GEOGRAPHY AND TOURISM, Vol. 6, No. 1 (2018), 77-85, Semi-Annual Journal
eISSN 2449-9706, ISSN 2353-4524, DOI: 10.5281/zenodo.1314034

G.L. Gladkov[1], V.M. Katolikov[2]

[1] State University of Marine and River Fleet by the name of Adm. S.O. Makarova, Saint-Petersburg, Russia, email: gladkovgl@mail.ru.

[2] State Hydrological Institute, Saint-Petersburg, Russia

Channel regime and navigation conditions of the Lower Don

Abstract: The work relates to navigation conditions of the Lower Don. The research was performed on hydrological and sediment regimes of the Don River, downstream of the Kochetovsky hydraulic engineering complex. The impact of the planned Bagaevskiy Dam construction on hydraulic characteristics of the flow and deformation of the riverbed was also assessed. Materials collected during engineering and hydrometeorological surveys, the results of mathematical modelling and hydraulic studies completed as part of the design works on the facility – "The Bagaevskiy Dam construction on the Don River" – were used as input data.

Keywords: hydrological regime, channel processes downstream of the dam, riverbed deformations, navigation, mathematical and hydraulic modelling

1. Introduction

The object of the present study is the section of the Lower Don River located downstream of the Kochetovsky hydraulic engineering complex, which has the most difficult navigation conditions in the area. The Lower Don is part of the Unified Deep Water System of European Russia and is one of the most congested sections of inland waterways of international importance in the Russian Federation. The scheme of waterways of the Lower Don is shown in Fig. 1.

The hydrotechnical construction in the Lower Don basin was started in the early years of the 20th century to ensure the supply of coal, building materials and grain from the Donbass in the regions of the Sea of Azov and the Black Sea. In this context, the decision about the necessity of locking the Seversky Donets was made by the Ministry of Railways in 1903.

A graduate of N.P. Puzyrevskiy Institute of Water Transport was the project developer. He carried out detailed surveys on the Seversky Donets in 1903–1904, and the project of the cascade of a low-pressure hydrosystem was prepared by 1908. The project involved three stages of construction. The implementation of the project was aimed at enabling the navigation on the Seversky Donets from the Don to Belgorod and Kharkov by vessels with a draft of up to 1.7 m.

The first stage of the construction of the Seversky–Donets system gateways – from the mouth of the Seversky Donets to the village of Gundorovskaya (near the modern city of Donetsk) was launched in May 1911 and largely completed by autumn 1913. The construction of the Kochetovsky hydraulic engineering complex, located on the Don River, was started in 1914. The official opening of the Seversky–Donetsk river sluice system took place on 5 July 1914, a few weeks before the outbreak of the First World War.

At present, the Lower Don flow (Fig. 1) is regulated by the Tsimlyanskiy engineering complex (1952) and low-pressure cascade hydrotechnical systems – Nicholas (1975), Constantine (1982) and Kochetov (1920).

