The Approach to Study the Kama Reservoir Basin Deformation in the Zone of a Variable Backwater

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Abstract. A reservoir floor starts to change since it has been filled up to a normal headwater level (NHL) under the impact of hydrosphere and lithosphere interactions as well as under the impact of chemical and biological processes that occur in its water masses. At that complicated and often contradictory “relations” between features of geo- and hydrodynamic processes are created. The consequences of these relations are the alterations of values of morphometric indices of the reservoir water surface, depth and volume. We observe two processes that are oppositely directed. They are accumulation and erosion. They are more complex at the upper area of the reservoir – the zone of a variable backwater. The basin deformation observed there is lop-sided and relatively quiet, but with time these deformations make difficulties for water users. To provide good navigation and to reduce harmful effect of waters on other water consumption objects, it is necessary to study and to forecast constantly the basin transformation processes that occur at this zone.

1. Introduction
Reservoirs are artificial reservoirs, the function of which is to regulate the flow. They are relatively young and developing systems. Reformation processes of different parts of reservoirs are a subject of multiple researches. They are studied by scientists of Russia [1-7], Europe [8-10], Asia [11], the USA [12, 13] etc.

The study of individual aspects of channel processes in variable backwater region was handled by N.I. Makkaveev, V.A. Kritsky and V.I. Litvinsky, V.V. Lysenko, R.D. Frolov, N.B. Baryshnikov, R.B. Uralsky, S.L. Vendrov, V.F. Nikolaev et al. [2-4]. However, there is no complete picture of the processes taking place in this region.

The zone of a variable backwater (which length is 145 km.) of the Kama reservoir is located at the upper area of the Kama reservoir. The zone starts near Ust’-Pozhva village and finishes near Kerchevskii urban village (Figure 1), but even so the backwater zone some years stressed 46 km. higher than the Vishera river estuary. The beds of the Kama and Vishera rivers within the studied area are cutting in and straightforward. In the upper area the backwater zone is within the original Kama riverbed. A partial flooding of the floodplain of 0.5 to 1 meter depth is observed in the southern part of the area. The water-surface area is 108 km² and water masses capacity is 0.31 km³ there. Point bar channel processes with the elements of mid-channel bars predominate at the Kama river. Sand and gravel are the main bed loads, sand and clay are the main floodplain sediments. Complex interrelation between the reservoir filling regime and spring tides periods at the main tributaries causes multiversion locations of boarders in a pinch zone in a variable backwater zone.
Channel deformation forms also have some peculiarities: a channel regime is characterized by a regression accumulation. We observe a self-regulated channel deformation in accordance to the altered erosion basis and the riverbed adapts to its new conditions. The consequences and the forms of this process are:

1. The marks of point bars and mid-channel bars rise and the size of both bars also increases.
2. Channel forms get larger because of the passing away of small point bars and the merger of adjacent point bars. As the result small single riffles get larger and more complex.
3. When the reservoir was built the channel cutting-in process increased at the territory between the river Vishera estuary and Tyul’kino urban village. Relatively fast increase of rivers confluence index (50-60 m/ year) and the angle decrease of their matching have led to the wash-out of the left bank estuary point bar of the Vishera river. In its turn it has caused the displacement of the dynamical axis of the Kama river water-course to its left bank and a left bank un navigable channel has appeared between Tyul’kino islands [14].

![Figure 1. The zone of a variable backwater of the Kama reservoir](image)

2. Material and methods
To determine the formation intensity of sediments accumulation and denudation zones during one year the channel surveys of several riffles (Kerchevskii, Ust’-Moshevskii, Malakhovskii, Verkhnii and Nizhne-Solomenskii, Teterinskii) have been matched.
The Kerchekskii riffle is located at 2575-2572 km along the navigable pass. There is an intensive growth of bottom sediments at the left bank and the channel erosion at the right bank. Ridges with 175 km length may appear during a year.

The Verkhnnii and Nizhne-Solomenskii riffles are located at 2.568-2.562 km along the navigable pass. There is a ridge increase in the middle course. Sediment accumulation zones are located randomly: at the right and left banks and in the middle course. As the result the number of shoals, point bars and riffles increases. The erosion zones are also located randomly and are observed everywhere. Significant basin depression deformations are observed within 2.563-2.562 km along the navigable pass: the left bank is characterized by intensive erosion, and the right one - by alluvion. The navigable pass shifts to the left bank.

The matching of the channel surveys of the Ust'-Moshevskii and Malakhovskii riffles has revealed how the Kama reservoir basin has changed during a year: the reservoir floor has been divided into two zones: a sediment accumulation zone has formed at the left bank and the right bank and bottom have washed out. As the result the navigable pass has shifted to the right bank.

