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## Simulation of velocity field changes in a backwater area of the Kama reservoir in different water regime phases

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# Simulation of velocity field changes in a backwater area of the Kama reservoir in different water regime phases

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**Abstract.** The area of variable backwater of any reservoir is a complex natural and anthropogenic system that changes significantly during a year. The changes are primarily determined by water balance dynamics during a year that is a correlation between input and output water masses into a reservoir or at any part of the water object. Secondly, the input and output of sediment load changes constantly during a year. Transition of sediments from one site to another significantly changes the morphometrical features and morphology of the latter. Finally, the cyclical nature of the changes mentioned above is caused by daily, weekly, and annual discharge regulation that is conducted according to the Kama reservoir operating regulations. The simulation results of the flow velocity changes at the site Tyul'kino village – Berezniki town during different phases of water regime for high water year and average water years are presented in the article. The calculation of continuous velocity field at the site under investigation (a hydrodynamic model) is based on a digital elevation model of the bottom (DEM), and water level, water surface gradient and bottom roughness have been also considered in the model.

## 1. Introduction

Issues related to water mass dynamics are significantly important in hydrology. As they have their own peculiarities of movement at different types of water objects. Reservoirs are artificial water objects and flow regulation is significantly important for their development. Moreover, operating regime is usually determined at the stage of their construction. Reservoirs are considered to be relatively young and developing systems. Hydro and geodynamic process at reservoirs are studied by many scientist in Russia [1-7] and abroad, in Europe [9-11], Asia [13], the USA [8,12], etc.

In contrast to rivers, which current is determined by gravity force and follows from the river headwater to its mouth, reservoirs are characterised with different types of flows (discharge, wind, compensation, etc.). The flow structure in reservoirs is complex with total flows. Meanwhile, non-standard flow systems with their own velocities are formed at different reservoir sites. For example, hydrodynamic active zones, where the main water flow passes at maximum velocities are typical for flooded channel. Zones with vertex circulation are observed at flooded floodplain, and hydrodynamic stagnation zones are located at extensive shallow coves [1]. Flow plans are visual representations of flow distribution.

## 2. Materials and methods

The site of the Kama reservoir characterised as a backwater area and stretched from Tyul'kino village to Berezniki town is described in the paper. Its length is 55 km. The investigation of the site from the



view point of hydrodynamics is significant as river features and reservoir characteristics change each other simultaneously during a year. The boundary of the pinching-out section transits along the site dividing river and reservoir conditions. Due to complex and morphological heterogeneity of the investigated area we have decided to use the simulation of flow velocity changes using DEM. Data obtained during field observations and calculations may be used as initial data for the construction of a flow velocity DEM. The first method definitely simplifies simulation but unfortunately the amount of such data is not enough or sufficient. This fact demonstrates the importance to calculate velocity field. It should be noted that the calculation results may be presented in a form of a digital flow model or in a form of a flow line (flow plan) that are less precise in their definition.

The Chézy formula is the key one to calculate an average velocity vertically:

$$V = C \sqrt{HI} \quad (1)$$

when the Chézy coefficient (  $C$  ) is calculated according to Manning's Roughness Coefficient:

$$C = \frac{1}{n} * H^{\frac{1}{6}} \quad (2)$$

where  $H$  – depth on the vertical (m);  $I$  – gradient of the free surface;  $n$  – channel roughness.

It should be noted beforehand that the Chézy formula is used to calculate an average flow velocity at steady uniform movement [13]. But unfortunately there is no other simple mechanism for calculation. As there are no huge tributaries and the site is short enough we have decided to use the formula.

Depth measurements at the site and observation data about the water level in Tyul'kino village and Berezniki town have been used as the initial data to make a DEM and a hydrodynamic model. The measurements have been made by Federal budget institution «Kamvodput'» in 2016. The depth value accuracy is centimetres. Spatial depth checkmark density is 6 – 8 checkmarks per hectare. Spatial positioning was made by means of satellite navigation (GPS). Bottom DEM was made by GIS-technologies using TIN and GRID-themes with 10×10 m. raster cells. Water surface gradient is a constant. The value of the bottom roughness coefficient is taken from the table by M.F. Sribnoi according to the granulometric composition of the sediments.

