Computer implementation of the mathematical model for water flow management by a hydro complex

R V Davydov, V I Antonov, D V Molodtsov
Peter the Great St.Petersburg Polytechnic University, Saint Petersburg, Russia

E-mail: davydovroman@outlook.com

Abstract. In this article computer implementation of the river flow regulation model for a hydro complex with a hydroelectric power plant on the main river during extreme water discharges is considered. Modes of operation for hydroelectric power plant with a reservoir are appointed using design dispatch schedules for annual flow regulation. The use of the proposed model makes it possible to determine the operating modes of the hydro complex, taking into account modern economic and environmental requirements, make adjustments to their parameters, assess the energy-economic and environmental effects.

1. Introduction
Nowadays, due to the severity of storm flooding problem, the task of managing floods throughout the river basin by creating a flood control system in the drainage basin has become an important task. In the flood conditions it is important to minimize their environmental and economic impacts, taking into account the location of various objects in the river basin. The flood control system includes a hydroelectric complex with a hydroelectric power plant (HPP) on the main river and smaller flood control facilities with temporarily filled reservoirs located at the side tributaries of the river. The practice of using such kind of systems has been widely spread in recent years in various countries of the world [1, 2].
As part of the research for the Russian Science Foundation grant, a mathematical model of long-term hydro complex operation with a HPP has been created in accordance with the current recommendations based on the methodology of a systematic approach to river flow regulation [3, 4]. In the model the specifics of the hydro complex operating conditions in a river basin with one of the most frequency of catastrophic storm floods in Russia are considered more fully than in other models which are used in the different regions of the world with milder flood effects [5-7]. Both the potential environmental risk of flooding during the operation of the hydro-complex, and the energy-economic aspect of the operation of HPP in various conditions are taken into account.
Using the developed model, we can solve the task of adjusting the flood control capacity of hydro complex, considering the current and prospective economic and environmental situation (in most cases, in the direction of decreasing) and redistributing the missing regulating volume to the flood control facilities on the side tributaries. For simulation the operating modes of HPP during the year, a project dispatch schedule of flow regulation can be also applied. Previous studies have shown that in modern conditions existing dispatch schedules allow operational services to operate the HPP’s operation modes relatively safely [8].


2. Mathematical model

The river flow management calculations are made for a high-water year, therefore the proposed model for includes three stages: the period of reservoir filling, the period of accumulation of flood flows, the period of reservoir draw-off [9].

At the first stage we have two cases, depending on the water level mark in the upper pool \( Z_{UP}^{HPP} \) (t). If it is above the upper limit of water surface level on the reservoir operating rule curves in the range:

\[
\text{DSL} \leq Z_{UP}^{HPP} (t) \leq \text{FRL}
\]

where DSL – Dead Storage Level; FRL – Full Reservoir Level.

Depending on the water head \( H(t) \) at the calculated time \( t \), the HPP operates with the power of \( N^{HPP}(t) \):

\[
N^{HPP}(t) = \begin{cases} 
N_A^{HPP}(t), & H(t) \leq H_R \\
N_R^{HPP}, & H(t) > H_R 
\end{cases}
\]

where \( H(t) = Z_{UP}^{HPP} (t) - Z_{LP}^{HPP} (t) - \Delta H \), \( N_A^{HPP} \) – available power. It is determined using the operating curve \( N_A^{HPP}(t) = f_1(H(t)) \), \( N_R^{HPP} \) – rated power, \( Z_{LP}^{HPP} (t) \) – water level mark in the lower pool, \( \Delta H \) – head loss, \( H_R \) – rated head.

According to the conditions of reliability and safety of hydro complex operation, there is a restriction on the rise rate of the water level in the reservoir:

\[
\frac{dZ_{UP}^{HPP}(t)}{dt} \leq h
\]

Here \( h \) – the maximum safe value of the rise of the water level in the reservoir per day.

