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Modeling the Impact of Planned Hydroelectric Power Plants on Ecosystems

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Abstract:

Estimates of the impact of hydroelectric power plants (HPP’s) on an ecosystem that are exemplified by the HPP's construction planned in transboundary Selenga river basin in Mongolia. Implementation of the HPP’s projects can lead to essential changes in natural hydrological regime of the Selenga river basin in the Russian Federation, which will influence the regional ecosystems and economy. The international status of natural objects in Russia, which can be affected by these projects, is an important factor. First of all, this concerns Lake Baikal, the World natural heritage site. The paper contains the main results of this problem research. Based on an analysis of hydrological characteristics of Mongolian and Russian parts of the Selenga river basin, and plans for the development of water supply systems and hydro power in Mongolia, the regulated flow of the Selenga river was modeled for different possible operating conditions of HPP’s and hydraulic structures (the projects of the Shuren HPP, the Egiin Gol HPP, and the Orkhon-Gobi water diversion system). Possible risks of the impact of potential Mongolian HPP’s are revealed, first of all, the risks for the ecosystems of Russian part of the Selenga river. The impact is estimated for separate and joined projects (cumulative impact). The risks of the impact of the HPP construction and operation mean the probability that the values of hydrological, hydro-morphological, morphometric, physicochemical and other abiotic and biotic characteristics of ecosystems will go beyond the limits of natural variability.

Keywords: Hydroelectric Power Plants; Hydrological Characteristics; Environmental Flow; Abiotic and Biotic Characteristics; Ecosystems.

DOI:

1. INTRODUCTION

According to the programs of the Mongolian government [1–3], the construction of large hydropower plants is considered to be the main direction of energy development in the country. Currently, 3 main projects are the Shuren HPP, the Egiin-Gol HPP, and the Orkhon-Gobi water diversion system (Fig. 1). Two projects (the Shuren and the Orkhon-Gobi) are implemented jointly with the World Bank in the framework of the MINIS (Mining Infrastructure Investment Support) project.

The main parameters of these projects (based on the

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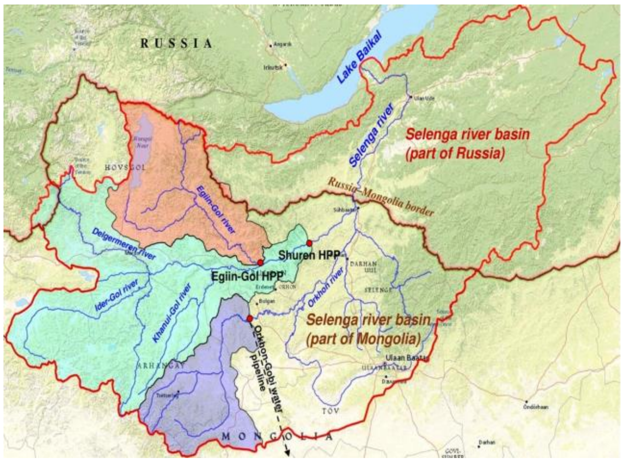

Figure 1. Location of the projected Mongolia's HPP's on the Selenga river and its basins.

data of a pre-feasibility study and project technical specifications) are:

1) The Shuren HPP with an installed capacity of 245 MW, an annual electricity output of 870 million kWh, and the reservoir storage capacity of 3.8 km^3;

2) The Egiin-Gol HPP with an installed capacity of 315 MW, an annual electricity output of 606 million kWh, and the reservoir storage capacity of 5.5 km^3;

3) The project of Orkhon-Gobi water diversion system, including an HPP with a capacity of 30 MW and a reservoir storage capacity of 0.73 km^3.

The assessment of possible impact of these projects on the transboundary Selenga river basin in the borders of the Russian Federation is the subject of the present study hydrological, and environmental) that are implemented as autonomous software components and perform a set of functions (receive inputs and parameters and transmit the results to other components).

