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Calculation of hydrological connection between the Volga river and the Akhtuba river using numerical hydrodynamic modeling

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Abstract. The hydrological regime of the Volga river near the Akhtuba river source below the dam of the Volga hydroelectric power station is studied. We use a hydrodynamic model based on the numerical solution of shallow water equations to study the dynamics of discharge water during spring floods. The main result is the determination of the hydrological connection between the water discharge (hydrograph $Q_V(t)$) of the dam of the Volga HPP and the hydrograph of the Akhtuba river source ($Q_A(t)$) depending on the dynamics of the water flow from the Volgograd reservoir to the Volga river. Numerical simulations of the spring flooding process were performed for the northern part of the Volga-Akhtuba floodplain for 2016, 2017 and 2021. The relationship between Q_V and Q_A is non-linear due to the peculiarities of the riverbeds and the interfluve topography. The results are important for developing solutions aimed at preserving the Volga-Akhtuba floodplain.

Keywords: hydrological regime, hydrodynamic model, spring flooding, hydrograph

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Особенности гидрологической связи между Волгой и Ахтубой по результатам численного гидродинамического моделирования

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Аннотация. Исследован гидрологический режим в русле реки Волга вблизи истока реки Ахтуба ниже плотины Волжской ГЭС. Мы используем гидродинамическую модель на основе численного решения уравнений мелкой воды для изучения гидрологического режима в периоды весенних паводков. Основным результатом является определение гидрологической связи между гидрографом плотины Волжской ГЭС $Q_V(t)$ и гидрографом истока реки Ахтуба $QA(t)$ в зависимости от характера сброса воды из Волгоградского водохранилища в реку Волга. Симуляции процесса весеннего затопления выполнены для условий 2016, 2017 и 2021 годов. Связь между Q_V и Q_A имеет нелинейный характер, обусловленный особенностями речных русел и береговым рельефом. Результаты важны для выработки решений, направленных на сохранение Волго-Ахтубинской поймы.

Ключевые слова: гидрологический режим, гидродинамическая модель, весеннее затопление, гидрограф

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Introduction

The hydrological regime of large river systems is essentially nonstationary and is determined by the balance of numerous spatially distributed factors [1–5]. Floodplains are areas that are very sensitive to any noticeable hydrological changes. Anthropogenic factors have a dominant impact on the state of such socio-environmental systems, affecting both the regime of water discharge and the orography [6, 7].

The interfluve of the Volga and Akhtuba Rivers is a unique natural object experiencing negative trends due to the regulation of the Volga River flow, especially in the spring [3, 6, 8]. The cascade of hydroelectric dams on the Volga River and the Kama River completely controls the spring flood, which is a key factor in floodplain moistening [9]. The landscape of the Volga-Akhtuba floodplain (VAF) is based on the regular spring flooding of the extended flat area between the Volga and Akhtuba rivers from the dam of the Volga hydroelectric power station to the Astrakhan City and beyond, where the floodplain passes into the delta extending into the Caspian Sea (Fig.1). The key point for the VAF is the entrance of the Volga water to Akhtuba branch, which is 6 km below the dam on the left side. The Akhtuba discharge is a few percent of the Volga discharge, but it provides the main flow of spring water to the interfluve plain.

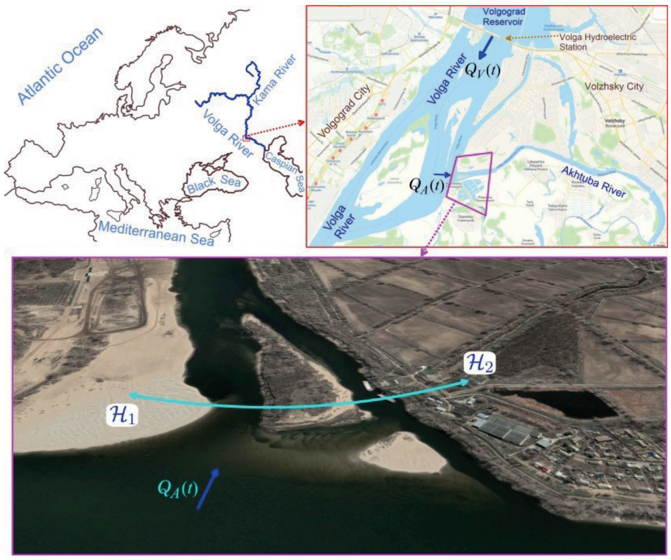

Fig. 1. The Volga River is the largest river in continental Europe, forming single water system with the Kama River (top left). The top right inset shows map of the first 12 km downstream of the Volga from the dam and the Volgograd Reservior (Yandex). The lower inset is image of the source of the Akhtuba, which branches off from the Volga and forms the left boundary of the Lower Volga valley (Google Earth)

The aim of this work is to determine the hydrological connection between the water discharge in the Volga (hydrograph QV(t) [m3/sec] of the HPP dam) and the water discharge in Akhtuba (hydrograph QA(t)). We use numerical model of the shallow water dynamics with real hydrographs QV(t) for recent years.

