed through passage of vessels along the Lower Don River during the entire navigation period.

Preliminary assessment of the consequences of the BHPP construction in terms of the fishery complex gives an extremely unfavorable forecast. The main reason for this is that the Bagayevskaya dam will cut off migration routes to fish spawning grounds. In order to overcome this problem, i.e., to separate the traffic flows of transport vessels and fish movement routes, a fish passage and spawning channel (FSC) of 5350 m length with a complex configuration was designed separately from the navigable fairway (Fig. 1).

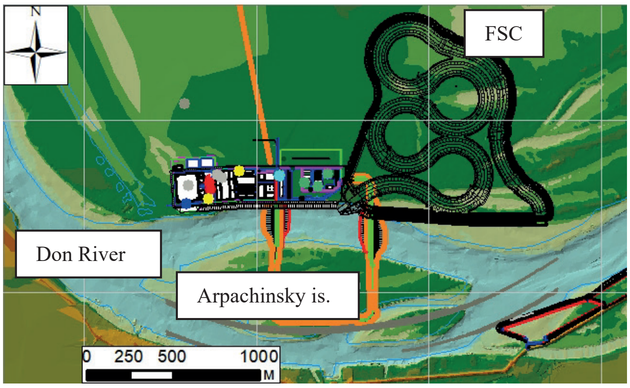

Figure 1. Scheme of the third stage of the BHPP construction period

The objective of this study is numerical modeling of FSC operation modes (Fig. 2) of the designed BHPP, determination of flow velocity characteristics along the length and width of the fish passage, forecasts of sediments at the fish passage channel and structures on it, selection of modes of hydraulic regulation of the channel.

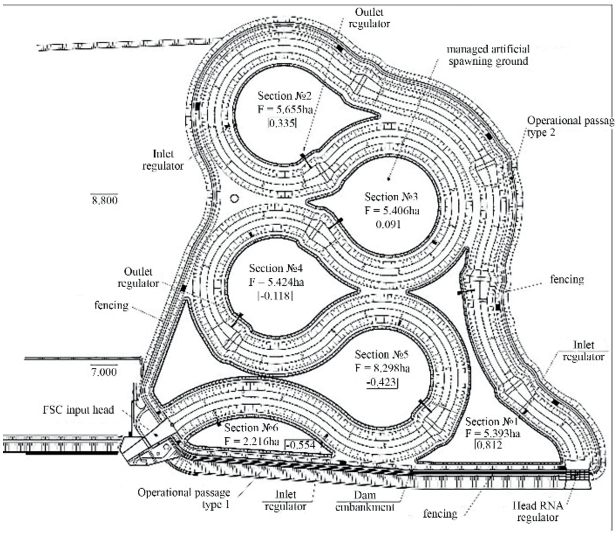

Figure 2. Schem Inlet regulatore of the FSC.

NUMERICAL HYDRODYNAMIC MODEL OF FSC

To calculate the hydrodynamic parameters of water flow and FSC siltation, we used the software package STREAM 2D CUDA [1], based on the original numerical algorithm for solving two-dimensional equations of shallow water on an uneven bottom. The latest version of STREAM 2D CUDA software package implements the new algorithm described in [2, 3]. The algorithm provides uniqueness and high accuracy of the solution in areas with complex bottom topography and hydraulic structures [4-6] and is parallelized on NVIDIA graphics processor with the use of CUDA technology to accelerate calculations. The algorithm, validation of the numerical model and numerous examples of applications to various problems of river hydraulics and hydrodynamics are also presented in the monograph [7].

Hybrid triangular-quadrangular meshes of irregular structure were used to build the FSC model. Such meshes are well adapted to the planned outlines of the calculation area and flow peculiarities. The schematization of the computational area on the slopes of dams, in artificial spawning reservoirs was carried out on the basis of a triangular grid with variable spacing. In the channel of the FSC, on its slopes, along the crests of dams, a quadrangular curvilinear grid was constructed (Fig. 3).

To construct a digital model of the FSC topography, the marks on the bottom of the spawning grounds, along the crests of the dams, the bottom of the inlet headrace and the head regulator of the FSC were entered from the provided drawings. Only two marks were given for the bottom of the FSC tract: at the inlet headrace -2.5 m and at the head regulator 0.25 m. Therefore, along the entire length of the FSC tract (≈5.3 km), the bottom marks were linearly interpolated between these two marks. As a result, the slope along the bottom of the RNA tract was ≈0.0005. The obtained DEM, interpolated on the computational grid, is presented in Fig. 4.

Since the calibration of this model is impossible due to the actual absence of the FSC object and its physical model in the hydraulic flume, the roughness coefficients in the calculation were initially assumed to be 0.025 for the bottom of the FSC tract, and 0.035 for the bottom of spawning grounds, based on the experience of previous works on the bottom of the FSC tract, on the crests and slopes of dams.

