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AN HYBRID SIMULATOR FOR MANAGING HYDRAULIC STRUCTURES OPERATIONAL MODES TO ENSURE THE SAFETY OF TERRITORIES WITH COMPLEX RIVER BASIN FROM FLOODING

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ABSTRACT

The present article demonstrates the necessity to develop strategies ensuring integrated land and water resources management due to a steady growth in the number of registered floods. Based on hybrid simulation a modern methodology of developing rules for the use of reservoirs is considered, and the basic criteria are formulated, which form the basis for planning the flow out of the reservoir. The effectiveness of the hydro technical structures' cascade compensating management and control mode is established using the proposed hybrid simulator based Systems Dynamics formalism. Computer simulation boundary conditions and mathematical apparatus are formulated. The developed software modules flowcharts are presented, which allows to control the water level in a reservoir and at all the subsequent river reaches depending on the predetermined hydrographs of water inflow and water pass through hydro technical structures. A case study is, finally, presented.

1. INTRODUCTION

Floods are considered to be the most hazardous natural disaster effecting population. In the territories exposed to regular flooding more than 1 billion people permanently reside (Abhas K. et al, 2016). Flooding of cities bears a serious threat to the population. Under the conditions of demographic growth, urbanization trends and climate change, the reasons for causing floods are changing, and the impact thereof is becoming more serious. This scale and permanently escalating threat mean that more is needed to be done in order to better understand current and future risks, as well as to effectively manage and control them.

As mentioned above, a steady growth tendency in the number of the registered cases of floods is observed (Fig. 1). This is connected not only with the increase in the peak sediment activity, but, to a greater extent, with the construction works started in territories, where construction was previously prohibited.

At the same time, it should be noted that the number of victims is increasing at a slower rate or even decreasing, which reflects the successful implementation of measures to manage and control the flood risks. However, the problem of territories and population protection has not yet been resolved (Ksenofontov et al, 2017).

As a first step on the way of finding a solution, it is required to understand the causes of flooding. Cities could be flooded by rivers, coastal water setups, storm water or groundwater, as well by overflows caused by the failure of artificial systems; but the major number of floods is registered as a result of seasonal showers. Special danger for cities is presented by occasional heavy rains.

One of the most devastating and discussed (i.e. by Ksenofontov et al, 2016) floods of the recent years in Russia was the flood in Krymsk in the summer of 2012, which resulted in deaths of about 160 people. According to the Hydro meteorological Center report, on the night of July 6 to 7, 2012 in Krymsk itself 220 mm of rainfall fell down, while in the neighboring Gelendzhik and Novorossiysk - 250 mm and 275 mm with the norm for this region of 70 - 100 mm.

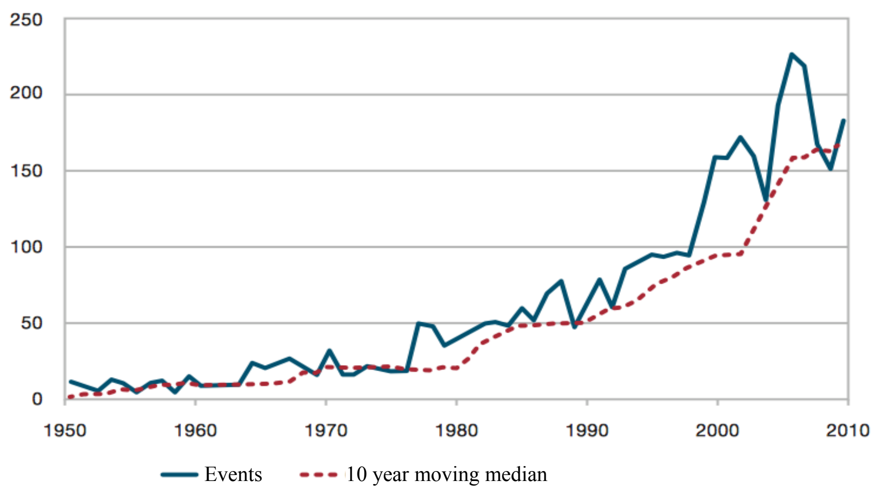

Figure 1: Growth trend in the number of registered flood cases (Abhas K. et al, 2016).