2. EXPERIMENTAL PROCEDURE

The main goal of the study is to identify the characteristics of environmental flow, taking into account the response of ecosystems to flow alteration under regulation. In the framework of the "flow – environment" approach, a special system of models was developed to assess the impact of regulated flow on the ecosystem of Russian part of the transboundary Selenga river basin. The system includes various models (of HPP operation management, water consumption and water use.

2.1. Hydrological Characteristics of the Selenga River Basin

The Selenga river is the biggest tributary of Lake Baikal, formed by the confluence of the Ider-Gol and Delgermeren rivers. The length of the river in Mongolia is 615 km, in Russia – 409 km. There are several tributaries

of the Selenga river on the territory of Mongolia and Russia. The largest of them are the Orkhon and Egiin-Gol in Mongolia, the Dzhida, Chikoi, Khilok, Temnik and Uda - in Russia (Fig. 1, 2).

The area of the transboundary Selenga river basin is 447060 km^2. It is 80% of the total water catchment area of Lake Baikal. Of the total area of the Selenga river basin, 148060 km^2 (33%) falls on the territory of the Russian Federation and 299000 km^2 (67%) - on the territory of Mongolia [4]. The value of the average annual flow in 1934-2017 in the cross-section of the Selenga river – crossing loop of the Mostovoy station is 878 m^3/s, which corresponds to 47% of the total average annual flow to Lake Baikal (1870 m^3/s over the period of 1899-2017).

The main hydrological feature of Mongolia's rivers is highly uneven intra-annual distribution of river flow. This is facilitated by a small amount of precipitation almost throughout the whole country and large quantities of evaporation caused by high temperature in summer. The observation data show that 92-95% of the Selenga flow in Mongolia is from April to October and only 5-8% is in winter period (November-March). The reason of the main precipitation falls in spring-summer-autumn period. In winter, the rivers are covered with ice, and a small flow is mainly provided by underground waters. Based on these observations, an average long-term flow of the Selenga river in the supposed cross-section of the Shuren HPP is 7.6 km^3 per year. The total flow on the border of Russia and Mongolia (the Naushki station), including the flow of the Orkhon river (4.4 km^3), is 12 km^3. This volume is about 40% of the total flow of the Selenga river, and about 20% of the total average long-term flow volume into Lake Baikal (about 59 km^3 per year, on average, over the period of 1899-2017).

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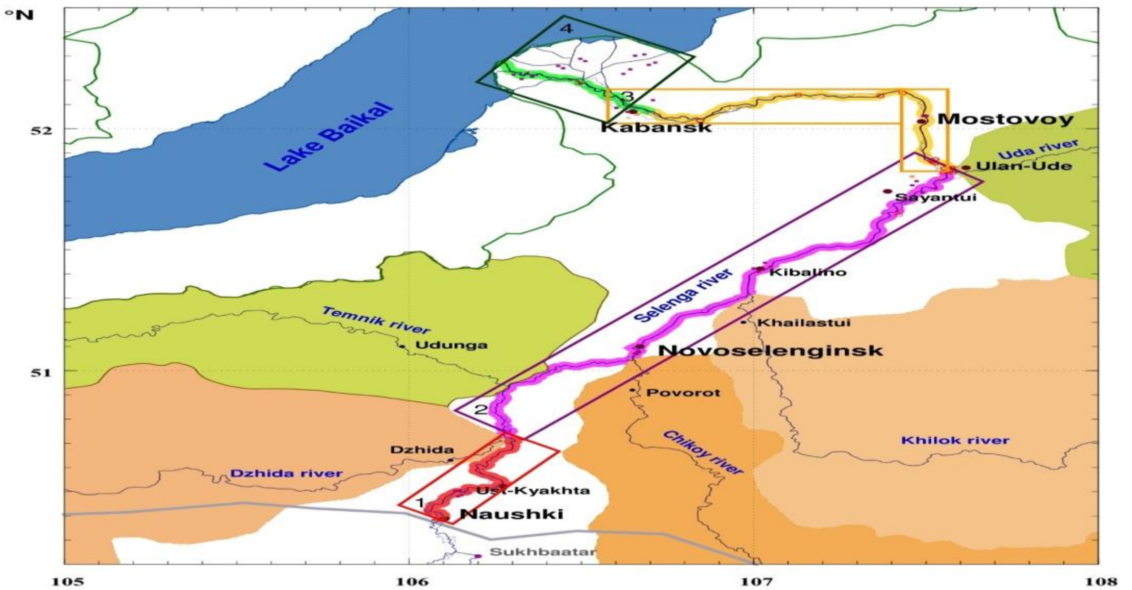

Figure 2. Modeling territories and cross sections of the Selenga river.

