Search for options to change the operation of the Krasnodar reservoir taking into account the shortage of water resources

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Abstract. Taking into account the increasing shortage of water resources due to climatic changes in the south of Russia, we considered the issues of searching options for changing operational and technical conditions of the Krasnodar reservoir. There have been changes in the construction of structures over a long period of continuous operation. Studies have shown that the reduction of the lower retaining level in 90 cm accelerated the processes of reducing the environmental characteristics of the Krasnodar reservoir. In this regard, this paper considers options of changing the regime of the Krasnodar reservoir in order to improve operational characteristics. It became possible after the operation of the Tikhovsky hydroelectric complex. Currently, the volume of irrevocable withdrawal of water resources of the Kuban River exceeded 4 times the permissible one. The necessary releases to the lower water body of the reservoir are carried out in full compliance with the rules of the use of water resources and additional volumes of water that allow increasing discharges.

1. Introduction

In the course of the work performed on the inspection of hydraulic structures of the Krasnodar reservoir, it was established that the structure performs its functions taking into account the safe operation. Prevention of premature wear of structural elements and their maintenance in working condition is achieved by a combination of organizational and technical measures for the care, supervision, operation and repair of the reservoir HES. During the years of operation, changes in the construction of buildings and their equipment, initially adopted in the project and implemented for the construction of waterworks, are due to: a change in the climatic conditions of the area of HES; changes and additions to the normative-legal documents of the Russian Federation (Rev. class HES) [1]; testing calculations (calculations of stability, filtration strength of structures, hydraulic calculations, etc.), made in the course of work on the reconstruction of the NRL; other changes in operating conditions of the HES.

The actual parameters of the HES generally comply with the current technical standards and rules in the field of HES safety, as well as with regulatory legal acts in the field of localization and liquidation of emergency situations, protection of the population and territories from emergency situations [2].
The length of the coastline of the Krasnodar reservoir is about 230 km. This figure is constantly changing within small limits, not exceeding 0.5% of the total length. The changes go both up and down, which is caused by the change in the curvature of the coastline in the process of the shores’ changing.

The change in the shoreline is mainly due to the wave load. However, there is another reason – it is the fluctuation of the ground water level at the border with the basin of the reservoir. This factor is most relevant for the right bank [3]. In some areas, confined to localities, the changing of coast is provoked by anthropogenic activity in the vicinity of the coastline. In some areas, all three factors work simultaneously and they have the highest intensity of the shore processing.

The problem of scarcity of water resources is very acute. In the course of the work performed on the inspection of hydraulic structures of the Krasnodar reservoir, it was established that the structure performs its functions relying on the safe operation. The necessary releases to the lower reaches of the reservoir are carried out in full compliance with the rules of the use of water resources and there are no additional volumes of water that allow changing (increasing) discharges. Therefore, it is not possible to change the discharge regime even if water resources are saved. In this regard, to improve the operational and environmental characteristics, this paper considers options of changing the level regime of the reservoir, which became possible after the operation of the Tikhovsky hydroelectric complex.

The object of the study is the Krasnodar reservoir, where we can justify the prevention of premature wear of the elements of structures and their maintenance in a working condition. It can be achieved by a combination of organizational and technical measures for the care, supervision, operation and repair of the reservoir’s hydrotechnical system.

The subject of the research is the analysis of the water resources deficit in the Kuban river basin, changing the discharge regime is practically impossible due to the fact that at present the volume of irrevocable runoff from the Kuban was exceeded 4.2 times the permissible level.

The scientific novelty of the study lies in the development of options for solving the problem: clearing shallow water areas without changing the level parameters of the reservoir. The maximum trouble-free discharge flow does not change even at increasing depths due to raising the NPU to the previous (design) mark.

The aim of this work is to increase the efficiency of the water resources using the Krasnodar reservoir. Measures are not envisaged for the reconstruction of reservoir structures: measures to combat sediment, bank protection works, measures aimed at improving water quality and combating overgrowth.

2. Materials and methods
Currently, the most dangerous areas from the processing point of view are fixed with reinforced concrete or stone drift. All fixed sections are in normal technical condition and fully comply with modern regulatory requirements. However, about 38.0 km of the coastline is subject to active processing [4]. This is the right-bank part of the reservoir from the village Lenin to the stanitsa Vasyurinskaya. At this site, the processing of banks is influenced by these three factors.

