A System Of Models To Study Long-Term Operation Of Hydropower Plants In The Angara Cascade

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***Abstract* — The paper provides a system of consistent models to study the integrated use of water resources of reservoirs and operating conditions of hydropower plants that constitute the Angara cascade. The system includes many different simulation and optimization models (hydrological, hydraulic, water management, and the hydropower cascade operation control) taking into account the hydrological, climatic and territorial features of the water systems of the Baikal, Angara and Yenisei basins; and the role of the Angara cascade in the operation of the Siberian electric power system. The paper presents a brief description of the models, their parameters, criteria and constraints, and their interaction principles. The models are designed to determine the long-term operating conditions of the Angara cascade of hydroelectric power plants. To this end, it is proposed to use global climate models with the data on the state of the atmosphere and ocean based on which the most probable characteristics of meteorological indices in the region are determined, to make estimates (scenarios) of inflows into the cascade reservoirs in the form of ranges of probability distributions for a period of up to one year. The results of modeling the long-term operation of individual hydroelectric power plants and the entire Angara cascade are presented for 2019–2020. Relying on the assumed long-term water scenario, the estimated water availability scenarios make it possible to evaluate the expected electricity output, the average used capacity and other parameters of the hydroelectric power plants operation, to form prospective energy balances in the power system, and to determine the the prospective load of thermal power plants.**

***Index Terms* — hydropower plant operation, Angara cascade, metamodels, inflow scenarios.**

I. Introduction

In the electric power system of Siberia, 50% of generating capacities are represented by hydroelectric power plants, including 30% of the Angara cascade hydropower plants and 20% of the Yenisei cascade plants. For comparison, the share of hydroelectric power plants in the Unified Power System of Russia accounts for about 17% of the installed capacity of all power plants. The share of hydroelectric power plants in other power systems is much lower: 12 % in the North-West; 10% – in the Central, and 3% – in the Urals [1].

The Angara cascade is located in the Angara river basin and includes Irkutsk, Bratsk, Ust-Ilimsk, and Boguchany hydroelectric power plants (HPPs) with reservoirs of seasonal and long-term regulation with a total live storage capacity of about 100 km3 [2–4]. Figure 1 shows a diagram of the Angara river basin divided into five main areas connected to the catchment basins of the reservoirs of the Angara HPP cascade. Area 1 refers to Lake Baikal [5–7] and the upper and lower pools of the Irkutsk reservoir. Areas 2–4 correspond to the catchment basins of the lateral tributaries to the Bratsk, Ust-Ilimsk, and Boguchany reservoirs. Area 5, 450 km long along the river bed, is important for summer navigation on the Lower Angara and the Yenisei rivers.

Since most of the electricity in the electric power system of Siberia is generated by hydropower plants, its operation and management of the operation largely depend on the natural fluctuations in the annual flow of the Angara-Yenisei basin rivers. Depending on the water availability, the range of changes in the electricity generation from the