The water discharge in the lower pool at the time \( t \) is:

\[
Q_{LP}^{HPP}(t) = Q_{PP}^{HPP}(t) + Q_S(t)
\]

where \( Q_{PP}^{HPP}(t) \) – water discharge through the hydro turbines, \( Q_S(t) \) – seepage discharge. Accordingly, the power of the hydropower plant is determined by:

\[
N^{HPP}(t) = k_N \cdot H(t) \cdot Q_{PP}^{HPP}(t)
\]

Here \( k_N = 9.81 \cdot \eta_T \cdot \eta_G \) – correction factor, which considering the turbine efficiency \( \eta_T \) and the generator efficiency \( \eta_G \).

Electricity production during estimated time interval \( T_1 \) is calculated by formula:

\[
E(t) = \int_0^{T_1} N^{HPP}(t) \, dt
\]

The volume of water in the reservoir at time \( t \) is calculated by [10]:

\[
V(t) = V(t - 1) + \left[ Q_{ENT}(t) - \left( Q_{HPP}^{T}(t) + Q_S(t) + Q_{ID}(t) + Q_{EV}(t) + Q_{EN}(t) \right) \right] \cdot T_1
\]

where \( Q_{ENT}(t) \) – natural water flow, entering the reservoir, \( Q_{ID}(t) \) – idle discharge through the spillways, \( Q_{EV}(t) \) – loss of water due to evaporation from the surface of the reservoir, \( Q_{EN}(t) \) – the water, taken from the upper pool of the hydropower plant for economic needs.

If the water level mark in the upper pool is below the upper limit of water surface level on the reservoir operating rule curves within:

\[
Z_{UP}^{HPP}(t) \leq \text{FRL} \text{ and } N^{HPP}(t) \leq N_R^{HPP}
\]

The spillways are closed \( (n_{SW}(t) = 0) \) and the water flow in the lower pool is determined by the requirements of water consumers \( Q_{WC}(t) \):

\[
Q_{LP}^{HPP}(t) = Q_{PP}^{T}(t) + Q_S(t) \equiv Q_{WC}(t)
\]

At the second stage (in the period of accumulation of flood flows) the water level mark in the upper pool is in the range \( \text{FRL} \leq Z_{UP}^{HPP}(t) \leq \text{MWL} \), where MWL – Maximum Water Level. There are several requirements for managing flood flows during accumulating extreme flows with low probability (1%). The water discharge in the lower pool of the HPP should not exceed the maximum allowable \( Q_{max,allow} \) (it is assumed to be equal to the peak natural flow with probability of 10%), providing safety requirements for economic activities. In this case, the flood-alluvial regime of the river is also preserved:

\[
Q_{LP}^{HPP}(t) \leq Q_{max,allow}
\]

The water level mark in the upper pool must not exceed the MWL:

\[
Z_{UP}^{HPP}(t) \leq \text{MWL}
\]
The additional requirements are minimization of economic damage and conservation of biodiversity in ecosystems. For this purpose, areas, types of flooded lands and duration of standing water etc. should be analyzed. Using the criteria of not decreasing the diversity and the ratio between anthropogenic and natural ecosystems, the MWL is corrected. When it decreases, the flood storage $\Delta V$ is redistributed into flood control facilities on side tributaries:

$$\Delta V = V_{MWL} - V_{MWL^*},$$

where $V_{MWL}$ – designed maximum volume of the reservoir, $V_{MWL^*}$ – revised maximum volume of the reservoir in accordance with environmental requirements.

The number of open spillways $n_{SW}(t)$ is determined in accordance with the spillways operating rule curve, depending on the actual water level $z$. In this case, each spillway is operating in the "full opening" mode: $0 \leq n_{SW}(t) \leq n_1$ spillways are opened when $FRL = z_1 \leq Z_{UP}^{HPP}(t) \leq z_2$, $n_2 \leq n_{SW}(t) \leq n_3$ spillways are opened when $z_2 \leq Z_{UP}^{HPP}(t) \leq z_3 \ldots n_{x-1} \leq n_{SW}(t) \leq n_x$ spillways are opened when $z_{m-1} \leq Z_{UP}^{HPP}(t) \leq z_m = MWL$. The additional requirement is the restriction on the frequency of opening/closing operations of the spillways – the minimum time between opening and closing according to ensuring reliability of a hydro complex under operating conditions.

