A System of Models for Studying the Impact of Hydropower Plants Planned in Mongolia on the Hydrological Regime of the Russian Part of the Selenga River Basin

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***Abstract* — The paper describes models designed to study the impact of hydropower plants (HPPs) planned in Mongolia on the hydrological regime of the Russian part of the Selenga river and Lake Baikal, considering various hydrological conditions and utilizing available technical information on the HPP projects. The developed models include software components for selecting an optimal dam site when precise coordinates are unavailable; constructing reservoir configurations and bathymetric curves demonstrating the reservoir water level-volume-area relationships; preparing hydrological statistics of water inflow into the planned reservoir by correlating meteorological indicators with flow; modeling HPP operating conditions based on different criteria. The primary object of this study is the Egiin Gol HPP on the Eg river, a left tributary of the Selenga river. Mongolia is planning to begin its construction in the coming years. The produced models assess the potential impact of the Egiin Gol HPP reservoir filling and operation on hydrological regimes across various water periods in the downstream pool, along its entire length from the HPP dam to the Selenga river inflow into Lake Baikal. The findings from the modeling serve as the basis for further research into the possible impact of the HPPs planned in Mongolia on the ecosystems of the Selenga river and Lake Baikal.**

***Index Terms* – Reservoir design, modeling of hydropower plant operating conditions, hydrological studies, flow management, transboundary basin, the Selenga river, Egiin Gol hydropower plant.**

I. INTRODUCTION

The development of Mongolia's hydropower industry began in the 1960s, when the Soviet Institute of Hydroproject and the Mongolian Ministry of Agriculture conducted joint preliminary studies of the Selenga, Egiin Gol, Orkhon, Tuul, and Khovd rivers, alongside other tributaries of the Selenga [1–3]. As a result, the potential hydropower capacity of the Selenga river basin was estimated at 1.5 GW, allowing for the annual electricity generation of 7.5 billion kWh. The total theoretical hydropower potential of all Mongolian rivers is even higher. According to research conducted by the Institute of Meteorology of Mongolia in the 1960s–1970s, the average annual flow of 3 800 small and large rivers in the west and north of the country is 34.6 km^3 per year with a potential capacity of 6.3 GW. The most significant resources, almost three quarters of all potential, are concentrated in the northern Mongolia (the basins of the Selenga, Onon, and Kerulen rivers). The remaining potential is found in the western part of the country, within the basins of the Khovd and Zavkhan rivers.

In 1973–1976, the Leningrad Branch of the "Hydroproject" Institute (Gidroproekt) developed a scheme for the placement of potential hydropower plants in the Selenga river basin, identifying future sites for their location and estimating the main parameters (head, installed capacity, and electricity generation) for 22 potential HPPs [3].

In the early 1990s, after the collapse of the USSR, Mongolia began to cooperate more actively with

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international hydropower companies on the design of hydropower plants [4–9]. Companies from Switzerland, Italy, and Mongolia carried out the first feasibility study and an Environmental Impact Assessment (EIA) for the Egiin Gol hydropower plant project between 1991 and 1994. The project was not developed further for various reasons. A new stage in the evolution of hydropower in Mongolia started in 2012. By this time, the demand for electricity had increased significantly, and there was a shortage of maneuvering capacities in the energy system due to the rapid growth of Mongolia's economy. The Government of Mongolia decided to implement the Shuren hydropower plant, the Egiin Gol hydropower plant, and the Orkhon-Gobi projects [9]. The World Bank was involved in the feasibility studies for these projects between 2013 and 2015.

In 2016–2017, commissioned by the Ministry of Natural Resources and Environment of the Russian Federation, the Irkutsk Scientific Center and several institutes of the Siberian Branch of the Russian Academy of Sciences (SB RAS), including the Melentiev Energy Systems Institute (ESI SB RAS), conducted a study titled “Assessment of the impact of planned construction of hydropower plants in Mongolia on the transboundary Selenga river basin within the borders of the Russian Federation.” The findings from the study indicated that future Mongolian hydropower plants, including the Egiin Gol HPP, could potentially have a significant impact on the ecosystem of the Russian part of the Selenga river basin, the primary tributary of Lake Baikal.

The Government of Mongolia included the construction of the Egiin Gol Hydropower plant in the list of priority projects for implementation in 2023. A joint meeting on this issue between the Ministers of Natural Resources of the Russian Federation and Mongolia, as well as the Presidents of the Russian and Mongolian Academies of Sciences, was held in Moscow in October 2024. Following the meeting, Russia and Mongolia agreed on an Action Plan for a collaborative study to assess the possible impact of the Egiin Gol HPP project on Lake Baikal and the Selenga river and decided to establish a Russian-Mongolian Expert Group. This assessment will involve investigating possible changes in the hydrological regimes of the Selenga river, relative to natural conditions, within the borders of the Russian Federation, due to the future construction of the Egiin Gol HPP in Mongolia. This analysis will also focus on the potential effects of the Egiin Gol HPP construction on the ecosystem of the Selenga river basin and Lake Baikal, highlighting the environmental and social aspects according to the internationally accepted frameworks of environmental impact assessment of hydraulic structures, and adhering to the UNESCO standards. ESI SB RAS is one of the participants in these studies.

Since 2013, ESI SB RAS has developed various models for energy, water management, hydrological, hydraulic, and environmental studies on operating hydropower plants and those under planning and design [10–15].

