From water-energy research to hydropower optimization

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Abstract. A simple method for optimizing hydropower parameters has been developed. Cost and revenue, net present value, and net present quotient criteria are used in this approach. It is noted that the most important criterion is the net present value quotient. The developed method was used to optimize the parameters of the Selemdzhinskaya hydropower plant and a small hydropower plant. Algorithms and methods for calculating hydraulic energy for watercourse tree have been created. Verification of algorithm and methods was done in the model region with an area of 172.4 th. km². The calculation made for approximately 500 rivers.

1. Introduction

Hydropower uses renewable, sustainable, and green energy. These qualities are what hydroelectricity has to offer today and for generations to come. Yet the worldwide hydro industry faces challenges: maximizing power from existing sites, developing new projects, and doing these things in ways that are environmentally and socially sound. Hydropower engineering development including hydropower plant (HPP) has a high social and economic importance for Russia. According to the government energy strategy, it is necessary to keep the level of the non-fuel energy sector in the structure of the generating capacities up to 2035. Today’s strategic planning is increasingly driving all aspects of operations, maintenance, and development [1, 2, 3].

The goal of the research is to develop a new approach to optimize hydropower development schemas. The object of research is the river systems. A model of a river system is considered a watercourse tree. The research subject is the optimal HPP parameters. The article discusses the solution to the problem of optimizing HPP parameters.

HPP is characterized by a complex of the characteristics that determine the efficiency of its functioning in various aspects. In the common case, these characteristics reflect economic efficiency, quality, and reliability of electric power production, environmental impact, economic and social consequences [4, 5, 6, 7, 8].

Optimization of the HPP parameters is a complex problem. Natural, social, ecological, economic, technical, and other factors make an influence on this problem. Different types of resources (limited ones) generating different flows of products are involved in the process of creation and operation of HPP. Their estimation (if achieving the main goal – power supply) determines the justification of their parameter choice.

It is necessary to take into account many factors (economic, resource, energy, social, environmental, etc.) when choosing the most advantageous locations for HPP construction and evaluating their social and economic efficiency. The key criteria include the following: economic, resource, social, and ecological significance of the object [4, 5, 7].
2. Methods
As a rule, at the first stage, based on an analysis of natural and economic conditions using stock materials, preliminary pre-design studies, and reconnaissance surveys of the channel network, an excess scheme of potential sections of the location of the HPP is created. In the course of the subsequent detailed survey of river beds and an assessment of the terrain, refinement of geological, hydrological, and cartographic materials, prospective sections for the location of hydraulic structures and their number are determined. For the selection of sections, as a rule, the following information are used: data on water flow rates of various levels of supply, sections of watercourses with the highest level difference per kilometer, relatively accessible places that allow arranging access to hydraulic structures. At the same time, it is necessary to minimize the impact of the HPPs being created on the environment and to eliminate the risks of technological hazards.

The location of each HPP is determined by the terrain, from the conditions for obtaining maximum pressure with the least amount of general construction work, the maximum possible use of the hydropower potential of a selected section of the river, taking into account the minimization of capital investments [4, 7]. Some issues of optimizing the parameters of hydropower plants have been explored [4, 5, 7, 9, 10, 11, 12]. The following methods were used in the study: mathematical modeling, optimization, and statistical methods.

3. Results and Discussion
3.1. About river system and hydropower scheme

Let there be some river system in the area shown in Fig. 1. Consider the planning period T. All electricity consumers are concentrated in the area of the river system. Based on the analysis of the prospects for socio-economic development, the electricity demand growth schedule \( E(t) \) is known and it is defined in the planning interval T. Suppose that a variant \( j \) of a HPP layout scheme has been built on the river system and the procedure for putting them into operation to cover demand \( E(t) \), which is determined by the vector \( (t_1, t_2, ..., t_{M_j}) \). Here \( M_j \) is the number of HPPs in the layout variant \( j \).

The task is to search for such an option for the layout of HPPs at which a minimum of integrated costs is achieved in the construction of HPPs, taking into account the connection to the electrical network; maximum income from hydropower operation, minimum energy costs for consumers, maximum reliability of energy supply, minimum environmental impact, minimum hydropower resources used, etc. Such a scheme will be called optimal or rational. This task is multi-criteria. In a simpler formulation, we can consider a single-criterion task (minimizing the price of electricity generated) while taking into account the requirements of a socio-ecological nature in the form of restrictions [5].

