

Environmental safety assessment in the influence zone of the existing Zelenchukskaya HPP-PSHS and Krasnogorsk HPP-1, HPP-2 under construction in the area of Ust-Dzhegutinsky reservoir location

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Abstract. «Environmental safety "in the considered spatial limits of the Upper Kuban basin geosystem ($F_w=11,0 \cdot 10^3 \text{ km}^3$, $W_l=3,3 \cdot 10^3 \text{ km}^3$, $W_{atm}=110 \cdot 10^3 \text{ Wb.g.U.K.}=124,3 \cdot 10^3 \text{ km}^3$) makes up about 21.4% of the spatial limits of the Kuban River, where water resources are formed according to the average long-term data about $3,0 \text{ km}^3$, which are used in various sectors of economic activity, including for the electricity generation at Zelenchukskaya HPP-PSHS and Krasnogorsk HPP-1 and HPP-2 under construction with installed power up to 25 mW, located below the HPP-PSHS Zelenchukskaya section and above the alignment (12 km) of the Ust-Dzhegutinsky reservoir. Such HPP-PSHS placement on a 15 km long section of the Kuban Zelenchukskaya riverbed and Krasnogorsk HPP-1 and HPP-2 under construction determined a highly active zone of influence (IV), which is caused by a change in the natural hydrograph of the Kuban River, with the formation of the channel flow movement unsteady hydraulic regime in the considered section of the river to the Ust-Dzhegutinsky reservoir. Unsteady changes in the water level in the Ust-Dzhegutinsky reservoir affects the pressure front structures safety, the functional operation of the water intake system in the Bolshoi Stavropol Canal (BSC) and hydraulic BSC operation. To assess the level of "environmental safety", it became necessary to develop a mathematical model of the impact of the HPP-PSHS functional work and Krasnogorsk HPP-1 and HPP-2 under construction at the level modes of operation of the Ust-Dzhegutinsky reservoir.

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1 Introduction

Operating Zelenchukskaya HPP-PSHS introduces certain changes in the hydrological regime of water flow formation within the catchment area ($11,0 \cdot 10^3 \text{ km}^3$) river hydrographic network of the Upper Kuban (Wb.g.U.K.= $124,3 \cdot 10^3 \text{ km}^3$), as the dominant factor of "environmental safety". Based on the comprehensive studies results of the changes under the influence of the processes of interconnection, interaction and relationship (IIR) natural (biotic, abiotic), social (living population) and technogenic (various types of hydraulic structures and related structures) components, the boundaries of the influence zones were determined among themselves within the considered spatial limits of the Upper Kuban basin geosystem.

At the Upper Kuban basin geosystem level, where the IIR processes between natural, social and technogenic components in the natural technological system (NTS) "Natural environment - Activity Object - Population" («NE-AO-P») take place, in which the "Complex of hydraulic structures and related structures" is considered for «AO». The integrity of the NTS «NE-AO-P» is provided due to the continuous flow of self-organization and transformation processes in intersystem structural formations (river network, flora and fauna, soil cover, upper layers of the lithosphere and surface layers of the atmosphere, etc.). Implementation «AO» into «NE» causes certain complications of inter-structural connections in the processes of self-organization between natural and man-made structural formations in the zones of its IIR. Studies have established that irreversibility in processes IIR «AO» with «NE» in the zones of influence leads to the emergence of new phenomena in the geological environment of the lithosphere upper layers, in hydrographs and the channel part of the considered section of the river, the coastal strip in the floodplain part of the river network channels, the surface layers of the air environment above reservoirs and open sections of the water channel, and basin geosystem as a whole (Fig. 1).

Based on the research results analysis of the identified impacts «AO» on «NE» within the spatial limits of the Upper Kuban basin geosystem with the boundaries' definition of the influence zones, which determined their classification characteristics: low-active, active and strongly-active (Fig. 1), of which the highly active zone of influence IV in the area (15 km) from the pressure front of the Ust-Dzhegutinsky reservoir (volume 37 mln. m^3) upstream to the alignment (left bank) of Zelenchukskaya HPP-PSHS (Fig. 2), on the one hand, is caused by a change in the natural hydrograph of the Kuban river, and on the other hand, by the Krasnogorsk HPP-1 and HPP-2 with total volume 11 mln. m^3 , which have a definite impact on NTN front pressure functional performance and hydraulic BSC operation.