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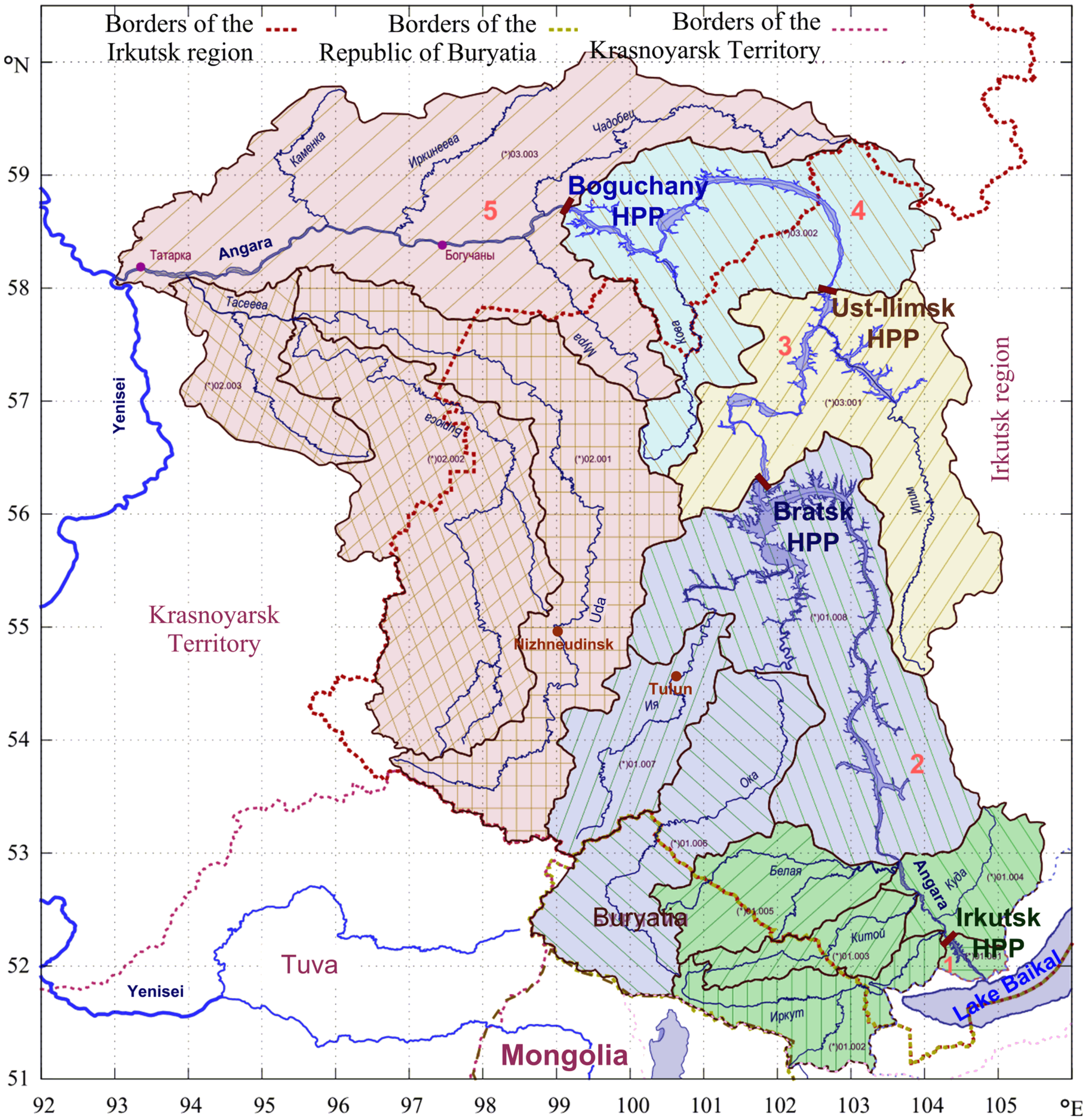

Fig. 1. Map of the Angara HPP cascade reservoirs with catchment basins (1–4) and Lower Angara area (5).

Angara-Yenisei HPP cascade can reach 50 billion kWh per year, including 30 billion kWh from the hydropower plants of the Angara cascade. For example, during the period of extremely low water observed in the Angara cascade of hydropower plants in 2014–2017 (2018), there was a significant decrease in the generation of electricity by hydroelectric power plants (up to 20% in some years). The low water period led to a reduction in the reserves of hydro resources in the reservoirs of the hydroelectric power plants, including the almost complete drawdown of long-term reserves in the Bratsk reservoir. As a result, the electricity output from the hydroelectric power plants decreased and the need arose to additionally load less economical and less environmentally friendly thermal power plants, which increased fuel consumption, electricity cost, and emissions of harmful substances into the environment. As a result, the efficiency and reliability of the entire power system of Siberia decreased.