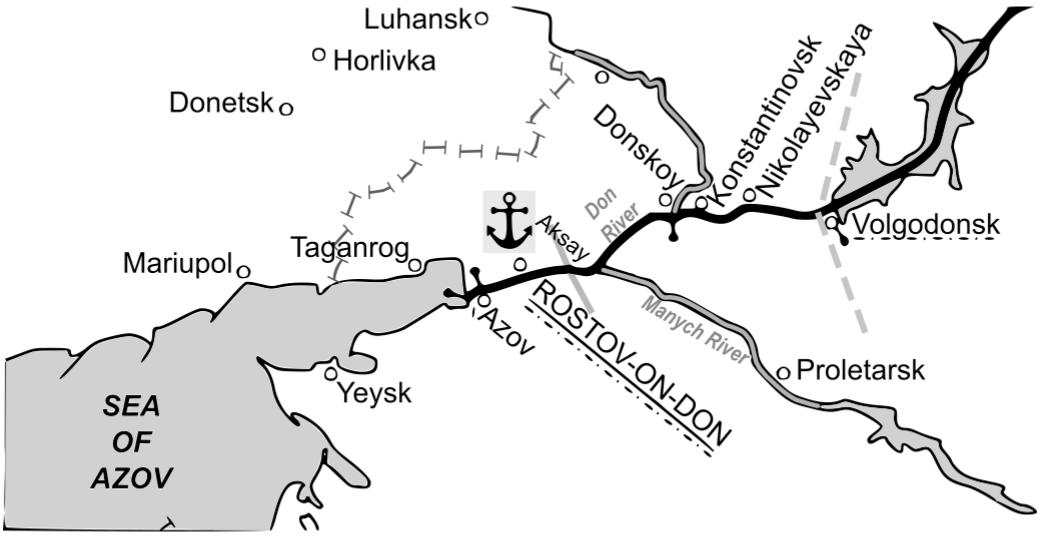

Figure 1. The scheme of the Lower Don waterways

Currently, the navigation conditions of the Lower Don are completely dependent on the water resources of the Tsimlyansk reservoir and, to a lesser extent, on the water flow in the Northern Donets River and the Manych River. During a regular water discharge from the Tsimlyansk reservoir, the guaranteed navigation depth (excluding surge phenomena of the Sea of Azov) supported by dredging is 340 cm, which is less than the depths of the Unified Deep Water System of European Russia.

2. Water-level regime and channel deformation downstream of the Kochetovsky Hydrotechnical Systems

The bottom and water levels in the studied section of the Lower Don have irreversibly decreased for the past 100 years. These changes are associated with the construction and subsequent operation of the cascade of waterworks on the Lower Don, as well as dredging works in the channel to ensure navigation conditions and mining of the river alluvium. Available data show that the decline in water levels was observed along the entire length of the considered navigable area, but the magnitude of this decline decreases with the increasing distance from the Kochetovsky hydrotechnical systems.

According to preliminary estimates, the water-level lowering downstream of the Kochetovsky hydrotechnical systems during 95% water consumption in the navigation season is about 180-190 cm. At the site of the Razdorskaya hydrological station, water levels in the same period decreased by 120-140 cm, and at the downstream Bagaevskiy station – by about 60 cm. And finally, in the section of the planned Bagayevskaya hydrotechnical complex, the water level in the hydrological conditions described above decreased by about 10–15 cm.

Channel processes downstream of the Kochetovsky hydrotechnical systems were studied in several aspects, including analysis of horizontal and vertical adjustment in the researched section of the Lower Don (Gladkov et al., 2017). After the implementation of the Bagayevskaya hydrotechnical systems, navigation problems occur mainly above the dam, in the backwater conditions.

After the commissioning of the Tsimlyansk hydrotechnical systems on the Lower Don, as a result of changes in the flow regime and due to erosion processes occurring downstream of the Kochetovsky hydrotechnical system, the depths near the riverbank and in the main current have been adjusted. Analysis of the hydrographic data for the period from 1961 to the present time shows that in the section of the Lower Don River located between the Kochetovsky hydrotechnical system and the town of Aksay, the distribution of depths in the navigable waterway has changed significantly, largely in line with changes in the channel regime downstream of the dam. Over the past decade, the intensity of bed deformations on the navigable waterway has decreased compared to the previous period.

Under the designed conditions, the greatest threat to the navigation will be posed by insufficient depths as a result of seasonal changes in the locations of riffles. In this regard, minimum depths at the shallows were analysed at this stage of the work. This analysis has shown that no significant high-altitude deformations of the riffles should be expected in the conditions of a regulated runoff.

In connection with the analysis of the planned changes in the river section and based on the materials collected during the channel surveys carried out in 2006 and 2016, the planned position of the initial profiles was corrected, which were plotted along the line of the greatest depths and along the isobaths corresponding to the expected depth of the waterway.

The results of the analysis of the obtained materials prove that to date the situation in the survey area has largely stabilised. The surveyed section shows small alternating planned differences in the channel depth. No significant unidirectional deformation has been identified in the channel section. This is primarily connected with the reduction of flood peaks by the Tsimlyanskiy reservoir and the limited water content in the river in recent years. In addition, the river banks within the boundaries of certain human settlements are protected from erosion by riverbank stabilization.

3. Impact of the planned Bagayevsky reservoir on the upstream water levels

The construction of the reservoir on the river section that has been currently exposed to anthropogenic factors will have a positive effect and some negative consequences. In this case, everything will depend on a water-level increase caused by backwater within the reservoir.

