Possibilities of enhancing the efficiency of the Angara cascade of hydroelectric power plants

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Abstract. The paper focuses on the reservoir regulation issues of the Angara cascade of hydroelectric power plants (HPPs). The current requirements of water users and the restrictions on the operating conditions of individual hydrosystems are analyzed. The inconsistency of the current legislation on water resources management in the Baikal and Angara basins is noted. Satisfying the requirements of water users and water consumers under normal and close-to-normal water availability, the management system cannot meet the standard needs and restrictions during the low and high water periods. One of the main reasons for the decrease in the reliability and stability of the water and energy systems in dry and wet years is a significant decrease in the regulation capabilities of the Irkutsk and Bratsk reservoirs versus design indices. The study involves an analysis of the operation of the Angara cascade of HPPs and the efficiency and reliability of the water management system of the Angara basin over the past 30 years. The optimal operating conditions of the cascade were modeled factoring in the current requirements of water users and socio-economic constraints for various hydrological conditions based on a 120-year statistical series of observations. Measures are proposed to enhance the effectiveness of managing the water resources of the Angara cascade reservoirs. The system of models developed by the authors was used to assess the effectiveness of the proposed measures. The assessments of the stability of the Angara water management system and the possibilities of increasing the probability of meeting the water users requirements are presented. We propose amending the current legislation to significantly boost the energy efficiency of the Angara cascade of hydropower plants, without violating the regulatory compliance of non-energy participants in the water management system of the Angara basin.

1. Introduction
Energy and water management systems are closely interconnected through the operation of hydroelectric power plants (HPPs) and cascades. Cascade of HPPs predetermines the interaction of reservoirs through water flow, heads, elevations of the upstream and downstream pools, and other indices. This interaction is especially relevant for Russia’s largest Angara-Yenisei cascade of HPPs, which generates about 50% of electricity in the Siberian power system (18% in the entire Russian Federation). The Angara cascade of HPPs plays a major role, in this case. It includes unique Irkutsk (Lake Baikal) and Bratsk reservoirs of long-term regulation with a total live capacity of 96 km³. The reservoirs of the Angara cascade of HPPs located in the basins of Lake Baikal and the Angara river are multiple-use reservoirs. They are used not only for the energy needs but also for the needs of water supply, water transportation, fisheries, and others. The multiple and integrated use of water resources of the reservoirs makes it almost impossible to fully satisfy the requirements of all water users and
sectors of the economy in all years (due to different water availability). Despite the significant regulation capabilities of the Angara cascade of HPPs (the design live capacity of the cascade reservoirs corresponds to the average annual flow of the entire Angara basin with consumptive water use of less than 1%), periodically there are problems of meeting the requirements of various water users, especially in dry periods. Therefore, the water use solutions are, as a rule, compromise solutions, in which restrictions of various degrees are unavoidable to achieve the most efficient use of water resources of the reservoirs as a whole. The restrictions can be introduced in certain years and periods within a year, they can limit the interests of all water users or part of them.

2. Current limitations on the operation of the Angara cascade of HPPs

The water management system (WMS) of the Angara river, which includes 4 large integrated hydrosystems with reservoirs of long-term and seasonal regulation (Irkutsk, Bratsk, Ust-Ilimsk, and Boguchany), is a single integrated natural, engineering, and socio-economic system. The operation of the Angara cascade depends on the requirements and restrictions of water users, as well as stochastic, naturally conditioned factors, primarily, the effective inflow to Lake Baikal and lateral inflow to the Bratsk reservoir, which account for more than 95% of the total inflow to the reservoirs of the cascade.