Taking into account the predominance of the most frequent wind directions, the wave acceleration length in these areas ranges from 20 m to 30 m. The wave height reaches 1.5-1.7 m. The height of the slope in this section is 15-20 m, and the outlet of ground water on the slope exceeds the mark of NRL = 32.75 mBs in 2-3 m, the damming of the almost vertical slope leads to a decrease in its bearing capacity and the collapse of the bank occurs through the entire height of the slope. The products of the coastal line processing are deposited at the bottom of the slope, creating a persistent prism and thereby gradually reducing the intensity of processing, and in some areas, completely stopping them [5].

The list and location of the fixed sections are shown in Table 1.
Table 1. List of fixed sections

| Title                                                                 | Length, km | Mount                                      |
|-----------------------------------------------------------------------|------------|--------------------------------------------|
| Earth dam                                                             | 11.40      | Monolithic reinforced concrete slabs, 0.25-0.40 m |
| Engineering protection of the right bank                              | 11.24      | Monolithic reinforced concrete slabs, 0.16-0.25 m |
| Engineering protection of the Psekups River valley. Protective dam   | 5.61       | Monolithic reinforced concrete slabs, 0.25 m |
| Engineering protection of the Psekups River valley. Left-banked dam of embankment | 13.76 | Gravel, 0.2 m |
| Engineering protection of the Pshish River valley. Transverse dam     | 0.30       | Rock drift, 0.3 m |
|                                                                        | 0.20       | Reinforced concrete slabs, 0.25 m          |
| Engineering protection of the Pshish River valley. Lengthwise dam     | 0.51       | Stone drift, 0.3 m                        |
| Engineering protection of the village Khatukai. Eastern dam           | 4.50       | Reinforced concrete slabs, 0.25 m          |
|                                                                        |            | Rock in reinforced concrete cages, 0.3 m   |
| Total:                                                                | 47.52      |                                            |

3. Results

On the right bank there were 4 sections, where treatment processes were shown, so the length of the 1st section in 1986, i.e. 10 years after the start of operation, was 5.57 km. In the second section it was 3.1 km and 6.0 km on the third section it decreased by 3.5 km and made up 2.15 km. On the fourth it decreased by 3.5 km and made up 4.97 km. The total length of the coastline of the right bank subject to processing was 18.69 km in 2016 [6].

The processing intensity of the right bank averaged by 1.5-2.0 m per year, and in the period from 1977 to 1992 it averaged in 30-35 m. In the period from 1992 to the present, the processing intensity decreased 2.5-3.0 times and did not exceed 0.5-0.8 m per year, it was 15.0 m for the period from 1992 to 2016. In total, the right bank receded in 45-50 m for the entire period of operation at the processing sites. The wind rose, the gently sloping coast, and the lower anthropogenic loads on the sections of the coastline are the reason that the processing of the left bank has a much lower intensity than the sections of the right bank. Taking into account the above factors, the reduction of the NRL by 90 cm in 1992 had a much smaller impact on this problem. Processing of the left bank is estimated at an average of 0.3-0.5 m per year and for the period of operation from 1975 to 2016 amounted to 15-16 meters. In general, the processing of banks of the reservoir is observed at the level of 2016 at a length of 43.59 km [7].

The engineering protection structures of the Psekups River valley protect an area of 3.420 ha from flooding and waterlogging, including 2.350 ha at the NRL=32.75 m. The Psekups River valley protection system consists of 2 sections: left-bank and right-bank with a total area of 3.420 ha, including at NRL= 32.75 m – 2.350 ha [8].

5 sections were subjected to the processing of the bank (5, 6, 7, 8, 9) at a total length of 28.16 km on the left bank of the reservoir at the level of 1986 and the length decreased from 3.16 km to 25.0 km in 2016. Table 2 shows the data on the processing of banks to the calculated levels.

There are two settlements on the left bank of the location: village Gatlukey and village Pchegatlukay. The territory of the site is protected from flooding by a protective dam with a length of 5634 m from the side of the reservoir and a left-bank embankment dam of the river Psekups with a length of 13.800 m.
Table 2. Bank processing on calculation levels

| Location                                         | 1986 | 2004 | 2016 |
|-------------------------------------------------|------|------|------|
| village Lenin                                    | 6.52 | 6.33 | 5.57 |
| village Starokorsunskaya                        | 9.1  | 6.69 | 6.0  |
| Between villages Starokorsunskaya and Vasyurinskaya | 5.65 | 2.90 | 2.15 |
| village Vasyurinskaya                           | 8.47 | 5.67 | 4.97 |
| village Kazazovo                                 | 3.6  | 3.6  | 3.6  |
| village Pshikuykhable                            | 9.7  | 7.7  | 7.7  |
| village Gigikhabl                               | 3.46 | 3.0  | 3.0  |
| village Gorodskoy                               | 5.0  | 4.7  | 4.7  |
| settlement Krasnogvardeyskoe                    | 6.4  | 6.0  | 6.0  |
| Total                                           | 57.9 | 46.59| 43.69|

