Non-linear multi-objective model for planning water-energy modes of Novosibirsk Hydro Power Plant

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Abstract. This paper presents a non-linear multi-objective model for planning and optimizing of water-energy modes for the Novosibirsk Hydro Power Plant (HPP) operation. There is a very important problem of developing a strategy to improve the scheme of water-power modes and ensure the effective operation of hydropower plants. It is necessary to determine the methods and criteria for the optimal distribution of water resources, to develop a set of models and to apply them to the software implementation of a DSS (decision-support system) for managing Novosibirsk HPP modes. One of the possible versions of the model is presented and investigated in this paper. Experimental study of the model has been carried out with 2017 data and the task of ten-day period planning from April to July (only 12 ten-day periods) was solved.

1. Introduction
Novosibirsk HPP is a part of the unified energy system of Siberia and it is one of the major large-scale technical facilities in Novosibirsk. Novosibirsk hydro power plant is a complex of hydraulic structures and equipment. Created over the hydroelectric power station Novosibirsk reservoir in operating mode makes it possible to manage the process of generating electricity and supplying water to a water consumer.

The key task to be solved in the Novosibirsk HPP management is associated with the planning water-energy modes in future periods. The planning lies in determining the basic water and energy characteristics of the Novosibirsk reservoir and hydroelectric power station for specified periods. Depending on the chosen discreteness of the period, planning is divided into short-term (days, decades) and long-term (months or more). For the Novosibirsk HPP the task of short-term planning is especially relevant in the spring-summer period, when the reservoir is filled due to the flood inflow and it is extremely important to take into account the conflicting interests of all water consumers (energy sector, agriculture sector and fisheries, water transport (waterborne traffic), water supply system.

Currently, the problem of water-energy planning at the Novosibirsk HPP is solved by simulation modeling. However, this method has several disadvantages. The main disadvantage of simulation modeling method is that the effectiveness of the obtained solution depends on the experience and knowledge of the specialist, consequently, the solution is neither globally nor locally optimal from the mathematical point of view. Furthermore the method is too time-consuming.

The statement and solution of the problem of planning water-energy HPP operation mode as an
optimization problem using the tools of mathematical programming is one of the promising directions. Numerous works are devoted to the optimization approach for solving problems of planning water-energy modes [1-7]. However, in the literature planning models are described in general terms, without reference to a specific situation. It also should be mentioned that each HPP has its own characteristics, which should be taken into account in the model to obtain adequate results for solving the problem of modes planning.

2. Problem statement
The optimization task is that the best of all possible variants of the operation mode of HPP in accordance with the defined optimality criterion (criteria) satisfying a set of constraints (water-energy, morphometric, regime, management, water consumers and other constraints) will be found. The paper [8] considers an optimization planning model that achieves the sum of squared deviations of the total discharge rate in the tailwater will be constant. Minimization of the sum of squared deviations of inflow rate for the planning periods from the average water rate is used as an optimization criterion.

In this research, the problem of planning is solved as a multi-criteria task, maximization of the hydroelectric power station head and minimization of the total discharge rate for the planning period are used as optimization criteria. This management strategy leads to an increase in electricity generation providing the working conditions of non-energy water users. The input data for modeling were given by the Novosibirsk PJSC RusHydro's branch. The problem was solved by using Microsoft Excel, "Solver Tool" module and MathLab 6.1.

3. Non-linear multi-objective model for planning water-energy modes
The model is based on the water balance equation, which describes the changes in water-storage volume for the planning period (the difference between the inflow in the storage reservoir and total discharge rate is equal to the change in the water-storage volume for the planning period). In the model, different optimality criteria or their combination can be used, i.e. the task of planning can be formalized and solved as one-criteria or multi-criteria, depending on the objectives of the planning. Also, the model includes a set of engineering, management and seasonal constraints.

The presented model allows determining an optimum water-energy mode of the Novosibirsk HPP for the spring-summer period (12 ten-day periods from April to July) in accordance with the defined criterions. Maximization of the hydroelectric power station head and minimization of the total discharge rate for the planning period are used as optimization criteria.