The boundaries of the hydrodynamic model of the FSC are the head regulator and the inlet headrace. The main requirement for the functioning of the FSC is to allow fish passage from the lower reach of the BHPP through the FSC pathway to the upper reach. Therefore, velocities in the channel should not exceed 1.1 m/s.

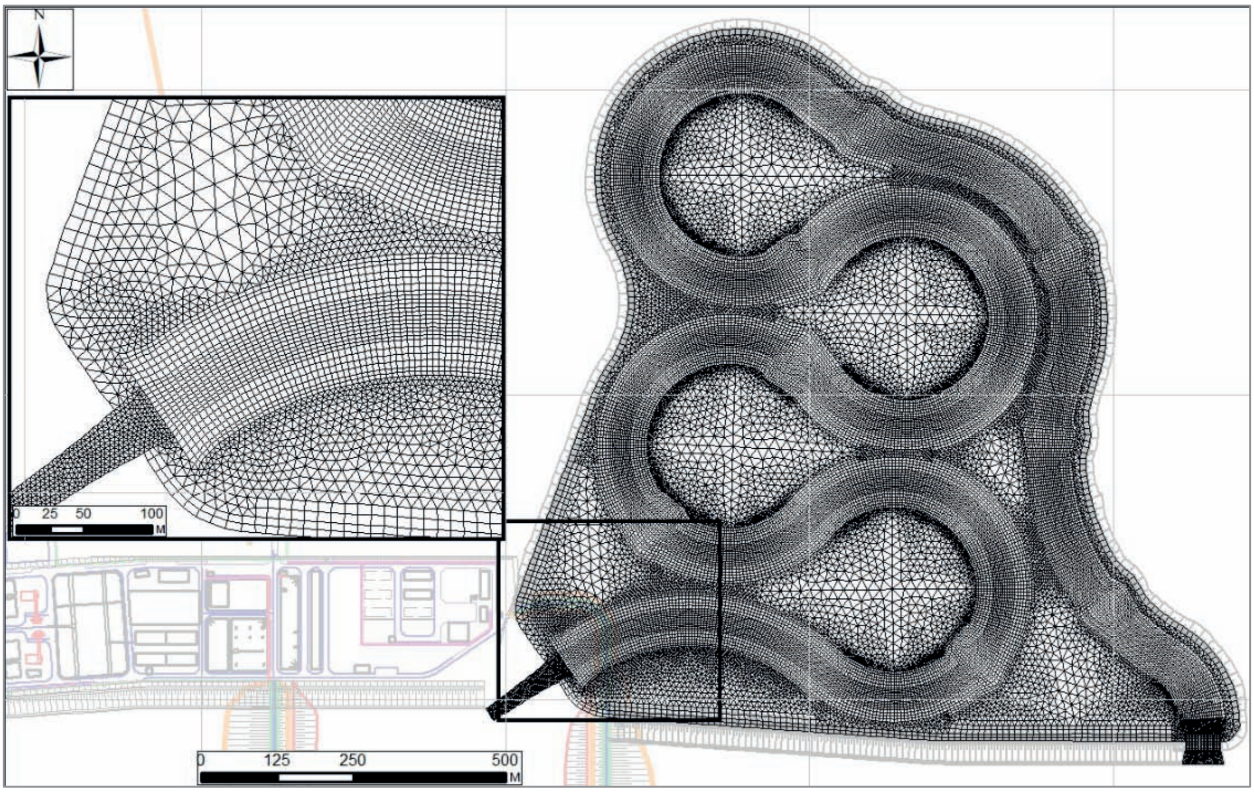

Figure 3. General view and fragment of the input section of the FSC calculation grid

CALCULATION RESULTS FOR LOW-WATER CONDITIONS

As a first computation, a low-water period was considered when the water level in the upstream BHPP was 2 m (head regulator) and in the downstream 0 m (inlet headrace). These water levels were set at the boundaries of the model and the calculation continued until "establishment", i.e., until the water discharge in the whole calculation area becomes the same and does not change anymore. For the case of the original bottom (Fig. 4), this calculation resulted in a flow rate of 82.35 m3/s in the FSC channel. The longitudinal profiles of water level and flow velocity are shown in Fig. 5. As a result, the water depth is ≈0.8 m greater at the inlet headrace compared to the depth at the head regulator, and the maximum velocity along the longitudinal channel is 1.3 m/s. This is higher than the maximum permissible maximum value of 1.1 m/s. Considering the unfinished junction of the head regulator and the FSC path, it became necessary to correct the initially proposed bottom variant.