For water reduction, self-draining vertical drainage wells are used, from which water is supplied to the discharge NS-5D with a capacity of 10.4 m$^3$/s. The protective dam is broken by pickets after 100 m, the beginning of the dam of PK is 3+66, the end of PK is 60+00, the maximum height is 11.5 m, the upper slope is fixed with monolithic reinforced concrete, the lower one is blackened.

The left-bank dam of the embankment of the Psekups River is divided by the pickets through 100 m, the beginning of the dam PK is 0 (the end of the parapet of the protective dam), the end PK is 138+00 and the maximum height is 9.0 m with a gravel mount of the upper slope [9].

The drainage protection system of the left-bank section includes:

1) Drainage protection along the protective dam: 210 wells operating in the mode of the self-discharge; the open drainage canal with a length of 710 meters is located 20 m from the foot of the dam; the open outflow channel along the fencing of the dam with a length of 3.48 km located 60 m from the dam to a depth of 4-5.5 m drain removes drainage water from wells of the self-discharge of the river Dysh [10].

2) Drainage protection along the left-bank embankment dam: 348 wells connected to the general collector; transverse drainage of 40 wells that are connected to the general collector of the left-bank embankment dam [11].

Drainage water from the self-discharge wells is passed through the observation wells of the general collector built along the protective dam and the left-bank embankment dam with a total length of 11.7 km, which consists of reinforced concrete pipes $d=500$-$1500$ mm [12].

3) The drainage curtain along the left side of the valley includes: vertical drainage wells – 33 pieces, pitch – 25 m; which have not worked since the beginning of construction; horizontal closed drainage of porous concrete pipes with a diameter of 300; 500 mm, 3.6 km long.

Drainage and surface water from the left-bank part of the protected area is pumped into the reservoir by the pumping station No. 5D with a total capacity of 10.4 m$^3$/s equipped with 8 pumps of the 1600-D30 type [13].

4) The Chetuk regulated pool includes: a reservoir with a volume of 2.7 million m$^3$ to the level of 35.2 m; the protective embankment (dam) with a length of 775 m stamped the crest of 36.2 m and mark the base of the shaft of 32.3 m; the spillway consisting of a pipe culvert with a diameter of 1.2 m, 2 threads; the outlet channel [14].

The right-bank section is protected from flooding by a right-bank embankment dam with a length
of 7762 m, a maximum height of 4.0 m, with a gravel attachment of the upper slope. The right-bank dam is broken by the pickets after 100 m, the beginning of the dam is PK 0, the end PK is 77+62, with a maximum height of 11.5 m with the upper slope fixed with monolithic reinforced concrete.

The dam parameters: the length of the dam – 7.762 km; the width of the dam crest – 6.0 m; the height of the dam -3-4.0 m; th mark of the dam crest - from 36.0 to 38.4 m; laying of slopes: top 1:4, bottom 1: 3. The dam is filled out from local soils.

On the right-bank section of the protected area, the drainage curtain is not provided. Surface water from the 8 km long upland channel located along the root slope and the 7.3 km long drainage channel along the embankment dam is pumped to the Psekups River by pumping station No. 7D, with a capacity of 5.4 m$^3$/s, 4 pumps of the OHG 8-70 type [15].

The regulating volume of the pool is 14000 m$^3$. For flood protection of pumping station No. 7D, a 1 km long embankment dam was built on the floodplain area to accumulate surface water.

Engineering protection of the valley of the Pshish River includes engineering protection structures of site No. 11 protects the territory with an area of 1350 ha from flooding, including at the NRL=32.75 m – 390 ha. The protected area is located in the Belorechensky district of Krasnodar Territory. The structure of engineering protection structures includes: the transverse protective dam; the adjacent drainage channel; the longitudinal (right-bank) embankment dam; the drainage and discharge pumping station No. 11 [16].

A transverse barrier dam protects the site from the reservoir side. Its length is 3.250 m, the maximum height is 5.0 m; the upstream slope at 300 m long fixed rock placement 40 cm thick layer of gravel-sand mixtures; the 200 m long by the reinforced concrete slabs.