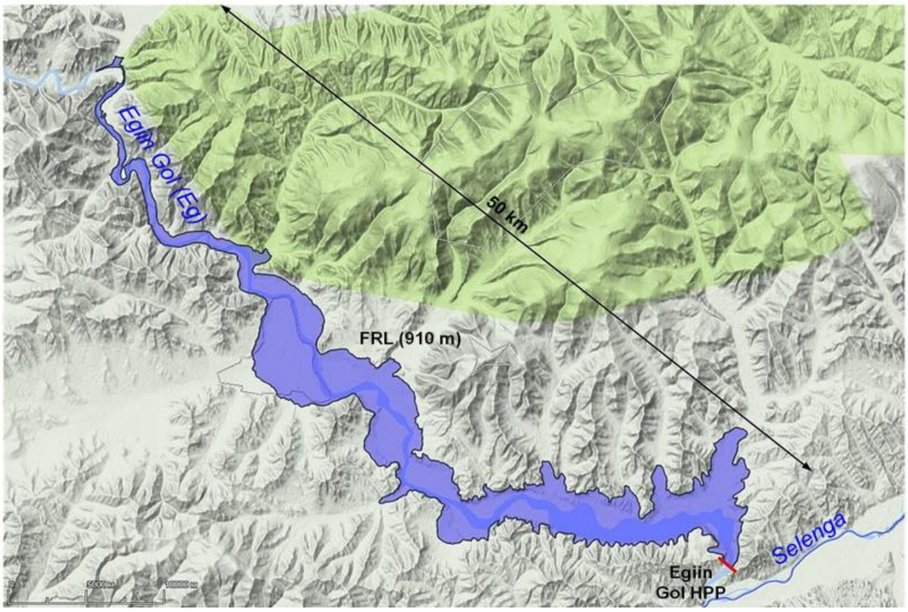

Fig. 1. Configuration of the Egiin Gol hydropower plant.

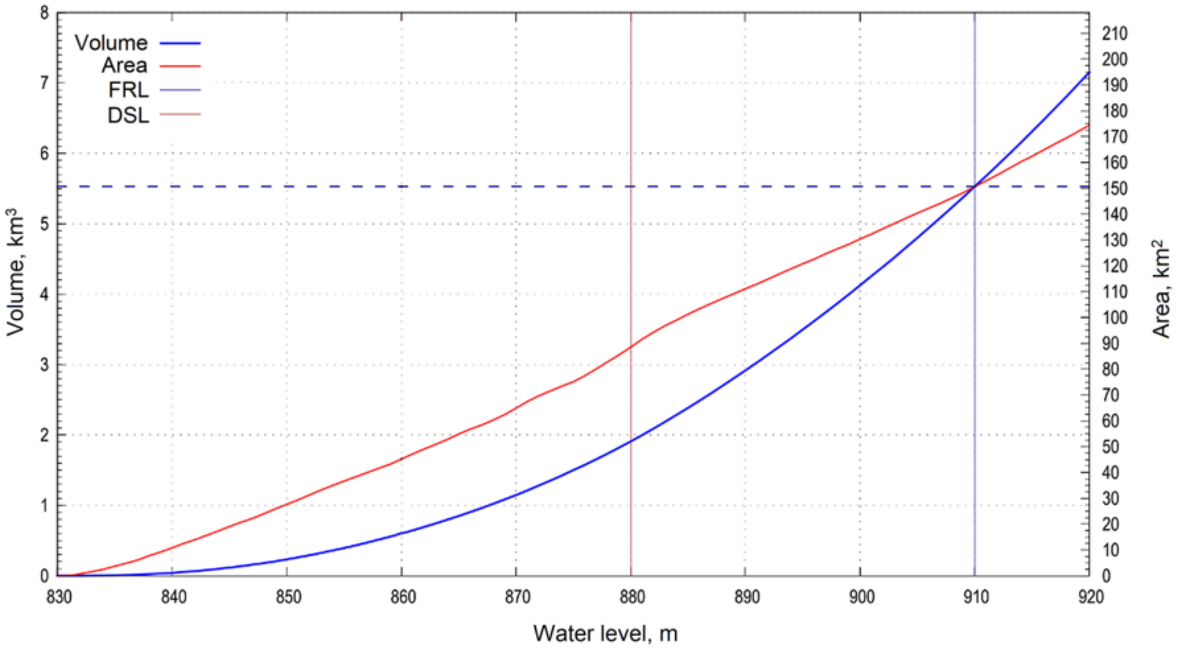

Fig. 2. The Egiin Gol HPP reservoir water level-volume-area relationships.

II. STRUCTURE OF MODELS OF HYDROPOWER PLANTS UNDER DESIGN (METHODOLOGY)

The study and analysis of the future operating conditions of the planned (potential) power plants require various pre-design engineering surveys, including modeling.

The choice of a dam site is based on three main criteria: 1) the minimum length (for economic reasons); 2) the optimal live storage of the reservoir (for various flow rates); 3) the maximum inflow of water into the reservoir (based on hydrological surveys). Geophysical, geological, water management, socio-economic, and environmental surveys are additionally required for the selected dam site and height. Modern GIS data of the digital relief (1 arcsecond or less) enable the creation of various algorithms for selecting the dam site. For example, one can select the dam with a specified interval from the center of the river, rotating it around the central point to find the minimum length at a given height of the dam on the digital relief. Figure 1 shows the reservoir configuration of the Egiin Gol hydropower plant. Figure 2 demonstrates the reservoir contour and its bathymetric curves of the water level-volume-area relationships, obtained by modeling.

The bathymetric curves, which show the reservoir water level-volume relationship, are successively determined by increasing the water level at specified intervals and identifying the configuration of the waterline through the construction of isolines. This process involves calculating the area for each water level elevation. If the specified interval is small, the volume (V) can be calculated using formula

$$V(h)=V(h-\Delta h)+\left(S(h)+S(h-\Delta h)\right)\Delta h/2\,, \quad (1)$$

where S is the area; h is the water level; Δh is the specified interval of the water level change (sampling accuracy).

Reservoir live storage refers to the volume of water between the Dead Storage Level (DSL) and the Full Reservoir Level (FRL). The volume between the FRL and the Maximum Water Level (MWL) is used exclusively to manage excess flow and protect the hydropower plant from potential destruction.

There are no reliable statistics on average monthly and ten-day flow rates for the poorly studied river basins in Mongolia. When statistical data are unavailable for the selected site, the flow rates are normally determined by precipitation over the drainage area, surface temperatures, relative humidity, wind speed, and the average gradient of individual river segments. The runoff parameters can be estimated using average meteorological values for the basin. Since meteorological data are much more representative (e.g., average monthly GPCC precipitation values with a resolution of 1°×1° for the period since 1901 and average daily NOAA temperatures since the last century [16–19]) and highly correlated with known flow rates in certain sites, the runoff of the Selenga river basin in the Mongolian part can be approximately estimated using the following procedure.

