Mathematical models of operating regimes of flood control facility's system

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Abstract. The rapid spread of storm floods over large areas requires flood management throughout the river basin by the creation of a system of flood control facilities of various functional purposes distributed in the area. The central part of the system is the hydro system with a hydroelectric power plant. Also, the flood control facilities on the side tributaries with the self-regulating reservoir are included in it. The development of mathematical models is needed to ensure the effectiveness of using flood control facilities, reflecting the specifics of their operation. We have developed unified mathematical models of a hydraulic structure with a hydroelectric power station and a means of protection against floods. These models are implemented in a computer program that provides the ability to determine the main parameters and operating regimes of hydro systems in a wide range of initial data. It makes possible specifying the parameters and operation modes of each hydro system with the current economic and environmental requirements, to assess the energy-economic and ecological consequences in the work of the flood control facilities distributed in the area.

1. Introduction

Today, in many countries of the world, there is an acute problem of protecting the land from flooding, which has always been considered a significant natural hazard in terms of economic losses [1-6]. The observed climate change has led to a sharp increase in the frequency of massive floods, accompanied by an increase in economic damage and the number of victims [7-11].

Particularly severe consequences cause storm floods. The main danger lies in their suddenness and a sharp increase in the volume of river flow, many times greater than the amount of the spring flood. In recent decades, many regions of the world have been subjected to severe flooding caused by heavy rains [12, 13].

Protection of the territory against flooding is currently carried out in ways that do not sufficiently consider the current situation and its uncertainty in the future - population growth, climate change, and land-use patterns (land development, deforestation, reduction of wetlands) [14-17]. As a result, costly measures are ineffective. In connection with this, the concept of flood control is changing from local land protection measures at a particular location to flood risk management on a river basin scale.

In recent years, interest in anti-flood hydro complexes has increased throughout the world, especially after the catastrophic floods of the beginning of the 21st century, which took place in Germany, Italy, Romania, China, the USA, Russia, and other countries. The construction of some
flood control facilities with hydroelectric power plants (HPP) can significantly increase the degree of protection of territories from flooding in the lower pool by cutting off floodwaters when they are accumulated in reservoirs [18-20].

Considering global climate change and, as a result, an increase in river flow, it is necessary to revise previously completed hydropower projects in terms of the powerful impact on extreme runoff. For example, with an increase in maximum water flow, the flood capacity of existing and projected hydro complexes may not be enough to transform the calculated flood. The maximum allowable level accepted as a condition for passing extreme water discharges cannot be exceeded, as a result of which the maximum discharge flow of water in the lower pool of the hydroelectric complex and, accordingly, the water level will increase, the flooding zone will expand.

To ensure the design conditions in the pools of the hydro complex, a part of the necessary additional capacity can be placed in intercepting self-regulating reservoirs created on the side tributaries of the river basin. Such flood control facilities are used only for cutting flood expenses. During the period of accumulation of floodwaters, the reservoir bed is flooded briefly (from several hours and days to several tens of days), and after self-emptying during the rest of the time (until the next flood) remains dry in its natural state. In the low-flow period, the flood control facility practically does not create backwater in the riverbed and does not interfere with the free passage of fish. Flood control facilities are usually performed with unregulated bottom and surface spillways without the use of gates, which provides the essential reliability of work and reduces the cost of maintenance. Such anti-flood reservoirs are successfully used in the United States, Germany, Austria, France, China, and other countries. For example, in Austria, from the 60s of the last century to 2011, 660 anti-flood hydro systems were built (85% have a volume of up to 100 thousand m³), including 107 hydroelectric complexes with an average dam height of 8.6 m in the Styria mountain region, where massive storm floods occur (figure 1).

Figure 1. An example of the flood control facility.

For flood control facilities on side tributaries, the main environmental requirements must be fulfilled: preservation of the flood-floodplain processes in the river system [21–24], maintenance of the biodiversity of ecosystems during their short-term flooding [25–27].