The authors proposed a new variant of the bottom, in which changes occurred only in the marks along the FSC tract and at the junction of the head regulator with the FSC tract. The new version of the bottom mark of the FSC tract at the inlet header was taken -2 m, at the head regulator 0 m, and along the whole length of the RNA tract (≈5.3 km) the bottom marks changed linearly between these two. As a result, the slope along the new bottom of the FSC tract decreased and became ≈0.00038. At the junction of the head regulator and the tract, the bottom elevation behind the gates was reduced to -4 m, and the head regulator elevation was gradually increased from 0.5 m to the tract elevation of 0 m (Fig. 6).

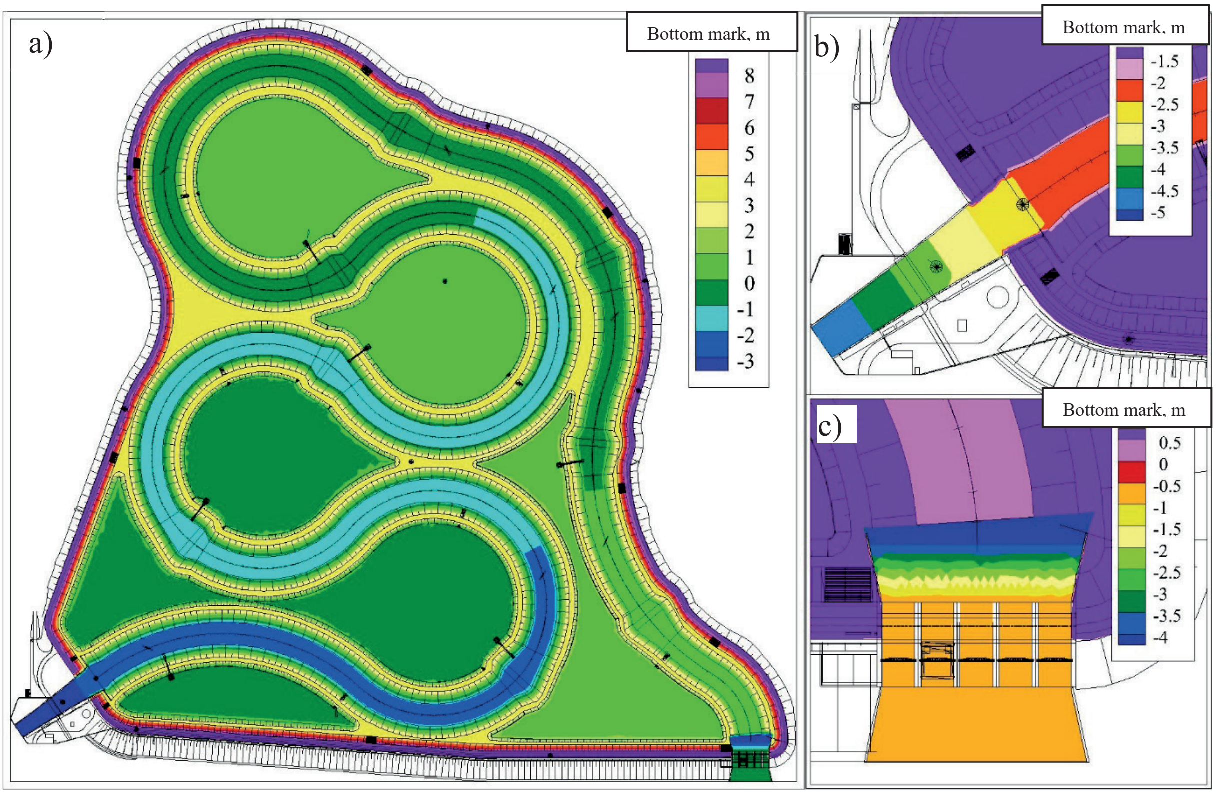

Figure 4. Initial topography of the FSC surface. General view (a), inlet header (b), head regulator (c)