![Figure 1](image-url). (a) River system, (b) Model of river system, consumers \((C1, C2, C3, C4, C5)\) and points of Hydropower plants.
Two interrelated tasks have to be solved to find optimal hydropower parameters. The first task is to build a variant of the hydropower scheme of the river system [4, 5, 7]. The second task is to optimize the hydropower parameters. The linking of solutions to these two problems is carried out in an iterative algorithm.

3.2. Water-energy studies of watercourse tree and restrictions

Future hydropower development requires research of river systems. Climate change is creating new challenges for society, energy, and hydropower. A deeper study of hydropower resources, taking into account climate change, is advisable. On the one hand, we need to update old materials on hydropower development schemas. On the other hand, regions do not need gigantomania but need new technical solutions and the development of new schemes that take into account new reality.

The model of the river system is the watercourses tree (WT). Algorithms for calculating hydraulic energy for such trees are developed. A new method for calculating hydraulic energy for small rivers has been developed. The verification of algorithms and methods was done on the model region with an area of 172.4 thousand km$^2$. Calculations made for approximately 500 rivers. The numerical results are compared with the calculations carried out analytically. The computer water-energy cadastre of the model region has been created (Figure 2).

Let’s consider an open watercourse or its part with known water-energy cadastre. Hydrological information at observation points over many years is known. Morphometric characteristics for the watercourse are specified. The requirements of the social-environmental nature and requirements of water consumers and users are specified in the form of limitations related to hydropower operation modes [4, 5, 6].

For tree watercourses, water consumption by different parties of the hydrologic system and return water flow rate are specified. It is assumed that a part of social and environmental requirements are taken into consideration in the form of the so-called “red line”. Herewith upper and bottom marks of “the red line” are determined by the equations:

$$Z^H(L) = \min\{Z_1^{\max}(L), Z_2^{\max}(L), \ldots Z_i^{\max}(L)\},$$  \hspace{1cm} (1)

$$Z^T(L) = \max\{Z_1^{\min}(L), Z_2^{\min}(L), \ldots Z_i^{\min}(L)\},$$  \hspace{1cm} (2)

where $L$ is a longitudinal coordinate counted along the river bed.

HPP together with its reservoirs can be situated only inside the admissible area limited by the mentioned lines. Mathematically the problem is formulated in the following way. The water-energy cadastre is given (Figure 2). We shall find: the vectors $L$ and $H$ that mark the points of HPP cascade site location and water heads in these points. We shall optimize: $f(L, H)$ provided the following restrictions:

$$Z^T(L) \leq Z(L) \leq Z^H(L)$$  \hspace{1cm} (3)

The problem associated with the choice of HPP points and the multi-criteria optimization algorithm in detail has been presented [4, 5, 6, 7].
3.3. Cost calculations
The cost of installed capacity of HPPs includes the cost of equipment, transporting it to places of installation, and the cost of construction. Determining the cost of HPP, as well as hydrological data analysis allows us to determine the cost of producing electricity and their effectiveness compared to other power generation techniques.

The capital cost of HPP $K_{HPP}$ (mln.$) is determined by the formula (4). This formula was obtained by Gordon [13, 14] based on the cost analysis of building HPPs worldwide. Costs for hydropower plant $U_{HPP}$ (mln. $ per year) include operating and maintenance costs and are determined by the formula (6) [8].