2. Mathematical model
The following mathematical models have been developed to assess the effect of regulating extreme water discharges by the system of flood control facilities distributed on the drainage area considering the requirements of environmental protection [28, 29]:
- operating modes of the hydro complex with HPP;
- operating modes of the flood control facility;
- joint work of them.

2.1. Hydro complex with HPP on the main river
To ensure the design energy output by a hydro complex with HPP, minimizing economic and environmental damages, in current and prospective conditions, the designed forced volume is adjusted, and the maximum water discharges in the lower pool complex of the hydro complex are specified.
During the floods, the water level in the upper pool of the hydro complex is between maximum water level (MWL) and reservoir level in standard condition (NRL):

\[ \text{NRL} \leq z_{\text{up}}^{\text{HPP}}(t) \leq \text{MWL} \quad \text{(1)} \]

Basic requirements for flood management:

- Water consumption in the lower pool of a hydro complex must not exceed the maximum allowable \( Q_{\text{max allow}} \), which ensures safety requirements for economic activity. At the same time the flood-flood regime of the river is preserved:
  \[ z_{\text{up}}^{\text{HPP}}(t) \leq Q_{\text{max allow}} \quad \text{(2)} \]

- The watermark in the upper pool should not exceed MWL:
  \[ z_{\text{up}}^{\text{HPP}}(t) \leq \text{MWL} \quad \text{(3)} \]

Additional requirements are the minimization of socio-economic damage and the preservation of biodiversity of ecosystems. For this, areas, types of land flooding, and standing time are analyzed. MWL mark is corrected according to the criteria for not reducing diversity and the ratio of anthropogenic and natural ecosystems. When it decreases, the corresponding accumulating volume \( \Delta V \) is redistributed to hydro-systems on the side tributaries.

\[ \Delta V = V_{\text{MWL}} - V_{\text{MWL}^*} \quad \text{(4)} \]

Here \( V_{\text{MWL}} \) - design maximum reservoir volume, \( V_{\text{MWL}^*} \) - the corrected reservoir volume regarding environmental requirements. The number of working spillways \( \text{num}_{\text{HPP}} \) is determined by the design dispatch schedule of control of the discharge structure, depending on the actual water level \( z \). Each spillway works in the "full opening" mode.

### 2.2. Flood control facility on the side tributary of the river

The volume of flood water in the reservoir \( V_{\text{fcf}}(t) \) at time \( t \) is determined using the dependence [30]:

\[ V_{\text{fcf}}(t) = V_{\text{fcf}}(t - t_{\text{step}}) + \left( Q_{\text{in}}^{\text{fcf}}(t) - Q_{\text{reg}}^{\text{fcf}}(t) - Q_{\text{evap}}^{\text{fcf}}(t) - Q_{\text{fil}}^{\text{fcf}}(t) \right) t_s \quad \text{(5)} \]

where \( Q_{\text{in}}^{\text{fcf}}(t) \) – water flow, which comes into the reservoir, \( Q_{\text{reg}}^{\text{fcf}}(t) \) – water flow in the lower pool, \( Q_{\text{evap}}^{\text{fcf}}(t) \) – losses of water by evaporation from the surface of the reservoir, \( Q_{\text{fil}}^{\text{fcf}}(t) \) – water flow for filtration purposes, \( t_{\text{step}} \) – current time, and \( t_s \) – time step size for the calculations.

The main requirements for managing water discharges on side tributaries are:

- Reducing the extreme water flow \( Q_{\text{fcf}}(t) \) to the values that preserve the floodplain regime of the river.
- Not to exceed the maximum allowable mark of the upper pool to minimize the area of flooded land and preserve the biodiversity of ecosystems.