The average annual flow rate of the river Q^y for year y is estimated using formula

$$Q^y = \bar{Q} + k_1 \sum_{t\in M_1} \Delta S_t^y - k_2 \sum_{t\in M_2} \Delta S_t^y \Delta T_t^y, \qquad (2)$$

where $\bar{Q}$ is the long-term average annual flow rate; ΔS_t^y, ΔT_t^y are deviation of average monthly precipitation and temperatures from the norm for year y and month t; $M_1 = \{10,11,12,1,\ldots,9\}$ is the set of months of the hydrological year (from the 10th month of the previous year to the 9th month of the current year); $M_2 = \{6,\ldots,9\}$ is the summer and autumn months; k_1, k_2 are coefficients that take into account the proportions of precipitation and evaporation depending on the temperature deviation from the norm.

Using the known actual flow data Q_{act}^y for year y, we find the unknown coefficients k_1, k_2 by applying least squares method:

$$\sum_{y\in Y} \left(Q_{act}^y - Q^y\right)^2 \to \min_{k_1,k_2}, \qquad (3)$$

where Y is the set of years of flow data.

The estimations of the flow during the summer-autumn months should consider the flow of the previous month through the following formula:

$$Q_t^y = \bar{Q}_t + r_1 \sum_{t\in M_1} \Delta S_t^y - r_2 \sum_{t\in M_2} \Delta S_t^y \Delta T_t^y + r_3 Q_{t-1}^y, \qquad (4)$$

where $\bar{Q}_t$ is the average annual flow for month t; Q_{t-1}^y is flow of the previous month; r_1, r_2, r_3 are empirical coefficients that take into account precipitation for the year, evaporation in the summer, and flow of the previous month.

The flow during the winter months is negligible and can be estimated based on that of the previous month and the winter temperature deviation.

Evaporation plays an important role in the water balance in the Mongolian part of the Selenga river basin, which is attributed to high air temperatures, winds, and low relative humidity. According to the simplified methodology developed by the State Hydrological Institute, evaporation can be determined using following formula [20–23]:

$$I(t,\tau) = 0.14\Big(1 + 0.72V(t,\tau)\big(e_w(t,\tau) - e_a(t,\tau)\big)\Big), \qquad (5)$$

where $I(t,\tau)$ is the evaporation depth from the water surface over period $[t, t+\tau]$, mm/ km^2; τ is the calculation period in days; $V(t,\tau)$ is the average wind velocity at 2 m height above ground level over period τ, m/s; $e_w(t,\tau)$ is the average water vapor pressure of saturated air depending on the water temperature over period τ, hPa or mbar; $e_a(t,\tau)$ is the average water vapor pressure in the air over period τ, hPa.

Empirical formulas for average water and air

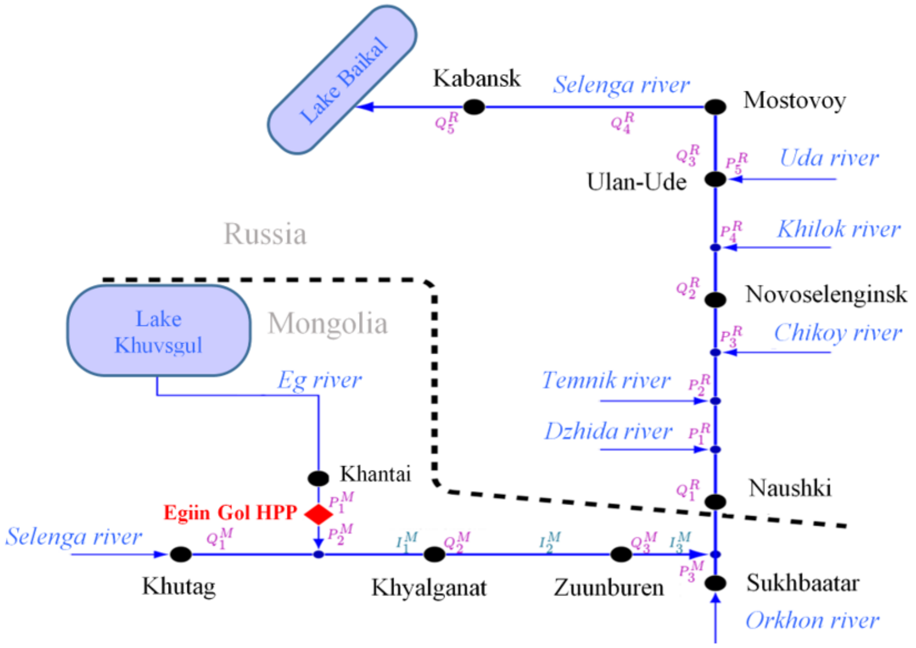

Fig. 3. Hydrologic map of the Selenga river designed to assess the potential impact of the regulated regime of the Eg river on the Russian part of the Selenga river and Lake Baikal.

temperatures over period τ, and average relative air humidity $f(t,\tau)$ are used to calculate $e_w(t,\tau)$, $e_a(t,\tau)$:

$$e_w(t,\tau) = \lambda_w \cdot 10^{\lambda_1 \frac{T_w(t,\tau)}{\lambda_2 + T_w(t,\tau)}}, \qquad (6)$$

$$e_a(t,\tau) = \lambda_a f(t,\tau) \cdot 10^{\lambda_1 \frac{T_a(t,\tau)}{\lambda_2 + T_a(t,\tau)}}, \qquad (7)$$

where λ_w, λ_a, λ_1, λ_2 are some numerical empirical coefficients; $T_w(t,\tau)$, $T_a(t,\tau)$ are temperature of water and air at time t over period τ.

Figure 3 shows a hydrologic map of the Selenga river, created to analyze the impact of the planned Egiin Gol HPP. The map reflects the main tributaries and assessment sites used to model the impact of changes in hydrological regimes after the commissioning of the HPP and during the reservoir filling period.

The map highlights the following gauging stations:

– Khutag, Khyalganat, Zuunburen, Khantai, Sukhbaatar in Mongolia;

– Naushki, Novoselenginsk, Ulan-Ude, Mostovoy, Kabansk in Russia.