The main principles of the Angara cascade are currently defined in the current Rules for the Use of Water Resources (RUWR) of the Angara cascade reservoirs (of the Irkutsk, Bratsk, and Ust-Ilimsk HPPs (1988) [1] and RUWR of the Boguchany HPP (2014) [2]. Taking into account the RUWR data, supplemented by legislative acts and modern requirements, we can distinguish the following main restrictions on the operating conditions of the Angara cascade hydropower plants:

1. Irkutsk hydrosystem (including Lake Baikal):
   – according to the RUWR and Technical Design (TD) of the Irkutsk HPP [3], the permissible range of regulation for Lake Baikal is 1.96 m (the maximum level, i.e. the maximum water surface, is 457.50 m, the Pacific Elevation System (PS), and the minimum, i.e. the dead storage level, is 455.54 m PS at the normal water surface of 457.00 m PS;
   – in high-water years, the water flow rates through the Irkutsk HPP should not exceed the value of 6000 m$^3$/s (currently they are limited to 2800–3200 m$^3$/s due to the possible flooding of the territories in the downstream pool);
   – in low-water years, the flow rates through the Irkutsk HPP should not be lower than 1300/1250 m$^3$/s to ensure the normal operation of water intake facilities in the downstream pool;
   – during the winter period, daily fluctuations in water flow rates in the downstream pool of the Irkutsk HPP should be taken into account to prevent ice clogs and jams due to the risks of flooding and minor flooding, and the amount of water flowing through the HPP should not exceed 1700–2500 m$^3$/s;
   – during the navigation period, the requirements of water transportation in the downstream pool should be fulfilled with a flow rate of at least 1500 m$^3$/s.

After the Government Resolution No. 234 of March 26, 2001, came into force [4], the level of Lake Baikal could not be above 457.00 and below 456.00 m PS. Since that time, the RUWR provisions that do not contradict Resolution No. 234 have only been effective.

2. Bratsk hydrosystem:
   – during the navigation period, the water level in the reservoir must not fall below the level of 394.73–395.50 m of Baltic Elevation System (BS) to meet the navigation requirements;
   – according to the RUWR and TD, for normal operation of water intake facilities, the water level in the reservoir should not decrease below the level of 391.73 m BS (currently it is limited to 394.73 m BS).

3. Ust-Ilimsk hydrosystem:
   – during the navigation period, the water level in the reservoir should be in the range of 295.5–296.5 m BS to meet the shipping and timber rafting requirements, and should not be lower than 293.00 m BS according to the operating conditions of water intake facilities;
4. Boguchany hydrosystem and Lower Angara: the flow rates through the Boguchany HPP during the navigation period should provide the minimum water levels at the Boguchany, Tatarka, and Yeniseisk cross-sections to ensure the northern delivery on the Angara and Yenisei rivers. The flow rates should be maintained not lower than 3100 m$^3$/s (Boguchany) and 7000 m$^3$/s (Yeniseisk).

5. All reservoirs of the cascade take into account fisheries restrictions as the main part of more general environmental requirements, which indicate that the water level fluctuations in the downstream pools of HPPs during daily and weekly regulation in spawning periods should not exceed 20–30 cm.

6. According to RUWR, the value of the total firm power of the Angara cascade (together with the Yenisei branch of the cascade) is set at 9800 MW (excluding the Boguchany HPP) with the 95% availability by the number of uninterrupted years.

It is however necessary to indicate some contradictions between the above restrictions and current legislation. They relate to inconsistencies between the primary indices stipulated by the HPP designs and RUWR, on the one hand, and more recent Resolutions of the Government of the Russian Federation and current conditions of water use, on the other hand [5, 6]. The main contradictions concern the Irkutsk (Lake Baikal) and the Bratsk reservoirs.

