Watering of the river delta Volga and Western sub-steppe ilmens based on simulation hydrodynamic modeling

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Abstract. To ensure the flooding of the Volga river delta and the Western sub-basin Ilmen and meet the requirements of the fisheries and agriculture, the following tasks were set and completed: to describe the current state and the main environmental, fisheries, agricultural and transport problems of the functioning of the Volga Delta and the Western sub-basin Ilmen; to develop a computer simulation model in the software package MIKE 11 plot of the Volga river from Verkhneye Lebyazhye village before flowing into the Caspian sea, with the specification of cross-sections along the river bed and the floodplain of the Volga river and its branches, spawning grounds, and western sub-steppe ilmen; to perform computer hydrodynamic modeling of the studied section of the Volga river; to develop possible scenarios to solve the problems of flooding of the Volga river delta and the western sub-steppe ilmen, and to meet the requirements of fisheries and agriculture. As the result, the requirements of the main water users for the operating modes of the Volga hydroelectric power station were presented and a hydrodynamic model was described, which allows determining the measures for watering the territory and using simulation modeling to evaluate their effectiveness.

1. Introduction
The commissioning of the Lower Volga waterworks at the beginning of the second half of the 20th century radically changed the hydrological conditions of the Volga, which is reflected in the decrease in runoff during floods, the increase in low-water runoff, and a blockage of migration routes for fish spawning. In particular, this affected the lower part of the Volga- Akhtuba floodplain, the Volga delta and the Western steppe ilmen. Western steppe ilmen are watered mainly in high-water years, within a narrow strip, which leads to their drying out, fishing value is lost, an intensive process of land steppe is under way, inter-mound depressions become swampy and saline. The greatest damage to water supply is caused by the uncontrolled overlap of large and small watercourses between ilmen and earth dams, as the result of which these territories are outside the zone of influence of spring floods.

Compensatory measures were planned to restore the potential of fishing and agriculture, as well as to water the zone of the Western steppe ilmen, provided for in the Scheme of the use of water
resources of the Lower Volga for 1981-1982, but these works were not carried out. In 1965, the Government of the USSR made a decision to implement an annual spring special release from the Volgograd hydroelectric complex, in order to meet the needs of fish and agriculture, which continues to this day. In recent years, the implementation of a special release was complicated by uncontrolled development in the downstream of the Volzhskaya hydroelectric power station (HPS) and conflicting demands of water users.

In recent years, colossal natural and anthropogenic changes took place, which led to the loss of relevance of developments in identifying the patterns of water exchange in the delta of the Volga and Western steppe ilmens. The study of the current state of water supply will make it possible to formulate an approach to solving the problem of sustainable functioning of the studied water bodies. Based on the hydrodynamic model of the Lower Volga, it will be possible to develop scientifically grounded measures to regulate the water regime.

More than 120 thousand inhabitants live in areas experiencing water shortage on the territory of the Western sub-steppe ilmen. The impact of environmental factors, which depend on the water supply of the territories, must guarantee the sanitary-epidemiological and economic well-being of the population (Ecological doctrine of the Russian Federation). The relevance of the work lies in the search for scientifically grounded solutions for the rational use of water resources, watering the delta of the Volga and Western steppe ilmens.

The problems of the Volga-Akhtub floodplain have been studied by many organizations, such as the Institute of Water Problems of the Russian Academy of Sciences, the Caspian Scientific Research Institute of Fishing Households, State Oceanographic Institute named after N.N. Zubov, Astrakhan State Technical University, Volgograd State University, All-Russian Scientific Research Institute of Hydraulic Engineering and Land Reclamation named after A.N. Kostyakov.

The Institute of Water Problems of the Russian Academy of Sciences developed a hydrodynamic model of the Volga-Akhtuba floodplain, on which the options for watering the territory were studied, a number of water management and environmental problems of the Lower Volga and ways of their solution were considered [1].

The staff of the Astrakhan State Technical University considered the influence of natural and anthropogenic factors on the river flow of the Lower Volga, the issues of water exchange and sustainable functioning of the Western steppe ilmen, as well as the peculiarities of the hydrological regime of the Volga-Akhtuba floodplain [2].