$$K^{HPP} = \alpha \cdot \beta \left( \frac{N_{IC}}{H} \right)$$  \hspace{1cm} (4)

$$K^{HPP} = K_{HPP} / K_0, \quad \bar{N}_{IC} = N_{IC} / N_0, \quad \bar{H} = H / H_0$$  \hspace{1cm} (5)

$$U^{HPP} = U_0 + u_1 \cdot \bar{N}_{IC}$$  \hspace{1cm} (6)

where $N_{IC}$ is the HPP installed capacity (kW), $H$ is the water head on the HPP (m), $\alpha, \gamma, \beta, \epsilon$ are some constants, $K_0 = 1$ mln.$, N_0 = 1000$ kW, $H_0 = 1$ m is the base constant, $\beta$ is the coefficient taking into account local conditions for the construction of hydropower plants; $U_0$ is the fixed cost (mln.$ per year), $u_1$ is the variable cost (th.$/kW per year). Values with a dash above are dimensionless quantities. To go to dimensional quantities, you need to use equations (5).
The generated electricity is the single most important factor in the cost of generating electricity. Hydro energy resource is one of the most important determinants of the profitability of hydro energy investment. In this study, we will use the cost of energy to assess the economic feasibility of a particular installation of HPP to select the optimal equipment that provides the minimum price of producing the electricity from HPP and investment profitability. If \( C \) is higher than the sale price of electricity, construction will not be possible.

We further believe that during the economic lifetime \( T_L \) the real interest rate \( r \) is constant and \( U_{IC}^{HPP} = U_E^{HPP} = const \) and \( E_T^{HPP} = E_G^{HPP} = const \). Under these assumptions, the cost of electricity produced by HPP can be written as \([4, 5, 7, 8]\):

\[
C = \frac{K^{HPP} \cdot CRF(r, T_L) + U_E^{HPP}}{E_G^{HPP}}, \tag{7}
\]

\[
\theta = \frac{N_{AC}^{HPP}}{N_{IC}^{HPP}}, \tag{8}
\]

\[
E_G^{HPP} = N_{AC}^{HPP} \cdot T = N_K^{HPP} \cdot T_U = \theta \cdot N_K^{HPP} \cdot T_U. \tag{9}
\]

Revenue from the sale of electricity \( B_E^{HPP} \) is determined by the formula:

\[
B_E^{HPP} = E_G^{HPP} \cdot C_T - U_E^{HPP}, \tag{10}
\]

\[
T_{PB} = \frac{K^{HPP}}{B_E^{HPP}}. \tag{11}
\]

The economic effect of using hydropower plant NPV is expressed in dollar or ruble and can be defined as the revenue, received from the use of hydraulic turbine through an economical lifetime:

\[
NPV = \frac{B_E^{HPP}}{CRF} - K^{HPP}, \tag{12}
\]

\[
NPV_Q = \frac{NPV}{K^{HPP}}, \tag{13}
\]

where \( CRF \) is a conversion factor non-recurrent capital cost into equivalent annual expenses during an estimated economical lifetime \( T_L \) with real interest rate \( r \).

### 3.4. Simple method of optimization

Installed capacity \( (N_{IC}) \) is considered as an integral parameter of the hydropower plant, which must be optimized. Maximization of net present value is accepted as optimization criterion: \( \text{NPV} \Rightarrow \text{max} \). Other parameters (technical and geometric) include a number of hydraulic units \( m \), turbine type \( R_{HU} \), turbine runner diameter \( D_1 \), HPP house type \( R_H \), etc. [7, 15].

Taking into account the found optimal power of the HPP, the selection of the above parameters will be carried out following the recommendations for the HPP design with appropriate engineering calculations. At the same time, it is necessary to exploit equipment with high efficiency and to have smaller sizes of the powerhouse and water passageways.

Based on the developed approach calculations were performed to optimize small HPP (SHPP) capacity. Fig. 3 shows the optimization of the results. This figure also shows the results of the calculation of economic criteria depending on the installed capacity of the HPP (revenue, NPV, and NPVQ). The optimal value of the installed capacity of SHPP was about 800-1000 kW.
The developed approach was used to optimize the parameters of the Selemdzhinskaya HPP. This hydropower plant is in the Far East. The calculations took into account climate change, which in the future will lead to an increase in water availability in this region.

4. Conclusion
A new approach has been developed to optimize hydropower development schemes (including small hydropower), which would minimize investment in its development and subsequent construction of hydropower plants.

The simple optimization algorithm for solving the problem has been developed. Based on suggested models of the energy-generating process, equipment, and constructions HPP parameters optimization algorithm was developed which takes into account some assumptions. This approach has been tested with a number of examples (Selemdzhinsk hydroelectric complex and small hydropower plant).

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