According to one of the possible explanations, the flood occurred due to the emergency water dump from the reservoir, because there appeared a threat of overflow over the edge. According to another possible explanation, the cause was found to be the insufficient water transmission capacity in the alignment of Adagum river highway bridge because of the accumulated domestic and natural waste, which resulted in a rapid accumulation of water. During the night this improvised dam could not resist to the water head; and the uncontrolled flow of water wiping away everything in its path gushed out in the city direction. These explanations both pointed out that through proper management of the reservoirs cascade similar events could be avoided (Ivanova and Ivanov, 2016).

Thus, the economic feasibility of implementing preventive methods of flood protection compared to costs of eliminating the consequences of emergency situations is obvious.

But even characterized by their destructiveness, floods could become beneficial to the society. For example, the floods provide the inflow of silt and nutrient substances in the floodplains. Obviously, in order to find the right balance between benefit and threat, strategies for risks integrated management and control shall be required.

Accordingly, such an approach is needed, which would ensure the balance between benefit and threat, i.e. the strategies for integrated management and control of land and water resources within the natural geographical, rather than administrative or political boundaries, are necessary.

Such an approach is required, which:

1. Provides maximum benefit from the use of water and land resources.
2. Minimizes human casualties.

This holistic approach shall integrate the land and water resources management and control, widen the knowledge about the risks of floods and be aimed at reducing vulnerability to flood consequences accompanied by a simultaneous understanding of the driving forces of the system as a whole. This involves implementation of an integrated approach within the river basins, which takes into account the natural geographical and hydrological boundaries, and not the administrative or political ones.

However, the integrated flood management and control within the frames of integrated water resources management and control also involves the risks management and control accompanied by recognition of the fact that floods consequences could become beneficial, but they could never be controlled in full.

This paper aims developing an approach in increasing the safety and security of territories during floods by forecasting the water flow, subject to the controlled release by the hydro technical structures system of the drainage network.

2. MANAGING WATER BASINS AND DAMS: RULES AND PROCEDURES

According to contemporary methodology adopted in the Russian Federation, when developing rules and regulations of reservoirs employment and operation the following factors shall be considered: integrated water resources usage, ensuring safe operation of the reservoir major hydro technical structures, safety and security of settlements and economic facilities, power generation, navigation and vital functions of flora and fauna.

Consider a cascade consisting of n reservoirs (Fig. 2.). Each of the reservoirs has a power plant (PP), and valves regulating amount of water diverted to power production, or to bypass. Each reservoir can be filled with water up to a certain level, which may be defined as follows: Dead Storage Level (DSL) – water level, below which electricity generation is not more possible. Normal Headwater Level (NHL) – planned water level in the reservoir. Surcharged Reservoir Level (SRL) – any water level above NHL, aimed for keeping extra water supplied in rainy periods. An excess of the SRL is the overfilling the reservoir that results in water spill over the edge, and hence is considered to be an accident.

In general, the flow cascade governing should be considered in the compensating operation mode. The efficiency of the indicated operation mode is achieved by:

1. Asynchronous flow in different rivers of a basin (as a result of a mismatch in the oscillation phases of the main river and its tributaries or different rivers flow).
2. Compensation of lateral inflow and unsustainable water or energy efficiency in rivers lesser regulated by reservoirs at other watercourses using the discharges from the compensating reservoirs.

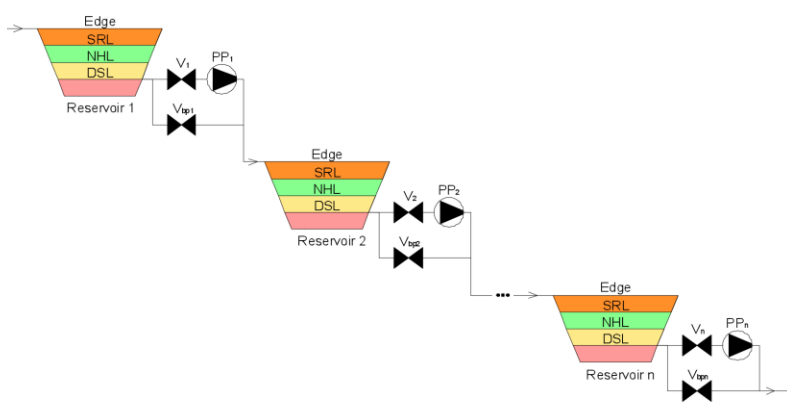

Fig. 2: Hydroelectric power plant cascades diagram (The following shorthand notations were accepted: SRL – Surcharged Reservoir Level, Normal Headwater Level (NHL), Dead Storage Level (DSL), PP – Power Plant, bp – bypass.