2.2. The risks of the HPP Construction Impact in Mongolia

Long-term studies on the impact of HPP, conducted in various countries, are most fully presented in the report of the world Commission on dams [5]. These studies show that the main target of HPP's is ecosystems [6, 7]. The risks of the impact of the HPP's construction and operation mean the probability that the values of hydrological, hydro-morphological, morphometric, physicochemical and other abiotic and biotic characteristics of ecosystems will go beyond the limits of natural variability. The main consequences of the HPP construction include:

1. Change in the annual hydrological regime due to the river flow regulation by HPP.

2. Transformation of thermal conditions (temperature changes, oxygen content).

3. Change in the sediment runoff, the sediment detention by reservoirs.

4. Change in the course and direction of river bed evolution.

5. Transformation of the river bed, hydro-biological and hydro-chemical properties of water bodies.

6. Reduction in the area and period of inundation of floodplains (loss of hydraulic connectivity between the watercourse and the floodplain).

7. Fragmentation of a single water basin as a result of dam construction on the river bed, the suppression of migration routes of biological species.

8. Change in the species composition, loss of and reduction in the number of individual populations of aquatic organisms and their biomass.

9. Change in the soil cover, flora and fauna of coastal ecosystems.

The above-mentioned consequences have an integrated effect on the river ecosystems and vary within one river basin in time and space. The HPP impacts can be divided into 3 groups [4]. The impacts of the first order include abiotic characteristics: hydrological, hydro-morphological, morphometric, physical, chemical. The impacts of the first order, in turn, cause the impacts of the second order: changes in primary biological productivity of ecosystems (biotic characteristics). The impacts of the third order are further changes in ecosystems as a response to the impacts of the second order: change in flora, fauna, fish, etc.

Studies performed at various facilities in different countries indicate that the changes in the intra-annual hydrological regime of the river are the primary factor that affects ecosystems and inevitably leads to alterations in ecosystems. The risk of negative impact on the ecosystem increases with the amplitude of hydrological changes (deviations) relative to natural conditions.

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2.3. A System of Models to Assess the Possible Impact

The main goal of the study is to identify the characteristics of environmental flow, taking into account the response of ecosystems to flow alteration due to regulation. In the framework of the "flow – environment" approach a special system of models was developed to estimate the impact of regulated flow on the ecosystem of Russian part of the Selenga river basin.

The modeling and study of the territorial impact factor involved 4 sections (3 sections in the main riverbed and 1 in the delta) and 10 cross sections (6 cross sections in the main riverbed of the Selenga river and 4 in the delta) (Fig. 2).

The system includes various models that are implemented as autonomous software components and perform a set of functions (receive input data and parameters and transfer the results to other components) (Fig. 3).

The main blocks of the system are:

– An energy block representing a set of models designed to control operating conditions of HPP (optimization, simulation) for various scenarios of their use.
– A hydrological block including a set of models for the formation of deviations of abiotic indicators depending on changes in the HPP flow rate.
– A water management block taking into account the limits for water withdrawal and amounts of permissible consumptive use; water consumption and water use for the studied areas at different time periods.
– An environmental block including models intended for an analysis of biotic indicators of water and riverside ecosystems.
– A block for simulation of the effects and reactions of the ecosystems and formation of environmental constraints.
– A block for formation of an environmental flow at a given cross section and reservoir releases for possible HPP's, given the requirements of the environmental flow.