### 2.3. Joint operation of a hydro complex with a flood control facility on the side tributaries of a river

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

\[ V(t) = V(t - t_{\text{step}}) + \left( Q_{\text{ent}}^*(t) - Q_{\text{t}}^{\text{HPP}}(t) - Q_{\text{s}}^{\text{HPP}}(t) - Q_{\text{id}}^{\text{HPP}}(t) - Q_{\text{en}}^{\text{HPP}}(t) - Q_{\text{ev}}^{\text{HPP}}(t) \right) t_s \quad \text{(6)} \]

Here \( Q_{\text{ent}}^*(t) \) – natural water flow entering the reservoir considering the regulated flow from side tributaries during the operation of flood control facilities:

\[ Q_{\text{ent}}^*(t) = Q_{\text{ent}}^{\text{HPP}}(t) + \sum_{k=1}^{K} \Delta Q_i(t - \Delta t) \quad \text{(7)} \]

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

\[ \Delta Q_i(t) = Q_{\text{in}}^n(t) - Q_{\text{reg}}^r(t) \quad \text{(8)} \]

Calculations are made considering the time \( \Delta t \) of running water from the flood control facility to the HPP. At the initial stage of hydraulic calculations [31, 32], the design parameters of the
hydroelectric system are taken as the main ones: the volume of the storage capacity, water level marks, the number of the bottom and surface spillways, their sizes, etc.

3. Results and discussion

For the implementation of the developed mathematical models, the software was created in the MATLAB language, with the use of which some possible scenarios for controlling extreme water discharge in a river basin by hydro systems were analyzed (figures 2-5).

![Figure 2](image2.png)

**Figure 2.** The change in the relative water level in the upper pool of the hydro complex (with an increase of 10% of the water flow rate). 1 - the water level for the hydro complex with HPP, 2 - the water level water flow during the joint work with a flood control facility, 3 – NRL mark, 4 – MWL mark.

![Figure 3](image3.png)

**Figure 3.** Changes in water flow rates in the pools of the hydro complex (with an increase of 10% in water flow relative to the project). 1 - estimated water inflow into the channel reservoir, 2 - water inflow into the channel reservoir during the operation of the flood control facility, 3 - water flow in the lower pool of the hydro complex with HPP, 4 - water flow during the joint work with flood control facility, 5 - design maximum allowed lower pool water flow.

As an example, we consider the option of increasing the design flood flow rate for one of the rivers in the Far Eastern region of Russia, where, due to climate change, an increase of about 10% of extreme runoff is predicted soon. The mark of the MWL remains design. Figure 2 and Figure 3 present the results of modeling the operation of the hydro complex.

On one of the side tributaries, an additional interception volume is created, which is a non-energy flood control facility with a temporarily filled self-regulating reservoir. Modes of its operation (considering environmental requirements) with an increase in the extreme consumption of water inflow by 10% are shown in figures 4 and 5.
Figure 4. Changes in the level of water in the flood control facility on the side tributary (with an increase of 10% in water flow relative to the design flow). 1 - the water level in the upper pool of the flood control facility, 2 - bottom level, 3 - design maximum allowable level in the case of the design flood.

Figure 5. Changes in the water flow in the lower pool of the flood control facility on the side tributary (with an increase of 10% in water flow relative to the design flow). 1 - natural water flood of 1% of probability, 2 - natural water flood of 10% of possibility, 3 - regulated water flow in the lower pool of the flood control facility, 4 - water flow through bottom spillways, 5 - water flow through the surface spillway.

In the case of operation of the hydro complex only, due to the lack of storage capacity, the maximum discharge of water in the lower pool in some periods will exceed the design allowable (by about 10%). Accordingly, the water level will rise, and the area of flooding will increase. When using a new intercepting anti-flood hydro system on the side tributary of the river, the water inflow into the channel reservoir decreases and the maximum permissible maximum discharge of water in the lower pool of the hydro complex is not exceeded.

4. Conclusion
With an increase in the maximum river flow due to climate changes, the design of the forced volume of the hydro complex with HPP on the main river is not enough to transform extreme floods. As a result of the simulation, the required capacity of the intercepting flood control facility on the side tributary of the river, as well as the modes of its operation, was determined.

The calculations for the joint work of the hydro complex, together with the flood control facility, showed the effectiveness of the measures being developed to minimize the risk of land flooding and
environmental impact. The considered approach to the regulation of extreme water discharge in the river basin can be useful in the development of a comprehensive program to combat floods in the Russian Federation.

5. References

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