Thus, in the river section where, as a result of backwater, the water level will rise to a level not exceeding the water levels recorded in historical times (corresponding to the hydrological situation in the 1920s), we cannot talk about degradation, but rather about the restoration of the hydrological regime of the river. In other parts of the river, where floodwater levels exceed the historical usual level due to backwaters, additional flooding together with accompanying adverse consequences are possible.

Data on the water levels and water flow rates collected during observations carried out at the Lower Don since the commissioning of the Kochetovsky hydrotechnical system (Polyakov, 1930) were analysed and compared with the results of hydraulic calculations. This made it possible to estimate the extent of changes in the water-level regime of the river. The obtained data indicate that in the immediate downstream section of the Kochetovsky hydrotechnical system, the water levels can exceed the corresponding level of the normal curve for 1923-1925 only if the water discharge is equal to or less than 200 m^3/s. Thus, the creation of the Bagaevskiy reservoir with the mark NWL 2.8 m BS, virtually in the entire range of water discharge exceeding the instream flow in extremely dry years, will not affect the level and channel regime of the river in the downstream section of the Kochetovsky hydrotechnical system.

In the lower reaches of the river, the value of the additional floodplain area will increase, which consequently will have an impact on the river regime. Thus, at the section of the Razdorskaya hydrological station, additional flooding (compared to 1917-1924) will occur when water discharge is about 600 m^3/s or less. Accordingly, with a water discharge of 363 m^3/s, the value of the additional water rise in the floodplain area will be approximately 0.6 m.

At the downstream Bagaevskiy hydrological post, additional (compared to 1927) flooding associated with the construction of the dam will occur when water discharge is equal to 930 m^3/s or less. When water discharge is equal to 363 m^3/s, the value of the additional water rise in the floodplain area will be approximately 1.9 m.

Finally, additional flooding will occur upstream of the planned dam when water discharge is equal to 1,700 m^3/s or less. The value of the additional water rise in the floodplain area will be about 2.3 m.

Thus, the analysis of the water level regime of the Lower Don, carried out while taking into account the lowering of the normal water levels downstream of the Kochetovsky hydrotechnical system, allows to reduce the issue of additional flooding in the coastal zone. In comparison with the present water levels within the boundaries of the proposed reservoir, the flood range will be relatively large.

4. Flow velocity regime in the backwater zone

The construction of the reservoir will change the flow velocity regime in the backwater zone. The largest scale of flooding will occur in the river section directly adjacent to the planned barrage. The impact of the planned barrage on the water level and the flow regime will decrease along the increasing upstream distance from its location.

To analyse the impact of backwater levels on the flow velocity regime along the river, hydrological measurements of the river channel conducted in 2016 were used. According to these data, plots presenting the relationship between the flow velocity and discharges were prepared along with plots presenting the above parameters for the increased water level upstream of the projected Bagaevskiy reservoir with two values of NWL, equal to 2.8 m BS, and 2.0 m BS.

The obtained results indicate that the strongest influence of the planned reservoir on the flow velocity regime can be observed at low water discharges in the immediate vicinity of the dam. In the conditions of backwater at NWL 2.8 m BS, the flow velocity will decrease 2.4 times (at NWL 2.0 m BS – 1.9 times). At the Bagaevskiy hydrological station, this ratio is already 1.7 times lower (1.4 times). In the area of Razdorskaya, these values will be significantly lower.

However, it should be borne in mind that, as a result of significant erosion of the bottom that occurred in the upper part of the analysed section of the river between the Kochetovsky dam and the village Razdorskaya and in the downstream section, the flow velocity has significantly decreased compared to the early 1950s.

The regime of flow velocities in the researched section of the Lower Don are presented in Fig. 2. The figure presents longitudinal profiles of average vertical flow velocity along the lines of the greatest depths with the water discharges of 1,100 m^3/s and 363 m^3/s in usual and project conditions (with NWL 2.0 m BS), according to the results of hydraulic calculations.
Based on these data, we can conclude that flow velocities in the main part of the channel are sufficient to support the bed load transport along the analysed section of the river (from the downstream section of the Kochetovsky hydrotechnical system to Aksay), when discharges related to fishery permits are not exceeded.