All blocks rely on the information database of the basic hydrological, water management, environmental and energy characteristics of various temporal (day, decade, month) and spatial (cross sections in four studied areas) resolutions and supportive data (meteorological characteristics in a studied basin; GIS-data on the riverbed in different time frames, given its changes, space images of various scales, etc.).

Block of HPP operation management allows estimating possible operating conditions of Mongolia's HPP's in the basin of the Selenga river, filling and drawdown of their reservoirs, including numerous energy, environmental and water management constraints. The regimes of HPP's are determined via a 2-step optimization: filling of reservoirs in the summer-autumn period, and their drawdown in winter.

Hydrological model includes a set of interrelated components for an analysis of abiotic characteristics.

– Hydrological (flow, level, speed).
– Morphometric (width, depth, slope) to study the characteristics of the riverbed at all cross sections, starting from the HPP site in Mongolia and ending with the Selenga river delta in Russia.
– Hydro-morphological (channel, characteristics of the bottom, the level and type of the bottomland, bottom sediments); the type of riverbed is essential to determine an average speed in a given cross section, determined by hydraulic formulas (Chezy, Manning, etc.).
– Physical (water temperature, turbidity, suspended sediment discharge);
– Chemical (concentration of different substances and compounds).

The block of environmental model considers microbiota, phytoplankton, zooplankton, zoo benthos and fish as indicators (indices) of biotic characteristics. The riverside characteristics included additionally are soils, vegetation, amphibians, birds and mammals.

To determine possible changes in the flow of the Selenga river on the border of the Russian Federation, the models of control of the considered HPP operation were developed. The calculations were performed using simulation models [8] that enable the simulation of HPP operation and allow for water balance, data on water inflow, characteristics of the reservoirs, installed capacity of turbines and other parameters of hydro systems. Different optimization models were used to take account of various criteria of HPP operation control and a system of constraints (environmental, energy, etc.).

Modeling of the regulated flow of the Selenga river was based on the classic "energy" option of HPP operation with a reservoir in the power system: the maximum filling of the reservoir during summer and drawdown of the reservoir during winter (from November to March). The regimes of seasonal regulation were determined for the

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reservoirs of the Shuren HPP and Orkhon-Gobi water diversion system, and long-term and seasonal regulation regimes were calculated for the Egiin-Gol HPP.

During the reservoir filling in summer, the minimum flow rate through the HPP was limited to sanitary water discharges in each month, determined by the 95% availability of natural flow at the cross section; for the extremely low water content, the flow rate was limited to the flow availability of 99%.

Requirements of the power system were considered in the form of constraints.

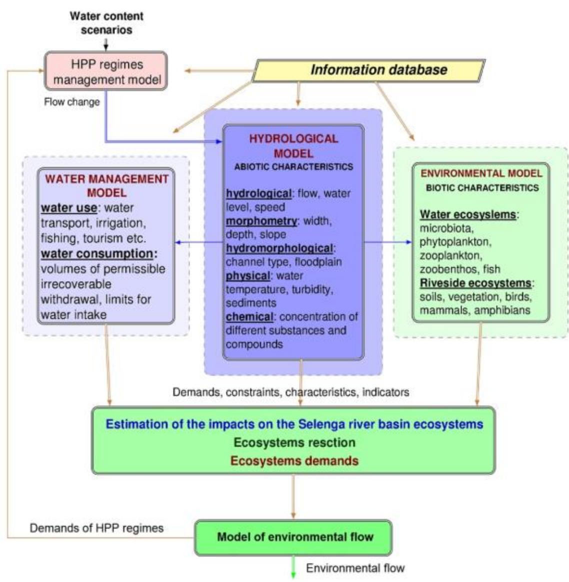

Figure 3. The system of models" flow-environment" of the Selenga river.

3. RESULTS

To regulate the Selenga river flow, 4 separate scenarios for modeling were considered: 1) the Shuren HPP, 2) the Egiin-Gol HPP, 3) the HPP of Orkhon-Gobi water diversion system, and 4) flow regulation by all considered HPP's (a cumulative impact).