### 3. Results and discussion

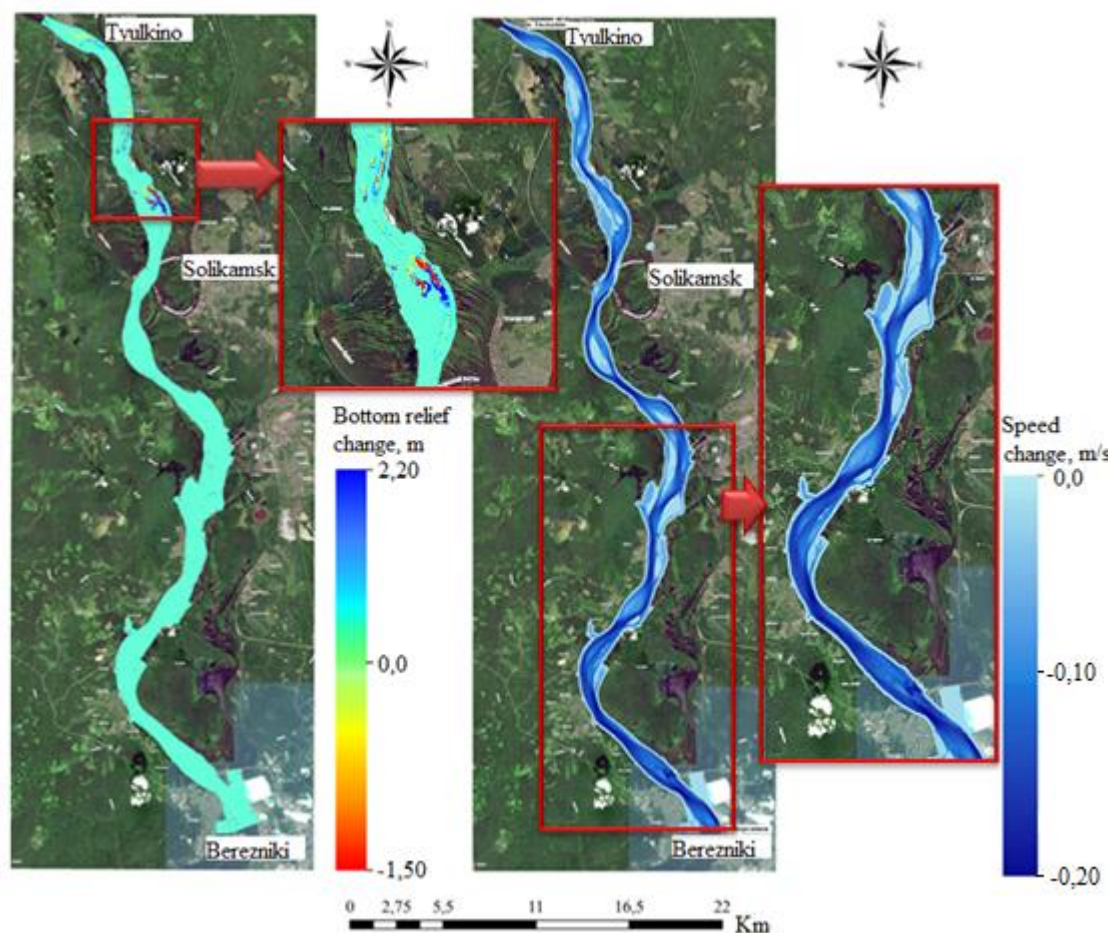
To simulate flow velocity changes, velocity field models have been constructed on the bottom DEM basis. Additionally channel cross-sections have been constructed every 500 m. and water level (m. BES) for each cross-section has been measured at a particular date by transferring water surface marks along the gradient. Average velocities have been calculated for each raster cell of the model using MAP-algebra and water level was considered to be a simple average between the nearest cross-sections. Thus, four hydrodynamic models for high water and average water years have been made for the filling (June, 15) and stabilization (July, 15) phases of the water level.

The models have been compared with the bottom DEM of the site under investigation for the same dates. The DEM calculations were made by a group of scholars from Perm State University (PSU) and the Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences (IWEP SB RAS) [14]. The construction of such DEMs is based on mathematical simulation data that was made using a special packet version with an open initial code Delft3D, that realizes a complex computer model of flow and channel sediment transportation.

We have revealed that flow velocity field at the Kama reservoir is heterogeneous as from the morphological view point a reservoir is the alteration of a lake-shape enlargements and narrow reaches. As a result flow velocities increase when passing through narrow water section and decrease when the section extends [15].

Water levels approximating to the normal backwater level (NBL, 108.5 m BES) are observed 5-6 months a year at the site. In average, Berezniki gets out of the backwater for 1-3.5 months [16]. The site is located in the upper part of the reservoir, the bank contours have remained to be the same as they used to be before the filling. The site width is heterogeneous and changes from 0.3-0.4 km in the narrowest areas (especially the bends) to 6-6.5 km in the areas of island enlargements. Predominant

depths on the waterway increase downstream from 4-5 m at Tyul'kino village up to 6-8 m at Solikamsk town. Maximum depths are observed at the site end at Berezniki town and they reach 12-16 m. The site cross-section is distinctly asymmetrical. The depths at the left bank are 10 m and even more, whereas they gradually decrease up to 4-6 m to the right bank. The sediments are sands of different size degree [17].



**Figure 1.** Change of flow velocity values and bottom checkmarks for different phases of water regime in a high water year.