Finally, at the last stage (the period of reservoir draw-off) we have $DSL \leq Z_{UP}^{HPP}(t) \leq FRL$. If the water level mark in the upper pool is above the upper limit of water surface level the HPP is operating with the rated power $N_{HPP}^{R}(t) = N_{HPP}^{R}$. If it is below the upper limit of water surface level the HPP is operating with the guaranteed power with the rated probability $N_{HPP}^{G}(t) = N_{G}^{HPP}$.

The water discharge through the turbines in this case is $Q_{T}^{HPP}(t) = Q_{G}^{HPP}$, where $Q_{G}^{HPP}$ – guaranteed water discharge with rated probability. The reservoir is drawing-off to the dead storage level in winter. And in the case when the water level mark in the upper pool is below the lower limit of water surface level the HPP is operating with the reduced power $N_{HPP}^{R}(t) = p^* N_{G}^{HPP}$, where $p < 1$ – reduction ratio of the guaranteed power.

3. Results

The developed model uses the necessary information (hydrological characteristics of the river flow, technical and economic properties of hydroelectric power plants, as well as smaller flood control facilities, characteristics of equipment and structures, etc.) to perform water-energy calculations. It is implemented in the form of software product with a graphical interface for a personal computer, written in Matlab language, which allows to perform automated calculations on various initial data for water flows, parameters of hydro complex and time step sizes for simulation.

The estimation of HPP’s operation modes and its energy performance indicators was held when the source data (the hydrological characteristics, the parameters of the spillways of the flood control facilities, the maximum allowable water flow in the upper pool of the hydro complex, the changes in the MWL, etc.) has the possible measurement error, which in water-energy calculations is considered acceptable within 5%. The analysis of the HPP operating modes based on the developed model showed a small influence of the measurement errors: the estimated value of the HPP’s electricity generation during the regulation period varied within 1%, in calculating water discharges in the lower pool of the river it did not exceed 5%.

Using developed program, the computer simulation of the hydro complex operation is carried out. The water level marks and the water discharges during extreme flood conditions with and without using additional flood control facility on the side tributary of the river are shown in Figure 1 and Figure 2. In both cases the maximum water level in the reservoir doesn’t exceed MWL and maximum water discharges are near the maximum allowable value.
But if the designed maximum water level is reduced, due to newer economic and environmental conditions, the situation is changed. The variant when the maximum water level is reduced by 0.5 meter is studied and found that putting additional self-regulated flood control facility on the side tributary is necessary to successfully operate the chosen hydro complex and satisfy both conditions (Figure 3 and Figure 4).
Figure 3. Water flow discharges for the hydro complex for reduced maximum water level.

Figure 4. Water level in the upper pool of the hydro complex for reduced maximum water level.

The simulation results by this model can be further used to visualize areas of flooding on the map and assess environmental and economic consequences using GIS, to model the ecological situation in the upper and lower pool of the complex hydro complex with HPP, to estimate the economic damage in the upper and lower pool under flood control.

For example, in Figure 5 the results of modeling flooding zones are shown with an indication of the forest boundaries for one of the preferred sections of the flood control system.
4. Conclusion
The developed model allow to analyze various basic scenarios for reducing the risk of floods by regulating the river flow of the hydro complex, such as reduction the MWL mark of the hydro complex with HPP (considering current and future socio-economic and environmental requirements in the upper pool), while the maximum allowable the water discharge in the lower pool corresponds to the design; situation when the MWL mark of the hydro complex remains the same, while in the lower pool the maximum permissible water flow should be reduced taking into account ecological requirements.

Moreover, it is possible that the river flow characteristics do not match the project now because of climate change (with no changes in the parameters of the hydro complex), but due to climate change it is forecasted an increase in storm drainage, and, consequently, of extreme flows. Using the developed computer program, the regulating effect of the hydro complex is determined, as well as the additional accumulation volume for cutting the peak of floods, which should be placed in self-regulated flood control facilities on the side tributaries.

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