ANALYZING THE PROCESS OF CHANNEL DEFORMATIONS IN THE VARIABLE-BACKWATER ZONE OF PLAIN RESERVOIRS (BY THE EXAMPLE OF THE KAMA RESERVOIR)

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Abstract

The paper deals with the specific features of hydrological regime of valley reservoir in the variable-backwater zone. The emphasis is on the level regime, used to identify three sections within the zone in question: upstream section (river conditions prevail), midsection (there are both river and reservoir conditions), downstream section (basic reservoir conditions). The distinctive characteristics of velocities within the identified sections were assessed through analyzing actual velocities and comparing them with the scouring ones. A non-dimensional coefficient was suggested that exhibits tendencies in the processes of transforming water facility basin. 3D hydrodynamic model was designed using Navier-Stokes equations. It takes into consideration turbulent exchange, special features of hydrological regime of a reservoir and grain size of sediments. Model testing using actual material showed that it can be utilized for applied purpose: to design the navigable channel project and forecast the reservoir basin topography in the variable-backwater zone.

Keywords: Reservoir, variable backwater, modelling, water level, velocities, direction of flows, grain-size analysis, bed sediments, basin topography/relief.

I. Introduction

Forms of channel deformations manifested in the variable-backwater zone have a number of distinctive features associated with a pattern of intra-annual water-level regulation. A boundary of transient backwater area shifts according to the level fluctuation that affects hydrodynamics of flow and sediments. The processes of basin

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deformation are rather complex here, since during drawdown in winter sediments are transported under the “river” conditions, and further in the conditions of a reservoir. The processes of re-formation in various sections of a reservoir are described in a number of works (Makkaveev N.I., Berkovich K.M., Baryshnikov N.B., Williams G.P., Wolman M.G. Babinski Z., Fu K.D., Rathburn S. et al.) [I-IX]. The work of Makkaveev N.I. “Channel processes in the variable-backwater areas” published in 1958, when the reservoirs had yet to be created, is the most widely known. Transient backwater area is also mentioned in the works of Baryshnikov N.B. (“Channel processes”, 2008), Kovalenko V.V., Viktorova N.V., Gaydukova E.V. (“Modeling of hydrological processes”, 2006), Georgievsky Y.M., Shanochkin S.V. (“Hydrological predictions”, 2007), Baryshnikov N.B. (“Dynamics of channel flows”, 2007), Kovalenko V.V. (“Partially infinite modeling and prediction of the river run-off formation process”, 2004), Chernov A.V. (“Flood plain and flood plain processes”, 2006), Doganovsky A.M., Malinin V.N. (“The Earth’s Hydrosphere”, 2004), Matarzin Y.M. (“Hydrology of reservoirs”, 2003) [X-XVI].

Kritskiy V.A. and Litvinskiy V.I., Lysenko V.V., Frolov R.D., Uralsky R.B., Vendrov S.L., Nikolaev V.F. [VI] were studying changes in bed-formation factors and transformations of channels in the upstream waters of hydraulic power systems, and in the transient backwater areas, in particular. Various types of channel processes are observed here: braid bar pattern, multichannel pattern, and less developed river winding bends. There are also newly created conditions for forming flood plain streams due to bottomland flooding and increased levels of bed-formation flow rates. This knowledge is required for ensuring safe navigation, and for other sectors of economy intending to use this area.

II. Materials and Study Methods

The level value and duration of its standing identify the velocity range and, at the same time, transformation of running off sediments brought to the reservoir by the river. Therefore, the data from observing water levels (from 1964 to 2017 by seven level gauges [XXIII]), flow velocities and sediments (2016 and 2017) were used. Study methods were as follows: descriptive (to characterize accumulation and abrasion topographic forms); cartographic (construction of a digital terrain model); mathematical modeling of transporting and depositing suspended and tractional sediments.