To ensure "environmental safety" in the influence zone of the Ust-Dzhegutinsky reservoir, especially the settlements and the city of Cherkessk located below this reservoir section, it became necessary of research to develop a mathematical model for calculating the unsteady movement of the water flow in the area under consideration (15 km) a highly active zone of influence IV (Fig. 1) at the first stage, which is caused by discharges of water flows from the Zelenchukskaya HPP-PSHS excluding the Krasnogorsk HPP-1 and HPP-2.

2 Mathematical model for calculating unsteady water flow in the area under consideration

The calculation of water movement in the channel is described using differential equations of unsteady water masses flow, well developed and studied in hydrodynamics. The model of slowly changing unsteady uneven motion of water masses includes the equations of continuity and momentum. The conservative form of the one-dimensional continuity equation for the river channels with lateral tributaries has the form:

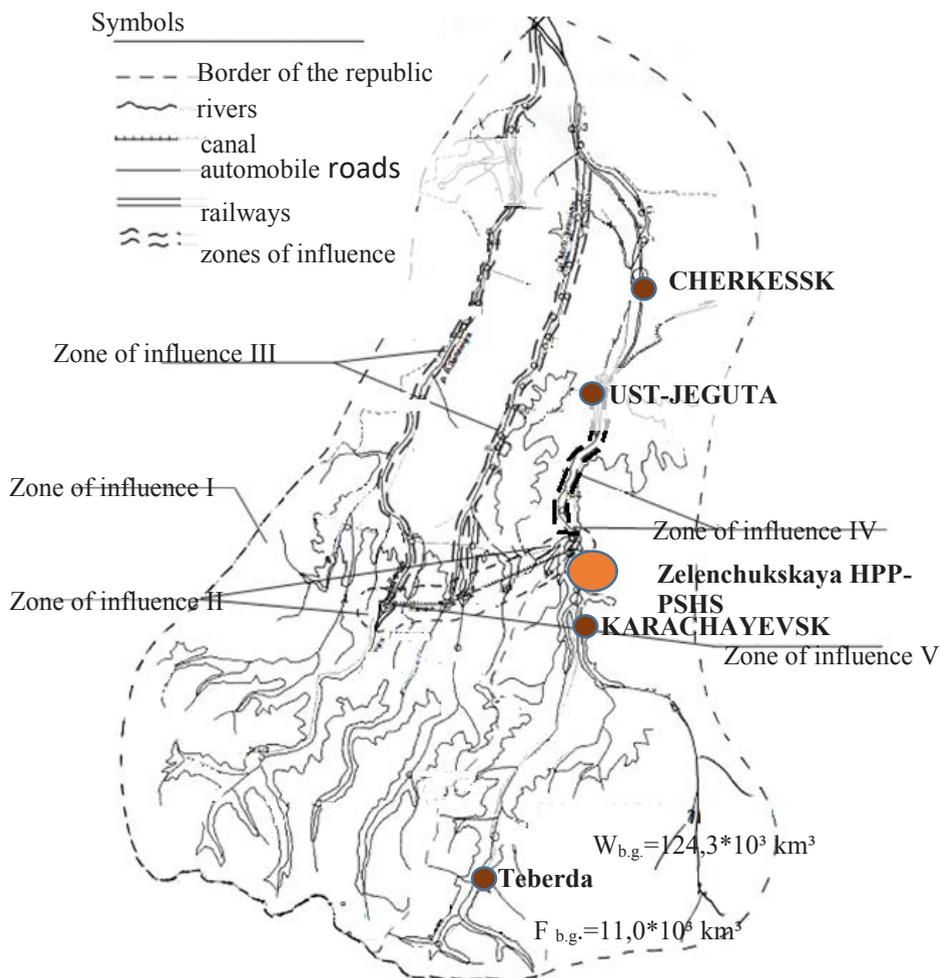


Fig. 1. Influence zones of the hydraulic structures Zelenchuksky HPP complex on the Upper Kuban basin geosystem environment: I – Inactive zone of influence within the catchment area of the upper river. Kuban (11000 km²); II – Active zone of NTN complex influence on microclimate parameters (P_{mc}); III – Strongly active zone of NTN complex influence on the rivers B. and M. Zelenchuk (P_{PDO}); IV – Strongly active zone of influence on the 15 km section of the river. Kuban (P_{VBRs}); V – Active zone of NTN reservoirs and complex influence on the geological environment (P_{SRB})

$$\frac{\partial Q}{\partial x} + \frac{\partial \omega}{\partial t} = q, \tag{1}$$

and in expanded form:

$$\omega \frac{\partial V}{\partial x} + V \frac{\partial \omega}{\partial x} + \frac{\partial \omega}{\partial t} = q \tag{2}$$

where: Q is water consumption, m³/s;

ω is free area, m²;

V is an average flow rate, m/s;

q is a lateral inflow per unit length, m²/s;

x and t are respectively spatial and temporal coordinates, m and s.