For the Irkutsk HPP, this concerns, first of all, Resolution No. 234, which restricts the permissible range of Lake Baikal regulation by 2 times compared to the design range and the range observed in natural conditions. The studies carried out earlier by the authors indicate that one-meter range of the lake level regulation is possible only under normal conditions (average availability and close to it), but cannot be performed in low-water and high-water years [7]. In high-water years, this is associated with increased flows through the Irkutsk HPP and flooding of territories in the downstream pool under a simultaneous rise in the level of Lake Baikal above the permissible value of 457.00 m PS. In dry periods, this can be related to a possible failure of the water intake facilities located in the downstream pool in the case of flow reduction below 1300 m$^3$/s and a forced decrease in the level of Lake Baikal below the permissible value of 456.00 m PS. The last conclusion was confirmed in practice during the extreme low-water period in the Baikal and Angara basins in 2014–2017. This allows us to talk about the insufficient validity of this Resolution and the need for its adjustment. In this regard, it is necessary to determine a scientifically grounded acceptable range of regulation of the Lake Baikal level, given current environmental, socio-economic, and water management factors.

For the Bratsk reservoir, the most controversial limitation is connected to the permissible dead storage level. In the current RUWR and TD of the Bratsk HPP, it is 391.73 m BS, however, even during the construction period, the technical conditions were violated, and some of the water intake facilities and piers were built 3 meters higher than it was designed. As a result, the live capacity of the two main reservoirs of long-term regulation has decreased by approximately 30 km$^3$ (approximately 30%). It was this capacity of the HPPs and reservoirs of the Angara cascade that was designed to regulate and use water resources during the low-water periods. The significant decrease in the regulation capabilities of the reservoirs relative to design affects negatively the management of water resources, especially during periods of extreme water levels. It also complicates the management of operation, reduces the reliability and stability of the water and energy systems, and their overall performance.

3. Avenues for enhancing the efficiency of the Angara cascade of HPPs

The study of the efficiency and reliability of the Angara cascade of HPPs can focus on the standards of calculated water availability to meet the requirements of water users (firm yield of reservoirs) in the Angara river basin. Within the framework of the current legislation, the standard ranges for the water availability to provide water consumption volumes for various water users and periods are determined by the Methodological Instructions [8]. For example, the following standards for the estimated water availability to provide water consumption by the number of uninterrupted years were adopted for the main water consumers: sanitary discharges - 97–99%; water supply - 95–99%; hydropower - 85–95%; shipping - 85–90%; and fisheries - 75–90%. In certain years and periods, or in the event of adverse
climatic conditions, the established standards allow reducing (neglecting) the requirements of some participants and increasing (fulfilling) the requirements of others within 10–30% of the amount guaranteed by the standards. At the same time, the rules for the distribution of water resources under the conditions of their shortage (surplus) are not stipulated by the current legislation. However, there are opportunities to overcome the unfavorable periods with minimal losses and greater efficiency.

To assess the possibilities of increasing the overall efficiency of the water management system as a whole, including the Angara cascade of HPPs, we conducted the studies (modeling) of its operation. The modeling factored in the design technical capabilities, current requirements of various water users, and socio-economic constraints for various hydrological conditions. These studies are based on 120-year statistical observations and analysis of the operating conditions of the water management system and the Angara cascade over the RUWR period.

An analysis of the Angara cascade operation over the past 30 years demonstrates significant potential to improve the management of water resources in the Angara river basin, which does not require significant investment for their implementation and does not imply nonfulfillment of the requirements of water users. The following main areas of efficiency improvement are proposed:

1. The redistribution of water resources of the cascade reservoirs from summer to winter, with an increase in winter firm power. This effect can be achieved by:
   - the summer navigation drawdown of the Boguchany reservoir to the level of 206.0–207.0 m BS;
   - the summer navigational drawdown of the Ust-Ilimsk reservoir to the level of 294.5–295.5 m BS (up to 293.00 m BS in the periods of extremely low water);
   - the minimization of the summer flow rates of the Bratsk reservoir by determining the minimum necessary navigation flows to Lower Angara (starting with the flow rate of 3050 m$^3$/s), and specifying the lateral inflows at key cross-sections;
   - the involvement of the Lake Baikal water resources when regulating the operation of the entire cascade (currently, according to Resolution no. 234, the Irkutsk HPP operates autonomously under individual conditions).