An estimate of changes in the regulated flow of the Selenga river was made at 3 key stations of the Russian Federation: Naushki, Novoselenginsk, Mostovoy.

Each of the 4 scenarios of HPP operation included 2 stages of modeling.

In the 1st stage, possible HPP operating conditions were simulated on a natural continuous hydrological series (1959-2017). In the model, the final reservoir levels of the current year became the initial conditions for the next year. Based on the calculations, the parameters of winter hydroelectric power generation were obtained for each HPP.

In the 2nd stage, the HPP operating conditions were simulated within one hydrological year with the inflow of given availability. For each scenario, the HPP operating conditions were calculated based on the set availability of the natural flow at the Naushki station: 0.01; 0.1; 1; 5; 50; 95; 99; 99.9 and 99.99%.

In addition, an "environmental option" of HPP operation was discussed. In this option, the flow rates of each HPP were determined by the constraints on the Selenga river environmental flow (upper and lower levels) on the border of Russia and Mongolia.

3.1. Changes in the Selenga River Discharge Relative to Natural Conditions

The Shuren HPP. For the conditions of normal water availability (Fig. 4a), the greatest (2-3 –fold) deviations of regulated discharges compared to natural ones are observed in summer on the border of Russia (the Naushki cross section). In the lower reaches of the Selenga river (Mostovoy station), these deviations do not exceed 15-20% relative to natural conditions. There is a significant (3–5-fold) increase in the discharge in winter beyond the maximum values observed under natural conditions, and under all water availability conditions. The greatest deviations from natural flow in summer occur under the conditions of extremely low water content, in particular at a flow availability of 99% and above, i.e. the lower boundary of the natural flow fluctuation range is violated (Fig. 5a).

The Egiin-Gol HPP. When regulating the operation of Egiin-Gol HPP (Figs. 4b; 5b), as well as the Shuren HPP, the largest deviations from natural flow are observed in winter under high water conditions for all considered cross sections. In this case, large deviations are common only for the upper part of the Selenga (Naushki). In general, the impact of the Egiin-Gol HPP on the territory of the Russian Federation is lower in magnitude of deviation of regulated regimes from the natural one with respect to the Shuren HPP, both in summer and in winter. This is due to the differences in these HPP's. The Egiin-Gol HPP is situated at a greater distance from the border. It has a greater effective storage capacity at a lower and more stable average annual flow.

The Orkhon-Gobi water diversion system project. With flow regulation in the Orkhon-Gobi water diversion

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system project (Fig. 4c; 5c), the deviation from the natural regime is very insignificant in the whole range of flow availability, both for winter and for summer, with the exception of theoretical extremely low-water periods (with the flow availability of 99% and more). The high-water periods have virtually no impact on the natural flow.

Cumulative impact. In the event that all these projects are implemented in the future and the operating conditions of the considered HPP's are jointly regulated, the range of deviations will be comparable with the operating parameters of the Shuren HPP, which in this case becomes the regulator of the cascade.

Territorial impact. The area to be affected most by the construction of the HPP's is the upper border territory of Naushki-Dzhida. With the approach to the Selenga river mouth, the impact of HPP's will decline. Territorial impact was estimated as a ratio of the regulated flow to the natural one for the period from April to September (Table 1). In the lower reaches of the river (the Mostovoy and Kabansk stations) the deviations from the natural regimes will be observed mainly in winter. Hydrological regimes in the Selenga river delta will be determined primarily by the regulation of the Baikal level. With the flow availability of less than 50% (normal and high water content), the effect of regulated flow is gradually reduced.

Periods of reservoirs filling. One of the most critical periods is the period of reservoir filling. While under normal conditions, quite a few months is enough for the reservoir to be filled, under low-water conditions this may take several years. For example, the Egiin-Gol HPP reservoir, that has a large capacity at a relatively low average annual flow, may require 5-6 years to be filled in the low-water period when the minimum releases to downstream are maintained during the entire period.