Flow rates for the main bed of the Selenga River at the gauging stations are indicated by Q_i^M, Q_j^R (the M index for Mongolian ith station and the R index for Russian jth station). Flow rates for the tributaries are indicated by P_i^M, P_j^R. The indicators I_i^M, ω_i^M, ω_j^R relate to evaporation (and dispersion), as well as discrepancies for Mongolian and Russian parts.

The flow rate balance relations are given below (time indicators are omitted for clarity):

$$\begin{gathered} Q_2^M = Q_1^M + P_2^M - I_1^M \pm \omega_2^M, \\ P_2^M = P_1^M \text{ for natural conditions of the Eg river,} \\ P_2^M \neq P_1^M \text{ for regulated conditions of the Eg river,} \\ Q_3^M = Q_2^M - I_2^M \pm \omega_3^M, \\ Q_1^R = Q_3^M + P_3^M - I_3^M \pm \omega_1^R, \qquad (8) \\ Q_2^R = Q_1^R + P_1^R + P_2^R + P_3^R \pm \omega_2^R, \\ Q_3^R = Q_2^R + P_4^R + P_5^R \pm \omega_3^R, \\ Q_4^R = Q_3^R \pm \omega_4^R, \\ Q_5^R = Q_4^R \pm \omega_5^R. \end{gathered}$$

The flow rate of the Selenga River into Lake Baikal is $Q_5^R(t,\tau)$ for any time t and the aggregation (averaging) period τ. The main hydrological model sections that necessitate flow rate balance check are: 1) Khutag–Khyalganat; 2) Khyalganat–Zuunburen; 3) Zuunburen–Naushki; 4) Naushki–Novoselenginsk; 5) Novoselenginsk–Mostovoy; 6) Mostovoy–Kabansk.

The regulated flow is modeled using the following main parameters of planned HPPs and reservoirs:

$Q = q + q^{spill}$ is the flow rate passing through HPP site, m^3/s;

q is the flow rate through turbines of HPP, m^3/s;

q^{spill} is the flow rate over spillway, m^3/s;

h^{UP}, h^{DOWN} are the upstream and downstream pool elevations, m;

$H = h^{UP} - h^{DOWN}$ is the water head, m, defined as the upstream pool elevation less the downstream pool elevation (in this paper, the gross head is used neglecting head loss);

W is the HPP capacity, kW, calculated by formula

$$W(t) = 9.81\eta H(t) q(t), \qquad (9)$$

where η is the efficiency of hydropower equipment;

W^{inst} is the installed capacity, representing the maximum power output of HPP;

W^{firm} is the firm capacity, i.e. the minimum power output, provided by the HPP to meet the power system load;

E is the power output of HPP, kW·h, over period T, calculated by following formula:

$$E(t_0, T) = \int_{t_0}^{t_0+T} W(t)\,dt; \qquad (10)$$

h^{DSL}, V^{DSL} are the Dead Storage Level (DSL) and its corresponding volume, representing the portion of the reservoir capacity not used under normal operating conditions;

h^{FRL}, V^{FRL} are the Full Reservoir Level (FRL) and its corresponding volume, representing the maximum water level maintained by the hydraulic structure under normal operating conditions;

h^{MWL}, V^{MWL} are the Maximum Water Level (MWL) and its corresponding volume, used for additional flood flow transformation (moderation);

V^{live} is the live storage of the reservoir used for active flow regulation;

$V^{total} = V^{DSL} + V^{live}$ is the total storage of the reservoir, comprising dead and live storage.

The primary indicator for HPP management is the flow rate passing through the dam $Q(t)$, which affects the storage volume of the reservoir $V(t)$, as well as the levels of upstream $h^{UP}(t)$ and downstream $h^{DOWN}(t)$ pools. The HPP capacity $W(t)$ depends on the water head $H(t)$ and is determined by changes in the flow rate passing through the turbines $q(t)$.

Given the complexity of the inflow structure, this study analyzes the net inflow $P(t)$, which includes filtration, evaporation, and groundwater flow in accordance with the water balance.

A model for HPP management [14] is presented as a mathematical programming problem, incorporating averaged HPP operating parameters for various time periods (ten-day, monthly, quarterly, and annual).

We consider the HPP management problem for a given vector of net inflow. The specified time interval $t \in [t_0, T]$ is divided into N equal periods of duration τ with constant values of variables within each interval.

The change in the reservoir storage volume depends on the net inflow and the flow rate passing through the HPP. These characteristics determine the water balance equation, which has the following form:

$$\frac{dV}{dt} = P(t) - Q(t),\ t \in [t_0, T]. \tag{11}$$

Equation (11) can be represented in a finite-difference form for the j^{th} period:

$$V_j = V_{j-1} + (P_j - Q_j)\tau,\ \ j = \overline{1, N}, \tag{12}$$

where P_j and Q_j are time-averaged indicators, V_{j-1} and V_j are the characteristics at the beginning of the intervals.

The input data include:

$P = (P_1, \dots, P_N)$ – the vector of the averaged values of net inflow into the reservoir;

$h^{UP}(t_0) = h_0^{UP}$, $h^{DOWN}(t_0) = h_0^{DOWN}$ – the initial levels of upstream and downstream pools;

$h^{UP} = f^{DOWN}(V)$ – the upstream pool level-volume curve;

$h^{UP} = f^{DOWN}(Q)$ – the curve of relationship between the downstream pool level and the flow rate passing through HPP.

The variables are:

$Q = (Q_1, \dots, Q_N)$ – the vector of the averaged flow rates passing through HPP;

$V = (V_1, \dots, V_N)$ – the vector of the storage volumes;

$h^{UP} = (h_0^{UP}, \dots, h_N^{UP})$, $h^{DOWN} = (h_0^{DOWN}, \dots, h_N^{DOWN})$ – the vectors of the upstream and downstream pool levels.

Based on equation (12) and unique relationships $h^{UP} = f^{UP}(V)$, $h^{DOWN} = f^{DOWN}(Q)$ known for the reservoir, we can use the vector of averaged flow rates Q to express the vectors of V, h^{UP}, h^{DOWN} and the indicators for periods $j = \overline{1, N}$ that include:

$E_j = k^E \tau W_j$ – the electricity generation over period τ, where k^E is numerical coefficient for converting dimensions;

$W_j = 9.81\eta q_j (H_j + H_{j-1})/2$ – the average power output of HPP;

$H_j = h_j^{UP} - h_j^{DOWN}$ – the water head;

$q_j = Q_j - q_j^{spill}$ – the flow rate through the HPP turbine, where q^{spill} is the flow rate over spillway, which depends on the operational characteristics of the turbines and constraints of installed capacity of HPP.