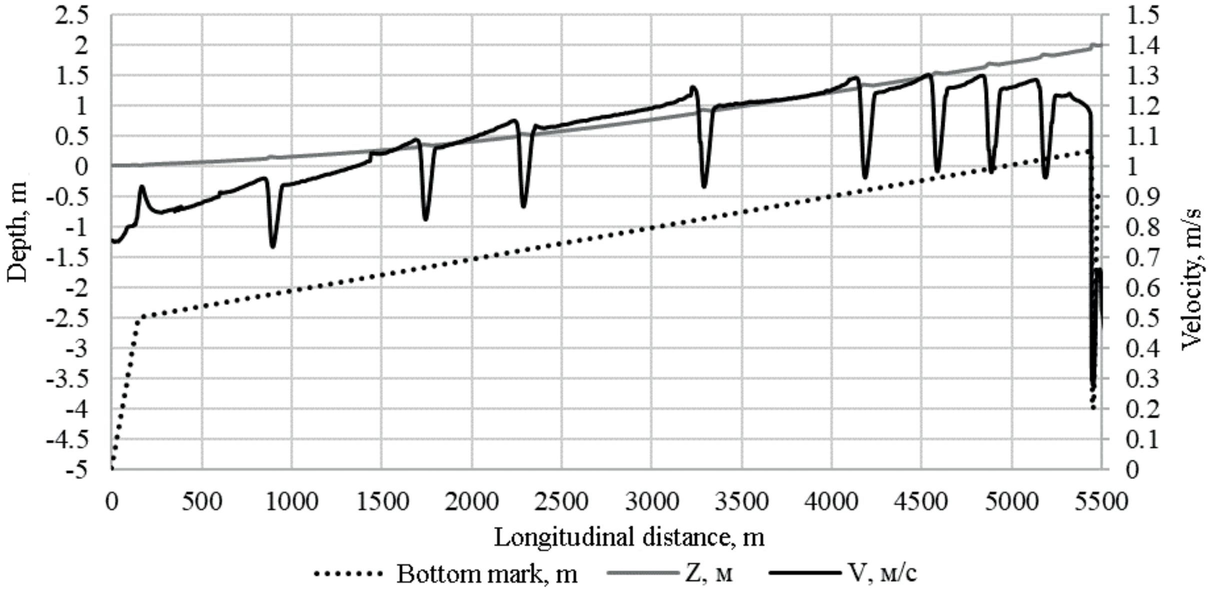

Figure 5. Longitudinal profiles of water level and flow velocity in the FSC under low-water conditions at the initial bottom

The same low water level case was recalculated on the edited FSC bottom, i.e., the water depth was set to 2 m in the upstream and 0 m in the downstream. Under these conditions, a constant flow rate of 88.44 m^3/s was established in the FSC. The difference of water depths at the FSC channel boundaries decreased to 6 cm. However, it should be noted that the maximum velocity in the channel remained 1.3 m/s, which is unacceptable for FSC functioning.

The next step was an attempt to reduce the velocity in the FSC channel by increasing the roughness coefficient along the bed and slopes of the FSC tract to 0.03 (corresponding to pebble backfilling of the bed and slopes). Under these conditions, a constant flow rate of 76.11 m^3/s was established in the FSC. The longitudinal profiles of water level and flow velocity are shown in Fig. 7 for two values of roughness coefficients in the channel 0.025 and 0.03. The water depth difference at the FSC channel boundaries decreased to 4 cm. The maximum velocity in the FSC channel decreased to 1.1 m/s.

It should be noted that the created numerical hydrodynamic model of the FSC allows to carry out further optimization of the fish passage design. For example, it allows to consider variable channel depth and variable lining roughness coefficient along the length of the channel. However, this requires clear criteria (restrictions) on the hydrodynamics of the flow (velocity, depth), formulated by the fish protection organization.

