Simulation of water flow management by the flood control facilities in the adjacent river basins

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Abstract. A systematic approach to reducing the risk of flooding is considered. The main idea of it is to switch from the flood control only by the one hydro system on the main river but to control the whole river system, including many adjacent river basins at various levels. This proposal expands the possibility of using a flood control system of self-regulating hydro systems distributed on adjacent drainage basins at multiple levels by organizing their joint work, ensuring that the maximum allowable water flow in the control sections of the river system is not exceeded. Using the proposed approach will allow protecting from flooding significant areas of land in the lower pool of the main hydroelectric complex in the context of climate change.

1. Introduction
Storm floods are a dangerous natural hazard due to the suddenness of their occurrence and flooding of vast territories. In the recent past, they mainly occurred in regions with a humid climate. Recently, due to global changes, storm floods have also occurred in many arid areas of the world (North Africa, Middle East, Arabian Peninsula, Mongolia, etc.) [1-4].

In Russia, considering economic losses, the problem of massive floods is most acute in the Far Eastern region. Due to climate change, rainfall is expected to grow in Russia by 4–7% over the period 2011–2030, by 13–20% over 2080–2099.

Without abandoning traditional local methods of flood control (clearing and straightening of the river bed, bank embankment, construction of big and complex hydro systems), it is also advisable to use more advanced flood management methods throughout the river basin by creating a system of the flood control facilities, distributed on it [5-9].

The essential element of such a system is a complex hydro system with hydroelectric power plants (HPP) on the main river. Also, on the side tributaries and in the headwaters of the main river, the intercepting flood control facilities with temporarily filled self-regulating reservoirs are used. The practice of using them is widely spread in many countries of the world (Austria, Switzerland, Germany, Italy, USA, China, India, Spain, etc.) [10-14].

Over the past few decades, a lot of effort has been made to improve flood modeling methods to predict their consequences in both rural and urban conditions [15]. The most interesting for this are hydrodynamic models. These models consist of physical equations related to hydrological processes, including water balance equations, conservation of mass and energy, momentum, and kinematics (Saint-Venant equations, Boussinesq equations, etc.) [16].
The more advanced a model - the more expensive it is in terms of computational resources. In the case of flood studies in large cities of a complex structure, 2D and 3D hydraulic models can produce good results, but the amount of calculations does not allow their use in real-time. Besides, for high accuracy of the obtained results, it is necessary to carry out frequent measurements in many control points of the river in terms of water level and flow, which is a rather complicated task [17].

When modeling floods in rural areas, especially large ones, the physical data is hardly available, but historical statistics, in combination with 1D or 2D hydraulic models, can still produce valuable results [18]. However, only one river or one river basin is often studied, where floods occur, while large-scale floods can affect several adjacent river basins, where there are reservoirs of hydroelectric power stations with different time schedules of regulation. In the article, a new way to reduce the risk of floods is proposed - regulation the maximum water discharges by flood control facilities not only within individual river basins but also in the river system by controlling extreme flow by hydro systems located in adjacent river basins of various levels. It will protect from flooding significant areas of land in adjacent river basins in the context of climate change. Despite the numerous studies that have been carried out, they practically do not consider multivariate flood control models, when waterworks are located not only on the main river but also on its side tributaries within environmental requirements are not sufficiently considered when creating flood protection volumes.

2. Mathematical model and simulation results

Let the river system consist of $n$ adjacent river basins of different levels. It is assumed in some of them (Figure 1) to create a system of $k_i$ flood control facilities ($i = 1 \ldots n$) of various functional purposes (complex hydro systems with HPP on the main river and self-regulating intercepting hydro systems on side tributaries). It is necessary to evaluate the joint regulatory effect of the flood control systems in adjacent river basins and ensure that the water discharge in the control location of the river system is not exceeded the maximum allowable:

$$Q_{\text{control}} \leq Q_{\text{max}}$$

Figure 1. The scheme of a fragment of a river system with anti-flood hydro-systems of various functional purposes in adjacent basins.
To solve this problem, we create two mathematical models of the operating modes of integrated waterworks in adjacent river basins for the following periods: long-term (one-year regulation, many-year regulation of river flow) and short-term (several hours, days, weeks).

The development of models for long-term operation of integrated waterworks is carried out by the recommendations outlined in [8, 9]. When performing water-energy calculations, a project dispatch schedule is used, which allows filling-out of the reservoir depending on the inflow of water and the requirements of water users and water consumers in the upper and lower pools of the hydroelectric complex, ensuring the guaranteed return of the hydroelectric power station. It allows modeling the annual and long-term hydrological situation (often asynchronous) in adjacent river basins at the time of the flood, to determine the level and volume of water in the reservoir, the area of flooded land, the discharge of water in the lower pool, and the energy output of hydroelectric power stations.

In short-term operation cases for calculating maximum water discharges, we use dispatch schedules of culverts, simulation models of operation modes of single, and cascades of waterworks on the side tributaries. It will make it possible to assess the risk of flooding in the river system when regulating the river flow by flood-control waterworks in adjacent basins.