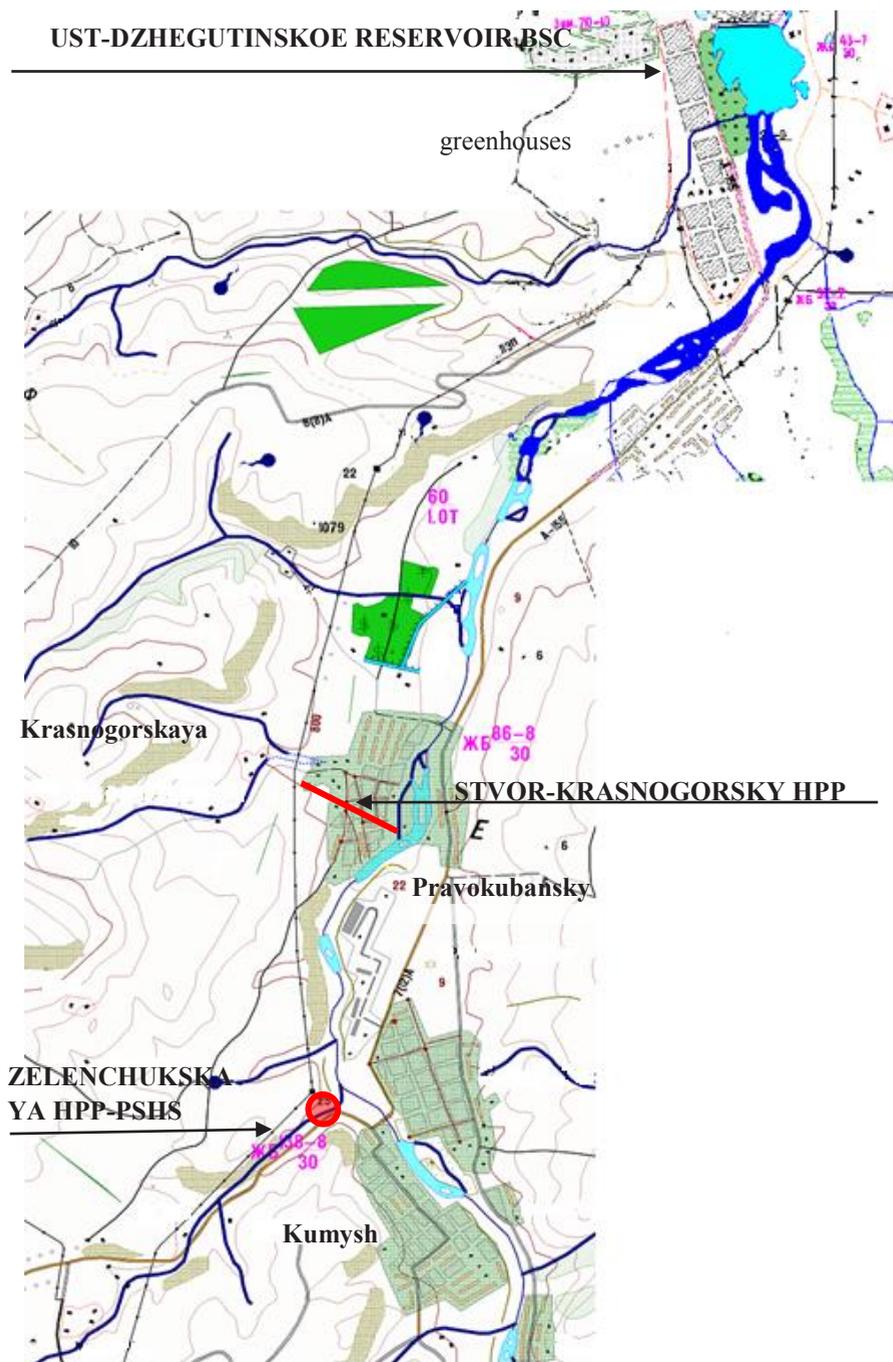


Fig. 2. Situational plan for the Zelenchukskaya HPP-PSHS and the Ust-Dzhegutinsky reservoir location on the Kuban river

The expanded form of the one-dimensional momentum equation for the river channels with a lateral tributary has the form:

$$\frac{\partial V}{\partial t} + V \frac{\partial \omega}{\partial x} + \frac{g}{\omega} \cdot \frac{\partial(\overline{H} \cdot \omega)}{\partial x} + \frac{V \cdot q}{\omega} = g(I - I_f), \tag{3}$$

where: g is gravity acceleration, m/s^2 ;

\overline{H} is the distance from the water surface to the center of gravity of the water section (in other formulas, instead of it, the flow depth averaged over the section is used);

I shows river bed slope, m/m ;

I_f is hydraulic gradient (friction slope),

$$I_f = \frac{Q^2}{K^2} \tag{4}$$

$K = C\omega\sqrt{R_h}$ - channel throughput, determined by the hydraulic radius (the free area ratio to the wetted perimeter) - R_h , free area ω and the aspect ratio C (Chezy speed coefficient), associated with the speed of the flow, as well as the roughness of the channel. There are various formulas for calculating it, taking into account the depth and the roughness coefficient. The latter is tabulated for the main characteristics of the bottom and is widely used in hydraulic calculations.

The continuity equation (1) - (3) can be rewritten as:

$$\frac{\partial \omega}{\partial t} = -\frac{\partial Q}{\partial x} + q \tag{5}$$

in the finite-difference interpretation, it is the channel balance equation of the site Δx :

$$\frac{dW}{dt} = -\Delta Q + q \cdot \Delta x \tag{6}$$

The equation (3.4) (momentum) describes the flow dynamics, characterized by viscosity, slope, roughness and gravitational forces. These parameters, correlated with the distribution of the flow mass along the channel (channel water balance), allow us to evaluate the hydraulic characteristics of interest to us at any given point t , and, first of all, the flow rate, level and speed of the current. The equation (3), if there are sufficient data on the hydraulic parameters of the channel based on long-term observations or specially performed instrumental measurements, can be replaced by the relationship $\omega = f(Q, x)$ (channel capacity curve) and then the continuity equation, if this dependence is substituted into it, will give the desired solution with an acceptable degree of reliability.

If there is an unambiguous relationship $\omega = f(Q, x)$ or $Q = \varphi(\omega, x)$, then the continuity equation in the form (1), (2) or (4) is called the kinematic wave equation (or the mass conservation equation), which makes it possible to use the channel balance models in the calculations of unsteady flow in the channel taking into account a specially selected ratio of finite intervals Δx and Δt without significant accuracy loss. Further approbation of the models under the conditions of real observations makes it possible to correct the parameters of the models and, in the future, their use in practice gives quite acceptable results from the point of view of their correctness of application and the obtained accuracy of calculations for specific sections and sections of rivers.