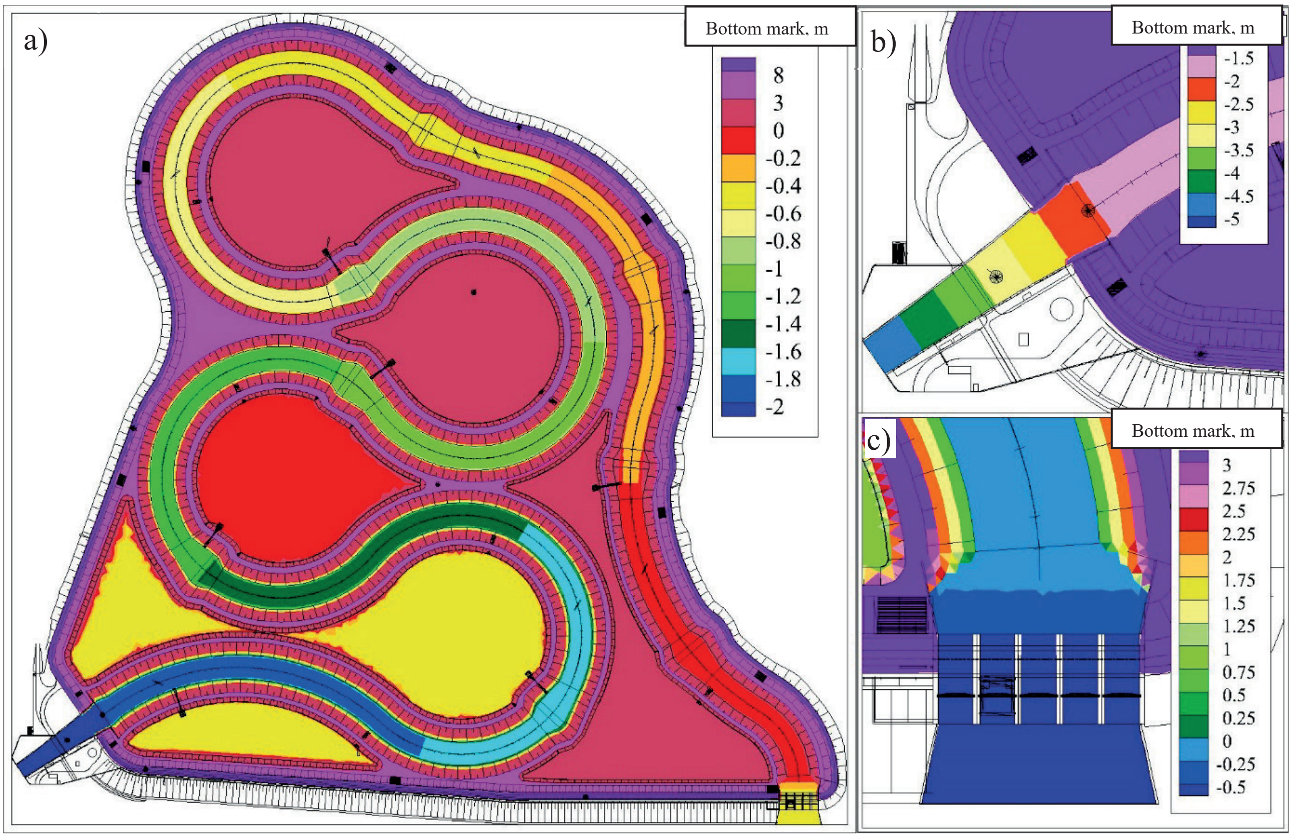

Figure 6. Edited topography of the FSC surface. General view (a), inlet header (b), head regulator (c)

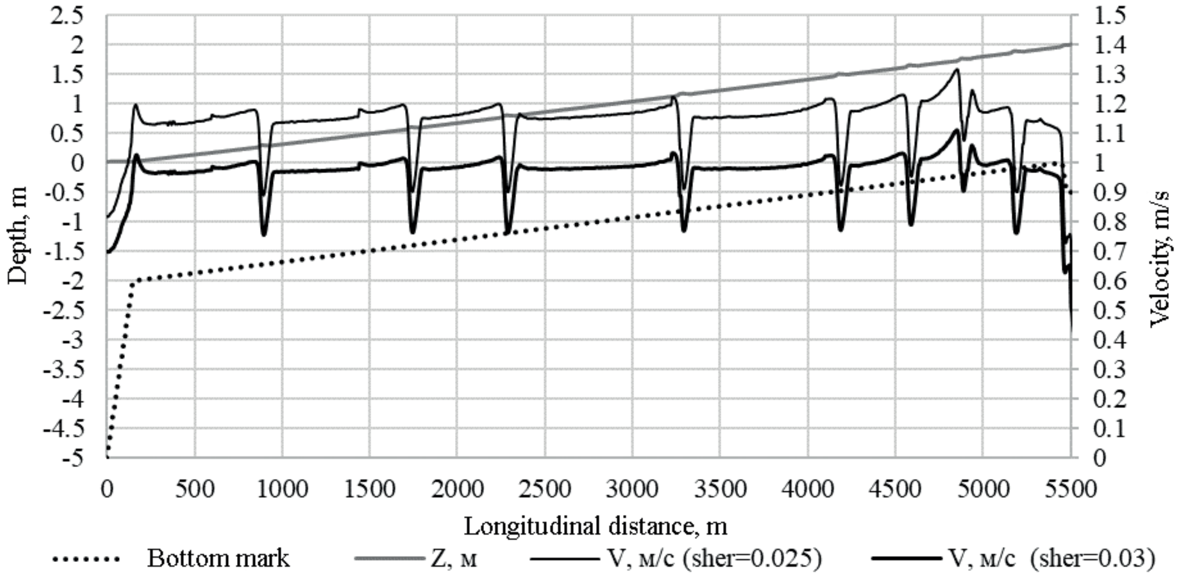

Figure 7. Longitudinal profiles of water level and flow velocity in the FSC under low-water conditions on the edited bottom

CALCULATIONS FOR 10% AND 1% SECURITY OF FLOOD

To run the calculations for 10% and 1% secured floods (7800 and 13200 m3/s respectively), it is necessary to set water level values in the upstream and downstream of the BHPP at the FSC. Based on the results of numerical hydrodynamic modeling of the BHPP in 2018. [8], the water levels at the BHPP FSC inlet and outlet were taken as 5.455 m and 5.56 m for the 10% flood security and 6.746 m and 6.815 m for the 1% flood security, respectively. These water levels were taken as boundary conditions for the FSC model at the newly edited bottom and with a roughness of 0.03 in the FSC channel. The calculation resulted in a flow rate of 223 m3/s for the 10% impaired flood and 229 m3/s for the 1% impaired flood in the FSC. The resulting longitudinal water levels and velocities are shown in Figures 8 and 9.