III. Results and Discussion

Three sections (Fig.1) have been identified in the variable-backwater area depending on the water level stand value [XXIII]. The second section (Tul’kino – Berezniki) is the most complex in terms of hydrodynamics.
Here, a dual nature of the variable-backwater area is obvious to the fullest: the river and the reservoir have equal rights. Wind and wave abrasion complements the river geodynamic processes. Maximum height of wave (35% exceedance probability) reaches 0.5-0.6m. There is a “wave-like” change in velocities from Tul’kino to Berezniki: a minor decrease first, then an increase (Fig.2). A change in the value of flow velocities depends on amplitude of the water level elevations’ fluctuation. During filling (when levels are 108.5m abs. and more), a “wave-like” form of curve $v = (f)L$ flattens, and a section functions as a reservoir. It was found that the wind blowing in the opposite to the current water flow direction forms a wind and wave flow on the surface. It is also confirmed by a decreased velocity of a surface flow (up to 0.2m/sec) (Fig.2). Measurements were made with 5m/sec and less wind velocity, therefore, a decrease in the flow velocity was observed only in the surface layer of water.
Examination of vertical-wise changes in the flow velocities indicated that maximum velocities are registered during spring flood and impoundment [XXII]. Their values average 0.73 and 0.63 m/sec on the surface and near bottom, respectively, with 1.92 and 1.0 m/sec maximum values. During summer-autumn stabilization of levels, velocities range in a more complex way and are defined on the one hand by the Kama hydroscheme operation conditions and power site water elevation, on the other hand by the conditions of the Kama River runoff at the section in question. Velocities are quite stable during this period with their maximum value of up to 0.49 m/sec. The principal direction of the flow velocity is in compliance with the current water flow, when wind blows in any direction. Field study results demonstrated that the velocity of flow rather than the wind waves contributes largely to the basin formation. To prove that, the scouring velocity of the flow was computed and compared with the actual one [XXIV]. Non-dimensional parameter $\eta$ may also be used to assess tendencies in transformation processes:

$$
\eta = \frac{v}{V_c},
$$

where $v$ – actual or designed velocity of flow (m/sec), $V_c$ – scouring velocity (m/sec). Here, if $\eta > 1$, scour occurs, $\eta = 1$ – stabilization, $\eta < 1$ – accumulation.

Scouring velocity is one of the critical velocities of flow. It represents an erosion resistance of soils in numerical terms, and is determined by the formula:

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**Fig. 2:** Length-wise change in surface velocities of flow taking into account water level stand elevations
\[ V_e = \lg \frac{8.8H}{d} \sqrt{\frac{2g(\rho_1 - \rho)d}{1.75\rho}} \]  

where \( H \) – vertical depth, m; \( d \) – diameters of sediments, m (here, there is a mean grain size of a mixture under the radical sign, and a diameter of sediments forming the main roughness is in the denominator); \( \rho_1 \)– density of sediments, 2650 kg/m\(^3\); \( \rho \) – density of water, 1000 kg/m\(^3\) [XII].

Scouring velocity initiates mass movement of particles. If actual velocities exceed average scouring velocity of flow, re-formation of a basin with scour and re-deposition of sediments downstream occurs. The designed values of flow velocity near bottom are defined for standard 25, 50, and 75\% quantiles of distribution curve. At the Tul’kino power site with all specified exceedance probabilities of flow velocities, scour processes prevail; at the Berezniki power site scour prevails when exceedance probability is 25\% and less.

Changes in hydrodynamic regime define the conditions, upon which soil-forming material is delivered and deposited. Particles are sorted and deposited along the length of the section in question according to their grain size. Sands of various grain size prevail in the vast majority of samples, often with gravel inclusions. Gravel soils are occasional, muds are found in one sample (Ogurdino power site, grey mud). Bed sediments of the section mostly involve sands of varied grain sized from flat accumulative shores. Coarse-grained sands found near Tul’kino settlement (top boundary of the section in question) with maximum content of 0.5-1.0 mm-sized particles and more than 1.0mm particles, alternate stepwise with fine-grained and medium-grained sands in the approach to the bottom boundary of the section. Loams found only in three selected samples are from loamy abrasion shores. The material from these shores is deposited right here with no carrying it out to the inundated river bed.