Other abiotic parameters may encounter the following changes:

Levels and speed. In summer, the levels and average speed vary according to the altered values of flow rates and speed-flow rate correlation curves. The speeds in winter will increase by 0.2–0.5 m/s, and the levels will rise by 0.5–1 m compared to the natural flow.

Temperature. A decrease in the temperatures in spring and summer will be 1-3 °C, but an increase in autumn will be in a range of 0.5–2 °C with the ice formed by 1-2 weeks later.

Turbidity and sediment load. Turbidity decreases, except for the cases of high water discharge of the Orkhon river at its inflow into the Selenga river. The construction of dams reduces the flow rate of the suspended sediment load, except for the cases of considerable fluctuations in daily flow rates when suspended particles can drift from downstream [9].

Riverbed characteristics. The duration and magnitudes of flood decrease and shift to autumn. The duration of high water stand reduces in the high-water period. During low-water periods, the dry spell lasts longer. Under normal (average) water content, there are no significant changes. With daily control of HPP operation, there can be considerable fluctuations in the flow rates at the HPP sites. This will inevitably lead to changes in the riverbed in Mongolian part of the Selenga river basin, which can eventually affect its basin in the territory of Russia.

The change in biotic characteristics. The change in the abiotic indicators, in turn, acts as a stressor for the biotic indicators (aquatic and riverine ecosystems). The decrease in the summer flow rate will reduce the quantitative characteristics of individual species of aquatic organisms (phytoplankton), productivity of communities with an increase in the species diversity, and an increase in proportion of limnophilic thermophilic species (zooplankton).

Of all the abiotic factors (discharges, temperature, ice phenomena, light), the elevated water flow in winter will be the most critical for fish, especially for Baikal omul. This will lead to an increase in stream velocities, separation of spawn from the substrate and its movement downstream, unfavorable conditions for the fish and, finally, reduce the survival rate and increase the probability of death. Flow change in the late winter period is most important in the upper reaches of the Selenga. The reduced water flow rates at this period (due to the end of drawdown of reservoirs), along with the chilled water discharge in winter, will change the conditions for hatching of fish larvae. The increase in water discharge in winter can reduce the quantitative development of phytoplankton organisms in the channels of the Selenga delta, erosion and drifting of zoo benthos organisms [10].

The most significant factor for vegetation is the decreased flow during summer period. There will be a reduction in the water flow and a related decrease in soil moisture. There will be a change in the duration of excessive moisture periods. Groundwater level in the floodplain and delta will decrease. This will lead to the spatial restructuring of the vegetation in the Selenga riverbank ecosystems. The reduction in the duration of flooding will result in a significant reduction in the area of

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floodplain plant communities, and development of desertification processes.

The conditions for reproduction of the organisms living in the riverine ecosystems (amphibians, birds and mammals) will worsen.

3.2. Environmental Flow

The environmental flow determines the required total flow of Mongolian part of the Selenga river basin on the border of the Russian Federation (the village of Naushki), which does not disturb the steady state of ecosystems. This flow is determined by the above-discussed environmental requirements.

The ranges of average monthly flow fluctuation under natural conditions that vary from 75-80% to 10% of flow availability are assumed to be the basis for the constraints on the regulated flow. The regulated flow should meet these constraints with the probability of 70-80%. In the other cases, the flow rates must not go beyond the range of natural variability.

As a result, the minimum and maximum permissible values of environmental flow by month were determined (Table 2). The main characteristics of the environmental flow for the Selenga river are the minimum permissible values in summer (April-October) and maximum permissible values in winter (November-March). Violations of these constraints have the greatest negative impact on ecosystems.

Apart from the range of variability in the average monthly flow, it is necessary to consider many daily, seasonal and long-term constraints in terms of amplitude and frequency of fluctuations, such as:

– discharges with the 10-20% availability in April (or early May for cold spring) during 3-5 days to move the larval fish downstream;

– discharges with the availability of up to 10% in June-August during high-water period, necessary to flood the floodplains;

– gradual reduction in the flow rates in September-October to provide spawning of valuable fish species in the upper reaches of the Selenga river;

– a special regime in November to avoid ice block and jam phenomena;

– limitation of daily flow rate fluctuations in spring and autumn periods (the amplitude of fluctuations should be no more than 10 m^3/s per day).