For the 10% and 1% floods, the entire FSC area inside the levees is flooded, as the FSC channel levees are 3.4 m high and overflow during floods. Swirling currents occur in the area of spawning grounds of Sections 1 and 5 (Figure 10).

FSC SILTATION CALCULATIONS

Calculation of FSC siltation was carried out for a flow rate of 10% probability. Water levels of 5.455 m and 5.56 m were set at the boundaries of the FSC, and a constant flow rate of 223 m^3/s was set in the FSC during the calculation process. As there are no data on the concentration of suspended sediment in the water flowing down the river (which is what will enter the FSC, as the inlet threshold is located 4 m above the river bottom), two options were considered: saturated water flow (natural (equilibrium) concentration of suspended sediment) and water flow with a given sediment concentration of 0.1 g/litre. The size of suspended sediment particles in both cases was assumed to be 0.05 mm. The results of the 18-day siltation calculation are shown in Fig. 11.

Regardless of the inlet concentration, the pattern of siltation is the same in both cases. The sediment is deposited on the head regulator upstream and downstream of the gates, then due to the high velocities in the channel of up to 0.9 m/s (see Fig. 10a), the sediment is not deposited in the channel of the FSC channel, but is deposited on the crest of the slope of the FSC channel and the slopes of the bund dam, but a little further on, as velocities decrease, sediment begins to be deposited in the channel itself. In the calculated variants, sediment deposition with a given sediment concentration of 0.1 g/l showed more intensive siltation (the thickness of the siltation layer is approximately 2 times greater).

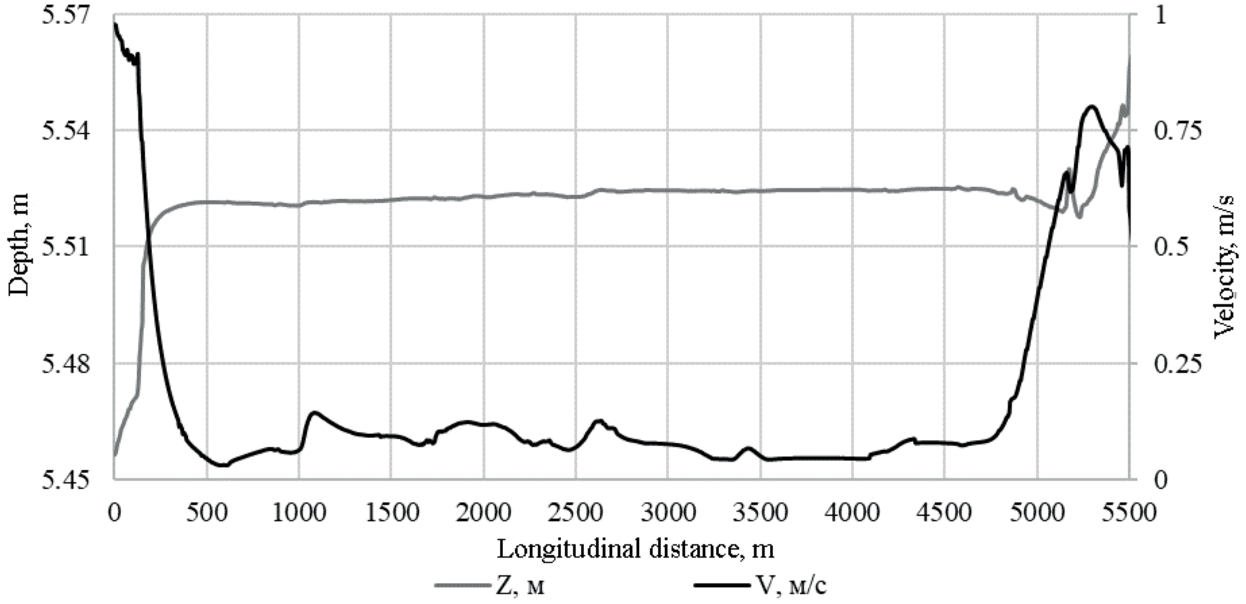

Figure 8. Longitudinal profiles of water level and FSC flow velocity during modeling of a 10% probability flood on the edited bottom with increased roughness in the channel