This paper describes software development in accordance with above mentioned criteria that could be used to support the execution of the following tasks by an operator:

1. Optimization of the reservoir cascades and hydroelectric power plants operation.
2. Water allocation under conditions of water resources shortage.
3. Evaluation and optimization of land reclamation activities.

The following limitations were chosen as the boundary conditions:

1. Performance criteria - water volume water above the Dead Storage Level (DSL) (electricity generation range), but below the Surcharged Reservoir Level (SRL) (excess is considered to be an accident).
2. Optimal mode of operation is considered to be the maintaining of the Normal Headwater Level (NHL).
3. Besides, it is required to know the maximum acceptable water lifting level in the channel for each channel section.

3. HYBRID SIMULATION MODEL

In literature it is possible to find many use of modeling related to water management for dam and reservoirs (Turner and Gaielli, 2017). Some of these models are specific focused on hydro geological characterization (Chen et al, 2016) or disaster flood modeling (Manenti et al., 2016) up to dynamic characteristic analysis of dams (Zhang et al., 2016). Among these models several techniques were proposed: discrete events simulation based on cellular automata and Markov Chain (Palmate et al, 2017) and Baeysian networks (Das et al, 2017) and continuous simulation (Castillo et al., 2016). Due to the particular nature of the physics involved in the dam/reservoir discharge, two different modeling techniques are required: discrete events for the action taken over the dams and reservoirs and continuous simulation for the overall discharge process that include free level modeling, river regimen calculation and flood event simulation. Since great part of such modeling activity is focused on the integration of many differential equations it appears quite useful to adopt a formalism that will speed-up the modeling phase and the concurrent validation phase. The authors have several successful previous experiences in adopting the System Dynamics (SD) formalism to model different real life systems including Supply Chains (Briano et al., 2010), Container Terminals (Briano et al. 2009) as well as complex flows of cryogenic liquids (Briano, Caballini et al., 2010). Such examples are demonstrating that the SD formalism is able to model correctly both the continuous and the discrete event parts of a complex simulation models. In a more recent paper (Damiani et al., 2017) a comparison among the various modeling strategies was presented highlighting the opportunity to adopt hybrid simulation based on SD formalism for very complex industrial and natural process. Based on such experience and after a deep analysis of the simulation issues to be addressed in the project the authors decided to adopt SD formalism as principal modeling technique for the entire system (dams/reservoirs, basins, river, surrounding area, etc.). Among various software available on the market (i.e. Stella/iThink, Vensim, Dynamo, Berkeley Madonna, etc.) PowerSim was chosen for its capability to interact actively with external datataset, provide very effective GUI for supporting logic validation and for its ability to check and enforce unit of measurement over the various equations. This choice was supported by the evidence that using a SD formalism it is more easy to understand the complex differential equations that drive the system and, at the same time, the modeling tool allows the possibility to animate the flows over the designed diagrams supporting effectively debugging and improving general awareness toward the model. For such reason the principal techniques used in Verification and Validation were based on structured walkthrough and Turing Tests.

In the course of this work, the software based on the PowerSim software was developed, which allows to determine the morphometric and hydrological characteristics of the river basin and, depending on the preset safety and security requirements, to determine the hydrographs of water release in the hydro technical structures.

In the course of this work, the software based on the PowerSim software and hardware complex was developed, which allows to determine the morphometric and hydrological characteristics of the river basin and, depending on the preset safety and security requirements, to determine the hydrographs of water release in the hydrotechnical structures. Compared to the studies mentioned before, the main feature of the developed approach is the software capability to perform an analysis over a river system consisting of many water dams to mitigate possible flood risks over all the river basin.