There is an additional local erosion base level – the Glotikha and Usolka rivers at the Teterinskii riffle. As the result the storage capacity of the main channel has been almost exhausted. There point bars increase intensively especially along the left bank and as a result the bank stretches with the speed of 80 m per year and has already prevented the passes to the docks of the petroleum storage depot and an industrial port. In 5-7 years this will seriously prevent the “Sil’vinit” Ltd. water supply point activity. The right bank channel erosion behind the Teterinskii island is also possible. The shoaling of the left distributary, that increased since the channel dredging has stopped, can accelerate this process 1 leading to unpredicted challenges and consequences for both navigation and the operation of water consumption objects located close to the riffle. Currently the uncontrolled deformation process of the basin increases. One reason for that is that the activity to straighten the channel and to clean navigable passes from sediments has stopped, another one is an early reservoir drawdown. These reasons affect the hydrodynamic regime of the reservoir.

Hydrodynamic regime plays a significant role in basin transformation as it determines a process (erosion and accumulation) trend. Process trend may be assessed by means of the dimensionless parameter η:

\[ \eta = \frac{v}{V_p} \] (1)

Where \( v \) is actual or calculated flow velocity (m/sec) and \( V_p \) is eroding velocity (m/sec). If \( \eta > 1 \), then we observe erosion, \( \eta = 1 \) - stabilization, \( \eta < 1 \) – accumulation.

Actual flow velocities were obtained by observation data generalization. The data were taken from 1964 to 2016. Totally 600 velocity values were used. The calculated near-bottom velocities of the predetermined exceedance probability were calculated according to SP 33 101 2003 [15]. Three ratings of exceedance probability – 25%, 50% and 75% were used as the quantitative assessment of the flow velocity in a variable backwater zone.

An eroding velocity is one of the crucial flow velocities (together with a non-eroding velocity) and it is a qualitative expression of erosion-preventive soil stability [16] that has been calculated according to the formula:

\[ V_p = \frac{g}{d} \sqrt{\frac{2g(\rho_1 - \rho)d}{1.75\rho}} \] (2)

where \( H \) - vertical depth, m; \( d \) - sediments diameter, m (at that an average diameter is under the root, a maximum diameter is in the denominator); \( \rho_1 \) - sediments density, 2650 kg/m\(^3\); \( \rho \) - water density, 1000 kg/m\(^3\). Eroding disruptive velocity \( (V_p) \) corresponds to the beginning of mass particles displacement. If actual flow velocities exceed the average eroding velocity, then basin transformation, sediments erosion and re-deposition take place. The actual flow velocities are determined by a level regime that is why predominant transformation processes of the reservoir floor should be determined.
3. Results and discussion
The studies devoted to the level regime peculiarities [17] that were previously made have distinguished three typical sites in the zone of variable backwater. They are the area between Kerchevskii and Tyul'kino urban villages (where river conditions prevail); the area between Tyul'kino urban village and Berezniki city (where river and reservoir conditions are equal); and the area between Berezniki city and Ust'-Pozhva village (where reservoir conditions are observed during a whole year). The basin transformation process trend has been determined within these sites with η parameter. The η parameter calculation has revealed that erosion processes prevail under all marked exceedance probabilities and levels in Tyul'kino urban village hydrometric section. In all the rest hydrometric sections (except Ust'-Pozhva village) erosion prevails under all considered levels when exceedance probability is 25% and lower. Stabilization and accumulation processes take place if exceedance probability is 25% and higher in the hydrometric section of Ust'-Pozhva village. The η parameter distribution in different months of a navigation process in the variable backwater zone of the Kama reservoir (Table 1) demonstrates that there is erosion under 107 and 108.5 m absolute levels in the area between Tyul'kino urban village and Berezniki city in May and June, the stabilization is observed in August and the sediment accumulation - in July and September. The washing-out processes are observed only in May in the area between Berezniki city and Ust'-Pozhva village. In all other months (June-September) accumulation processes prevail (Table 1) and accumulative forms of a bottom relief develop.

Table 1. The η parameter in different months of navigation period in variable backwater zones of the Kama reservoir

|       | Tyul’kino urban village-Berezniki city | Berezniki city- Ust’Pozhva village |
|-------|----------------------------------------|------------------------------------|
|       | 107 m above the sea level | 108.5 m above the sea level | 107 m above the sea level | 108.5 m above the sea level |
| May   | 1.97 | 1.94 | 1.20 | 1.17 |
| June  | 1.48 | 1.45 | 0.86 | 0.83 |
| July  | 0.71 | 0.70 | 0.46 | 0.44 |
| August| **0.92** | **0.91** | 0.51 | 0.50 |
| September | 0.80 | 0.79 | 0.29 | 0.28 |

* Values that illustrate washing out/erosion processes are printed with a bold type and values that demonstrate stabilization are printed in bold italics