The described equations, taking into account the simplifications made, give sufficiently reliable results if:

- the flow is relatively straightforward and the velocities are approximately the same throughout the entire live section;
- the pressure across the free flow area obeys the hydrostatic law;
- the slope of the river is relatively small compared to the length;
- the speed of water flow in the channel is determined by the Chezy-Manning formula, i.e., there is an unambiguous dependence of the water flow rate on the level;
- lateral inflow enters the channel normally towards the latter, and its speed does not significantly exceed the speed of the flow itself;
- the value of the lateral inflow, reflects the spatial and temporal variation of the lateral inflow, for areas without inflows, the component $q=0$.
- a reservoir, if it is included in the general section as a closing section, is stretched along the channel and has an average depth of no more than 3 m, or is a lake-like pool relatively small in length compared to the total length of the entire calculated section.

3 Numerical implementation of the unsteady flow propagation model in the area affected by the Zelenchukskaya HPP-PSHS discharge

It is necessary to set the initial and boundary conditions at the site for calculation according to the equations (1) - (2), describing the unsteady uneven movement of water masses. The term "initial conditions" means the flow state, its velocity or flow rate at all points of the channel at a time $t=0$. Boundary conditions determine the water layer height, its speed or discharge in the upper and lower sections of the river section at any time $t>0$. The linear design diagram of the section under consideration is shown in Fig. 3.

