Modeling parameters of the flood control facilities adapted to climate change

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Abstract. The article analyzes the results of modeling the regulation of flood flow in a river basin by the flood control facility on a side tributary of the river under conditions of climatic changes. The use of geographic information system for assessing the impact of the flood control facilities on the environment when justifying their parameters is considered. The need to create anti-flood hydro systems on side tributaries exists because the water capacity of existing and projected hydro systems may not be enough to transform the flood in conditions of economic and climatic changes. The problem arises of determining the required water capacity of the flood control facility and its location considering environmental requirements.

1. Introduction
With climatic changes, accompanied by an increase in river flow, including extreme water discharges, the design volume of reservoirs, operating and projected hydroelectric complexes with a hydroelectric power plant (HPP) on the main river may not be enough to ensure the required conditions during the transformation of the calculated flood. Under these conditions, it is proposed to create an additional anti-flood volume in intercepting hydro systems with self-regulating reservoirs on the side tributaries. The practice of their use is widely spread in many countries of the world [1-4].

Being an element of the natural-technical system of a river basin, flood control facilities even with short-term flooding of the reservoir can have a certain impact on the natural environment [5-10]. For such hydro systems, it is necessary to develop special methods for assessing their environmental impact, since the processes occurring in them are characterized by a high rate of change in the parameters of accumulation of flood water discharges, instability and are poorly predicted.

An urgent task is the organization of environmental monitoring in areas of possible placement of flood control facilities, the creation of simulation models for predicting the damageability of forest stands, as well as peat in flooded swamps, violations of fisheries conditions, changes in water quality during flooding, etc. [11-14]. The most promising and reliable for express control of water are devices developed based on nuclear magnetic resonance methods and various optical phenomena [15-25].

2. Regulation of extreme water discharges by the system of flood control facilities during climate change
To determine the parameters of the flood control facilities, as well as the regulatory effect of the system of hydro complexes distributed on the catchment area of various functional purposes, considering the requirements of environmental protection, the authors developed mathematical models and computer programs [26-28]. Their use makes it possible to assess the effect of increasing extreme runoff on the use of the forced volume of the water reservoir $V_F$, the maximum water discharges in...
lower pool of the river, etc. When exceeded, an additional volume $\Delta V$ is determined, which is placed in the intercepting flood control facilities on the side tributaries. The criterion for achieving the minimum required total water capacity $\hat{V}$ of the riverbed HPP and flood control facilities - the water discharges are not exceeding the maximum allowable discharge in the lower pool of the river ($Q_{\text{max}}$):

$$\hat{V} = V_F + \Delta V \rightarrow \min \quad \text{and} \quad Q_{\text{HPP}}^{\text{t}}(t) \leq Q_{\text{max}}$$  \hspace{1cm} (1)

The volume of water in the reservoir at time $t$ is is described using the water balance equation:

$$V(t) = V(t-1) + \left[ Q_{\text{ENT}}^*(t) - \left( Q_{\text{HPP}}^{\text{t}}(t) + Q_S(t) + Q_{\text{ID}}(t) + Q_{\text{EV}}(t) + Q_{\text{EN}}(t) \right) \right] \cdot t_{\text{step}}$$ \hspace{1cm} (2)

where $Q_{\text{HPP}}^{\text{t}}(t)$ – water discharge through the hydro turbines, $Q_S(t)$ – seepage discharge, $Q_{\text{ID}}(t)$ – idle discharge through the spillways, $Q_{\text{EV}}(t)$ – loss of water due to evaporation from the surface of the reservoir, $Q_{\text{EN}}(t)$ – the water, taken from the upper pool of the hydropower plant for economic needs, $t_{\text{step}}$ – time step size of the calculations, $Q_{\text{ENT}}^*(t)$ – natural water flow entering the reservoir considering the regulated flow in side tributaries during the operation of flood control facilities:

$$Q_{\text{ENT}}^*(t) = Q_{\text{ENT}}(t) + \sum_{i}^{k} \Delta Q_i(t - \Delta t)$$ \hspace{1cm} (3)

where $Q_{\text{ENT}}(t)$ - natural water flow entering the reservoir, $k$ is the number of flood control facilities in the river basin, $\Delta Q_i(t)$ - difference between the natural $Q_i^{\text{in}}(t)$ and regulated $Q_i^{\text{reg}}(t)$ water discharges in the lower pool of the $i$-th flood control facility on the side tributary of the river:

$$\Delta Q_i(t) = Q_i^{\text{in}}(t) - Q_i^{\text{reg}}(t)$$ \hspace{1cm} (4)

Calculations are made considering the time $\Delta t$ of running water from the flood control facility to the HPP. Were modeled and analyzed options for controlling the extreme flow of water (considering possible climatic changes) by the flood control system, including a hydroelectric complex with HPP on the main river and a flood control facility on the side tributary, which made it possible to determine the minimum required anti-flood volume in the flood control facility.