Underwater ridges are the examples of accumulative forms. Their values parameters depend on average turbidity in the course channel and hydraulic parameters (water level and discharge, flow velocity and sectional area). We have made nomograms for Tyul’kino urban village that are based on long-term research data and recommendations provided in the Departmental building codes (DBC) [18]. The hydrometric section selection is explained by the fact that there are differentiations of river and reservoir conditions. Nomogram feature is that it is necessary to have only turbidity value that is easily obtained under field conditions to determine ridge parameters (length and height). The ridge parameters are obtained by stages:

1. First we determine water discharge that corresponds to the present average turbidity value. The turbidity dependence on the water discharge constructed on long-term observation data for the hydrometric section in Tyul’kino has two point clouds (Figure 2). The first point cloud is presented by a direct linear dependence, the second one - by an inverse linear dependence. The second point cloud is formed from the beginning to the middle of May during a spring tides peak when the reservoir is filled and water level rises to a normal headwater level (NHL). So a backwater appears: water masses go upstream. At this period water mass “faces” the river water masses. In this connection the low point clouds correspond to river conditions and the upper point clouds correspond to the reservoir conditions.
2. The dependence between water level and flow velocity is made and a pair correlation coefficient is calculated on the basis of long-term observation data. In accordance with the obtained equation a flow velocity for level values with a 40 cm-step under different depths (a 5 cm-step) is calculated. We have obtained 3.240 values that have been used to build nomograms.

3. We calculate a ridges length \( l_r \) (m) under the determined water movement regime according to the dependence: 
\[
l_r = \frac{H^3 \sqrt{C}}{g},
\]
where \( C \) is Chezy’s coefficient at the designed vertical line that takes an average incline value into account; \( H \) is a vertical flow depth; \( g \) is gravity acceleration. The obtained value is used to make the ridge length dependence on a flow velocity (Figure 2).

4. We calculate a ridges height \( h_r \) (m): 
\[
h_r = \begin{cases} 
0.25H & \text{if } H < 1 \text{ m} \\
0.20 + 0.10H & \text{if } H > 1 \text{ m}
\end{cases}
\]
(Figure 2). As we can see from the nomogram, the ridge height-flow depth function is linear. In the case study the correlation between values is strong, the correlation coefficient is 1. Ridges shift velocity \( C_r \), m/sec) is calculated by the formula: 
\[
C_r = 0.019\sqrt{v^3},
\]
where \( v \) is an average flow velocity above the
place where a ridge is being determined, m/sec; Fr is the Froude number. If Fr > 1, water flow is considered to be rough, if the dependence is inverse the flow is quiet. At the case study area rough water masses finish at the 50 cm-depth and starting from the 55 cm-depth the flow becomes absolutely “quiet”.

We calculate ridges shift period of the particular profile during a day using the formula: \( \tau = \frac{l}{v} \).

The largest observed ridge shifting occurs at low depth (up to 45 cm) and the 0.54 m/sec flow velocity.

The possibility to use the obtained nomograms has been proved in the case study of the hydrometric section located near Kerchevo village (0.5 km lower the Kerchevka river estuary). The turbidity in this area is 60 g/m³. First we calculate water discharge corresponding to the present average water turbidity according to the dependence. If average water turbidity is 60 g/m³, the water discharge will be 190 m³/sec. Then using the dependence of water discharge on a water level, we calculate the level value (using the equation or the dependence curve), which is 157 cm. At that using a flow velocity dependence on a water level, we see that the velocity is 0.33 m/sec. Then using the obtained flow velocity, we calculate the ridge length (2.54 m), its height (using the flow depth) is 0.05 m, the Froude number is 0.108 and the ridge shifting velocity is 0.000056 m/sec. We have revealed that if the flow velocity during a year was constantly 0.25 m/sec, then we would not observe the evident movement.

Thus, the obtained dependences allow calculate possible parameters of the change of a ridge- a base bottom relief form, if there is an absence of field observation data.

During our research the following conclusions were made:

1. The reservoir construction has led to the formation of channel deformation processes. The reason for that is a lop-sided character of a regression accumulation that leads to a self-regulated reservoir basin transformation in a variable backwater zone. The \( \eta \) parameter is an index of a basin deformation trend.

2. Development of underwater ridges obviously demonstrates the process of a basin transformation. The forecast of the ridges development is based on the data of average turbidity and hydrological parameters (water level, water discharge and flow velocity).

3. Ridge development is characterized by its length and height. We suggest using nomograms to calculate these parameters in variable backwater zone of the Kama reservoir. The nomograms are based on dependences: a). the water discharge on an average turbidity and water level; b). the water level value on the flow velocity; c). the ridge length on the flow velocity and the ridge height on the flow depth. To calculate ridge parameters it is necessary to know only a turbidity value that is easily obtained under field conditions.

4. Acknowledgements
The research has been conducted with the financial support of RFBR grant № 16-45-590546 p.a.

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