In the upper part of the section from the dam to the mouth of the river Aksay (3,050.0–3,051.0 km along the navigable waterway), average flow velocities (with the exception of some calculated oscillations) are in the range of 0.95-1.05 $m \cdot s^{-1}$ with no trend regarding changes along the river. Under these circumstances, we

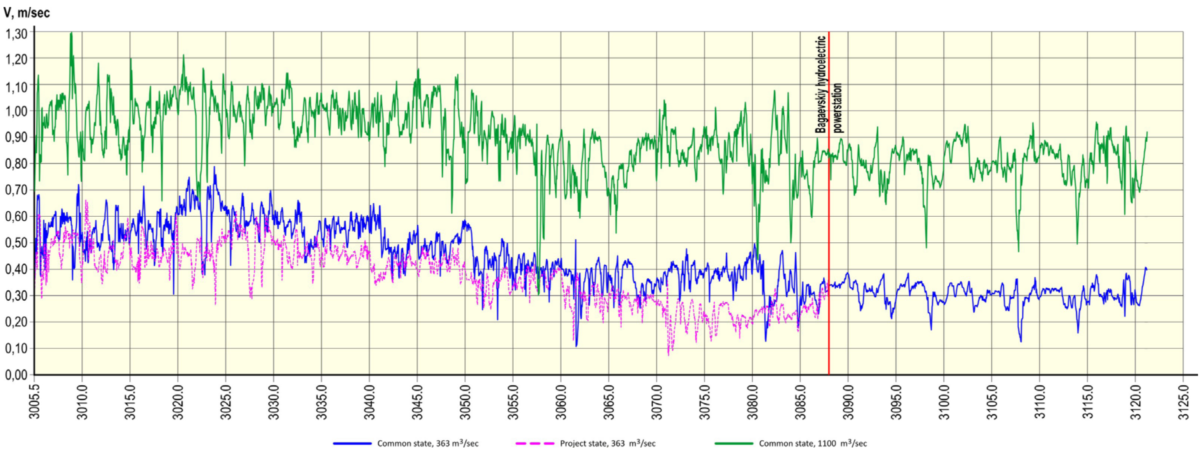

Figure 2. Longitudinal profiles of flow velocities in the navigable waterway

should expect the movement of bedload sediment as ripple marks with minor vertical and horizontal deformation of the channel.

Along the section from the mouth of the Aksay river to the estuary of the Old Don river (3,050.0-3,065.0 km), flow velocities along the river are consistently reduced and reach an average of about 0.8 $m{\cdot}s^{-1}$. Compared with the above site, a decrease in the intensity of sediment transport and the predominance of alluvium accumulation are to be expected. In this case, ripple marks are gradually flattened, similarly to the upstream section of the river.

Approximately the same values of flow velocities (0.7-0.9 $m{\cdot}s^{-1}$) will be observed in the lower reaches of the river, in the section between 3,065.0 km and the Aksay town. Moreover, the amplitude of flow velocities from the upper boundary of the section to the designed hydrotechnical system reaches a larger variation of the calculated values than in the lower part of this site.

In the autumn low-water period, the designed Bagaevskiy hydrotechnical system will work in backwater conditions. The average flow velocities along the navigation course at the water discharge of 363 m^3/s for contemporary and design conditions presented in Fig. 2 allow to estimate changes in the flow velocity in backwater conditions created at NWL 2.0 m of BS.

Under regular conditions, the flow velocity of the midstream varies along the length of the considered section of the river. Along the section from the Kochetov hydrotechnical system up to 3,020.0-3,025.0 km along the navigation route, the average flow velocity increases by 0.5–0.65 $m{\cdot}s^{-1}$. In this section, limited sediment movement and slight deformation of the bottom are possible at individual shallows.

Downstream flow velocities vary considerably. In the section from the Porechensky branching to Kh.Bagaevsky, the average water velocity gradually decreases along the navigation route. At 3,065.0-3,070.0 km along the navigation route, the flow velocity in regular conditions (without backwater conditions) will be 0.30-0.40 $m{\cdot}s^{-1}$. At such flow velocities, transport of sediments in the river ceases.

In the lower section, the tendency for reducing the water velocity along the river will continue, but with a lesser intensity. The average flow velocity values on the navigation route near the Aksay town will be about 0.30 $m{\cdot}s^{-1}$.