3. Use of GIS for assessing the environmental safety of flood control waterworks and results
To assess the environmental impact of the flood control system, it is proposed to use thematic computer maps of river basin fragments created in the geographic information system (GIS) environment based on mathematical modeling of the flood zone dynamics depending on the flood hydrograph and parameters of the flood control system.

As an example, figures 1-3 show the results of the calculation of the operation modes for the flood control facility on the side tributary with a possible increase of flood discharge hydrograph by 10% relative to the design estimated provision due to climate changes.
Figure 1. Changes in the water flow in the lower pool of the flood control facility (with an increase of 10% in flood flow relative to the design flow). 1 - natural water consumption of 1% probability, 2 - natural water consumption of 10% probability, 3 - regulated water flow in the lower pool, 4 - water flow through bottom spillways, 5 - water flow through the surface spillways.

Figure 2. Changes in the relative water level in the flood control facility (with an increase of 10% in flood flow relative to the design flow). 1 - the water level in the upper pool of the flood control facility, 2 - the bottom mark, 3 - the design maximum allowable level.

Using the obtained results, a raster layer is formed, each element of which has an attribute - flooding time. By analyzing the share of flooding and its duration of each ecosystem type in the GIS environment, we can conclude about the environmental safety of the proposed activity. The damageability of forest stands can be considered as the main environmental impact factor. This factor is of importance for promising waterworks on the territory of Russia, including as the one most often manifested during the temporary flooding.

The environmental safety assessment of flood control hydropower stations begins with the creation of a digital elevation model (DEM) in a GIS environment for the studied river basin area, which is a grid of square cells of the GIS database raster layer (DB). Associated with each raster cell is an attribute - elevation of the relief, thus it is assumed that the elevation does not change within the cell. The usual accuracy of such a GIS database is about $30 \times 30$ m in plan (raster cell size) and 1 m in height.
Figure 3. Changes in the flooding area in the upper pool for the flood control facility (with an increase of 10% in flood flow relative to the design flow). 1 - changes in the flooding area, 2 - design maximum area of flooding for the flood control facility.

Moreover, a GIS database is created for the basin territory, reflecting information on relatively homogeneous parts of the basin (landscape sections) - BL ecosystems. In this case, the basin-landscape principle of differentiation of the territory is implemented.

In the GIS database, the parts should also contain additional attributes to assess the damageability of forest stands:  $T_1$ is the duration of safe flooding (minor damage), $T_2$ is the maximum possible flooding time (allowable damage) and $T_3$ is the flooding time, after which irreversible destruction of the landscape ecosystem occurs (after the flood, another ecosystem will appear in its place). There are also watercourses in the GIS database, the axes of which are coordinated with the digital elevation model and pass along thalwegs.

As a result of the use of a simulation model of flow regulation by the system of the flood control facilities for a design flood determines for each instant $t$ the water level in the upstream of the reservoir $Z(t)$. These data serve as the basis for modeling the boundary of the flood zone for each mark (each point in time) based on the DEM. The recommended time resolution for calculations is about 24 hours.

Means of the GIS are built flood zones at each time point $F(t)$. These zones have the same accuracy (discreteness) as a digital elevation model. Thus, we get $N$ raster layers. Based on these layers by means of GIS (overlay with summation) a raster layer is formed, which contains in each cell of the raster the flooding time during the accumulation of flood in the upper pool of the hydroelectric complex - $TZ$.

Next in the GIS environment is carried out overlay layers of ecosystems $BL$ and $TZ$. Moreover, if $TZ$ intersects with any $BL$ element by no more than 10%, then such elements are not considered further. As a result, a subset of $BL1$ is formed - a selection, more than 10% of which is subject to flooding.

To consider the environmental impact, all elements of $BL1$ are analyzed, and an overlay with $TZ$ and $BL1$ is divided into parts for each element. After such an operation has been carried out with all elements of $BL1$ - each element has from 2 to 5 zones. Then, in the GIS environment, an operation is carried out to combine the zones of $BL1$ elements with the same indices to obtain the following zones, which reflect the environmental impact of the mode being modeled on ecosystems in the upper pool of the flood control facility:

- flood zones that are safe for ecosystems;
- flood zones, which are moderately dangerous for ecosystems;
• flood zones that are dangerous to ecosystems;
• areas in which flooding will destroy existing ecosystems.

As an example, in figure 4 the flooding zone in the upper pool of the flood control facility during the accumulation of floods is shown.

![Figure 4](image)

**Figure 4.** An example of the calculation in the GIS environment of the flood zone in the upper pool of the flood control facility.