The longitudinal (right-bank) embankment dam is located along the Pshish river on its right bank. Its length is 7.36 km; width at the top is 4.5 m; maximum height is 6.5 m; laying of slopes: top 1:2.5, bottom 1:2; the upper slope at a length of 510 m is fixed with a rock cover in 30 cm thick on a layer of gravel-sand mixture. The longitudinal dam meets the protective rampart of the Pshish River in the area of the village Bratsky [17].

The drainage function is performed by the near-dam canal with a length of 1.8 km. The drainage and discharge pumping station No. 11, located on PK 40 of the longitudinal dam, receives filtration and surface water and discharges it into the Pshish river. The pumping station No. 11 is equipped with four pumps AD 6300-27b-3, the flow rate of one pump Q=1.2 m$^3$/s and one pump AD 2000-21-2-06, Q=0.4 m$^3$/s. The minimum water level in the avancamera is 31.20 m, the maximum is 31.50 m.

The structures of the engineering protection of the "Hatukay" valley protect the territory with an area of 3.800 hectares from flooding and waterlogging, including 920 hectares at the NLR=32.75 m. There are 5 localities on the territory: village Khatukay, Naberezhnyi, Svoobodniy, Vodnii and Lesnoy settlements with a total population of about 4.64 thousand people. After the flood of 2002, residents of the settlements Vodnii, Lesnoy and Svoobodniy were relocated. At present, however, the inhabitants live in settlements Vodnii and Svoobodniy.

The protected area is located within the boundaries of the Krasnogvardeysky district of the Republic of Adygea. The site is located within the left-bank floodplain of the Kuban River. The facilities include: the eastern dam; the dam embankment of the Kuban river; the drainage system. The eastern dam of the former Tschik reservoir with a length of 4550 m and a maximum height of 6.0 m is filled out of loam. The design mark of the dam crest is 37.70 m. The upper slope of the dam is fixed with a rock in reinforced concrete cages and monolithic or composite reinforced concrete slabs.

The embankment dam of the Kuban river with a total length of 12787 m and a maximum height of 4.2-4.5 m is filled out of loam. The slopes are fixed by sowing grasses. The picket line is not broken. The drainage system consists of open drainage channels in the amount of 9 pieces with a total length of 13.7 km; there are channels along the dam of the Kuban River [18].

The village Gorodskoy is located on the territory above the NRL, but below the FRL, and is protected from periodic flooding by a dam with a length of 2.0 km and a height of up to 2 m with loose slopes. The protected area at the FRL is 205 ha. At the foot of the dam, a drainage channel with a length of 2.2 km is laid. A temporary drainage pumping station with a capacity of 1.0 m$^3$/s pumps
drainage water into the reservoir. The buildings are classified as Class III.

The Krasnodar reservoir is for a complex purpose, one of the main tasks of which is the flood control function. In accordance with the current regulatory documents, at the time of putting the reservoir into operation, it corresponded to the 2nd Class. The flood capacity and the flood pass mode allowed for passing the standard flood of 0.1 % of the capacity.

After the tightening of the requirements for the safety of the HES in the late 80’s, the reservoir had to be transferred to the 1st Class facilities, i.e. it should pass floods of 0.01 % of the capacity in an accident-free mode [19].

In this regard, in 1992, the level mode of operation of the reservoir was changed. To increase the flood capacity, the reservoir's HES was reduced by 90 cm to the level of 32.75 mBs, which allowed to increase the flood capacity and brought its volume to 995 million m$^3$.

The increase in the flood capacity was due to a decrease in the useful capacity and thus the provision of water consumers was lower than the regulatory requirements. And only after the operation of the Tikhovsky hydroelectric complex in 2005, all participants in the water management complex began to be provided with water in standard rates. The reconstruction of the structures of the reservoir's pressure in the period from 2013 to 2016 made it possible to bring all the technical parameters of the reservoir to the standard limits and to transfer the reservoir to the 1st Class in 2017.

However, the requirements to increased safety were implemented due to the deterioration of the ecological state of the reservoir and adjacent territories [20]. The regime of the reservoir from the point of view of the implementation of the regulatory dumps and passing of floods practically has not changed, but the level regime of regulation has undergone significant changes, which have led to significant environmental degradation in the reservoir, which indirectly leads to the deterioration in performance.

The reservoir performs seasonal regulation of the flow of the Kuban River, which means the annual discharge of the reservoir up to the LDV (level of the dead volume) and its subsequent filling by the beginning of the growing season, since irrigation of agricultural crops is the main function of economic activity and the most moisture-intensive. That is, every year by the end of the growing season, up to 75 % of the basin area of the reservoir is without a layer of water [21, 22].