It is worth noting that the presence of a powerful cascade of hydroelectric power plants in the power system is characterized by both advantages (the use of efficient renewable energy resources) and disadvantages of the power system. The main disadvantage is the uncertainty of the available water resources in the estimated period.

The existing system of planning and management in the electric power industry envisages the estimation of long-term operating conditions and balances of electric power and capacity for a period of 1–2 or more years. To this end, to plan the operation of hydropower plants, it is necessary to take into account the long-term forecast scenarios of water availability, which are probabilistic in nature. The development of such scenarios is an extremely complex problem that does not have unambiguous solutions. In practice, the water-energy calculations for the long-term prospects normally involve statistical average long-term values of water inflows into reservoirs. Under normal (medium) water conditions, this approach does not cause problems but it cannot be applied to low-water and high-water periods.

The noted features of the power system and the hydropower plant cascade, as well as the need to improve the reliability of their operation call for a study of various operating conditions of the hydrosystems based on a variety of simulation and optimization models with the determination and minimization of energy, water, environmental and social risks.

II. Research Methodology

Many effective algorithms and techniques have been developed to study the operation of hydropower plants in recent decades. Many of them have been created since the early 1960s and used in automated dispatch control of power systems to perform water-energy calculations aimed at regulating the storage reservoirs. The mathematical methods (linear, nonlinear, dynamic programming) [8–10] designed to optimize the hydrological regimes, including stochastic [11–14] and multi-criteria [15–17] optimization found wide application.

The development of global climate models brought about the studies on their application in the estimates of future river flow and calculations of hydropower water-energy regimes [18, 19]. Some studies suggest the use of an integrated approach to managing cascades of reservoirs (using the Volga-Kama cascade of hydroelectric plants as an example) with focus on the water system requirements based on various methods of determining surface runoff, allowing for weather parameters, and using digital models of river catchment relief [20].

Given the role of the Angara cascade of hydropower plants and its reservoirs in the operation of the regional power system of Siberia; the water-management systems of the Baikal, Angara and Yenisei basins, as well as the hydrological, climatic and territorial features of the studied object; it is necessary to build a great variety of models (hydrological, hydraulic, water management, simulation, optimization, stochastic and others), because consideration of all aspects of the object operation in one model greatly complicates its use in practice. Figure 2 shows a system of