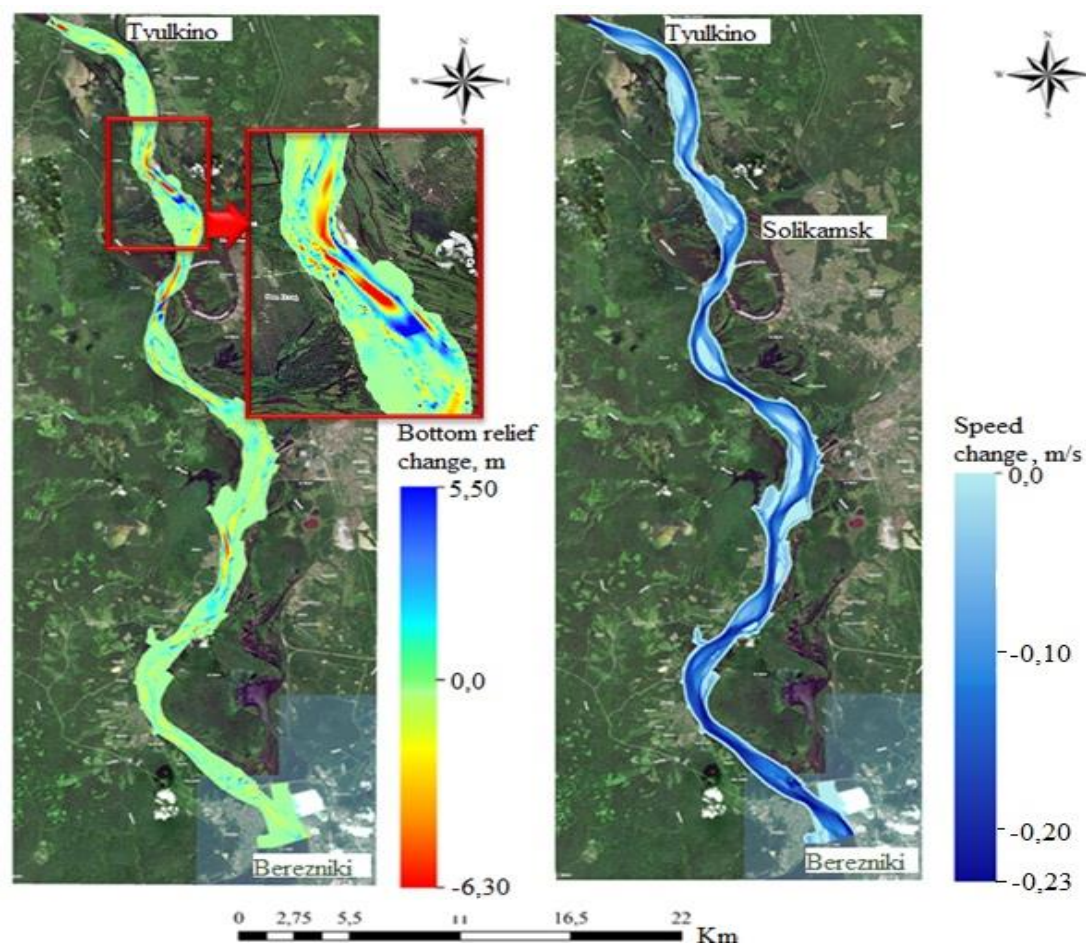
#### 4. Conclusion

The analysis of actual measurements of surface and bottom flow velocities in different months of a navigation period has revealed [18], that the highest flow rates are observed during the spring flood, i.e. during the reservoir filling. The average velocity values are 0.73 and 0.63 m/sec on the surface and at the bottom correspondingly and the maximum values are 1.92 and 1.0 m/sec. The character of velocity regime is more complex during the next summer-autumn stabilization phase. It is mainly determined by the Kama hydroelectric complex operation mode and the water level at the Kama hydroelectric power station, as well as runoff conditions of the Kama River at the site under consideration. Velocities and water levels at the period are quite stable. Their maximum does not increase 0.49 m/sec. Average values of surface and bottom velocities fluctuate from 0.32 to 0.49 m/sec. and from 0.23 up to 0.48 m/sec correspondingly during the period. The hydrodynamic models, we have obtained, characterise the dynamics of average flow velocities at the site in the filling phase (June, 15) and at the water level stabilization phase (July, 15). We did not observe the change of bottom checkmarks and velocity field for different phases of water regime in a high water year (the water discharge was 7,000 m<sup>3</sup>/sec on May, 1 in Tyul'kino village). Flow velocities decreased (its



maximum was 0.2 m/sec) only at the end of the site near Berezniki town on the flooded channel. Slight bottom transformation was observed at the area located approximately 7 km. above the Borovskaya volozhka (figure 1).

Significant changes of bottom checkmarks are observed in an average water year (the water discharge was 2,500 m<sup>3</sup>/sec on May, 1 in Tyul'kino village): accumulation and erosion change each other along the site up to Nizhnie Novinki village. Erosion zones are mainly located within the flooded channel, and along the contour they are surrounded by accumulation zones. Flow velocities decrease at the end of the site in average 0.2 m/sec (figure 2).



**Figure 2.** Change of flow velocity values and bottom checkmarks for different phases of water regime in an average water year.

Analysing the dynamics of average flow velocities during the period under investigation in high water and average water periods, we have observed the trend for the distribution of the highest velocities in the area of the flooded riverbed of the Kama river, especially in narrow bending areas. It also should be noted, that the greatest intensity of velocity reduction in the above considered period is also typical for these areas.

Thus, the constructed hydrodynamic models correlate to the channel changes of the investigated site of the Kama reservoir during the dates under consideration as well as they correspond to actually measured flow velocities.

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