   It is worth noting that the use of the summer navigation drawdown of the Boguchany and Ust-Ilimsk reservoirs can simultaneously increase both energy efficiency and the efficiency (availability) of transportation.

2. Extension of the range of reservoir regulation levels with the restoration of design restrictions on minimum and maximum levels for the main reservoirs of the Angara cascade of HPPs, i.e. Irkutsk and Bratsk HPPs:
   - for the Irkutsk HPP – an increase in the possible range of Lake Baikal regulation level to design levels (455.54–457.50 m PS) with the maintenance of a one-meter range of variation in the lake level (456.00–457.00 m PS) under the conditions of normal and close-to-normal water availability.
   - for the Bratsk HPP – a reduction in the minimum permissible level of the Bratsk Reservoir to the level of 393.73 m BS to meet the requirements of water transportation, and to the level of 392.73 m BS under extreme low water to ensure the normal operation of water intake facilities.

3. Development of the unified RUWR of the Angara-Yenisei cascade, considering the possibility of compensated regulation using a single reservoir operating curve for the joint use of the reservoirs of the Angara and Yenisei branches of the cascade (currently there are separate RUWR for each reservoir, except 3 reservoirs of the Angara cascade). Due to the specific features of the Angara-Yenisei cascade of HPPs (high heads, high regulation capabilities of the reservoirs, high specific weight of HPPs in the structure of generating capacities of the power system, etc.), this approach makes it possible to increase the overall guaranteed index of its average firm power in winter and improve the efficiency of energy and water management systems.

The implementation of these proposals will require, first of all, the introduction of appropriate amendments to the current legislation, i.e. RUWR, and Government Resolution no. 234.
4. Modeling results

Given the above activities, a system of models developed at Melentiev Energy Systems Institute SB RAS (ESI SB RAS) \[9, 10\] was used to calculate the operating parameters of the Angara cascade of HPPs and estimate their effectiveness.

4.1. The drawdown of the Boguchany reservoir

The results of modeling the drawdown of the Boguchany reservoir during the navigation period were used to exemplify the calculations. The drawdown is one of the most promising measures to boost the efficiency of the cascade while meeting the requirements of all non-energy participants of the water management system. The main idea of this activity is to employ the resources of the Boguchany reservoir, which is the lower stage of the cascade, through its drawdown to the minimum permissible level (206 m BS) to ensure the required flow rates during the navigation period in the Lower Angara (in the downstream pool of the Boguchany HPP). This will allow the reservoirs of the upper stages (first of all, the Bratsk HPP) to minimize water flows in summer, and increase flows through the HPP, and hence the power output and electricity generation in winter during the maximum load in the energy system when the electricity cost is higher.

The operation of hydropower plants was modeled relying on the data on inflows over 120 years (1899–2019). Three operation options were considered: 1) The base option (the current RUWR for the Angara cascade) stipulates limited regulation of the Irkutsk reservoir (Lake Baikal), the drawdown of the Boguchany reservoir to the level of 207 m BS, the drawdown of the Bratsk reservoir to the level of 394.73 m BS, and the set guaranteed 95% availability of firm power in winter in the entire Angara-Yenisei cascade; 2) The operating conditions according to RUWR (as in option 1), but with the additional drawdown of the Boguchany reservoir to the level of 206 m BS; 3) operating conditions with the drawdown of the Boguchany reservoir to the level of 206 m BS and the possibility of reducing the minimum permissible level of the Bratsk reservoir to the level of 392.73 m BS.

Modeling the operating conditions took into account the coordinated operation of the Angara and Yenisei HPPs cascades through the regulation of the Bratsk reservoir operating in a compensation mode to ensure average winter firm power. The energy indices obtained from the modeling of the aforementioned options of the cascade operation are given in Table 1.

The modeling results demonstrate a significant improvement in the energy performance of the cascade in options 2 and 3 relative to option 1. When the navigation drawdown of the Boguchany reservoir is used alone, the increase in the average winter firm power of the cascade will be 480 MW with an additional electricity output of 2090 million kWh per year (option 2). The additional use of the Bratsk reservoir resources, with its possible drawdown to the level of 392.73 m BS, will increase the average winter firm power by 1000 MW with an additional electricity output of 4350 million kWh (option 3).

