Modelling a system of intercepting reservoirs distributed on the side tributaries of a river to prevent flooding of agricultural land

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Abstract. One of the areas of engineering protection of lands from flash floods is the use of intercepting waterworks on the side tributaries, which help to reduce the peak of the flood on the main river and redistribute it over time. With an increase in rainfall, flood protection capacity of existing or designed structures may not be enough to transform the river flow. The paper considers a mathematical model of flow control by a system of reservoirs, where a part of the accumulating capacity of the flood protection structure on the side tributary is redistributed into gabion waterworks located upstream of the river. This model allows to clarify the parameters and modes of operation of waterworks and evaluate their functioning, considering current and future economic and environmental conditions.

1 Introduction

Floods occupy the first place among natural disasters in terms of frequency, coverage of the territory. Moreover, they affect almost all regions of the planet [1]. The observed climate change has already led to a sharp increase in the frequency and scale of large floods and an increase in economic damage and the number of victims. That makes the issue of land protection from floods an increasingly important problem [2, 3]. Especially severe consequences are caused by flash floods [4, 5].

The increase in the number of floods and flood areas requires the development of reliable and affordable ways to ensure the safety of populated areas. A promising direction in the fight against rain floods is the creation of intercepting reservoirs distributed on the side tributaries of the main river. Flood intercepting waterworks can be used both as an independent method of flood protection and as an auxiliary method, which provides additional capacity for regulating runoff by a complex waterworks [11, 12]. The regulation of runoff by intercepting waterworks is expected by creating them on the side tributaries of the river to form temporary reservoirs that are filled only during the flood. Their quantity and volume are established based on the conditions for the detention of the volume of flood flow and its gradual discharge into the downstream with expenses not exceeding the permissible ones. In substantiating the volume of accumulation of the flood protection system, it is

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necessary to fulfil environmental requirements aimed at maintaining the flood-floodplain regime of the river [13].

Given the increase in maximum river flow with a limited number of suitable locations on the side tributaries (for economic, environmental, and other reasons), it is proposed to develop a system of land protection against flooding in stages: by constructing intercepting waterworks on the river basin into which flood-control capacity is redistributed. In this case, environmental monitoring of the state of water resources and coastal zones at intercepting waterworks occupies a special place [14-16]. Stagnant waters are formed in these zones, in which foreign impurities accumulate. In this situation, it is advisable to use several types of devices for monitoring both the current flow of water and for the analysis of samples of a liquid medium in a stationary state [16-22]. The most significant preference is given to devices based on the phenomena of nuclear magnetic resonance and refraction [20-32]. Radar methods for studying the water surface [33-39] in this case, are not practical.

2 Methods

At the initial stage, the main waterworks are determined on the main river, which has the most significant effect on the characteristics of the maximum flow, ensuring safe flow to the lower pool [40]. Over time, for example, due to an increase in maximum water discharge in the context of climatic changes, the capacity of existing or designed structures may not be enough to transform the estimated flow. There is a need for the construction on the side tributaries of the river of intercepting flood control with temporary-filled reservoirs, in which the missing capacity is redistributed. Waterworks must meet the requirements of minimizing land flooding and environmental impact. As a result, a system of intercepting reservoirs distributed over the basin is created, which ensures the protection of territories not only in the lower pool but also in the upper pool of the main waterworks (Figure 1).

![Fig. 1. The scheme for the development of the river basin by flood-control waterworks: 1 - the main riverbed; 2 - side tributaries; 3 - flood zone; 4 - protected territories (settlements, agricultural lands, nature conservation facilities); 5 - the primary flood control hydro system; 6 - additional waterworks on the side tributaries.](image)

Flood waterworks should perform two main tasks: transforming floodwaters and allowing low-flow runoff for free passage of fish on spawning rivers [41]. Considering that the construction of waterworks is carried out in mountainous, often inaccessible terrain (in the flood formation zone), the waterworks should be self-regulating, i.e. they should pass water into the downstream, without requiring constant monitoring by humans. One of the conditions is the possibility of their construction using local building materials and labour.

In various regions of the world, there is the successful experience in the construction of flood-control waterworks, where the main choices are dams of soil or concrete materials with the regulation of water discharge through bottom openings, surface and slotted spillways [42 - 44]. In conditions of inaccessible areas, a promising scheme for regulating the maximum flow may be the construction of concrete waterworks on the side tributaries in their lower
reaches, in areas with developed infrastructure. In off-road conditions and mountainous terrain, filtering dams from gabion masonry can be located upstream. Part of the flow rate is passed through the gabion body due to filtration, and culverts and weirs are arranged from the gabions themselves, which reduces the use of concrete structures (Figure 2).

![Fig. 2. The schemes of waterworks from gabion masonry: 1 - gabion masonry; 2 - culverts; 3 - surface spillway; 4 - slotted spillway; 5 - the water level in the lower pool; 6 - the water level in the upper pool; 7 - the maximum permissible water level in the upper pool.](image)

The use of gabions in the construction of flood control hydraulic systems is due to a number of their advantages: low cost; ease of delivery and assembly of gabions at the construction site; use of local building materials as aggregate; the relative flexibility of the body of the structure, which reduces the possibility of dam damage during uneven sediments of the base. Gabion dams organically fit into river landscapes and do not reduce their aesthetic, recreational values. However, the height of such dams should not exceed 10-12 m to ensure sufficient stability of the structure and the strength of the gabion cage. It determines the scope of such dams – overlapping secondary side tributaries to create an additional regulatory capacity [45].