Thus, the results of the calculations indicate that with low water consumption without backwater conditions, transport of bedload is possible in negligible amounts in the upper third part of the analysed river section, located approximately at 3,040.0 km from the Kochetov hydrotechnical system along the navigation route. In the regular downstream conditions, the flow velocities will not be sufficient to move sediment.

In the design conditions, with a reduced flow velocity resulting from the distribution of backwater over the entire length of the analysed section, a complete cessation of sediment transport should be expected.

5. Measures to improve the navigation conditions and to maintain the riverbed in the backwater zone

At present, navigation conditions of the Lower Don are significantly limited due to problems with the movement of vessels within the meanders. Molchanovskoye and Semikarakorsk shallows and the Porechenskoe meander are the most difficult rapids on this waterway at the highest average annual volume of dredging and at the greatest radius of curvature within the meanders.

In this regard, recommendations were developed within the framework of the project for the major improvement of the navigation conditions in these areas. The effect of the planned works on the hydraulic characteristics of the flow, riverbed deformation and the water levels were also assessed.

Hydraulic calculations for different values of water discharges downstream of the dam of the Kochetovsky hydrotechnical system were performed. The results of these calculations have shown that to assess the sustainability of the proposed meander trimming measures, the amount of the discharge corresponding to the fishery water release under regular conditions should be adopted. At lower values of water discharges, under backwater conditions (in navigation period) and without backwater conditions (in non-navigation period), the transport capacity of the stream is insufficient to transport the sediment down the river.

Hydraulic calculations were performed at different water discharges for temporary conditions and conditions of straightening the navigation route in the areas of the Semikarakor meander and the Porechen meander. These calculations have shown that straightening of the navigation route does not lead to an intensification of the channel process in the sections subject to dredging and will not cause additional lowering of the water levels downstream of the Kochetovsky hydrotechnical system.

Therefore, implementation of certain measures and facilities is possible in areas where major improvements in the navigation conditions are required. All types of the planned river bank protection works, depending on their purpose and the type of construction, should be conditionally divided into three groups.

The first group of facilities for river bank protection should include capital structures, which are supposed to be situated within the boundaries of towns. Their inclusion in the project of the hydrotechnical system and the reservoir is connected with the need to protect the shoreline in urban boundaries from flooding and possible destruction.

The second group of measures for bank protection should include such facilities, which will need to be built on the river banks outside the towns to protect the banks from possible erosion by the stream, especially during spring flood conditions and fishery water releases. Particular attention in this case should be paid to fishery releases, as proper management of water resources after the construction of the dam can have positive effects. Such facilities should prevent uncontrolled erosion of the river banks, which could eventually lead to the deterioration of shipping conditions.

Finally, the third group of structures should include facilities designed to protect the river banks from the impact of waves generated by passing vessels at a normal backwater level in the reservoir. This impact will be significant, particularly if the navigation rout is close to the river bank.

6. Analysis of the Bagaevsky hydraulic engineering structures on the hydraulic model

Modern design of hydraulic structures incorporates hydraulic modelling of these structures and sections of riverbeds, within which these structures are located. There are various methods of modelling, but in principle all of them are divided into two groups: methods of mathematical hydrodynamic modelling, starting with simple hydraulic calculations, and methods of physical hydraulic modelling on a spatial hydraulic rigid or deformable models, starting with experiments in hydraulic flumes. The worldwide practice of the optimal design of hydrotechnical objects follows the path of using "hybrid" modelling, which combines both mathematical methods and methods of physical modelling on spatial hydraulic models (Gladkov et al., 2016).

The methodology of designing and constructing rigid spatial hydraulic models was developed at the Department of Channel Processes of the State Hydrological Institute during the long-term experimental studies. To date, the method of hydraulic modelling has been successfully tested in the study of a large number of hydraulic structures and engineering activities on water bodies (Klaven et al., 2011).

Experimental studies of the Bagaevsky hydraulic engineering structures were carried out at the Hydraulic Laboratory of the State Hydrological Institute (SHI) on the spatial hydraulic model of the Don River section and the structures built at a scale of 1:100 (see Figure 3).

Hydraulic studies of the model were carried out for several versions of the channel conditions, corresponding to different stages of construction of the designed structures. The modern natural condition of the Don riverbed was adopted as the first option, for which the hydraulic model was verified with the actual data.