The following information is used as input data in the model:

\[ P^m = (p^m_i) = \text{mean in ten-day periods forecasted inflow to the hydrosystem (april-july) with confidence interval, m}^3/\text{s}; \]

\[ P^k = (p^k_i), i = 1, N \] - mean in ten-day periods forecasted inflow to the power site (april-july), km\(^3\);

\[ P^w = K \cdot P^m, \text{where } K = (k_i), i = 1, N \] - coefficient of transfer of flow rate m\(^3\)/s to the inflow volume km\(^3\);

\[ k_i = t_i \cdot 24 \cdot 3600 / 10^9, \text{where } t_i \text{ - number of days for } i\text{-th period (ten-day periods);} \]

\[ Z_0^a = 108.5 \] - affluent level on the 1st of April, m;

\[ Z_{\min}^a = 108.5 \] - minimum affluent level (dead-storage elevation), m;

\[ Z_{\max}^a = 113.7 \] - maximum affluent level (conservation storage elevation), m;

\[ N = 12 \] - number of periods (ten-day periods);

\[ S = (s_i), i = 1, N \] - difference of Trash-Rack-Structure (TRS) for i- th period, m;

\[ K^w = (k^w_i), i = 1, N \] - winter coefficient that determines the calculation error of the tailwater level
from the total discharge rate in the tailwater by formula (2);

\[ H_{\text{min}} = 13, \quad H_{\text{max}} = 22 \] — minimum and maximum net head of a hydroelectric power station, m;

\[ q_{\text{min}}, \quad q_{\text{max}}, \quad i = 1, N \] — minimum and maximum total discharge rate for the \( i \)-th period, \( m^3/s \);

Variables of the model:

\[ Q = (q_i), \quad i = 1, N \] — total discharge rate for the \( i \)-th period, \( m^3/s \);

\[ Z^a = (z_i^a), \quad i = 1, N \] — affluent level for the \( i \)-th period, m;

Derivative characteristics of the HPP operating mode that are also output of the model are calculated based on the values of the variable:

\[ Z^t = (z^t_i), \quad i = 1, N \] — tailwater level for \( i \)-th period, m;

\[ H = (h_i), \quad i = 1, N \] — net head of a hydroelectric power station, m.

The model also uses morphometric information:

Dependence of the static storage volume on the affluent level is described by a second degree polynomial:

\[
V = f(Z^a) = 45.449 \cdot (Z^a)^2 - 9213.2 \cdot Z^a + 469005. \tag{1}
\]

The coefficients of the model are estimated by using results of full-scale measurements of the static storage volume and the corresponding affluent level.

Dependence of the tailwater level on the total discharge rate is also described by a second degree polynomial:

\[
Z^t = f(Q) = -0.84 \cdot 10^{-7} \cdot Q^2 + 0.1 \cdot 10^{-2} \cdot Q + 91.95. \tag{2}
\]

The coefficients of function \( Z^t = f(Q) \) are estimated by using the results of full-scale measurements of the total discharge rate and the corresponding tailwater level.

Two optimality criteria are used in the model, the former is optimization of the hydroelectric head:

\[
C_1 = \sum_{i=1}^{N} h_i \rightarrow \text{max}, \tag{3}
\]

the total discharge rate is the second optimization criteria:

\[
C_2 = \sum_{i=1}^{N} q_i \rightarrow \text{min}. \tag{4}
\]

Normalization and convolution of criteria were made to reduce the task to a one-criterion one.

The objective function of the model minimizes the total loss in criteria taking into account the weight coefficients and is as follows:

\[
C = c_1 \sum_{i=1}^{N} \left( \frac{h_{\text{max}} - h_i}{h_{\text{max}} - h_{\text{min}}} \right) + c_2 \sum_{i=1}^{N} \left( \frac{q_i - q_{\text{max}}}{q_{\text{max}} - q_{\text{min}}} \right) \rightarrow \text{min}, \tag{5}
\]

where \( c_1 \) and \( c_2 \) are the weights coefficients determining weight of each criterion in fractions of one in the objective function.

The constraints of the model are described below.