The choice of locations of intercepting waterworks on the side tributaries and the justification of their parameters is a difficult task due to the lack of available, necessary information on the topography of the terrain, natural and climatic conditions. The use of geographic information systems (GIS) for modelling allows to consider various control options flood flow with a detailed analysis of potential flood zones in the upper and lower pools, take into account the socio-economic and economic aspects of the territory, such as: minimizing land flooding, the absence of protected areas in the area of short-term flooding, proximity to highways or settlements [46].

The parameters of the flood control water system can be refined using a mathematical model of flow control modes during extreme flows. Simulation models allow to examine the regulatory effect from the creation of each specific waterworks and their joint work, to rank the targets to determine the sequence of development of watercourses.

In our previous works [47-48], a mathematical model of the operating modes of a flood-control hydro system on the lateral inflow of both a single structure and in combination with a hydroelectric power station was described. To assess the effect of the hydraulic units distributed on the lateral tributaries, a model of their operation modes has been developed.

The peculiarity of the model in this paper is the account of the joint work of the main flood control waterworks and additional intercepting waterworks made of gabions. The main criterion for achieving the necessary regulatory capacity of flood control waterworks is not to exceed the maximum allowable water discharges in the lower pool of the waterworks and to minimize the area of flooding in the upper pool.
The water flow entering the reservoir of the main hydro system, taking into account the regulated flow rate on the side tributaries, is determined by the dependence:

\[ Q_{\text{ent}}(t) = Q_{\text{ent}}(t) \pm \sum_i \Delta Q_i(t) \]  

(1)

where \( Q_{\text{ent}}(t) \) is the flow rate of water entering the reservoir of the main hydroelectric complex in a domestic state; \( \Delta Q_i(t) \) is the difference between the natural \( Q_{\text{nat}}(t) \) and the regulated \( Q_{\text{reg},i}(t) \) water discharge in the downstream of the \( i \)-th waterworks on the side tributary:

\[ \Delta Q_i(t) = Q_{\text{nat},i}(t) - Q_{\text{reg},i}(t) \]  

(2)

The water discharge in the downstream of additional waterworks is determined for the case of using a gabion dam and is made up of the flow rate through the culverts \( Q_{\text{reg},i}(t) \) [21-23] and the filtration flow in the body of the structure \( Q_{\text{fit},i}(t) \):

\[ Q_{\text{reg},i}(t) = Q_{\text{culv},i}(t) + Q_{\text{fit},i}(t) \]  

(3)

The filtration flow rate through the body of the \( i \)-th dam:

\[ Q_{\text{fit},i}(t) = q_{\text{fit},i}(t) \cdot B_i \]  

(4)

where \( B_i \) is the width of the dam; \( q_{\text{fit},i}(t) \) specific filtration flow rate through the dam body, as applied to gabions, can be determined by the dependence:

\[ q_{\text{fit},i}(t) = k_i(t) \cdot \frac{H(t)^3}{3L} \]  

(5)

where \( k_i(t) \) is the filtration coefficient of the gabion masonry; \( H(t) \) water pressure on the structure, defined as the difference between the elevations in the upper and lower pools; \( L \) is the average width of the cross-section of the dam.

Calculation of the flow rate coming to the main waterworks is made taking into account the time it takes for the flood wave to arrive according to the formula [49]:

\[ U = 15.5 \cdot Q_{\text{reg},i}(t)^{1/4} \cdot t^{1/3} \]  

(6)

where \( i \) is the longitudinal slope of the river.

3 Results and Discussion

We create the software based on MATLAB to implement developed mathematical models for flood control waterworks and investigate possible scenarios for regulating extreme water flow in the river basin using it. The assessment of the operating conditions of the hydraulic system is carried out using the necessary initial data: hydrological characteristics, maximum permissible water flow in the upper pool of the main hydro system. In determining the hydrological characteristics, an increase in extreme costs of 10% is included.

As an example, the operating mode of the flood control hydraulic system in the lower reaches of the river with rain feed in the Far Eastern region of Russia is considered. The lateral inflow of the river to create an additional intercepting reservoir is selected during the analysis of the relief of the river network in the GIS environment (Figure 3). The location of intercepting flood-control waterworks on the relief model of the river network obtained using GIS technologies are shown in Figure 4.
In the case of operation of only the main waterworks due to a lack of storage capacity, the maximum water discharges in the downstream will exceed the permissible values. The water level in the lower pool will increase, and, accordingly, the amount of flooded land. When using an additional intercepting water system on the lateral inflow, the flow of water into the reservoir of the main structure is reduced, ensuring that admissible water discharges are passed into the downstream (Figure 5).

The optimal parameters of the additional waterworks were determined: the width of the slotted spillway - 6.0 m, the length of the pressure front of the filter gabion dam - 300 m, which is in good agreement with the technical capabilities of the hydraulic gabion structures.

4 Conclusions

The mathematical model of the operating modes of intercepting flood control waterworks located on the side tributaries is developed: downstream – concrete waterworks with a spillway through bottom openings and a surface spillway; upstream - a flood control facility with a filter dam from a gabion masonry. The joint regulatory effect of intercepting waterworks on the side tributary is determined; the parameters of additional reservoirs on the lateral inflow are substantiated.

The locations of intercepting waterworks are selected using the technology of GIS modelling, considering the existing and prospective economic-environmental situation, the parameters of the waterworks, potential flood zones in the upper and lower waters are determined.
Additionally, in eastern Siberia, in the zones of intercepting reservoirs, alternative sources of electricity are being installed [50, 51]. In some cases, this is more efficient than using a hydraulic unit.

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