Opposite Berezniki settlement in the channel segment, there is a local sedimentation of partially anthropogenic nature. Deposition of these sediments is cyclical and depends on regulation regime and hydrological regime phases. When water exchange slows down, a suspended material of the discharged waste waters is deposited on the layer of sand, and is washed away down when flow water speeds up.

The obtained data were used when developing a computer model of channel processes based on a digital terrain model (DTM) for the examined reservoir section. Calculations were made utilizing a regular 2026 x 82 x 4 three-dimensional grid. A mathematical model based on non-steady three-dimensional (3D) hydrodynamic equations together with the plan 2DH model of bed sediment transport [VIII, XV, XII, XIV, XXVI] was used to describe the processes of transporting and depositing sediments in the variable-backwater zone of the Kama Reservoir. A hydrodynamic 3D-model is based upon Navier-Stocks equations obtained on the assumption of hydrostatic approximation. Turbulent exchange coefficients are computed using a
two-parameter (k-ε)-turbulence model. A system of determining equations is as follows:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -g \frac{\partial \xi}{\partial x} + \frac{1}{\rho} \left( \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) \right). 
\]

(3)

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -g \frac{\partial \xi}{\partial y} + \frac{1}{\rho} \left( \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right) \right). 
\]

(4)

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, 
\]

(5)

\[
\frac{\partial k}{\partial t} + u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} + w \frac{\partial k}{\partial z} = \frac{1}{\rho} \left( \frac{\partial}{\partial x} \left( \mu \frac{\partial k}{\partial x} \right) \right) + P' - \varepsilon, 
\]

(6)

\[
\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial x} + v \frac{\partial \varepsilon}{\partial y} + w \frac{\partial \varepsilon}{\partial z} = \frac{1}{\rho} \left( \frac{\partial}{\partial x} \left( \mu \frac{\partial \varepsilon}{\partial x} \right) \right) + \frac{\varepsilon}{k} \left( C_1 \cdot P' - C_2 \cdot \varepsilon \right), 
\]

(7)

\[
P' = \frac{\mu_r}{\rho} \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right], 
\]

(8)

\[
\frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x} + v \frac{\partial S}{\partial y} + w \frac{\partial S}{\partial z} = \frac{1}{\rho} \left( D_v \frac{\partial S}{\partial z} \right) + S_c', 
\]

(9)

Here, \(u, v, w\) - velocities along coordinates \(x, y, z\) respectively, \(g\) - gravitational acceleration, \(\xi\) - free surface level, \(\mu\) - coefficient of (turbulent) viscosity, \(k\) - turbulent kinetic energy, \(\varepsilon\) - dissipation rate of turbulent energy, \(S\) - concentration of suspended solid phase, \(\rho\) - density of water.

\[S_c = \eta N(C_\ast - C)(1 - \eta)w + R_w\] defines interchange of suspended and tractional sediments.

Below the following shall be stated:

\[\eta = \frac{1}{\sigma^2} \int_{-\infty}^{\infty} \exp \left( -\frac{(\xi - u_b)^2}{2\sigma^2} \right) d\xi\]

- parameter of intensity of exchange with the bottom.
\[ \sigma_u = 0,1 \cdot |i|, \quad u_c = 0,96 \cdot \sqrt{gd^{0,4}} (d + 0,0014)^{0,6} \left( \frac{h}{d} \right)^{0,2} \]

- nonscouring velocity

\( d \) - diameter of (spherical) solid phase particles.