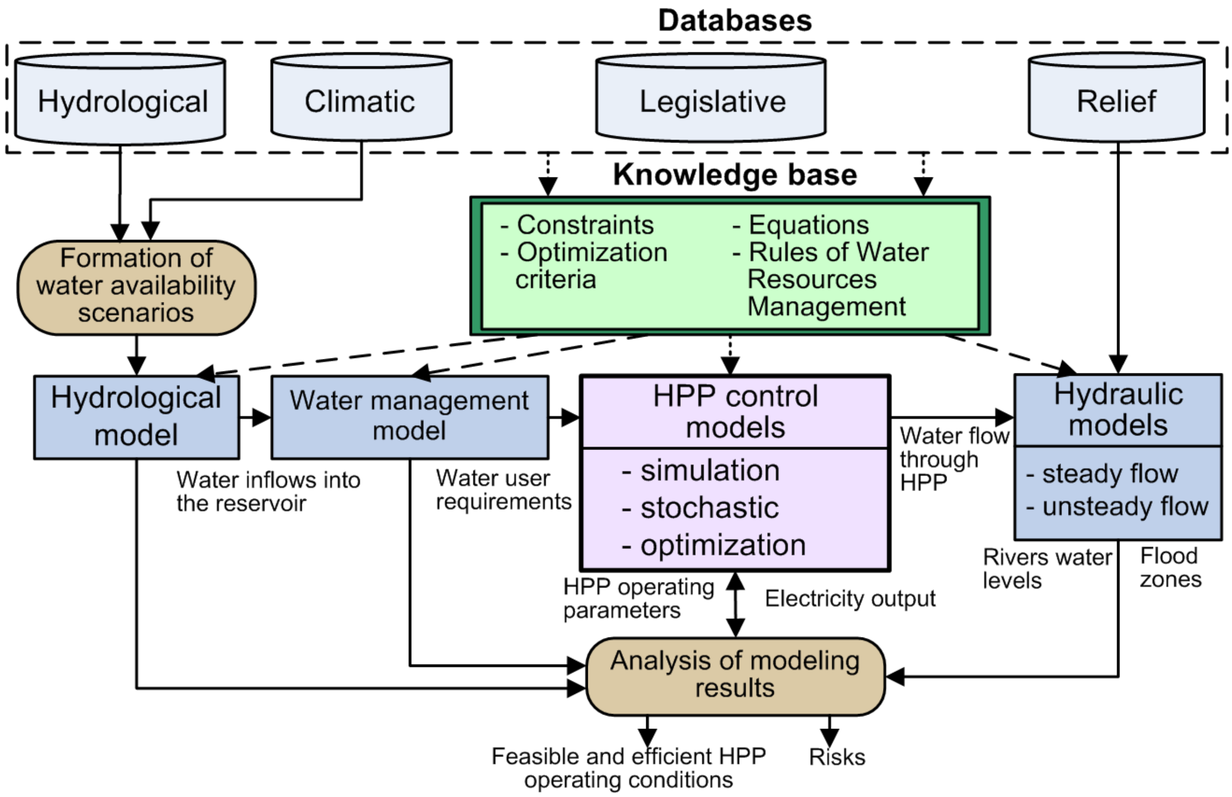

Fig. 2. A system of models for studying the integrated use of water resources of reservoirs and operation of the Angara cascade hydropower plants.

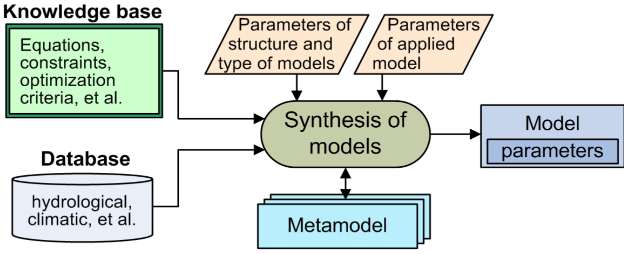

Fig. 3. A diagram of constructing consistent models to study HPP operating conditions.

models developed by a research team from the Laboratory of Hydropower and Water Management Systems at the Melentiev Energy Systems Institute (ESI) SB RAS to study the integrated use of water resources of reservoirs and operation of the hydropower plants of the Angara cascade [21, 22].

The hydrological database includes the collected statistics on the water inflows into the reservoirs of the hydropower plants. The climatic database, including the state of atmospheric meteorological indices for a long period of observations, together with the forecast ensembles of global climate models, is used to build long-term prognostic scenarios of water availability in the cascade reservoirs with the aid of the GeoGIPSAR system developed at ESI SB RAS [23, 24]. The relief database of the Angara river areas is used to build hydraulic models for steady (stationary) and unsteady (non-stationary) flow. These models can be used to determine river levels and, accordingly, periods of water level reaching the specified cross-sections, zones and boundaries of potential flooding. The knowledge base includes formalized current rules for the use of water resources of the reservoirs, as well as various constraints on operating conditions of the Angara cascade of hydropower plants with different criteria for their optimization.

The hydrological model includes balance equations for water inflows and flow rates. The water management model takes into account transport, energy, social, and environmental constraints; the requirements for uninterrupted operation of water intakes, and other requirements of the water management system.

Formation of feasible and optimal operating conditions normally requires multiple uses of various models with a block for analysis of the complex modeling results. There are periodic changes in regulatory documents, significant changes in hydrological and climatic characteristics in recent decades, various criteria used for the formation of effective conditions, which makes it necessary to constantly update the models.