The model is based on the water balance equation:

\[
p_i^k - k_i \cdot q_i = d_i, \quad i = 1, N. \tag{6}
\]

The changes in the water-storage volume are described as the difference of reservoir volumes at the
end and at the beginning of the i-th period:

\[ d_i = f(z_{i+1}^u) - f(z_i^u), i = 0, N. \]  

(7)

The tailwater level depends on the total discharge rate, taking into account the winter coefficient for the i-th period, m:

\[ z_i^l = f(q_i) \cdot k_i^w, i = 1, N. \]  

(8)

The water head for the i-th period is defined as difference between the affluent and tailwater levels and the SRM difference:

\[ h_i = z_i^u - z_i^l - s_i, i = 1, N. \]  

(9)

The constraint that prevents the reservoir drawdown during the storage time (the affluent levels in the i+1-th period is not lower than in the i-th period):

\[ z_{i+1}^u - z_i^u \geq 0, i = 1, N. \]  

(10)

The affluent levels should be in the range from dead-storage elevation (108.5) to conservation storage elevation (113.5):

\[ Z_{\text{min}} \leq z_i^u \leq Z_{\text{max}}, i = 1, N. \]  

(11)

Constraints on the minimum and maximum allowable water head for the i-th period:

\[ H_{\text{min}} \leq h_i \leq H_{\text{max}}, i = 1, N. \]  

(12)

Constraints on the total discharge rate for the i-th period:

\[ q_{\text{min}} \leq q_i \leq q_{\text{max}}, i = 1, N. \]  

(13)

Further, derivative characteristics of the HPP operating mode are calculated based on the values of the model’s variable, they are: \( Q^i = (q_i^t), i = 1, N \) - water rate through the HPP turbines for the i-th period, \( m^3/s \) and \( Q^s = (q_i^s), i = 1, N \) - idle discharge for the i-th period, \( m^3/s \);

The total discharge for the i-th period is defined as the sum of the water rate through the HPP turbines and the idle discharge:

\[ q_i = q_i^t + q_i^s, i = 1, N. \]  

(14)

Value \( q_i^t \) is determined by using table \( Q_{\text{max}}^t = f(H, Z^d) \) dependence of the maximum water rate through the HPP turbines on the water head and the tailwater level.

Capacity of hydroelectric station for planning period \( W = (w_i), i = 1, N \) is determined by the table \( W = f(H, Q^t) \) dependence of capacity on the water head and the water rate through the HPP turbines.

4. Experimental results

The ten-day planning of the water-energy mode for April - July period according to the data of 2017 was carried out with the help of the developed optimization model.

Variations of the mode with different combinations of coefficients and in the objective function (5) were calculated. Figure 1 shows the obtained from the simulation results graph of the change in the affluent level, when \( c_1=1 \) and \( c_2=0 \) (maximization of the total head), \( c_1=0 \) and \( c_2=1 \) (minimization of
the total discharge rate), $c_1=0.1$ and $c_2=0.9$ (compromise solution).

![Graph showing the affluent level for the planning periods in 2017](image)

**Figure 1.** The affluent level for the planning periods in 2017 taking into account the weight coefficients in the objective function.

Figure 2 shows the graph of changes in the water-power characteristics of Novosibirsk HPP in 2017 corresponding to the compromise solution $c_1=0.1$ and $c_2=0.9$. The graph shows the change in the affluent level, discharge rate in the tailwater and forecasted volume of inflow for ten-day period.

![Graph showing the water-power characteristics of Novosibirsk HPP in 2017](image)

**Figure 2.** The water-power characteristics of Novosibirsk HPP in 2017.

Considering the fact that forecasted inflow is determined taking into account the confidence interval at the input of the model, the mode calculations are performed for three variants (minimum, maximum and average values of forecasted inflow to the hydrosystem). Figure 3 shows the graph of changes in the total discharge for the planning period for three variants of input data.
The specialist can calculate different variants of the water-energy mode using the constructed model, by varying the weights of the $c_1$ and $c_2$ optimality criteria in objective function (5), guided by the planning objectives and taking into account the specifics of a particular situation.

5. Conclusion
The developed model can be used successfully for the calculation of water-energy modes of the Novosibirsk HPP.

In future, it is planned to perform a comparative analysis of different approaches (simulation, optimization) and models for planning of Novosibirsk HPP water-energy modes and develop a uniform calculation methodology and relevant software.

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