The assessment of the effect of water flow regulation in adjacent river basins is carried out in stages. At the first stage, the possibilities of regulating the maximum flow for each i-th river basin are determined using developed mathematical models and computer programs for calculating the operating modes of the anti-flood hydro systems distributed in the catchment area [19, 20]. The joint operation of them is simulated, considering possible changes in the maximum water flow in the river basin. The mathematical model includes a complex hydroelectric complex with a hydroelectric station on the main river and intercepting self-regulating flood control facilities on side tributaries. The operating modes of them at the regulation of the maximum flow are determined, as well as the maximum water flow in the lower pool of the complex hydro system. In case the maximum water discharge exceeds the maximum allowed, an additional volume ΔV is placed on the side tributaries. The criterion for achieving the required total flood control capacity of the riverbed hydroelectric power station and intercepting flood control hydro systems is not to exceed the maximum allowable flow in the lower pool (Q_{maxHPP}):

\[ Q_{LP}^{HPP}(t) \leq Q_{maxHPP} \] (2)

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

\[ V(t) = V(t - t_{step}) + \left[ Q_{ENT^*}(t) - (Q_T(t) + Q_S(t) + Q_{ID}(t) + Q_{EV}(t) + Q_{EN}(t)) \right] \cdot t_{step} \] (3)

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

\[ Q_{reg}(t) = Q_{natural}(t) + \sum_{j=1}^{k_i} \Delta Q_j(t - \Delta t) \] (4)

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

\[ \Delta Q_j(t) = Q_j^{in}(t) - Q_j^{reg}(t) \] (5)

For the flood control facility with a temporarily flooded reservoir, a mathematical model is proposed, considering the various design and operating modes for the system. The volume of floodwaters accumulating in the reservoir at time \( t \) we calculate by the balance method:
\[ V_{\text{stor}}(t) = V_{\text{stor}}(t - \Delta t) + \left( Q_{\text{in}}(t) - Q_{\text{reg}}(t) - Q_{\text{evap}}(t) - Q_{\text{filt}}(t) \right) t_{\text{step}} \] 

where \( Q_{\text{in}}(t) \) – water inflow, which comes into the reservoir, \( Q_{\text{evap}}(t) \) – losses of water by evaporation from the surface, \( Q_{\text{reg}}(t) \) – water discharge in the lower pool, \( Q_{\text{filt}}(t) \) – water discharge for filtration purposes.

The following ecological requirements are imposed on flood management at the lateral tributaries:

- maintenance of water discharges in the lower pool as part of environmental protection requirements:
  \[ Q_{\text{reg}}(t) \geq Q_{\text{env}} \]  

where \( Q_{\text{env}} \) – water flow in the river, providing its environmental flood-floodplain regime.

- not to exceed the maximum permissible water discharge in the upper pool to minimize land flooding to preserve the natural environment:
  \[ Z(t) \leq Z_{\text{max}} \]  

where \( Z(t) \) – the water level in the reservoir.

The water discharge in the lower pool is calculated depending on the mode of operation of the system:

- in unflooded mode, the hydro system provides a free, near-natural flow of water through the bottom openings. To calculate the water flow formula for a spillway with a wide threshold is used (support from the lower pool is not considered) [15]:
  \[ Q_{\text{reg}}(t) = n_{1} m b_{1} \epsilon \sqrt{2g(Z(t) - Z_{1})^{3/2}} \]  

where \( m \) – coefficient of flow, \( b_{1} \) – width of bottom culverts, \( \epsilon \) – coefficient of lateral compression, \( Z_{1} \) – bottom mark of bottom culverts, \( n_{1} \) – number of bottom culverts.

- in the flood period, bottom culverts operate as flooded holes with variable pressure. Considering the possibility of clogging them (partially or completely), additional surface spillways are used in the flood control facility. When \( Z(t) \leq Z_{2} \), where \( Z_{2} \) – bottom mark of surface spillways, water flow in the lower pool is calculated according to the following formula:
  \[ Q_{\text{reg}}(t) = n_{1} \mu \omega \sqrt{2g(Z(t) - Z_{1} - a/2)} \]  

where \( \mu \) – coefficient of flow for bottom culvert, \( \omega \) – cross-sectional area of bottom culvert, \( a \) – height of the bottom culvert. When \( Z(t) > Z_{2} \), water flow in the lower pool is calculated as:
  \[ Q_{\text{reg}}(t) = n_{1} \mu \omega \sqrt{2g(Z(t) - Z_{1} - a/2)} + n_{2} m b_{2} \epsilon \sqrt{2g(Z(t) - Z_{2})^{3/2}} \]  

where \( n_{2} \) – number of surface spillways, \( b_{2} \) – width of surface spillways.

The dependence \( Z(V) \) is given in the tabular form, and for computer calculations, the method of approximation is needed for it. This dependence is a monotone or piecewise monotone function, and we use interpolation by piecewise cubic Hermite polynomials to obtain a smooth continuous function \( Z(V) \).