4. **Conclusion**

An analysis is made of the method of protection against flooding in a river basin under conditions of increasing flood flow during climatic changes when the forced volume of complex waterworks is insufficient. The necessary additional storage capacity is proposed to be redistributed in intercepting flood control facilities with temporarily filled self-regulating reservoirs on the side tributaries or in the headwaters of the river. The models of river flow regulation and software complex are created, which allow to determine the minimum required anti-flood volume considering climatic changes for the period, located in the intercepting hydro system, the parameters of its water discharge structures when it is working together with the hydroelectric complex with HPP on the main river.

Considered the possibility of using GIS technologies to justify the choice of location and parameters of flood control systems in the river basin considering the requirements of environmental safety.

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**References**

[1] Arnell N W and Gosling S N 2016 *Climatic Change* **134**(3) 387-401
[2] Winkler N S 2006 *Optimierung der Steuerung von Hochwasserrückhaltebeckensystemen* (Stuttgart: Institut fur Wasserbau der Universität Stuttgart) p 210
[3] Alfieri L, Burek P, Feyen L and Forzieri G 2015 *Hydrology and Earth System Sciences* **19**(5) 2247-2260
[4] Lange B and Metz G 2012 Dresdner Wasserbauliche Mitteilungen 47 493-502
[5] Pankratyev P S and Shakirov V A 2012 Systems, Methods, Technologies 3 71-80
[6] Aref’ev N V, Badenko V L and Osipov G K 1998 Power Technology and Engineering 32(11) 660-663
[7] Makarov A, Mihailova A, Aref’ev N, Pavlov S, Chashchina T, Terleev V and Badenko V 2015 Procedia Engineering 117 225-231
[8] Fedorov M P, Maslikov V I, Badenko V L, Chusov A N and Molodtsov D V 2017 Power Technology and Engineering 51(4) 365-370
[9] Davydov R, Antonov V, Molodtsov D and Trebukhin A 2018 Advances in Intelligent Systems and Computing 692 915-920
[10] Fedorov M, Badenko V, Maslikov V and Chusov A 2016 Procedia Engineering 165 1629-1636
[11] Nikonorov A, Badenko V, Terleev V, Togo I, Volkova Y, Skvortsova O, Nikonova O, Pavlov S and Mirschel W 2016 Procedia Engineering 165 1731-1740
[12] Rykin E V, Moroz A V, Smirnov K J, Davydov V V and Yushkova V V 2018 MATEC Web of Conference 245 12002
[13] Davydov V V, Dudkin V I, Velichko E N and Karseev A Yu 2015 Journal of Optical Technology (A Translation of Opticheskii Zhurnal) 82(3) 132-135
[14] Fedorov M, Badenko V, Maslikov V and Chusov A 2016 MATEC Web of Conferences 73 01002
[15] Davydov V V, Cheremiskina A V, Velichko E N and Karseev A Yu 2014 Journal of Physics: Conference Series 541(1) 012006
[16] Davydov R V, Antonov V I and Moroz A V 2018 Proceedings of the 2018 IEEE International Conference on Electrical Engineering and Photonics, EExPolytech 2018 (Saint-Petersburg) 8564378 p. 236-239
[17] Nepomnyashchaya E K, Velichko E N and Aksenov E T 2016 Journal of Physics: Conference Series 769(4) 012025
[18] Nepomnyashchaya E K, Akenov E T, Bogomaz T A and Velichko E N 2015 Journal of Optical Technology (A Translation of Opticheskii Zhurnal) 82 162-165
[19] Nepomnyashchaya E K, Cheremiskina A V, Velichko E N, Aksenov E T and Bogomaz T A 2015 Journal of Physics: Conference Series 643(1) 012018
[20] Davydov V V, Myazin N S and Velichko E N 2017 Technical Physics Letters 43 607-610
[21] Davydov V V, Dudkin V I and Karseev A Yu 2014 Measurement Techniques 57 912-918
[22] Davydov V V, Myazin N S and Velichko E N 2017 Technical Physics Letters 43 607-610
[23] Davydov V V, Dudkin V I, Myazin N S and Rud’ V Yu 2018 Instruments and Experimental Techniques 61 140–147
[24] Myazin N S, Davydov V V, Yushkova V V and Rud’ V Yu 2018 Journal of Physics: Conference Series 1038 (1) 012088
[25] Davydov V V, Velichko E N, Myazin N S and Rud’ V Yu 2018 Instruments and Experimental Techniques 61 116-122
[26] Davydov R, Antonov V, Molodtsov D, Cheremisin A and Korablev V 2018 MATEC Web of Conferences 245 15002.
[27] Chusov A, Maslikov V, Molodtsov D and Manukhina O 2018 Advances in Intelligent Systems and Computing 692 1046-1054
[28] Davydov R V, Antonov V I and Molodtsov D V 2018 Journal of Physics: Conference Series 1135(1) 012088