To eliminate the contradictions in the use of different models, the ESI SB RAS has developed an approach to the development of a system of consistent models based on common data and knowledge bases and various model structures based on a metamodeling mechanism, which makes it possible to quickly synthesize unique models based on the description of parameterized model classes, i.e. metamodels [25–28]. A general diagram of this approach is shown in Fig. 3.

The metamodel is a parameterized structure that includes many relations with knowledge base and database objects.

Based on a single knowledge base and a single database, models of different classes (mathematical programming, stochastic, simulation, and others) are synthesized. Planning the operating conditions of the HPP cascade involves consideration of various control methods: setting reservoir levels by the end of the time interval, setting average water flow rates through HPP turbines, assigning a guaranteed average power or electricity output from hydropower plants.

The problem of operating the hydropower plants in the power system and in the water management system lies in the difficulty of describing and considering a large number of processes and their parameters: the requirements of the participants in the water management, including energy industry, the influence of natural, climatic, economic, and social factors.

The proposed approach is characterized by:

- the development of many models based on a single database and a single knowledge base, coordinated with respect to input and output parameters and constraints;
- the creation of an environment for the synthesis of the management models with various water and energy optimization criteria based on the processing of long-term hydrological statistical data and their model options (for example, the formation of artificial time series for 1000 years or more);
- the modeling of long-term operating conditions of hydropower plant cascades according to synthesized prognostic scenarios of water availability with their different probabilities;
- the development of a flexible parameterized software environment for the synthesis, start, and development of models based on the creation of universal and specialized libraries of support programs;
- the combination of the use of own and external software;
- the consideration of the specifics of the basins of Lake Baikal, the Angara, theYenisei, and the Angara cascade.

III. Research models of Angara HPP cascade

The hydrological model serves as a basis for the study of the Angara HPP cascade operation. The water inflows and discharges in the cascade are schematically presented in Fig. 4.

For the Bratsk reservoir, additional lateral tributaries (the Irkut, the Kitoy, and the Belaya rivers) were considered, which is associated with the potential flooding of large areas in the lower reach of the Irkutsk HPP, determined by the flow through its hydrosystem and these lateral tributaries [29].

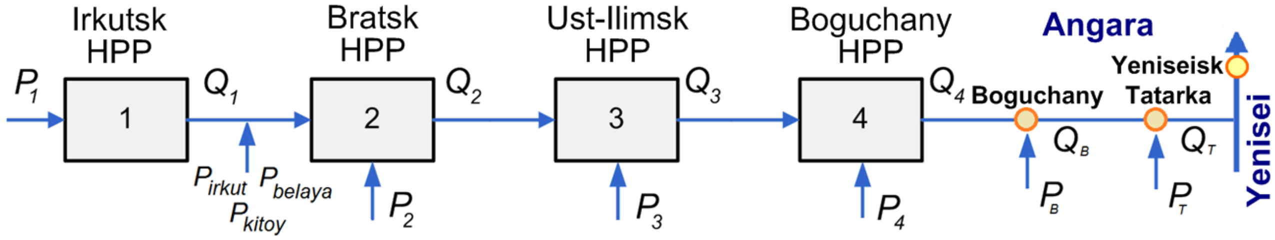

Fig. 4. A scheme of the Angara HPP cascade

The hydrological model of the Angara cascade can be represented by the following equations:

$$\begin{aligned}&\frac{dV_i}{dt} = P_i(t) - Q_i(t) + \overline{Q}_{i-1}(t) - \Lambda_i(t),\\ &Q_B(t) = Q_4(t) + P_B(t),\\ &Q_T(t) = Q_B(t) + P_T(t), Q_0(t) = 0,\\ &\Lambda_i(t) = R_i^{isp}(t) + R_i^{filtr}(t) + R_i^{pz}(t) + R_i^{tr}(t),\\ &t \in [t_0, T],\ i = \overline{1,4},\end{aligned} \tag{1}$$