As seen from figure 1, despite possible significant changes in water inflow to the reservoirs and long dry periods, in most years (with the 95% availability), the cascade can provide uniform winter power, which increases the reliability of the entire power system and make it possible to plan the operating conditions of thermal power plants and combined heat and power plants.

It is worth noting that in options 1 and 2, there is a slight decrease in the average long-term power (up to 5 MW) due to a decline in the head at the Boguchany HPP. Option 3 allows non-fulfillment of navigation requirements at the Bratsk reservoir in May-June. In addition, the normal operation of some small water intake facilities in the water areas of the Bratsk reservoir can require their reconstruction.

The considered options of operation do not take into account an important measure, which is an increase in the possible range of regulation of Lake Baikal level to design elevations (455.54–457.50 m PS). The implementation of the measure additionally increases the efficiency and reliability of the entire Angara-Yenisei cascade.
Table 1. The power and electricity output indices of the Angara-Yenisei HPPs cascade by modeling option.

| No. | Modeling option                                                                 | Power, MW | Electricity output, m kWh/year | Firm index (availability of 95%) |
|-----|---------------------------------------------------------------------------------|-----------|--------------------------------|----------------------------------|
|     |                                                                                 | Average long-term | Average winter | Long-term | Winter | Average winter power, MW | Winter electricity output, m kWh |
| 1.  | Base (RUWR –88)                                                                | 12 610    | 11 030                        | 47 990                           | 10 700 | 46 480 |
| 2.  | The drawdown of the Boguchany reservoir to 206 m BS                             | 11 460    | 11 050                        | 49 840                           | 11 180 | 48 570 |
| 3.  | The drawdown of the Boguchany reservoir to 206 m BS at the minimum level of the Bratsk reservoir of 392.73 m BS | 12 720    | 11 770                        | 111 470                          | 11 700 | 50 830 |

Figure 1. The availability of average winter power of the Angara-Yenisei cascade of HPPs by modeling option.

4.2. Stability assessment of the Angara water management system
Stability of the water management system (WMS) is understood as a state of the system in which the needs of all water users and water consumers are met within a given range of standard reliability for all regulated hydrological, environmental, economic, social conditions and other restrictions.

The system of models developed at ESI SB RAS [10] was used to study various scenarios of the operation of the Angara cascade reservoirs with a focus on the possible increase in the stability of the Angara WMS. Two modeling options are given as an example: 1) Current and 2) Optimal.

The current option allows satisfying the requirements of water users and water consumers within the standard values, except for fulfilling the requirement of non-flooding of the city of Irkutsk. The disadvantage of this option is also the risk of a decrease in the minimum level of the Bratsk reservoir below the water intake facility requirements of 392.73 m BS (RUWR allows the minimum design level of regulation of 391.73 m BS in extremely dry periods), and the failure to fulfill the standard requirements of water transportation on the Bratsk reservoir in case of low inflow.

The optimal option allows design levels of Lake Baikal regulation of 455.54–457.50 m PS (457.85 m PS at the availability of 0.1% and below) depending on the hydrological conditions under the current provisional (until 01.01.2021) Government Resolution No. 1667 [11], which is important for
increasing the stability of the Angara WMS during the years of extreme water availability. Moreover, in the years of normal and close-to-normal water availability, the regulation of Lake Baikal levels is limited to a meter range according to Resolution no. 234. For the Bratsk Reservoir, in extremely dry years its drawdown can reach the level of 393.62 m BS (currently the level cannot be decreased below 394.73 m BS), which guarantees the fulfillment of the minimum permissible water transportation requirements during the navigation period.