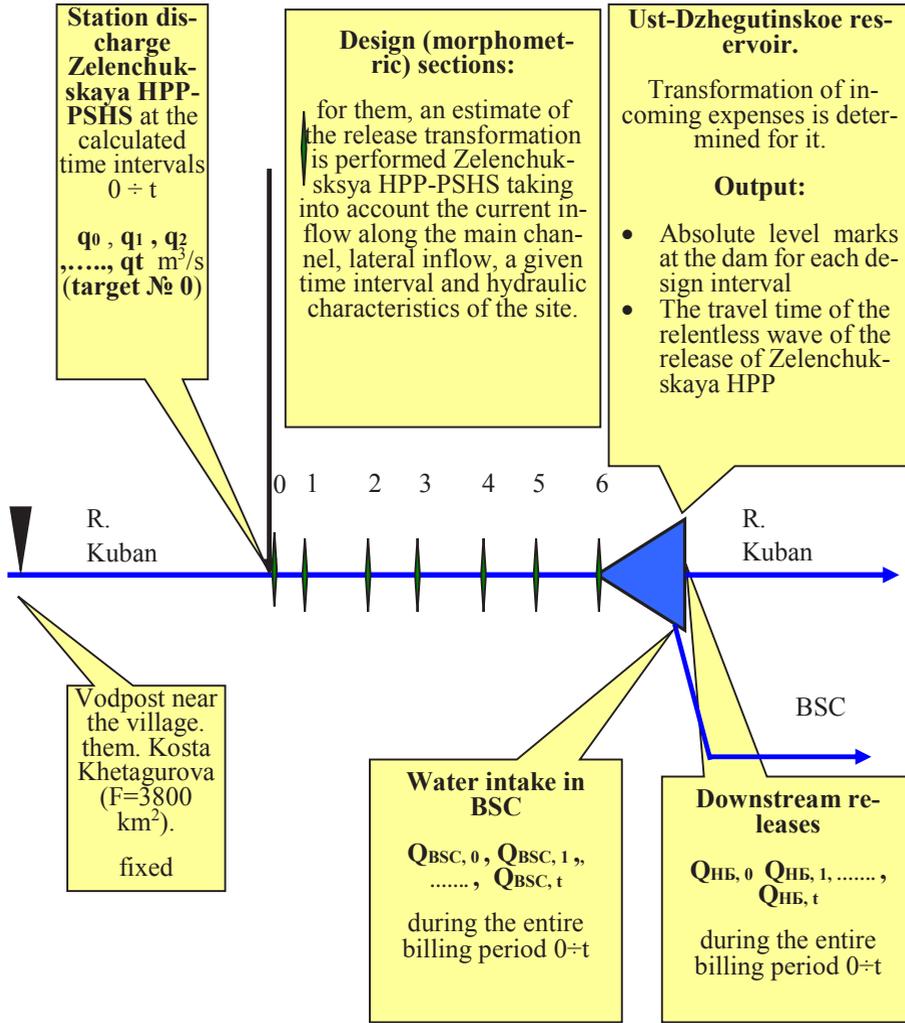


Fig. 2. Calculated linear scheme of the river Kuban section

The parameters of a uniform steady flow are set as an initial condition. It is described by the flow rate calculated on the basis of the flow rates' current observation data in the section of the drainage station named after K. Khetagurov, recalculated taking into account the area of water collection in each of the calculated sections 0, 1, 2, 3, 4, 5, 6. Thus, there are only 7 calculated sections and 6 calculated sections in which the input flow transformation is calculated, entering the section No. 0 (the discharge place of Zelenchukskaya HPP-PSHS). If the flow at the initial moment of calculation is unsteady, then individual values of flow rates for all sections should be set according to the data of the previous calculation or known (assumed) values. It is considered that if the flow is steady, then the flow rates in the sections are the same and differ only by the correction associated with an insignificant increase in the sections' catchment area.

As the boundary conditions are set in the upper section No. 0 the values of the incoming flow rates on the river Kuban (according to the settlement of K. Khetagurov) are adjusted for the catchment area) plus the discharge by Zelenchukskaya HPP-PSHS. In the lower section, the flow rates of releases into the Kuban River plus water intake into BSC are set for each t .

For real river channels in conditions of uneven movement, the cross-sectional area changes along the river (coordinates x). Unsteady motion entails its change with time, i.e., $\omega = \omega(x, t)$.

However, since detailed morphometric parameters of river channels are not always available, averaged characteristics for the sites are used based on the available morphometric data. Thus, the entire area is divided into "characteristic" areas within the limits of which it is considered that the morphometric characteristics are unchanged. At the same time, for the starting section No. 0, the hydrograph is set in accordance with the current hydrological situation and the planned discharge costs of Zelenchukskaya HPP-PSHS:

$$Q_{0t} = Q_0 + q t \quad (7)$$

where: Q_{0t} is hydrograph in the initial section No. 0, in intervals $0 \div t$;

Q_0 defines natural hydrograph arriving at site No. 0, at all intervals $0 \div t$ (since a short period of up to one day is considered, then it is considered unchanged);

$q_0, q_1, q_2, \dots, q_t$ are the planned discharges of Zelenchukskaya HPP-PSHS at estimated time intervals $0 \div t$, m^3/s .

Next, the flow transformation in the first section and the output hydrograph are calculated, which in turn serves as the input hydrograph for the second section, etc. Such an algorithm makes it possible to significantly simplify the calculation and avoid many mathematical and computational difficulties.

For each "characteristic" section, the kinematic wave equation is solved, taking into account the agreement of the solution according to the morphometric and slope characteristics known for this section, the roughness and the compiled longitudinal profile, on the basis of which analytical dependences are constructed in the form of piecewise continuous curves:

$Q(H)$ is the dependence of the flow rate in the section on the level;

$H_{av}(Q)$ is the dependence of the average water level on the flow in the section;

$w(Q)$ is the dependence of the free area on the flow rate in the section;

$H(Q)$ is the dependence of the absolute level mark on the flow rate in the section;

$Q(w)$ is the flow rate versus cross-sectional area.