3.1 Computer Simulation

The basis for the computer simulation carried out in the developed software is the water balance equation, which is written in the following form (Methodical Guidelines, 2011):

$$Q_e + Q_{gr} + Q_{rt} + Q_{trf} + Q_{res} - Q_{wdr} - Q_{trt} - Q_l - Q_{abs} - Q_{wr} \gtreqless 0$$

where:

Water-budget input:

Q_e – natural surface flow;

Q_{gr} – share of the groundwater operating costs of the groundwater, which hydraulically is not connected with surface water;

Q_{rt} – returnable, drainage, mine and waste waters coming to the river within the limits of the basin or its section;

Q_{trf} – water transferred from other basins;

Q_{res} – volume of reservoir evacuation within a calculated time interval.

Water-resources output:

Q_{wdr} – water withdrawn from the river above the cross section used for irrigation, lakes replenishment, as well as for municipal, public utility and industrial water supply (less the return flow rate, if the water disposal is performed above the cross section);

Q_{trt} – water transferred to other basins;

Q_l – water losses because of additional evaporation from the surface of reservoirs and ponds;

Q_{abs} – losses of river flow caused by the abstraction of drained ground water;

Q_{wr} – water release output below the designed cross section.

A network section representing one section of a cascade was presented in the PowerSim software package. The indicated section flow chart is shown in Fig. 3.

The flow chart includes a reservoir (operator Dam), which is described by its volume (Dam_vol0), maximum allowable water height in the reservoir (Max_Dam_H), and maximum possible discharge rate on the outflow from the reservoir (Discharge_rate operator). The reservoir receives the inflows of various origins: precipitation, groundwater and water inflow from the river upstream. Total water arriving is described with the Inc_flow operator, which sums Rainfall discharge (Rainfall), underground water supply (Underground) and amount of water arrived from the previous segment of the river basin (Prev_Discharge). Hydrographs of these inflows are defined as the source data for simulation and taken from the Scheme of water objects of Kuban river (2016). At the dam outlet, the water discharge through turbines for the purposes of electricity generation (normal operation) is determined. Besides, a possibility for the discharge of water through the gates cross section is envisaged to bypass the turbine (ByPass operator, which is activated when the water level in the dam exceeds the max. allowable value). Upon reaching the SRL, the water discharge is conducted through the bypass (discharge is equal to the water inflow in the reservoir). Wide arrows indicate the direction of the watercourse. Thin arrows indicate the logical and structural relationship between the operators and the flow chart elements. A series of hydrographs is set as input data, such as: “Hydrograph”, which defines the water discharge from upstream with time, “Rain”, which defines the rainfall discharge with time, and “undergroundData”, which describes the amount of water infiltrated from soil to the reservoir with time. The output data is the outflow and bypass water discharge with time.

In addition, the reservoir characteristics are determined as the input data for simulation. Fig. 4 presents the flow chart of the reservoir geometric parameters connection: absolute water level in the reservoir, water surface area, average depth and storage volume; and, as the result, the current reservoir water level is determined. It is calculated by the "hcorrV" operator that is later used in the water movement in the reservoir flowchart. This operator is defined by the following statement:

$$\begin{cases} If\ DAM\ \leq v_N\ \ then\ h_{corrV} = \frac{h_N - h_0}{v_N - v_0} * (DAM -\ v_0) \\ If\ DAM\ > v_N\ \ then\ h_{corrV} = \frac{h_S - h_N}{v_S - v_N} * (DAM -\ v_N) + h_N \end{cases},$$

where v_N, v_S, v_0 – reservoir volumes for NHL, SRL and DSL levels respectively, and h_N, h_S, h_0 are the relevant water depths.

This approach allows to take into account the irregularity of the bottom and other features of the reservoir, and to determine the current value of water level to insert it into the main flowchart. A curved line in the figure graphically illustrates the dependence of changes in the average water height in the reservoir depending on its size.