Volgograd State University developed a two-dimensional model of a section of the top of the Volgo-Akhtuba floodplain, on which the features of the various hydrographs passage were investigated, taking into account the evaporation and infiltration of water [3].

By the team of the State Oceanographic Institute named after N.N. Zubov in 2006-2019 a complex of scientific research works was carried out in order to develop measures for the preservation of the unique ecosystem and biodiversity of the Lower Volga, including the Volga-Akhtuba floodplain, delta and Western sub-steppe ilmen. The hydrological regime of the Lower Volga was examined in detail, on the basis of multispectral satellite images, the restoration of wetland ecosystems of the Volga-Akhtuba floodplain after extreme low water was assessed, a concept of rational use of water resources was proposed [4].

To meet the requirements of the fisheries the Caspian Scientific Research Institute of Fishing Households Katunin developed the schedules of releases into the downstream of the Volgograd hydroelectric complex during the spring flood (II quarter) for the years 50, 75 and 95% of availability [5].

Water resources management in Europe is a complex functional structural system, largely determined by the national environmental policies of states. The legislation of the European Union is the basis for defining the tasks assigned to national water resources management in the states of Western and Southern Europe. The countries of Central and Eastern Europe are currently continuing to develop water management systems with a particular focus on environmental policy objectives and, in particular, applying and adapting to EU water policy. The new EU water policy presents an
integrated approach to water resources management, which should be river basin-oriented and take into account the requirements of society and nature.

In France, six water agencies have been set up at the basin level to take the lead in rationalizing water use and represent the interests of regional authorities, farmers, industrialists, environmental associations, consumer associations and the state. The foundation for rational water use is the 1992 Water Law, which is based on two main principles:

- Water is a common good that needs to be managed in an integrated manner, balancing the needs of users with those of nature.
- The principle of subsidiarity should be applied to achieve decentralized, coherent and collective water management at the most appropriate level.

Thanks to the work of Allan [6], the concept of virtual water was developed. In the production of products that are exported from country to country, this concept creates an opportunity to reduce the demand for water, especially in countries with water scarcity. In the Middle East countries such as Israel and Jordan, this concept was demonstrated as a means of survival for the country when water availability was less than 500 m³ per year per person. Hoekstra and Chapagain made great contribution to the spread of this concept [7].

2. Materials and methods
To ensure water supply of the Volga river delta and Western steppe ilmen and meeting the requirements of fishing and agriculture within the framework of the grant of the Russian Foundation for Basic Research 18-45-342002_r.mk “Development of a hydrodynamic model for solving the problems of watering the river delta. The Volga and the zone of the Western steppe ilmen (WSI) in the interests of the reproduction of aquatic biological resources, the preservation of a unique ecosystem and water supply to water users” with the financial support of the Committee for Economic Policy and Development of the Volgograd Region, the research team set and completed the following tasks:

- to describe the current condition and basic environmental, fishery, agricultural and transport problems of Volga delta and WSI functioning;
- to develop a project in a geographic information system, covering the entire study area, containing cartographic information, information about spawning grounds, agricultural land, as well as data required for the preparation of a computer hydrodynamic model;
- to develop a digital relief models comprising information marks levels in ground Baltic height system (BHS);
- to prepare computer hydrodynamic model in software complex MIKE 11 plot of the Volga river from the village Verkhneye Lebyazhye before the confluence with the Caspian Sea, with the refinement of the cross-sections along the river bed and Volga floodplain and its branches, spawning areas and WSI;
- to perform computer hydrodynamic simulation of the studied plot of the Volga river, and analyze the results;
- to develop possible script on solving the problems on the Volga river delta and WSI watering, and meeting the requirements of fisheries and agriculture.

The main water users of the Volgograd reservoir are hydropower, fishing and agriculture, ecology, water transport and drinking and industrial water supply.

To ensure the uninterrupted generation of electricity from the Volzhskaya HPS throughout the year, it is necessary to ensure that all the reservoirs of the cascade are filled up to the level of the normal reservoir level by the end of the flood. To ensure navigable depths, releases from the Volgograd reservoir of at least 5 thousand m³/s are required. Aggregate requirements of ecology, agriculture and fisheries depending on the volume of spring floods, the parameters of the “agricultural shelf” are expressed in the following: discharge flow is 23-28 thousand m³/s, duration is 5-9 days; parameters of the “fishery shelf” are: discharge flow - 14-21 thousand m³/s, duration - 13-21 days. To avoid the threat of emergencies, the maximum permissible discharge flow of the Volgograd hydroelectric complex should not exceed 27 thousand m³/s.
As the main reference point for the watering of the Volga river delta and WSI, according to studies [2], the water level at the hydrological station in Astrakhan was taken. If the water level is above the minus 23.5 m mark, then the water enters the WSI with a volume of 4-5 km$^3$, which ensures the flooding of the ilmen.