The optimal option also envisages the possibility of summer navigation drawdown of the Ust-Ilimsk and Boguchany reservoirs to design dead storage levels (DSL) with the simultaneous accumulation of long-term water reserves in the Bratsk reservoir. Additionally, this option assumes that in the extremely low-water periods, in the absence of water resources in the Bratsk reservoir, the navigation drawdown of the Ust-Ilimsk and Boguchany reservoirs can reach the dead storage level below its design marks by 1.5 and 1 m, respectively, (taking into account the mandatory fulfillment of the requirements of the water intake facilities located in the water areas of the reservoirs and downstream pools). This option also makes it possible to prevent significant flooding in the downstream pool of the Irkutsk HPP due to the restriction on the maximum permissible flows and thus to fulfill the important social requirement.

The results of the calculations of the availability to meet the requirements of water users for the considered options of regulation are presented in Table 2. Figure 2 shows the results of modeling regimes of Irkutsk HPP with Lake Baikal for the optimal option under all possible water conditions over the 120-year series of inflows.

![Figure 2](image-url)

**Figure 2.** Inflow and regimes of Irkutsk HPP with Lake Baikal (optimal option): a) Inflow to Lake Baikal; b) Water flow through the Irkutsk HPP; c) Water level in Lake Baikal.

With minor changes in the current legislation, the absence of financially costly measures and changes in design solutions, in the optimal option the calculated availability of water resources for all water users meets or exceeds the standard one. As a result, the overall stability and reliability of the entire water management system of the Angara river basin and the Siberian energy system increases.
At the same time, the availability for meeting the main requirements of water users can be increased to 94–100% in comparison to the existing indices (62–100%).

### Table 2. Calculated availability to meet the main requirements of water users and the operating parameters according to the regulation options for hydropower plants of the Angara cascade.

| Index | Regulation options | Current | Optimal |
|-------|--------------------|---------|---------|
| Irkutsk reservoir (Lake Baikal) | | | |
| Availability to comply with the level of maximum water surface (457.50 m PS) | ≤ 457.50 m | 100 | 99 |
| Availability to comply with the level of normal water surface (457 m PS) | ≤ 457.00 m | 76 | 63 |
| Availability to comply with the level of 456 m PS | ≥ 456.00 m | 91 | 87 |
| Availability to comply with the dead storage level | ≥ 455.54 m | 100 | 100 |
| Availability to comply with navigation requirements in the downstream pool of Irkutsk HPP | ≥ 1500 m³/s | 85 | 90 |
| Availability to comply with water intake requirements | ≥ 1300/1250 m³/s | 99 | 100 |
| Availability not to flood the city of Irkutsk | ≤ 3500(3200) m³/s | 62 | 94 |
| Bratsk reservoir | | | |
| The minimum permissible level of the Bratsk reservoir, m BS | 391.73 | 393.62 |
| Availability to fulfill the navigation requirements in the Bratsk reservoir | ≥ 394.73 m | 93 | 98 |
| Availability to comply with the requirements of water intakes in the water areas of the Bratsk reservoir | ≥ 392.73 m | 99 | 100 |
| Ust-Ilimsk reservoir | | | |
| Availability to fulfill the transportation requirements on the Ust-Ilimsk reservoir | ≥ 295.5 m | 96 | 97 a |
| Boguchany reservoir | | | |
| Availability to comply with navigation requirements in the Lower Angara | ≥ 3050 m³/s | 89 | 95 a |
| Angara-Yenisei cascade | | | |
| Average firm (at 95% availability) winter power, MW | 11 400 | 11 400 a |

5. Conclusion
The reservoirs of the Angara cascade of HPPs have significant potential to increase the availability of water resources for water users, and hence the overall stability of the water management system of the Angara river basin, under various water conditions, given the imposed constraints.

In the context of current constraints, with optimal regulation and introduction of some amendments to the legislation in effect, the energy efficiency of the Angara cascade of HPPs can be significantly
improved without failing to meet the standard requirements of non-energy participants in the WMS of the Angara river basin.

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