The second option for conducting the research was the so-called "construction case".

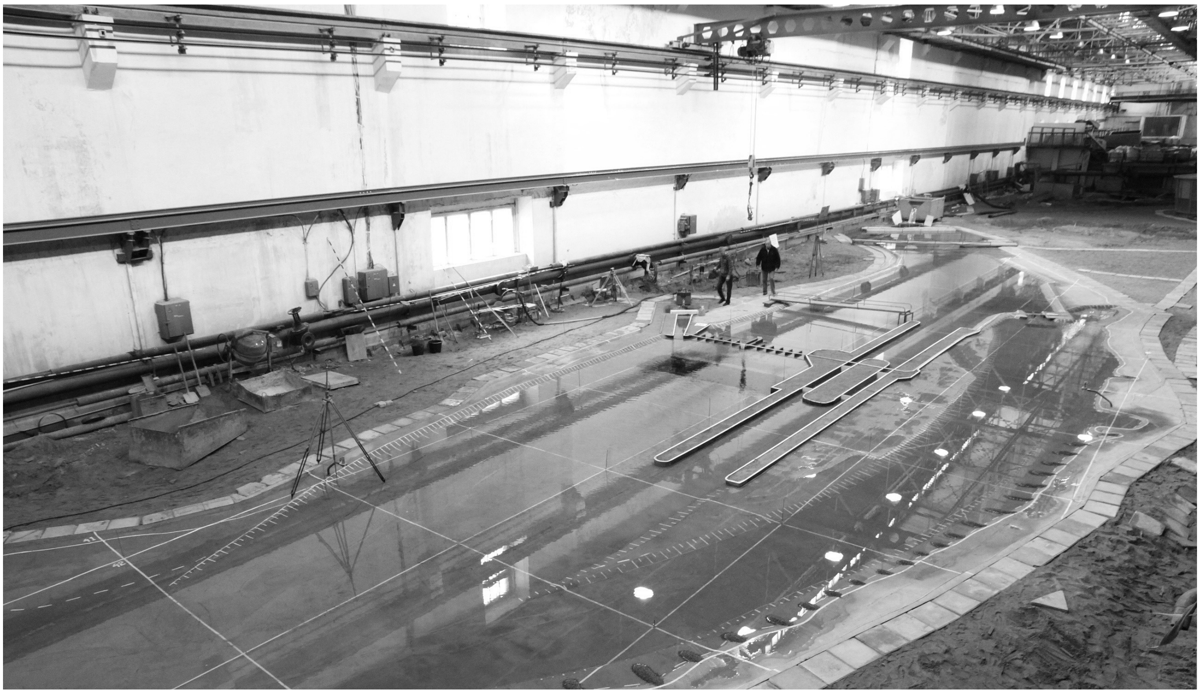

Figure 3. General view of the hydraulic model of the Don river section

In this case, the right branch of the river is blocked by temporary dams for the whole period of construction of the spillway dam, and the water flows through the left branch. To ensure navigation in the left branch during the construction period, a shipping slit is designed with sufficient dimensions to allow the floodwater flow.

And finally, as the third option in the hydraulic model, the design state was considered, when all facilities were built and operated in the regular mode. Within the framework of this research cycle, the kinematics of the river flow was studied under different operating conditions of the spillway structures.

All variants were investigated at different water flow rates and water levels in the river, covering the most minimal and the highest calculated values. As a result of these studies, fields of surface current velocities and bottom jets, longitudinal profiles of the free water surface and the boundaries of possible deformations of the river bottom and the river banks were obtained.

The performed research has revealed the main features of the kinematic structure of the flow under different operating conditions of the hydraulic engineering structures at various water flow rates and water levels. The obtained data made it possible to develop some recommendations on the structural improvement of individual structures of the hydroelectric complex to ensure safe navigation conditions, and to evaluate their effectiveness experimentally.

The physical model was calibrated based on the materials of engineering-hydrometeorological surveys in natural conditions. The distribution of water discharges between the arms obtained on the model, the regime of current velocities and the relief of the free water surface are in satisfactory agreement with the actual data.

First of all, the hydraulic flood conditions were studied on the model during the construction period of the hydraulic engineering structures, when the right navigable branch of the river would be blocked and the 150-m-wide shipping slit will be created in the left branch.