Results of modeling water dynamics in the Northern part of the Volga-Akhtuba floodplain

An important component of the numerical hydrodynamic model is the Digital Elevation Model (DEM), which determines the topography of both riverbeds and flooded interfluve (See Fig. 1). We use the DEM built in [3, 10]. The surface water dynamics model is based on the numerical integration of the Saint-Venant equations system [3, 11, 12] using the numerical algorithm CSPH-TVD (Combined Smoothed Particle Hydrodynamics – Total Variation Diminishing) [13]. The numerical model is based on the parallel implementation of the CSPH-TVD method for graphics accelerators (GPUs) using CUDA technology [14].

The computational domain with cell size of 15×15 (m) covers an area of 2500 km². Modeling starts from low-water levels (5000–7000 m³/sec) and continues until the end of the spring flood lasting 60–90 days for different years, which differ in the behavior of the hydrograph through the Volga dam (Fig. 2, *a*). The volume of water during the low season entering the Akhtuba branch is only 1.5 percent of the total water discharge through the dam. This value can increase up to 10 percent during the flood period, ensuring further flow of water from the Akhtuba River into the network of smaller canals (the so-called eriks) at sufficiently high values of the Q_V hydrograph. We have constructed hydrographs of the source of the Akhtuba River $Q_A(t)$ through the alignment $\mathcal{H}_1 - \mathcal{H}_2$ (See Fig. 1), which are shown in Fig. 2, *b* for the corresponding hydrographs of Volga Hydroelectric Station Dam of $Q_V(t)$.

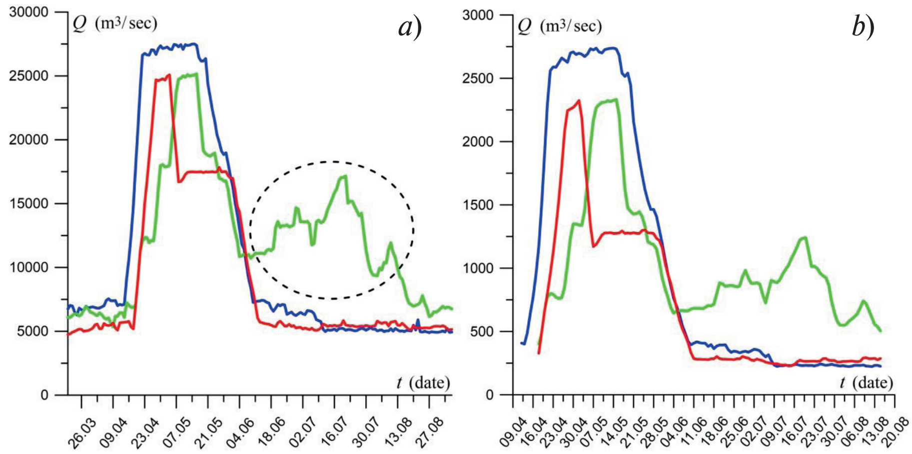

Fig. 2. The hydrographs of the Volga HPP for 2016 (blue line), 2017 (green line) and 2021 (red line) (*a*). The corresponding Akhtuba hydrographs across the river source section according to the results of numerical simulations (See the cross section of the river $\mathcal{H}_1 - \mathcal{H}_2$ in Fig. 1) (*b*)

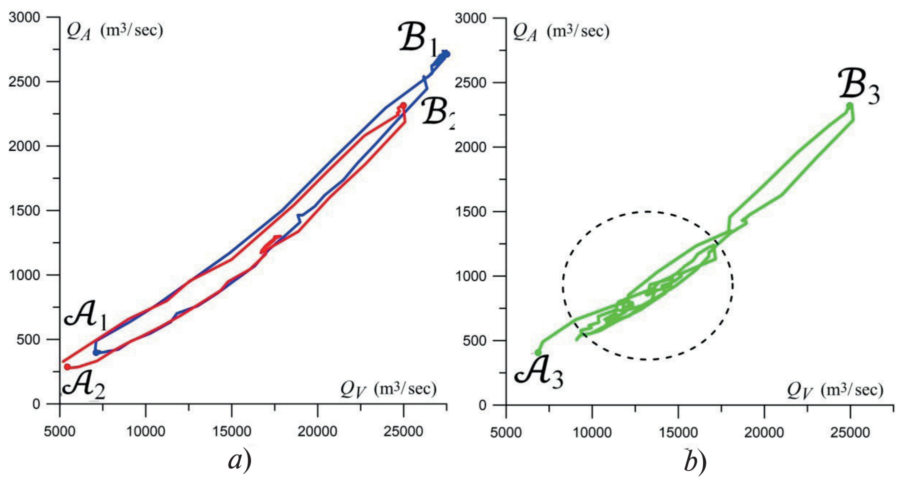

Fig. 3. Dependencies $Q_A(Q_V)$ for spring floods: (*a*) 2016 (blue line), 2021 (red line); (*b*) 2017 (green line). The dotted line indicates the part of the curve as shown in Fig. 2, *a*. The points $\mathcal{A}_{1,2,3}$ show the beginning of the flood. The maximum values of water discharge are indicated by the points $\mathcal{B}_{1,2,3}$