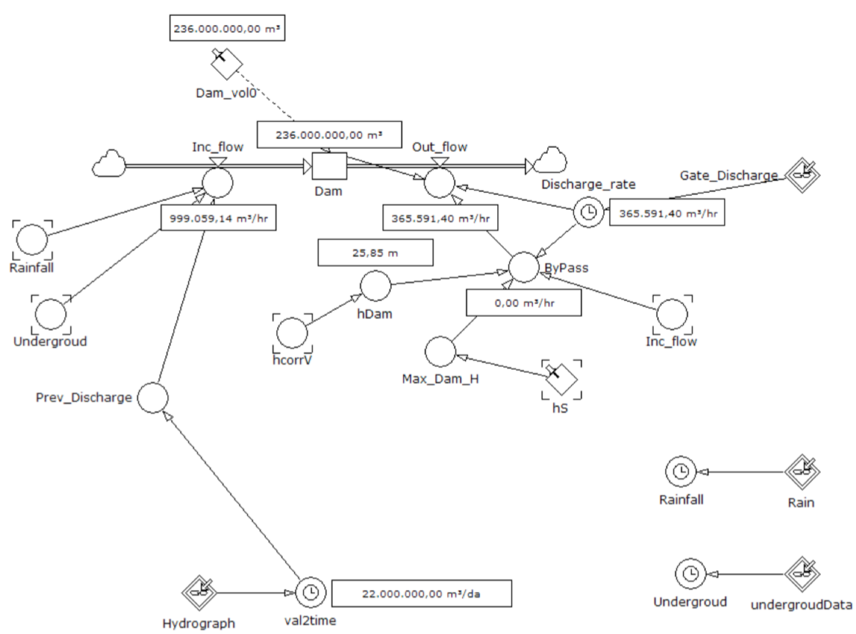

Figure 3: Flow chart of water movement in the reservoir.

Fig. 5 presents the flow chart of water distribution in the river segments. As the water inflow, the hydrographs sum is predetermined: natural river flow from the preceding river section (Out_to_Seg operator), groundwater and precipitation (Out_flow operator). The water flow rate mode from the reservoir is based upon the preplanned hydrograph outflow dispatcher schedule (Max_Seg_Discharge operator). Additionally, this module, as a boundary condition, sets the maximum acceptable flow of water in the given section (Max_Level_Seg operator), which excess could lead to flooding at the given section of the river network. The wide arrow indicates the water flow motion; and the thin arrows indicate the logical and structural relationship between the operators and the flow chart elements. The module calculates current water level in the segment (Curr_Seg_Level operator) and compares it to the maximum allowable level. If it is exceeded then the flood event occurs (Seg_Flood) with a certain impact dependant of the water level height.

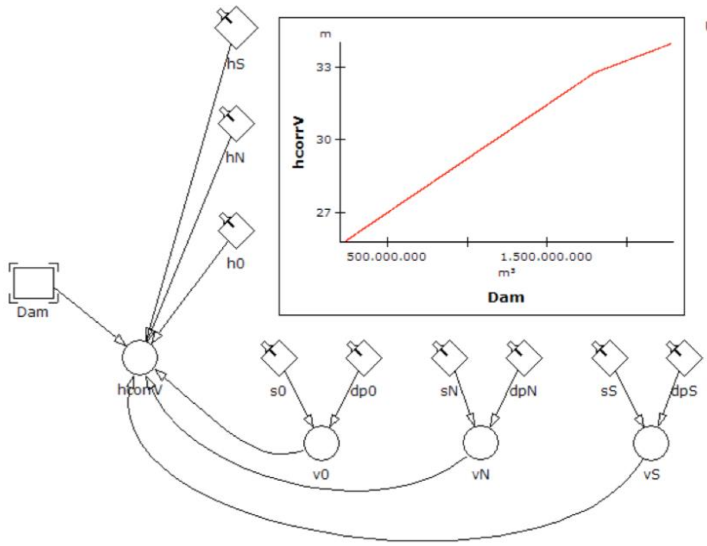

Figure 4: Flow chart of the reservoir water level in the reservoir (Y axis) and reservoir capacity (X-axis) dependence (h_0 – DSL, h_N – NHL, h_s – SRL, s - reservoir surface area, d – reservoir average depth, V – reservoir storage volume).