The mathematical programming problem for HPP management is formulated as follows: for a given vector P, optimization criterion, equality constraints B, and inequality constraints G, it is necessary to find the optimal vector $X = \{Q, q, q^{spill}, h^{UP}, h^{DOWN}, V, E, W, H\}$, defined as follows:

$$F(P, X) \to \min_X, \tag{13}$$

$$B = \left\{ b_k(X) = 0 : k = \overline{1, N^B} \right\}, \tag{14}$$

$$G = \left\{ g_k(X) \ge 0 : k = \overline{1, N^G} \right\}, \tag{15}$$

where F is a given function; b_k is a set of equality constraints; g_k is a set of inequality constraints; N^B, N^G are the numbers of components in B and G.

The optimal vector X obtained from problem (13–15) is employed to determine the above-described HPP and reservoir management indicators.

Function F can take various forms depending on the reservoir filling or drawdown conditions. The primary optimization criteria include: maximum firm capacity of the HPP during the winter period; maximum HPP electricity output value (in monetary terms), reflecting the total electricity output from the HPP across periods, taking into account penalties for deviations from planned targets, as well as penalties from the flow rate over spillway in summer period.

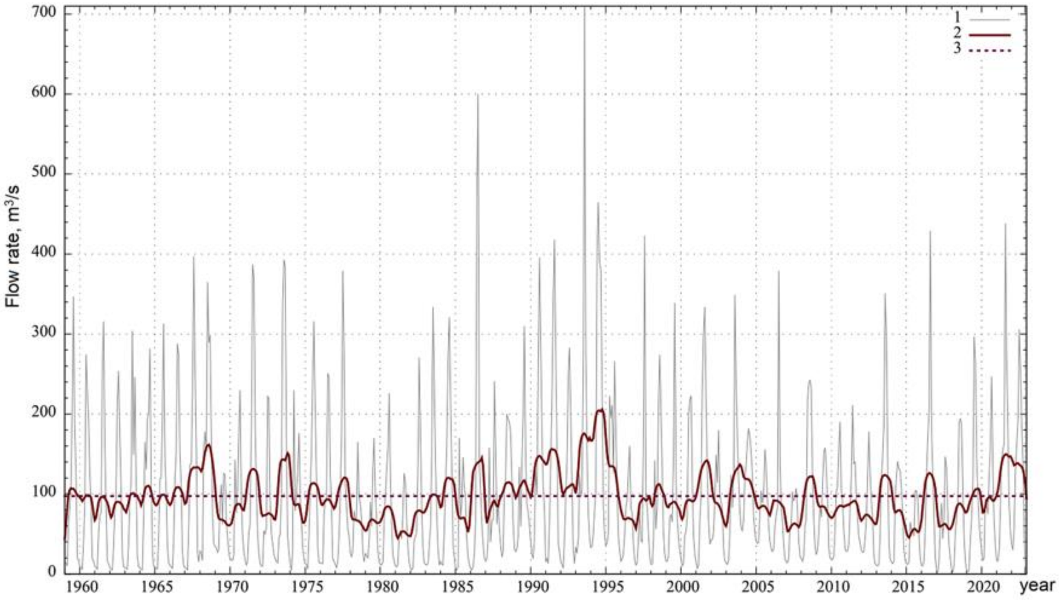

Fig. 4. Dynamics of changes in the monthly average flow rate of the Eg river (Khantai) between 1959 and 2022 (1 – average monthly flow rate, 2 – average moving annual flow rate, 3 – average annual flow rate).

The equality constraints (14) of the model include the water balance equation (12) and various empirical relationships between parameters.

The inequality constraints (15) include groups of constraints for periods $j = \overline{1, N}$, based on the following classification:

1) Technical constraints, which are defined by the characteristics of the hydroelectric facility:

$Q_j \le Q^{max}$ – flow capacity through HPP;

$q_j \le q^{max}$, $q_j^{spill} \le q^{spill\ max}$ – maximum flow rates passing through the HPP turbines and the spillway;

$h^{DSL} \le h_j^{UP} \le h^{MWL}$ – operating range of the reservoir;

$H^{min} \le H_j \le H^{max}$ – permissible change of the water head;

$W_j \le W_j^{inst}$ – installed capacity of HPP;

2) Energy constraints, which are defined by the capacity of HPP:

$W_j \ge W_j^{firm}$ – firm capacity of HPP;

$\hat{W}_j^{min} \le W_j \le \hat{W}_j^{max}$ – dispatching constraints of minimum and maximum capacity of HPP;

3) Environmental constraints, which are defined by flow rates passing through HPP and reservoir levels:

$Q_j \ge Q_j^{min}$ – environmental flow requirements;

$\left| Q_j - Q_{j-1} \right| \le \Delta Q_j$ – constraint on changes in flow through HPP.

4) Water management constraints, which encompass various additional requirements for water users and consumers (for example, water transport, water intakes).

In the process of feasibility studies on the hydropower plants in the Selenga River basin, technical parameters of these plants, including planned electricity output and capacity, alongside the parameters of their reservoirs varied constantly. For example, the Shuren hydropower plant, according to the estimates of the Lengidroproekt Institute in 1976 [3], had various options for installed capacity: 1) 300 MW with a reservoir volume of 4.8 km^3; 2) 268 MW with a volume of 4.2 km^3; 3) 240 MW with a volume of 3.3 km^3.

The river flow at the proposed locations for the HPPs shows high intra-annual variability, therefore, it is crucial to estimate the required live storage of the reservoirs that would smooth out flow irregularities and ensure the target electricity and power output. The live storage has a significant impact on the firm capacity, which requires considering the reliability of average daily power outputs based on long-term flow data, particularly during the winter period.

III. RESULTS AND DISCUSSION

Modeling the hydropower plant operation requires representative statistics of the monthly average indicators. Figure 4 shows the dynamics of the Eg river flow rate for 1959–2022.