The indicated relationship curves were plotted for six available morphometric sections:

R. Kuban, target No. 1 950 m below the territory of Zelenchukskaya HPP-PSHS

R. Kuban, target No. 2 3080 m below the territory of Zelenchukskaya HPP-PSHS

R. Kuban, target No. 3 1090 m below the road bridge Krasnogorskaya-Cherkessk

R. Kuban, target No. 4 246 m below the road bridge Krasnogorskaya - Cherkessk

R. Kuban, target No. 5 2933 m below the road bridge Krasnogorskaya - Cherkessk

R. Kuban, target No. 6, 24 m above the cable-stayed crossing of the gas pipeline, 1 km south of Vazhny village.

In addition, the transverse profiles have been compiled to more accurately take into account the distribution of the reservoir volume along the length when calculating the dynamic capacity under the conditions of the inflow of unsteady flows in the inlet section for the Ust-Dzhegutinsky reservoir. The general characteristics of the reservoir are described using the compiled bathymetry curves:

$F(H)$ is the dependence of the reservoir surface area on the level at the dam;

$W(H)$ is the dependence of the reservoir volume on the level at the dam;

$H(W)$ is the dependence of the level in the reservoir on the filling volume.

Estimated time interval Δt is selected based on the length of the calculated section Δx taking into account the travel time of the flow τ at a given flow rate or level at the site, so that Δt was close to it, but at the same time $\Delta t \leq \tau$. Otherwise, the calculation by the formula

of the kinematic wave gives distorted results - there is, as it were, the effect of a backwater from the side of the downstream section.

On the other hand, Δt is set by the experimenter proceeding from the division of his interest to the entire calculated interval T . If the size of the interval is set larger than the time of reaching the flow rate in accordance with the average speed of the flow in the section, then the calculation is performed for a smaller interval for the averaged data, and then the result obtained is generalized for the larger set.

The final result of calculations for "characteristic" sections is generalized for the main 4-sections and the Ust-Dzhegutinsky reservoir for the levels at the BSC water intake.

The calculation algorithm is as follows:

Calculate the hydrograph $Q_{i,t}$ in alignment i for all calculated time intervals $t = 0, 1 \dots T$ based on input hydrograph $Q_{i-1, t}$. For the first section, this is the boundary hydrograph determined by the formula (6).

The calculation is carried out for the section under consideration for each individual time interval t by solving the flow propagation equation (kinematic wave) from the upper section of the section to the lower in the form (5), as a result of which, we determine the flow rate and level at the end of the current calculated time interval.

According to the hydraulic connection formulas, we determine the remaining hydraulic characteristics, taking into account the test connections. At the same time, we determine the discrepancy arising when calculating the average level in the lower section of the site. Taking this into account, we make a series of iterative clarifying calculations, as a result of which we determine the final flow rate and level values for the section under consideration at the end of the interval t (and, accordingly, at the beginning of the interval $t+1$): $Q_{i,(t+1)}, H_{i,(t+1)}$.

On the next calculation interval $t+1$ is obtained at the previous time step $Q_{i,t+1}$, we consider the lower boundary flow rate, and the upper boundary flow rate - $Q_{(i-1)(t+1)}$ and continue the calculation according to the previous paragraphs 2 and 3 until all time intervals are exhausted.

The design sequence 1-4 is performed sequentially for all sections and sections' downstream. At the end of the calculation, we take the obtained calculated hydrographs and the corresponding levels in the sections as the desired solution for finding the costs and levels.

The algorithm for such a calculation is implemented as a program for hardware and was used to develop dispatching rules for managing the integrated water-economic BSC system, Zelenchukskaya HPP-PSHS and creating HMI.

4 Conclusion

In the systematic study of IIR "Activity Object" processes consisting of NTS «NE-AO-P» it was found that the criterial quantitative indicator (P_j) for the considered highly active zone of influence IV in the section from Zelenchukskaya HPP-PSHS to the structures of the pressure front of the Ust-Dzhegutinsky reservoir in quantitative terms is determined by the ratio of the local spatial limits of the highly active zone of influence IV to the spatial limits of the basin geosystem of the Upper Kuban, where water resources and the indicator $P_j = WIV/Wb.g.U.K. = 0,0008(0,08\%)$ are present, which is 0.08% and determines the dominance of natural processes between the components NTS «NE-AO-P» and, accordingly, "environmental safety".

The developed mathematical model can be implemented as a program for the hardware development of dispatching rules for the management of the BSC integrated system and Zelenchukskaya HPP-PSHS.

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