Fig. 6 presents the scheme of water distribution in the river segments. A river along its entire length is divided into segments, each of which is characterized by the preservation of geographical and hydrological characteristics along the entire length. The set of segments is predetermined as the vector-column. The water inflow in the first segment is equal to the sum of hydrographs of water flow in reservoir and bypass. The water inflow in each subsequent segment is equal to the water flow in the preceding segment.

For each segment the maximum accepted water level is assigned. In case water exceeds in a segment above the permissible level, the flood will occur.

Accordingly, the assignment of initial conditions in the form of the reservoir inflow hydrographs and characteristics, as well as introduction of the desired water discharge hydrograph through the reservoir will ensure determination of the resulting water rise level in the downstream river within the given network section. At the given stage of the model development, the operator, who controls the dam and performs such simulation, will be able to evaluate the reservoir preplanned mode of operation. Such sequential operations could reasonably determine the water release optimal hydrograph through the dam cross section.

The above-described water movement modules in the reservoir, reservoirs geometric parameters connections, as well as water distribution in the river segments allow to simulate the behavior of water in the head water and downstream of a single dam at the given network section. At the same time, the developed computer model could be easily scaled to n cascades by copying the segments. The scaling may be limited only by the computing capacities of the facilities available and is sufficient enough for solving most of the known water systems.

Consequently, it becomes possible to simulate complex multi-cascade river networks by assigning the individual network characteristics to each cascade and setting individual limits on the river floods in each cascade, as well as to carry out differential simulation of water movement in all sectors of the water network. At the same time, as the result of the entire river system simulation, hydrographs of water releases for each separate network section could be received designed in order to ensure safe water level along the entire river system length.

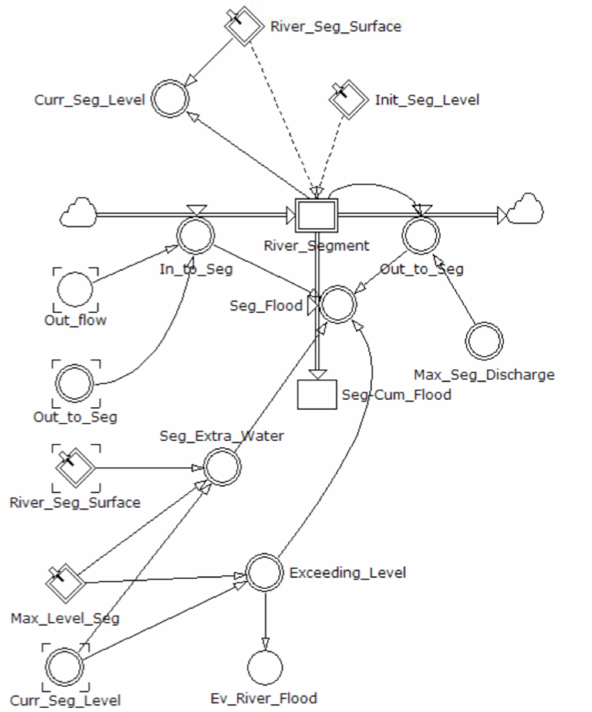

Figure 5. Flow chart of water distribution module in the river segments.

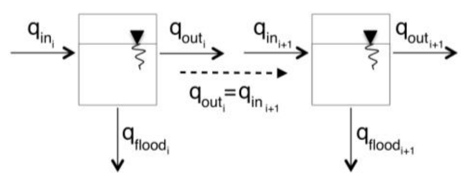

Figure 6. River division into segments
(q_{in} - inflow to segment, q_{out} – water flow from segment,
q_{flood} – water flow at underflooding (in case of exceeding the maximum acceptable level)).

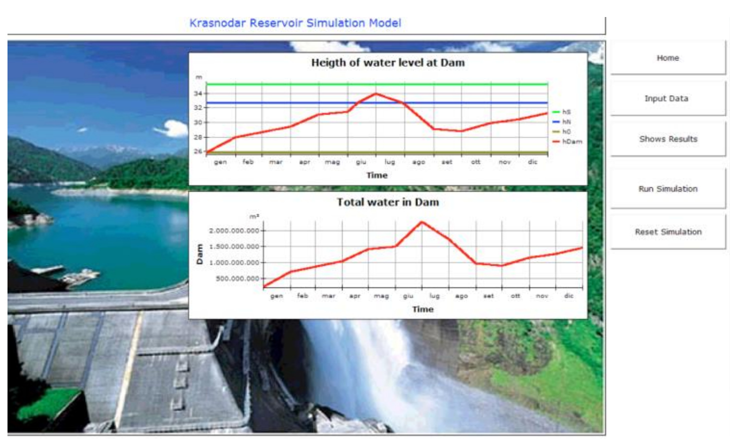

Figure 7. Main dialog box controlling simulation and displaying results.