Figure 4 demonstrates the average monthly and moving annual flow rates, as well as the average annual flow rate (97 m^3/s) for the time span from 1959 to 2022. The maximum average monthly flow rate of 709 m^3/s was recorded once in August 1993, while minimum values (below 4 m^3/s) were observed several times during various winter months. Using the 63-year average monthly statistics shown in the Figure, we can generate various rule curves based on specified criteria for the operation of the hydropower plant.

The study focuses solely on the case with a set maximum power output during peak load hours in the Mongolian energy system. We have developed a model for managing the Egiin Gol HPP, taking into account the specific characteristics of the hydropower facility and its structures. The steps for modeling the Egiin Gol HPP and its reservoir are as follows:

1. Collect and analyze hydrological data on the Selenga river basin and its lateral tributaries, building inflow scenarios for different reliability levels at the Egiin Gol HPP dam site;
2. Model the Egiin Gol HPP reservoir and its characteristics;
3. Establish the relationship between changes in the downstream pool level and the flow rate of the Egiin Gol HPP to determine the water head;
4. Assess the reservoir filling time of the Egiin Gol HPP under various parameters of environmental flow requirements and inflow availability;
5. Set the scenario parameters (operational rules) for regulating the Egiin Gol HPP;
6. Model daily (hourly) operating conditions of the Egiin Gol HPP depending on regulation scenarios;
7. Model long-term operating conditions of the Egiin Gol HPP depending on water conditions and constraints;
8. Determine indicators for possible changes in the natural flow of the Selenga river at both the border of the Russian Federation and the gauging stations across the country.

The system of models developed at the ESI SB RAS allows for modeling the Egiin Gol HPP reservoir, while defining its characteristics. It also models various operating conditions of the Egiin Gol HPP, examining limitations and establishing rules for managing the hydropower plant flow rates.

Modeling the hydropower plant relies on three power output scenarios built using an hourly time step: *Scenario 1* for average water conditions, *Scenario 2* for high water conditions, and *Scenario 3* for low water conditions.

Scenario 1 describes the primary increase in power output (158–315 MW) from November to February during

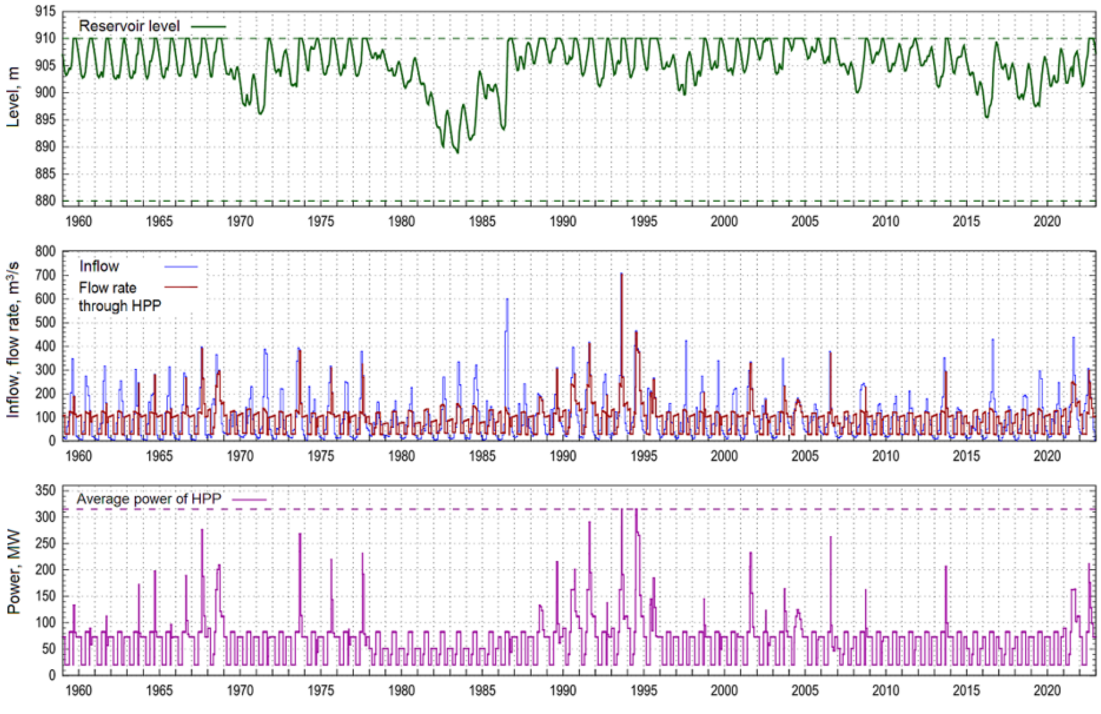

Fig. 5. Operating conditions of the Egiin Gol HPP in 1959–2022.

peak load hours (5 pm to 9 pm), with the HPP operating at its installed capacity of 315 MW from 6 pm to 8 pm. During the summer months (June to August), the output reaches 100 MW during the daytime (7 am to midnight).

Scenario 2 suggests the increase in power output both from November to February and from July to October, with the highest level occurring between 6 pm and 9 pm. From November to December, the output rises to 158, 206, and 315 MW from 3 pm to midnight, while during January and February, it reaches 158–315 MW from 4 pm to 10 pm. From July through September, after the reservoir is filled, the HPP operates around the clock with an output ranging from 109 to 315 MW.

Scenario 3 is similar to Scenario 1, yet it features a narrower power output range of 138 to 275 MW during the winter months.

Modeling of the Egiin Gol HPP during its normal operating conditions rested on the above-described power output scenarios (the main one for an average-water year, and those for high-water and low-water periods). The developed simulation model calculates the required hourly turbine flow rate based on the needed HPP power output, considering changes in upstream and downstream pool levels, and the operating head. Next, all operational parameters are calculated for the current hour before transitioning to the next interval. The hourly results are then averaged to establish daily operating conditions and identify peak indicators.

Due to the high intra-daily variability of power output and water flow rates, the Egiin Gol HPP project includes a buffer dam and a reregulation reservoir, which would smooth out the fluctuations in the intra-daily flow into the downstream pool.