A similar pattern was observed both before and after the decline in the NRL. The difference is only in the time of finding this territory without a layer of water. If this period was 4 months before 1992, when the active growing season of moisture-loving plants accounted for no more than half, then after the reduction of the NRL, it increased for 6 and 4 months, respectively. For 4 months of active growth, reeds, willows and other moisture-loving vegetation manage to grow by 80-100 cm and do not die during the subsequent filling of the reservoir, i.e. its tops are above the water even with the NRL. This situation has led to an increase in the intensity of overgrowth of shallow areas of the water area.

The decrease in the NRL also led to an active increase in drifts in the useful capacity of the reservoir. Insufficient depth in the reservoir led to the fact that most of the suspended sediments did not reach the reservoir dead volume. Overgrowth and siltation of the reservoir led to the formation of stagnant zones, deterioration of water exchange, a decrease in the oxygen content in the water, and degradation of the ecosystem of the reservoir.

Table 3 below provides a comparative description of the elements that affect changes in the environmental and operational characteristics of the reservoir.
Table 3. Characteristics of the elements

| Titles of rates | Change of the process | Impact on operational and environmental performance | Physical indicators of the process for the period from 1992 to 2016 |
|-----------------|-----------------------|-----------------------------------------------------|---------------------------------------------------------------|
| Siltation       | Increase in siltation intensity 1.5 times | Negative | Increase in drifts by 227.0 million m$^3$. Increase in the intensity of siltation from an average of 6.1 to 9.1 million m$^3$/w per year |
| Overgrowing     | Increase in overgrowing intensity 2.8 times | Negative | Increase of areas of overgrowing to 50.4 km$^2$. Increase of intensity from 0.5 km$^2$ to 1.4 km$^2$ per year |
| Bank processing | Decrease of intensity 2.5-3.0 times | Positive | Decrease of length of bank processing from 57.9 to 49.69 km. Intensity of processing 1.5-2.0 m/w per year |
| Flooding of the territory | The reclamation situation has improved | Positive | Decrease of land waterlogging of 2.8 km$^2$ |
| Water resources quality on hydrochemical rates | For most indicators, it has not changed; for the BOD - it has worsened | Negative | Increased pollution of water resources with organic compounds in excess of MPC 1.5-2.0 times |
| Quality of water resources by bacterial rates | not changed | Negative | Exceeding the MPC 3 or more times |
| Pollution of bottom drifts and their composition | Not changed, volume increased 1.5 times | Negative | There were no qualitative changes |

4. Conclusion

In general, the impact of the 90 cm reduction in the NRL is assessed as the negative on environmental and operational characteristics of the reservoir.

Taking into account the shortage of water resources in the Kuban River, it is practically impossible to change the discharge regime due to the fact that at present the volume of irrevocable withdrawal of runoff from the Kuban River is exceeded 4.2 times in comparison with the permissible one. The necessary releases to the lower reaches of the reservoir are carried out in full compliance with the rules for the use of water resources and there are no additional volumes of water that allow changing (increasing) discharges. Therefore, it is not possible to change the discharge regime even if water resources are saved.

In this regard, to improve the operational and environmental characteristics of the reservoir, this paper considers options of changing the level regime of the reservoir, which became possible after the operation of the Tikhovskoye hydroelectric complex. The option of transferring the reservoir from seasonal to multi-year regulation is not considered, since 95% of water resources are already regulated and an increase in water volume by up to 5% will not give a tangible improvement, since only for environmental releases it is necessary to increase the volume of discharge by 22%. The options of inter-basin and intra-basin transfers are also not considered due to the lack of unused water resources in the Kuban River basin and in the basins of adjacent rivers.

In the course of the research, the following solutions were identified: clearing shallow water areas without changing the reservoir level parameters, i.e. the FRL, NRL and LDV remain unchanged. The
maximum accident-free discharge flow rate also does not change and remains equal to 1.200 m$^3$/s; an increase in depth due to raising the NRL to the previous (design) level. At the same time, the FRL mark also changes. Discharge to the NB remains 1.200 m$^3$/s; raising the NRL in 90 cm and increasing discharge costs from 1.200 m$^3$/s to 1.500 m$^3$/s (in accordance with the original design).

Measures are not provided for the reconstruction of the reservoir structures, i.e. the mark of the NRL, and, consequently, the FRL is not changed. These are measures to combat drifts, shore protection works, measures aimed at improving water quality and combating overgrowing.

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