Thus, the characteristics of environmental flow are only the basis for the development of more detailed rules for flow regulation of the considered HPP's in the case of their implementation.

Table 1. Territorial impact of HPP (%).

Hydrological station	Deviation of regulated flow from natural one for different values of flow availability					
	50%	95%	99%	50%	95%	99%
	Shuren HPP			Egiin-Gol HPP		
Naushki	38.9	12.2	4.5	19.4	8.2	2.0
Novoselenginsk	16.5	5.9	1.8	8.2	1.7	0.8
Mostovoy	11.8	4.4	1.4	5.9	1.3	0.6

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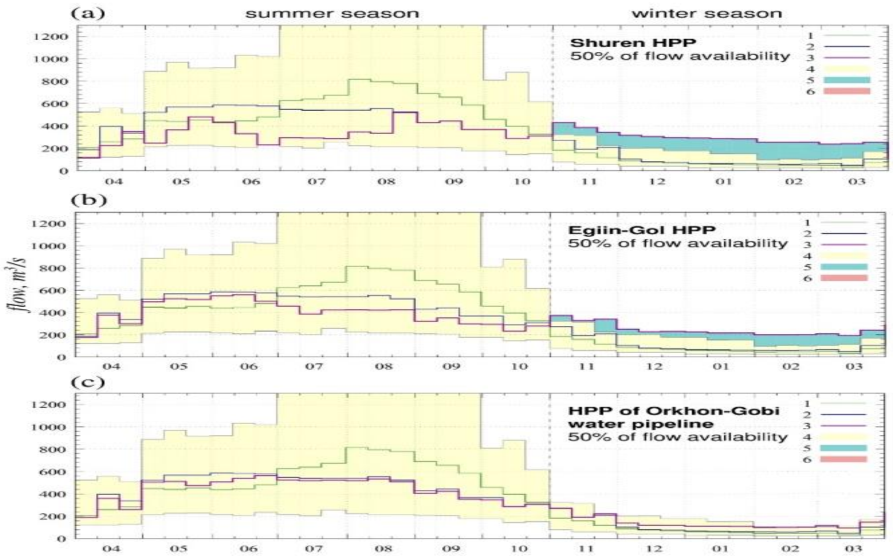

Figure 4. Change in the Selenga river flow under regulation of Shuren HPP **(a)** Egiin-Gol HPP **(b)** HPP of Orkhon-Gobi water diversion system **(c)** at Naushki station for 50% of flow availability
(1 – norm; 2 – environmental flow; 3 – regulated flow; 4 – range of natural flow changes; 5 – upper level overrange of environmental flow; 6 – lower level overrange of environmental flow).