3.2 Major Results

The above-described computer model was developed on the basis of the PowerSim software package, which resulted in creation of an application for simulating the water release at multi-cascade river systems and for supporting the decision-making process at the mode selection of water release through each dam in the network.

The main software dialog box demonstrates the name of the created model, program control devices, as well as the simulation results (in case the modeling has already been conducted).

In order to start simulating, it is necessary to enter initial data in the model. The software dialog box designed to ensure entering of the initial date is presented in Figure 7.

In the present case, the approximate values characteristics of the Krasnodar reservoir were introduced as the model example.

The input data shall include the following:

1. Flowage hydrographs (natural surface runoff, precipitation and groundwater).
2. Water runoff hydrograph out of the reservoir.
3. Reservoir DHL, NHL SRL.
4. Reservoir storage capacity under appropriate levels.
5. Reservoir water surface area for appropriate levels.
6. Set of segment cross-sections.
7. Average water flow rate in a channel for each segment.
8. Safe crash water levels for each segment.
9. Initial conditions – water level in the reservoir and segments.

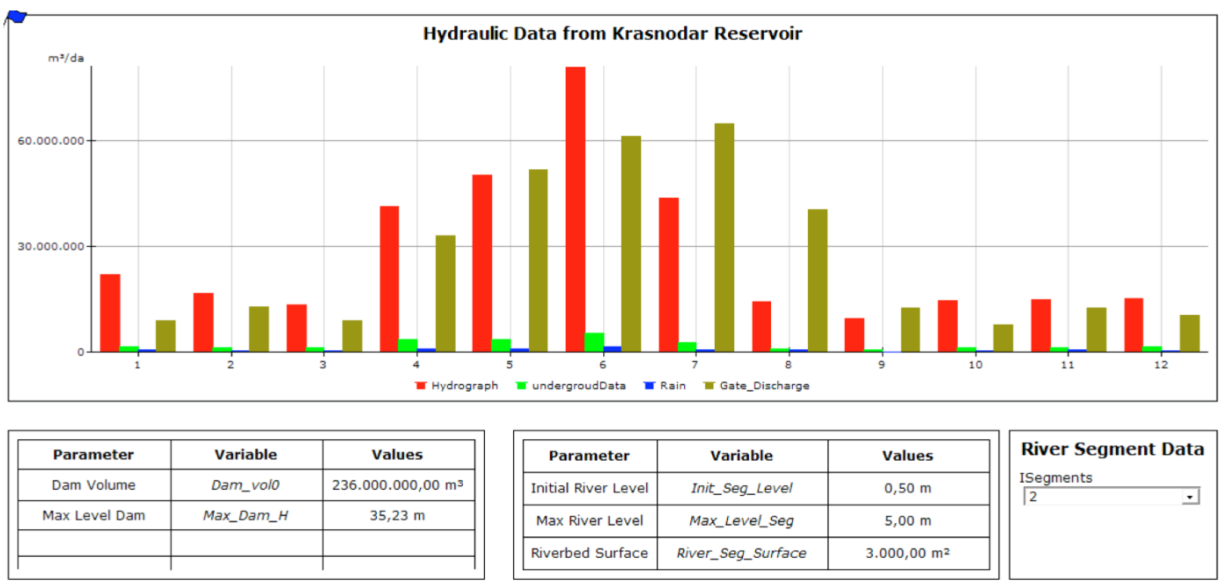

Figure 8. Dialog box for entering the input data.

After entering all the required data, it is necessary to perform the simulation by pressing the relevant button on the control panel. After that, the main dialog box will display the diagrams demonstrating the water level and volume in the reservoir in the course of time (see Fig. 8).