Calculations on the whole basin are made considering the time \( \Delta t \) of running water from the flood control facility to the complex hydro system with HPP. Based on them, the reduction of the maximum water discharge in the lower pool of the hydroelectric complex and the corresponding decrease in the maximum flow from the drainage basin to the river system is determined.

As an example, Figure 2 presents the results of calculations of the operating mode of the flood-control hydroelectric complex at a possible early or later onset of maximum flow peaks in comparison with the design hydrograph. Figure 3 shows the change in water discharge in the lower pool of the integrated waterworks, taking into account the operating mode of the flood protection waterworks on the lateral inflow with the asynchronous peak floods (early peak - 1 day in relation to the peak of the calculated hydrograph or late peak - 2 days in relation to the peak of the calculated hydrograph). The obtained results make it possible to evaluate the effect of regulation of extreme water discharges by the...
system of flood control facilities in each of the adjacent river basins. There is a possibility of their ranking in terms of regulating maximum flow in the control location of the river system.

Figure 2. Change in water flow in the lower pool of the flood-control facility on the side tributary (with a 10% increase in flood discharge relative to the design). 1 - the natural flood flow rate of 1% of the probability, 2 - the natural flood flow rate of 10% of the probability, 3 - the regulated flow rate in the lower pool at an early peak of maximum flow rates, 4 - the regulated flow rate of water in the lower pool at the calculated hydrograph, 5 - regulated flow in the lower pool with a late peak of maximum flow.

Figure 3. Change in water flow in the pools of a complex waterworks (with an increase of 10% in flood discharge relative to the design). 1 – floodwater inflow into the channel reservoir, 2 - water inflow into the river reservoir during flood protection operation with an early peak of maximum discharge, 3 - water inflow into the river reservoir during flood protection according to the calculated hydrograph, 4 - water inflow into the channel reservoir during flood protection works with a late peak of maximum flow rates, 5 - water flow in the lower pool of the hydro system during the anti-flood water system operation with an early peak, 6 - the water flow in the lower pool according to the calculated hydrograph, 7 - water flow in the lower pool with a late peak, 8 - design maximum allowable water flow in the lower pool.
The next stage is the creation of an integrated simulation model for regulating the maximum flow in a river system based on the use of mathematical models for controlling extreme water flow by a system of flood control facilities in adjacent river basins at various levels:

\[ Q_{\text{control}} = \sum_{i=1}^{n} Q_{ni} + Q_{\text{addit}} \]  

(12)

where \( Q_{ni} \) is the regulated water flow in the lower pool of the closing hydro system in the \( i \)-th river basin, \( Q_{\text{addit}} \) is the additional unregulated dispersed flow of water from the side slopes.

Automated calculations are made of regulated water discharges \( (Q_{reg}) \), water levels and flooded areas in the lower pools of flood-control waterworks (Figure 4), as well as the maximum flow in the control section of the river system \( (Q_{\text{control}}) \) under various scenarios for the placement of flood-control waterworks in adjacent river basins, taking into account their structure and parameters, changes in time of river runoff characteristics, socio-economic and environmental restrictions [21-27].

![Figure 4.](image)

**Figure 4.** Thematic computer map of the dynamics of the flood zone, depending on the hydrograph of the flood and the parameters of the flood control system.

In order to provide information support for decision-making on regional planning and development of territories in adjacent river basins, it is planned to use the principle of using digital twins [28, 29]. The digital twin of a river system includes geographical databases and simulation models describing natural-anthropogenic processes and phenomena in their territory (Figure 5).

The technique of using digital twins assumes the formation of complex indicators reflecting the reduced risks of flooding due to the implementation of anti-flood measures and simulation of joint operation of anti-flood systems in adjacent river basins in the context of climate change. This technique can be used for supporting flood risk management solutions considering the requirements of environmental protection.
Figure 5. An example of an image combining a digital elevation model and satellite images.

Solving the scientific problem of reducing flood risk in adjacent river basins should make a significant contribution to resolving the existing contradiction between the need for regional development and the ever-increasing frequency of catastrophic flood events caused by climate change. The proposed methodology for development will thus be a significant contribution to the development of the digitalization of the Russian economy.

3. Conclusion
The recent global climate changes have revealed a tendency towards synchronous development of the flood situation in adjacent river basins of various levels, affecting large areas. This requires a transition from the principle of regulation of extreme water flow within individual river basins to the joint regulation by a system of anti-flood control facilities in the river system.

To assess the effect of regulating extreme water flow in adjacent river basins, it is advisable to create an integrated simulation model for regulating maximum water discharges in a river system based on the use of mathematical models for controlling extreme water flow by a flood control system in adjacent river basins of various levels.

The possibility of using digital twins of the river system, including geographical databases and simulation models describing nature-anthropogenic processes and phenomena in their territory to assess flood risk is analyzed, according to computer modeling results of joint operation of the flood control systems in adjacent river basins under climate change conditions.

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