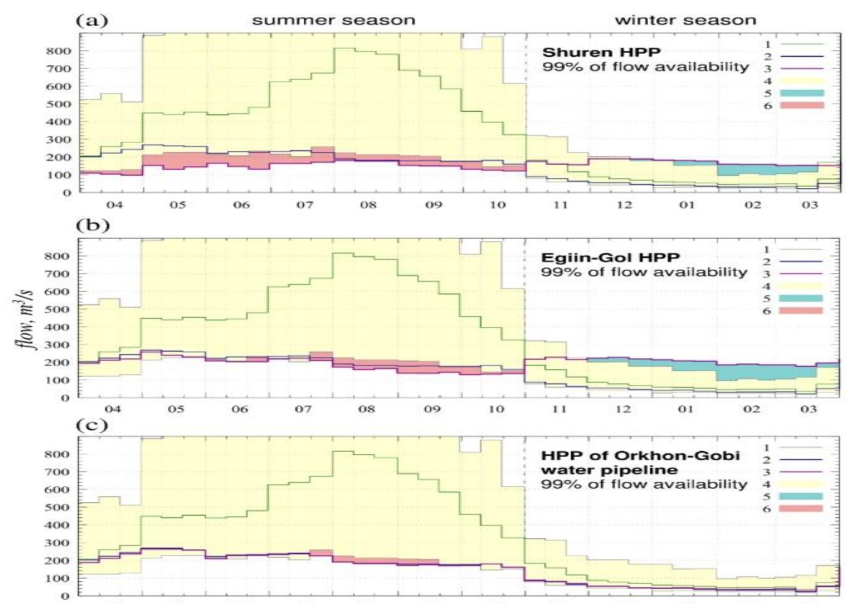

Figure 5. Change in the Selenga river flow under regulation of Shuren HPP **(a)** Egiin-Gol HPP **(b)** HPP of Orkhon-Gobi water diversion system **(c)** at Naushki station for 99% of flow availability
(1 – norm; 2 – environmental flow; 3 – regulated flow; 4 – range of natural flow changes; 5 – upper level overrange of environmental flow; 6 – lower level overrange of environmental flow).

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4. CONCLUSIONS

1. The construction of HPP's in Mongolia will inevitably lead to negative changes in ecosystems. Under certain water content (extreme low water) and flow regulation, there is a high probability that the abiotic and biotic characteristics of ecosystems will go beyond natural variability limits (environmental flow).

2. The main risks for the ecosystem are changes in the intra-annual hydrological regime, including elevated flow rates in winter, which will lead to an increase in flow speed, reduce the efficiency of natural reproduction of omul, as well as other types of fish (spawning migration, spawning, spawn incubation, larvae movement to the delta) in the Selenga river. Under low flow rates during summer, the floods will have smaller impact on soil formation, groundwater level will decline, especially in the border area of the Selenga river. Changes in water regime may affect the working conditions of water users, primarily water transport in extremely dry periods.

3. Among all the considered HPP's in Mongolian part of the transboundary Selenga river basin, the Shuren HPP will have the greatest negative impact on the territory of the Russian Federation. The impact of the Egiin-Gol HPP will be relatively smaller. However, the risks of negative impact on ecosystems, similar to those due to the Shuren HPP, remain. The project of the Orkhon-Gobi water diversion system has the minimal impact.

4. The regulation of the Shuren HPP and Egiin-Gol HPP operation will cause the greatest (3-5-fold) deviations from natural flow in winter period all over the Selenga river in the Russian territory. The greatest deviation from the natural flow in summer period occurs under extremely low water content. At the flow availability of 99%, the lower boundary of the natural flow fluctuation range is violated.

5. Territorially, the upper border area of Naushki-Dzhida is affected most. With the approach to the Selenga river mouth, the impact of Mongolian HPP's will decline. In the lower reaches of the river (Mostovoy and Kabansk stations), the deviations from the natural regimes will be observed mainly in winter. Hydrological regimes in the Selenga river delta will be determined primarily by the regulation of the Baikal level.

6. In the event of flow regulation, the Mongolian HPP's should set the environmental requirements to establish the average monthly permissible values of the environmental flow on the border of the Russian Federation and Mongolia, including the minimum in summer and maximum in winter. Violations of these constraints will have the greatest negative impact on ecosystems.

7. Consideration of the environmental requirements and the adoption of reservoir releases will reduce the negative impact but will be unable to guarantee the preservation of ecosystems in the state close to natural. These measures are extremely challenging to implement in practice.

8. This study shows just some of the possible impacts of the flow regulation. There is a significant number of effects that currently cannot be estimated and need additional research. In this regard, it is first of all necessary to consider the options alternative to the construction of HPP's in Mongolia.

9. The electricity supply (import) from the Russian Federation to Mongolia on the basis of a long-term contract stipulating a sufficient amount and a rate, which makes the electricity import from Russia more profitable than the construction of HPP's, could be considered as the first-priority alternative.

Table 2. Environmental flow of the Selenga river in Naushki.

Month	Average monthly flow, m^3/s	
	min	max
April	170	360
May	300	740
June	350	790
July	350	1360
August	350	1690
September	300	1290
October	200	610
November	100	220
December	80	125
January	60	100
February	60	75
March	60	90

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