The hydrological connection between these rivers is characterized by the function $Q_A(Q_V)$ (Fig. 3). The hydrograph of 2017 is atypical due to the strong increase in water discharge in summer (Fig. 3, *b*). This significant excess volume of water does not lead to additional wetting of the flat part of the floodplain due to the decrease in Q_V in the period June 4 – June 19. The characteristic nonlinear form of the dependence $Q_A(Q_V)$ is due to the release of water from the main channel (riverbed) of the Volga at the high water stage $Q_V \leq 15\ 000$ m³/sec, when the effect of increasing water discharge does not leads to both a proportional increase in Q_A and an increase in the flooded area.

The dependencies of water discharge at the stages of growth and decline are asymmetric, which leads to a hysteresis of the $Q_A(Q_V)$ curve. This effect is associated with a slowdown in the response of the water flow in the Akhtuba channel due to the accumulation of large volume of water in the floodplain. There is another typical feature on the growing branch $Q_A(Q_V)$ in Fig. 3, when the active flooding of the plain begins after the break (See the arrow in the Figure). The Fig. 4 demonstrates such changes in the hydrological state of the floodplain in the numerical model.

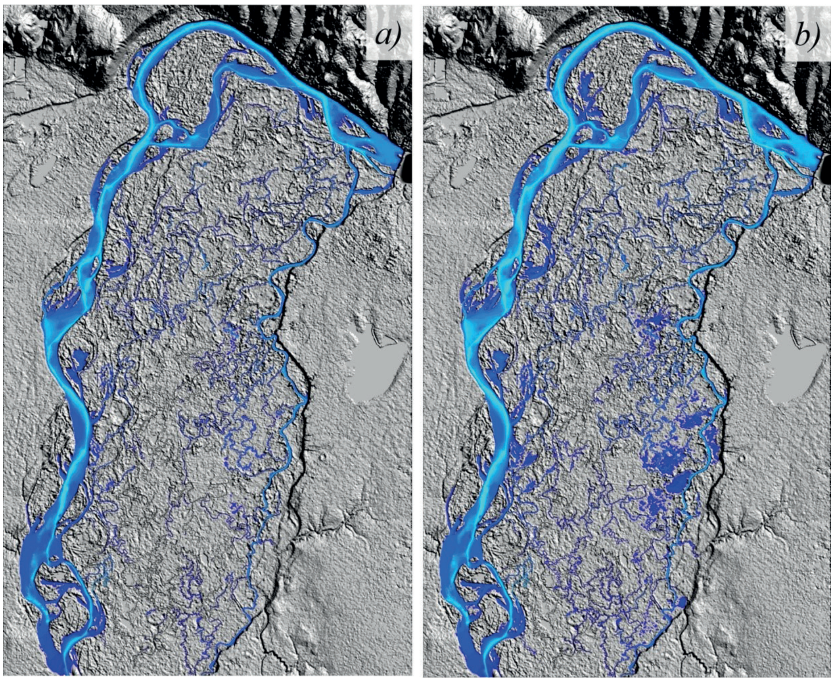

Fig. 4. Examples of flooding in the Northern part of the VAF for two times in 2021: April 22 (*a*), April 26 (*b*)

Our preliminary estimates show that the contribution of the Akhtuba is 70–80 percent to the flooding of the interfluve, depending on the type of $Q_V(t)$. The direct contribution of the Volga through the left bank does not exceed 30 percent. Therefore, the hydrograph Q_A, and not the traditionally considered hydrograph of the Volga hydroelectric power station, has a decisive role for the Northern part of the VAF.

Conclusion

The series of computational hydrodynamic experiments were performed to simulate the process of spring floods in the Northern part of the Volga-Akhtuba floodplain in order to determine the influence of the Volga HPP hydrograph on the water flow in the Akhtuba River, which is the main channel for moistening the interfluve.

The hydrological connection between the Volga and Akhtuba rivers is quite complex and significantly depends on the degree of flooding of the plain part during the spring flood. The water volume passing through the Akhtuba is only a few percent of the annual water flow in the Volga. Numerical models give for water volumes: $V_V^{lw} = 136.2$ km³ for the low water, $V_A^f = 5.8$ km³, $V_V^f = 77.6$ km³ for the stage of flooding in 2021.

The entrance to Akhtuba is very sensitive to bottom morphology, so various options are being considered to enhance the hydrological connection between these rivers. A possible solution is a local increase in the water level in the Volga through new dams [15], which can only be temporary due to the secular lowering of the riverbed in the vicinity of the HPP [9]. A more efficient project is the construction of bypass canal from the Volgograd reservoir to the Akhtuba.

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