Figure 5 shows the results of modeling the Egiin Gol HPP based on a continuous inflow series for the timespan from 1959 to 2022. Under normal water conditions, the reservoir level ranges between 900 and 910 m. In summer, the average HPP output is 82.5 MW, with flow rates of 115–130 m^3/s, while in winter, it averages 73 MW, with flow rates of 100–110 m^3/s (Scenario 1). Two periods are observed in the low-water years. These are 1978–1983, when the reservoir level drops to 889 m, and 2014–2017, when it decreases to 895 m. During these periods, the average winter HPP power output is reduced to 51 MW, at flow rates of 70–90 m^3/s (Scenario 3). In high-water years (1968, 1990, 1991, 1993, 1994, 2021), the summer power output reaches 82.5–163 MW, at flow rates of 115–230 m^3/s. The winter power output ranges from 89 to 112 MW, with flow rates of 130–170 m^3/s (Scenario 2). After the reservoir is filled to the Full Reservoir Level (FRL) in high-water years, the average daily HPP output can rise up to the installed capacity of 315 MW, with a maximum turbine flow rate of 445 m^3/s.

To assess the impact of reservoir filling on downstream pool flows, three flow scenarios (average, low, and high) and three environmental (minimum) flow scenarios were

TABLE 1. Changes in Average Monthly Flow Rate at Naushki Gauge Station According to the Egiin Gol HPP Reservoir Filling Scenario During Average Water Years (1999–2002)

Year	Month	Natural flow rate, m^3/s	Deviation (regulated), m^3/s			Exceedance probability (regulated), %			Exceedance probability (natural), %
			Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	
1999	8	609	–299	–244	–239	96.1	91.6	91.1	59.6
2000	7	279	–160	–155	–130	98.9	98.7	97.7	88.1
2000	8	276	–178	–123	–118	99.9	99.9	99.9	97.9
2000	9	329	–183	–143	–133	99.1	97.4	96.9	83.4
2000	10	220	–73	–68	–53	99.2	99.0	98.1	92.2
2001	7	443	–258	–253	–228	95.9	95.7	93.9	68.2
2001	8	442	–294	–239	–234	99.9	99.8	99.7	82.6
2001	9	339	–183	–143	–133	98.7	96.9	96.2	82.1
2001	10	263	0	–85	–70	83.2	97.4	96.0	83.2
2002	5	313	0	0	–99	0	0	97.5	80.3
2002	7	272	0	0	–110	0	0	97.2	88.8
2002	8	217	0	0	0	0	0	99.7	99.7
2002	9	210	0	0	0	0	0	96.0	96.0
2002	10	202	0	0	0	0	0	95.0	95.0

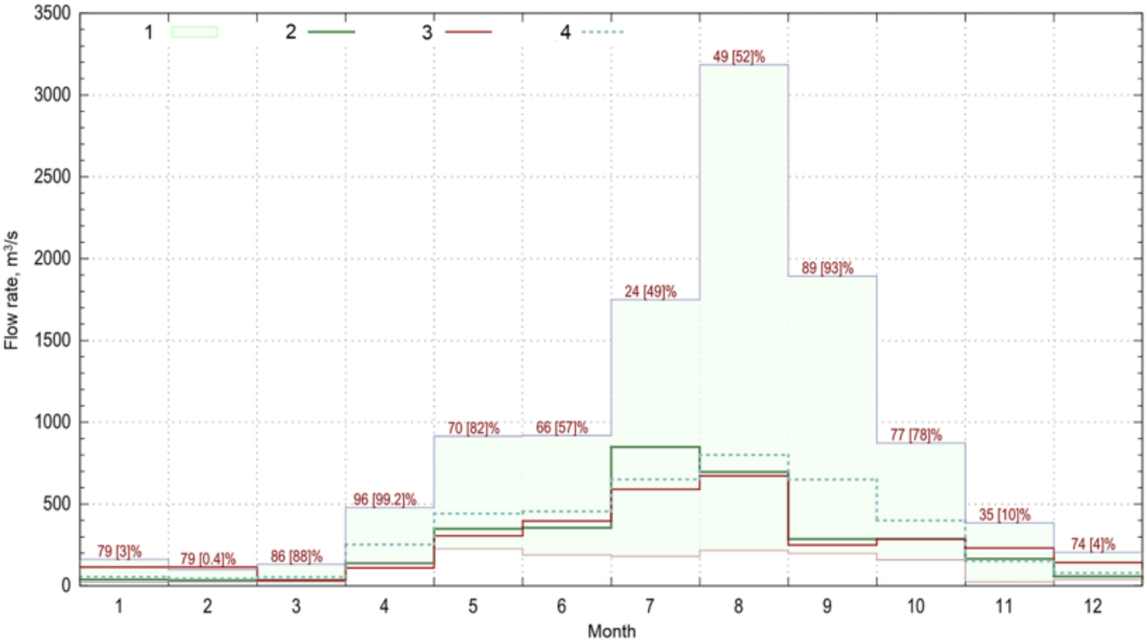

Fig. 6. Flow rate variation chart for the Selenga river (Naushki gauging station) for 2006, showing the 50% annual inflow exceedance probability for the HPP reservoir (1 – boundaries of natural flow, 2 – actual flow for 2006, 3 – regulated HPP flow, 4 – average natural flow).

used: 1) a baseline scenario with a constant design flow rate of 40 m^3/s (except for months when inflows are below 40 m^3/s); 2) a flow rate with at least 99% exceedance probability for each month; 3) a flow rate with at least 95% exceedance probability for each month.