To refine the hydrodynamic model of the Integrated Digital Elevation Model (IDEM), which is based on the Shuttle Radar Topography Mission dataset, it was supplemented with information about the depths of water bodies (ilmen) and channels between them, as well as the characteristics of the main streams.

The hydrodynamic model of the Lower Volga section consists of the main components: Network editor - the route of the river network is plotted on the background map (scale 1:100,000); Editor Cross - sections - on the basis of IDEM cross-sections were constructed along the river Volga bed and main branches; Editor Boundary data - external boundary conditions are set at the end of cross-sections (Caspian Sea Level), the starting point (village Verkhneye Lebyazhye) is given flow rate corresponding to the observed data for the average year 2015 (75% security year); HD Parameters editor - the roughness coefficients are assigned based on the basic (along the channel sections) and vertical (within the cross-sections) calibrations, the initial modeling conditions are set. Figure 1 shows the route of the hydrodynamic model of the Lower Volga section with applied cross-sections (about 250 pieces) and a diagram of the river network with the main branches [8].

![Figure 1](image_url)

**Figure 1.** River network route with cross-sections in MIKE 11 (a), flow model diagram in MIKE View (b).

For approbation of the model, the simulation results were compared with the observed data for gauging stations in Astrakhan and village Olya (branch Bakhtemir). The comparison results are shown in Figure 2 and indicate a fairly adequate functioning of the model at the control sections (the error is within 20 cm).
3. Results and discussion

To solve the problem of watering the delta of the Volga river and WSI and the water level rise in the Astrakhan settlement to minus 23.5 m it was proposed to design a narrowing channel of the hydraulic engineering structure (HES) (narrowing to 200 m) at the source of the branch Kamyzyak, as shown in Figure 3. As a narrowing structure, it is possible to choose an underwater diving dam made of rock fill of coarse material with an average diameter of joints of 200-300 mm. Previous studies [9] showed that this type of structure effectively dampens the flow rate, thereby creating an additional backwater.

Figure 2. Comparison of the simulation results with the observed data (a - the Astrakhan station, b - the Olya station).

Figure 3. Configuration and location of the retaining structure.

Figure 4 shows the course of water levels in the Astrakhan and the village Olya taking into account the work of the HES at branch Kamyzyak in comparison with the results of a model calculation of the hydrological situation in 2015. Taking into account the calculation error, we can say that the condition for maintaining the water level at minus 23.5 m BHS in the Astrakhan station with a retaining
structure is fulfilled within 23 days, which meets the total requirements of fishing and agriculture (shelf duration 13-21 days), and also allows watering the WSI zone and ensuring flooding of ilmen with fresh Volga water.

![Figure 4](image)

**Figure 4.** Comparison of simulation results without and with the GTS (a - the Astrakhan station, b - the Olya station).

However, there is a need to assess the impact of this type of HES on the discharge and level modes of branch Kamyzyak, to determine the losses caused to the fish industry. To study the influence of the levels in the branch Bakhemir, for the watering of the WSI, it is necessary to conduct expeditionary studies and to identify modern patterns of water exchange in the territory of the Volga and WSI, depending on releases to the lower pool of the Volzhskaya HPS. Also the hydrodynamic model should be complemented by the Volga-Akhtuba floodplain water bodies territory, as these areas are connected hydraulically.

**4. Conclusion**

In order to preserve the unique ecosystem and improve water supply in the Lower Volga is necessary to understand the processes occurring in the nature and development of nature-like ecosystem management technologies with an integrated second evaluations of the results of a particular water management strategies. To ensure the sustainable functioning of water bodies of the Volga river delta and the WSI require the development of scientifically based measures for additional watering and drainage of the territory during the flood period, which can be carried out by using hydrodynamic modeling methods.

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