By the Van Rijn formula

\[ u_h = \left( 9 + 2,6 \log D_s - 8 \sqrt{\frac{\theta_c}{\theta}} \right) u_{c,c} \]

Where

\[ D_s = d_{50} \left( \frac{\rho_c - 1}{\rho} \right)^{1/3} \quad \text{- non-dimensional diameter of particles,} \quad \mathbf{u} = \begin{pmatrix} u \\ v \end{pmatrix}, \]

\[ \theta_c = \begin{cases} 0,24D_s^{1} & \text{for} \ 1 < D_s \leq 4 \\ 0,14D_s^{0,64} & \text{for} \ 4 < D_s \leq 10 \\ 0,04D_s^{0,1} & \text{for} \ 10 < D_s \leq 20 \\ 0,013D_s^{0,29} & \text{for} \ 20 < D_s \leq 150 \\ 0,055 & \text{for} \ D_s > 150 \end{cases} \quad \text{- critical parameter of mobility}, \]

\[ \theta = \frac{ghi}{(\rho_c / \rho - 1)gd_{50}}, \]

\[ u_{c,c} = \sqrt{gRi}. \]

Here, \( R \) - hydraulic radius, \( i = \frac{|i|^2}{hC^{a^2}} \) - «energy gradient»,

\[ C' = 18 \log \left( \frac{12h}{k_s} \right) \quad \text{- Chezy coefficient for the near-bottom layer,} \quad k_s = 3d_{90} \]

- height of «roughness», \( N = u_*, \) coefficient of exchange with the bottom,
\[ C_e = \frac{\rho}{\rho_c} \frac{u_i^2}{gh} \left( \frac{e}{\tan \varphi} + 0.01 \frac{|i|}{w_g} \right) \] - equilibrium value of concentration, computed by

the Bagnold formula, \( \frac{\rho_c}{\rho} \) - ratio of solid phase material density to water density (is often assumed to be 2.65), \( \tan \varphi \) - angle of natural bottom material slope (with no data is usually assumed to be 0.6), \( e = 0.1, \ w_g = a \sqrt{\frac{4}{3C_d}} \left( \frac{\rho_c}{\rho} - 1 \right) gd \) - hydraulic size, \( a \) - empirical particle-form dependence coefficient from 0.5 to 1.2.

Then, \( C_d = \frac{24}{Re_d} \) - Stokes drag coefficient for a particle; \( R_w \) - source of suspended sediments from bottom waves.

Equation for bed sediment transport:

\[ (1 - p) \frac{\partial \delta}{\partial t} + \frac{\partial q_{hx}}{\partial x} + \frac{\partial q_{by}}{\partial y} = - \sum_i S_{C_i}, \]  

(10)

Here \( \delta \) - bottom surface level, \( p \) - soil porosity (0.3 – 0.55).

The Van Rijn formula is used to compute the flow of bed sediments \( q_b = \left( \begin{array}{c} q_{hx} \\ q_{by} \end{array} \right) \):

\[ q_b = \frac{0.005uh}{((\rho_c/\rho-1)gh)^{1.5}} \sum_i |i| \left( u_{i}^{cr} - u_i \right) \frac{P_i}{100}. \]

Here

\[ u_{i}^{cr} = \begin{cases} 0.19(d_{s0})^{0.1} \log(12h/3d_{s0}) & 0.0001 \leq d \leq 0.0005 \\ 8.5(d_{s0})^{0.6} \log(12h/3d_{s0}) & 0.0005 \leq d \leq 0.002 \end{cases}, \]

\( P_i \) - percentage of particles of the \( i \) th fraction of soil in a mixture.

The aim of computer modeling was to study channel processes at the examined section of the Kama reservoir under unsteady conditions of hydrological cycle active phase: from the moment of ice break-up to the autumn low-water season.

To model sediment transport and vertical channel deformations, the following information is needed: a) parameters of size of bed-forming sediments; b) their initial
reserves (thickness of bed layer); c) value of bed sediment discharge at the inlet to the specified area within the entire modeling period.

Numerical calculations were made for a scenario (model) year with average discharges over the period from April 15 to September 01. Initial conditions were formed through solving quasi-stationary problem.

The model enabled to compute daily water levels and construct water surface profiles along navigable channels at the various moments of modeling period (Fig.3).