The period between 1999 and 2002 was selected to represent an average flow year. For this period, the operating conditions were modeled using three reservoir filling scenarios, identifying months with critical exceedance probabilities (above 95%, Table 1). As seen in the Table, the third filling scenario is the closest to the natural conditions, having minimal impact on the change in the hydrological regime at the Naushki gauging station. Under natural conditions, the exceedance probability of average monthly flow rates exceeded 95% only four times during the observation period: in May 1998, August 2000,

TABLE 2. Changes in the Average Monthly Flow Rates of the Selenga River (Naushki) with the 50% Exceedance Probability of Annual Inflow into Hydropower Plant Reservoir in 2006

Month	Flow rate, м^3/s		Deviation		Exceedance probability, %	
	Natural	Regulated	m^3/s	%	Natural	Regulated
1	39	114	75	192.3	78.7	2.6
2	33	114	81	245.5	78.6	0.4
3	35	34	–1	–2.9	86.2	88.3
4	138	110	–28	–20.3	96.3	99.2
5	348	305	–43	–12.4	70.4	82.2
6	355	396	41	11.5	66.1	56.8
7	849	590	–259	–30.5	24.3	49.5
8	696	672	–24	–3.4	48.8	51.6
9	286	250	–36	–12.6	88.8	92.5
10	287	285	–2	–0.7	77.2	77.8
11	165	231	66	40	34.7	9.5
12	58	143	85	146.6	73.8	4.0

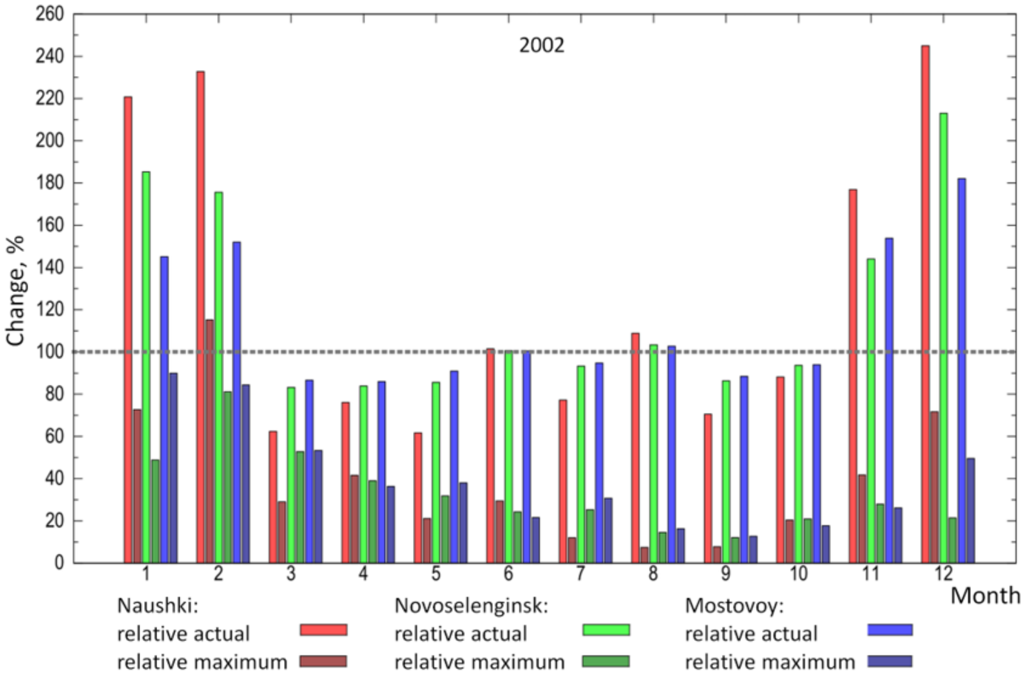

Fig. 7. Changes in hydrological regimes for three Russian gauging stations for 2002 (in % of actual and maximum average monthly values).

August 2002, and September 2002. For all considered scenarios, the exceedance occurs in 8 or more months.

The exceedances partially persist for the Novoselenginsk and Mostovoy gauging stations. The flow rate at the Mostovoy station determines the inflow into Lake Baikal, which could potentially conflict with its environmental requirements.

The primary role of the Egiin Gol HPP in the power system is to cover intraday load variations. Varying hydrological conditions must be factored in by modeling for various Eg River flow rate exceedance probabilities, ranging from 99% to 1%.

Figure 6 illustrates flow rate deviations in the regulated regime compared to natural conditions at the Naushki gauging station under average water conditions. The Figure highlights the range of natural flow rate variations based on accumulated statistics, along with actual and regulated average monthly indicators.

The chart shows that the winter months are critical, particularly February, when the average monthly exceedance probability drops from 79% to 0.4% (the flow rate exceeds the maximum recorded historical indicator for February). Table 2 presents the changes in flow rates, the difference in absolute and relative indicators, and the exceedance probability for both natural and regulated conditions.

The exceedance probability surpasses 95% in April, when the flow rate declines from 96.3% to 99.2%. The violations of exceedance probability below 5% are observed during the winter months: January (a decrease from 78.7% to 2.6%), February (a drop from 78.6% to 0.4%), and December (a decline from 73.8% to 4%). These winter months show an increase in flow rates by 192.3%, 245.5%, and 146%, respectively. Overall, the exceedance probability violations occur at the Naushki gauging station during the winter months, characterized by a significant increase in flow rates, and in certain summer months.

Figure 7 shows the regulated flow deviations from natural conditions across all months for the low-water year 2002.

Winter flow rates vary significantly for all gauging stations, which underscores the necessity of special environmental research. The charts are generated automatically after modeling the regimes with the specified parameters. Particular attention should be paid to flow rates that exceed the recorded maximum average monthly indicators. For example, at the Naushki gauging station, the flow rate increases by 120% in a low-water year and by 180% in an average year relative to the maximum indicator recorded in February based on statistics accumulated for the timespan from 1955 to 2023.

IV. CONCLUSION

The system of models designed to assess the impact of HPPs planned in Mongolia on hydrological regimes makes it possible to conduct comprehensive studies on the selection of optimal dam sites and construct bathymetric curves of reservoirs for identifying the hydropower and water management scenarios that enable the assessment of the impact of regulated operations on the downstream hydrological regime. The models built were employed to preliminarily assess the impact of the planned Egiin Gol HPP on the hydrological regime of the Russian part of the Selenga river. The findings indicate significant potential changes in flow rates during the winter months. These changes create potential threats to the health of the ecosystems of both the Selenga river and Lake Baikal. Furthermore, during low and average water years, risks of reduced flow rates arise, which may also negatively affect the river and lake ecosystems.

The developed models and software are fully adaptable to the new operational management requirements of the planned Egiin Gol HPP and can also facilitate the exploration of other hydropower projects.

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