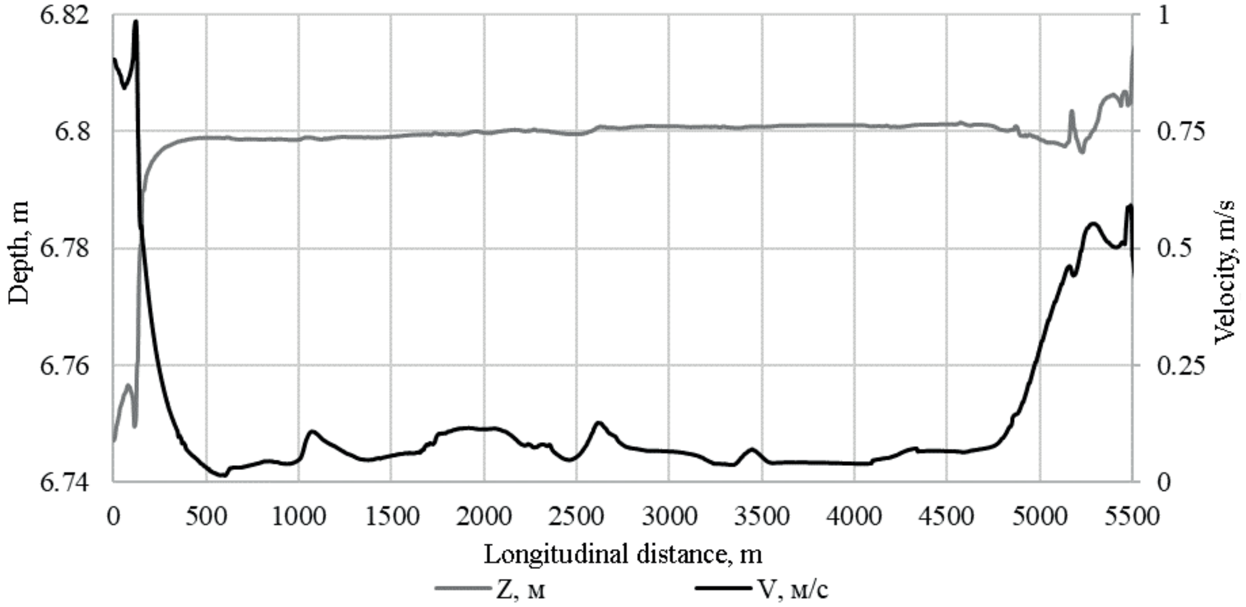

Figure 9. Longitudinal profiles of water level and FSC flow velocity during modeling of a 1% probability flood on the edited bottom with increased roughness in the channel

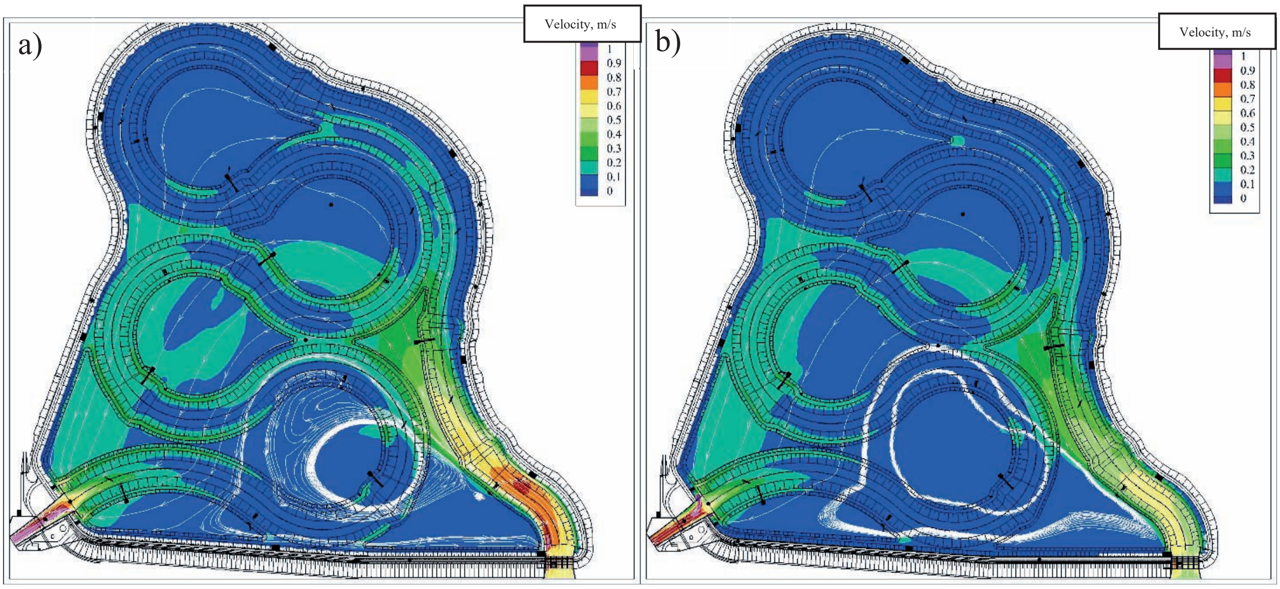

Figure 10. Water velocities and current lines in the FSC during simulations of a 10% (a) and 1% (b) secured flood on an edited bottom with increased roughness in the channel