Furthermore, in order to ensure a more detailed analysis, it is possible using the developed tool to display the current situation in each of the segments, as well as the dependence of the water level upon time for each particular segment (Fig. 9).

Currently, the developed program allows to conduct the assessment analysis of capabilities of the hydraulic power system within the entire river network basin in regard to water release with different flow rates ensuring, at the same time, the controlled water spreading in the floodplain. Consequently, the governing body of the river network is entitled to determine the maximum water expenditure through each of the hydro technical systems ensuring, at the same time, protection against floods.

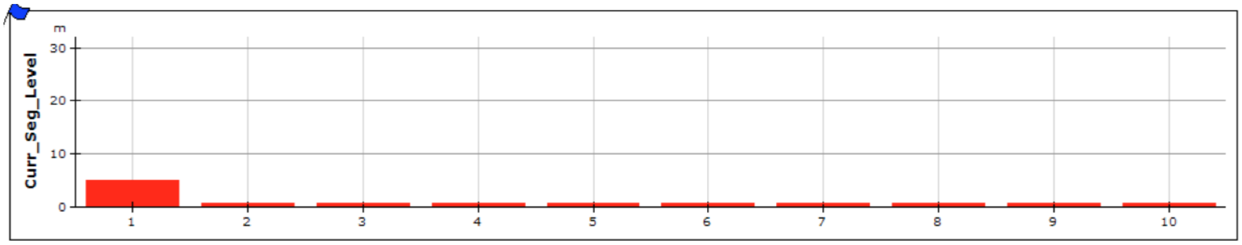

Figure 9. Water level in the river channel depending on the segment.

The developed software is characterized by a vast potential of its development and improvement. In particular, in the course of the further works execution it is planned to add the Energy module, which will allow to evaluate the hydroelectric power station energy production.

In addition, it is required to augment the system with Optimization module, which will be able to automatically calculate the most effective mode of the reservoir operation based on conditions of minimizing damage and maximizing benefits from electricity generation.

The next step will comprise the increase in the model operating accuracy. For this purpose it is envisaged to implement several stages to introduce modules describing the physical processes that occur at different stages of the river network operation. For example, it will be necessary to add a more accurate calculation of the wave propagation in accordance with the Saint-Venant shallow waters equations (A.J.C. de Saint-Venant, 1871):

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q}{\partial x} = q \\ \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\dfrac{Q^2}{A}\right) + gA\left(\dfrac{\partial h}{\partial x} + S_f\right) = 0, \end{cases}$$

where:
x – length along the watercourse;
t – time;
$A(x,t)$ – free area;
$Q(x,t)$ – flow of water;
$q(x,t)$ - external source related to the watercourse unit of length;
g - gravitational acceleration;
$h(x,t)$ – depth;
$S_f(x,t)$ – flow friction slope.

In addition, to ensure maximum adjustment of the developed software with the current methodology and also a more full-fledged analysis, it is necessary further to take into account the navigation and environment requirements that could also be carried out by improving the given computer model.

4. CONCLUSION

The paper demonstrates the trial of developing a computer model and software to support an administrative body in executing such tasks as the optimization of the reservoirs and hydropower plants operation accompanied by providing the maximum safety and security from flooding caused by large values of the water outflow; the integrated distribution of water resources under conditions the shortage thereof, as well as the land reclamation activities.

The developed software allows to carry out the analysis of possibilities of water engineering systems in order to assess the optimal water releases through the river network hydro technical structures providing safety and security against floods in its entire flow length.

At the same time, there are no limitations in regard to the given software with respect to its applicability: the software could be used to simulate the dams' construction and operation both on rapid mountain rivers with significant vertical drops, and on major river networks, the type of Volga or Amur river system basins, which are characterized by enormous volumes of water and relatively small water drop levels.

Separately it should be noted that the high potential of the developed software corresponds to further improvement, which will enhance its utility purposes and the accuracy of the simulation, i.e. it will be enhanced in order to allow to evaluate the hydroelectric power station energy production, automatically calculate the most effective mode of the reservoir operation based on conditions of minimizing damage and maximizing benefits from electricity generation.

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