Fig. 3: Water surface profile along navigable channel

as the various moments of modelling period

As snow melt flooding intensifies, water level across the major part of the section (up to Novinki district) has quite a “river-like” behavior, i.e. varies abruptly and, by and large, linearly. Water surface slope amounts here to about 4.4cm/km. Impact of backwater is felt only within the last 15km. It results in the slope decreased to 1.7cm/km. However, already by June 15, as flooding declines and a reservoir is filled, backwater affects almost all the section of interest. A minor slope of water surface (0.8cm/km) is observed only in the upper part of the section (Tul'kino settlement – Teterino settlement). The velocity of flow varies adequately in compliance with the water level dynamics. During snow melt flooding, the velocity of flow averaged depth-wise is about 1m/sec throughout the major part of the section; in its downstream part the value of velocity decreases to 0.6–0.8m/sec. As backwater extends, velocities sharply decrease, and by the end of modelling period, they are merely 0.1–0.3 m/sec that fully corresponds to the actual data.

According to the above results, the following should be noted. There is an area of significant sedimentation in the beginning of the section. It means that the fully
sediment-laden flow (as per the specified conditions) that pertains to the modelling area, almost completely discharges right there. Hence, all reformation of bottom relief, further observed in the area in question, are mostly resulted from redistribution of sediments inside the area as such. In the lower reach of the section, from NizhniyeNovinki to Berezniki settlement, exactly where there are backwaters effects during snow melt flooding, almost no changes in the bottom relief occur.

A widespread scouring of braided depressions in ground (relatively deep sections) and a rise in bottom elevations in the shallower water zones (cripples) are seen throughout the remaining part of the modeling area in question. In the course of scouring braided depressions, virtually all bed sediments were removed in some locations, i.e. the value of scouring reached 0.5 m.

BorovskoyZaton-Grigorovo area has the most significant sedimentation. Here, a clearly discernible submarine ridge was formed that blocks the flooded Kama River bed at an acute angle. It should be noted that the initial model of relief in this region really involves shallow-water area, separating two braided depressions.

It is known from the theory of channel process that during snow melt flooding crests of submarine ridges are washed-in (depths in them decrease), and braided depressions are washed-out (depths in them increase); a vice-versa process occurs during low-water season, namely, crests are scoured, and depressions are filled with sediments [XXVI]. The above results of modelling bottom relief changes as of the end of snow melt flooding well corresponds to this regularity. However, there are no any further considerable changes in the bottom relief, and the final picture as of September 01 looks no different from that as of June 15. To demonstrate this fact, a time-wise change in the volume of accumulated Grigorovo cripple sediments was considered. A scaled-up image of this section is presented in Fig.4, and the respective values of sedimentation volumes (Table 1) are given. It can be seen that the volume of accumulation in zone No.1 corresponds to the volume of scouring in zone No.2 (braided depression in ground).

### Table 1: Volume of accumulated sediments in zone No.1

| Date          | Volume of deposited sediments, m³ |
|---------------|-----------------------------------|
| May 01        | 57584                             |
| May 20        | 223380                            |
| June 15       | 253608                            |
| July 15       | 253666                            |
| August 15     | 253666                            |
| September 01  | 253666                            |
Further, it is found that in wash of ridge was complete after snow melt flooding recession, however, there was no further scour of the river cripple, as per the above-mentioned regularity, which appear to be attributable to the impact of backwater.

**IV. Conclusions**

Thus, the obtained data of field surveys, analysis of archive materials, and numerical modeling enabled to find out the following:

1. There are three sections within variable-backwater area: upstream section (river conditions prevail), midsection (there are both river and reservoir conditions),

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*Fig. 4:* Resulting change in bottom elevations (scour/in wash) in the vicinity of Grigorovo settlement as of September 01. Initial thickness of bed sediments layer is 0.5m

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downstream section (basic reservoir conditions). Midsection has the most complex hydrodynamic regime.

2. The principal role of level and velocity regimes, and grain size of bed sediments, which represent the main aspects of forming channel deformations, varies along the area length.

3. A relationship is established between the major factors that specify hydrodynamic features of variable-backwater zone and the respective consequences (development of abrasion and accumulation processes).

4. A mathematical model of transporting suspended and tractional sediments is constructed and applied. It enabled to compute the volumes of accumulated sediments and identify the relationships between changes in the basin bottom topography and hydrodynamic features of the section.

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