Model studies showed that under these conditions in the left branch at the cross-section of the Bagaevsky engineering structures, the maximum of current velocities at the maximum water discharges increases 1.7 times and reaches 1.90 $m{\cdot}s^{-1}$. At the sites located downstream from the site of the engineering structures, the river channel narrows and the current velocities increase even more, reaching values of 2.30 $m{\cdot}s^{-1}$. An increase in the current velocities during the floods in this period was observed along the entire left bank of the river, which may cause its dangerous erosion.

Therefore, in order to ensure the stability of the left bank of the river during the construction period, it was recommended to strengthen the left bank of the branch with rubble groynes. The location of these groynes and their dimensions, providing the most effective protection of the bank, were determined during the research on the model.

In addition, it was found that during the floods in the construction period, raising the water level (at 0.1-0.15 m) upstream from the construction site and increasing the average slope of the free water surface will be insignificant and not dangerous.

Materials of the experimental studies of the kinematic structure of the flow and its hydraulic characteristics confirm the validity and reliability of the adopted design decisions and parameters of culverts (gates). Under the design conditions, after the completion of the Bagaevsky engineering complex, the possibility of local bottom erosion in the lower part of the site under normal conditions is reduced.

Analysis of the model has shown that when the water discharges exceed 600 m3/s, velocities of the transverse current at the entrance to the navigation channel increase and exceed 0.25 $m \cdot s^{-1}$, which does not comply with regulatory requirements.

To regulate the structure of surface currents and to create favourable conditions for navigation at the entrance to the navigation lock channel, additional experimental studies on the hydraulic model were carried out and relevant recommendations were developed.

The results of the experiments carried out by the SHI have shown that the spatial structure of the flows at the boundary of the apron is complicated and detached currents arise on the boundary of the apron. It leads to the formation of the local erosion pits on the unprotected bottom and erosion of the apron.

In this regard, to ensure the stability of this facility in the lower part of the Bagaevsky hydrotechnical complex, it was recommended to reinforce the river bottom adjacent to the apron by a 30-m-wide stone backfill. It was recommended to use a stone with a diameter of 0.20 m.

In general, the studies carried out on the physical model have confirmed the high efficiency and validity of the basic design engineering solutions and allowed to make individual adjustments to improve the safety and reliability of the operation of the Bagaevsky hydraulic engineering complex.

7. Conclusions

There is a long history (over 100 years) of hydraulic engineering construction on the Don River and its tributaries. During this time, due to the interception of the flow by a higher cascade of waterworks, water levels on the Lower Don decreased in one direction. This had a negative impact on the status of navigation and the water supply in floodplains in the coastal area of the river. In this study, we have examined hydrological and riverbed regimes of the Don River to ensure the safety of navigation in its lower reaches.

The planned Bagaevsky hydrosystem is the lower stage of the cascade of low-pressure hydrosystems on the Lower Don. The construction of this cascade will ensure the free passage of large-capacity fleet in this area and will contribute to the rational use of water resources for the benefit of all water users.

The research on the hydraulic model made it possible to assess the validity of the decisions on the main parameters of the planned Bagaevsky Hydrosystem. The creation of a low-pressure hydrosystem with a reservoir on the Lower Don will facilitate the completion of the hydraulic engineering construction and will allow to obtain an additional effect from the operation of the whole construction complex.

References

Gladkov G.L., Chalov R.S., Berkovich K.M., 2016. Hydromorphology of channels of navigable rivers. [In:] Gladkov G.L. (Ed.), SPb.: GUMRF [in Russian with English Abstract].

Gladkov G.L., Katolikov V.M., Shurukhin L.A., 2017. Ensuring of the navigational conditions in the Lower Don. [In]: Design, construction and operation of hydraulic structures of waterways: Proceedings of the conference, GUMRF: 196-216 [in Russian with English Abstract].

Klaven A.B., Kopaliani Z.D., 2011. Studies and Hydraulic Modeling of River Flow and Cannel Processes – Spb. Nestor-History, [in Russian with English Abstract].

Polyakov B.V., 1930. Hydrology of the Dona River Basin – Rostov on Don. Office of the chief engineer of the construction of the Volga-Don [in Russian].