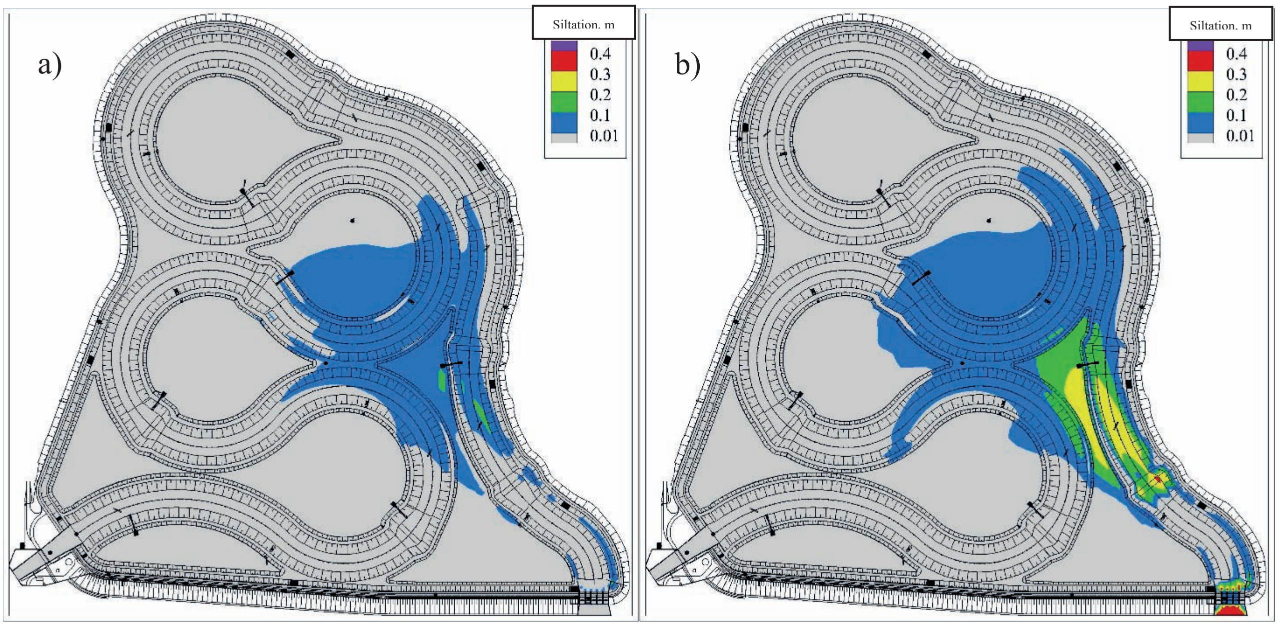

Figure 11. Siltation of the FSC in a simulated 10% flood event with natural sediment concentration at the inlet (a) and with an inlet sediment concentration of 0.1 g/l (b). 18 days

CONCLUSIONS

The article presents three variants of calculations for low-water conditions. The first calculation was performed for the design version of the FSC, reconstructed according to the drawings. It turned out that the maximum velocity in the fish passage channel exceeds 1.3 m/s, the flow depth along the length of the channel is essentially uneven, and a smooth junction between the bottom marks of the head regulator of the FSC and the inlet section of the channel is not ensured. When the model was corrected, the hydraulic parameters of the FSC improved, the depths along the length were equalized, but the maximum velocity decreased insufficiently. Then the calculation was performed with a slightly increased roughness coefficient of 0.03 in the channel. At such roughness maximum flow velocities in the FSC do not exceed 1.1 m/s, total water flow rate in the channel was 76.11 m^3/s, water depth in the channel was 2.0 m with fluctuations of several centimeters.

For the last variant, calculations of hydraulic operation of FSC in 10% and 1% floods were performed. For these modes, the flow rates through the FSC are very close, equal to 223 m^3/s and 229 m^3/s, respectively. In the case of the 10% and 1% floods, the entire FSC area inside the levees is flooded, as the FSC channel levees are 3.4 m high and overflow during floods. Swirling currents occur in the area of the spawning grounds of Sections 1 and 5. Current velocities in the FSC channel do not exceed 1 m/s. However, there are localized zones with slightly higher velocities in the areas of the head regulator and inlet headrace. Siltation calculations have shown insignificant (0.1-0.2 m layer) siltation in some sections, which can be easily eliminated after flooding.

Based on the obtained modeling results, it is recommended to change the slope of the channel bottom in comparison with the design slope, to improve the junction of the FSC head regulator with the channel inlet section, to create a coating of the channel bottom and sides providing increased roughness of 0.03 Manning (e.g., bottom vegetation in the channel or filling the bottom and sides with pebbles with a diameter of 0.1 m).

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