where i – an HPP index (1 – Irkutsk, 2 – Bratsk, 3 – Ust-ILimsk, and 4 – Boguchany HPPs);
t – time on the set interval $[t_0, T]$; V_i, (t) – the volume of water in the reservoir;
P_i, (t) – lateral (full) water inflow into reservoir; Q_i, (t) – flow through HPP cross-section; $\overline{Q}_{i-1}(t)$ – water consumption of the upper stage of the HPP cascade, given the lag time; Q_B, Q_T, P_B, P_T – flows and lateral inflows into the Lower Angara for the Boguchany and Tatarka points where the Angara river levels are monitored; $\Lambda_i(t)$ – function of an additional impact of evaporation from the reservoir surface $R_i^{isp}(t)$, filtering through the dam $R_i^{filtr}(t)$, changes in the subsurface component $R_i^{pz}(t)$, changes in the volume of a water area between the reservoir and upper stage of the HPP $R_i^{tr}(t)$. The indices of inflows $P_i(t)$ can be taken from the hydrological base or specified by various prediction scenarios built by the GeoGIPSAR system.

The values of functions $\Lambda_i(t)$, except for evaporation, can be neglected for practical calculations, which is due to the complexity of estimate of the listed indices and their relatively small influence on the total inflow. Evaporation plays a significant role in dry periods on Lake Baikal, therefore, its indices are included in the final available inflow into the Irkutsk reservoir.
For the given time interval, equation (1) can be approximately written in the finite difference form:

$$\begin{aligned}\Delta V_i^{\tau}(t) = [&Q_{i-1}^{\tau}(t) + P_i^{\tau}(t) - Q_i^{\tau}(t) -\\ &R_i^{isp}(t)]\cdot\tau,\ Q_0^{\tau}(t) = 0,\ i = \overline{1,4}\end{aligned} \tag{2}$$

Constraints on the upper reach:

$H_i^{UMO} \le H_i\,(t) \le H_i^{NPU}$ – for normal water conditions;
$H_i^{UMO-} \le H_i\,(t) \le H_i^{FPU}$ – for extreme water conditions;

Constraints on the flow rates:

$$q_i^{turb}(t,j) \le q_i^{\max}(h_i), \quad q_i^{hol}(t,k) \le q_i^{hol,\max}(h_i)$$

Statistical calibration functions:

$$z_i = \varphi_i^z(Q_i, H_{i+1}^{vb}), \quad E_i^{\max} = \varphi_i^E(Q_i, h_i),$$
$$H_i = \psi_i(V_i), \quad V_i = \psi_i^{-1}(H_i)$$

where $\Delta V_i^{\tau}, P_i^{\tau}, Q_i^{\tau}, R_i^{\tau}$ – average values of the function on the time interval $[t, t+\tau]$. The lag time of the changed water flow from the Boguchany HPP is determined by the average speeds for the respective sections.

Water inflow functions $P_i^{\tau}(t)$ have large interannual and seasonal variations, which significantly complicates the management of the regimes. The hydrological model makes it possible to calculate the natural regimes of each reservoir using the equations of water volume dynamics. This model can also be used to determine the natural flow from Lake Baikal based on the family of curves of correlation between its level and the level of upper reaches of the Irkutsk hydropower plant dam. All lateral inflows and effective inflow into Lake Baikal are determined by the corresponding probability distribution functions (Kritsky-Menkel three-parameter distribution, Pearson type III distribution, etc.), which are built based on hydrological statistics in ten-day and monthly temporal resolution for the period of 1903–2018.

The water management model allows for the consumptive water use in different parts of the Angara river. Then equations (1) will take the form:

$$\begin{aligned}&\frac{dV_1}{dt} = P_1(t) - Q_1(t) - \Lambda_1(t) - \beta_1(t)\ ,\\ &\frac{dV_2}{dt} = Q_1(t) + P_2(t) + P_{irkut} + P_{kitoy} + P_{belaya}\\ &-Q_2(t) - \Lambda_2(t) - \beta_2(t)\ ,\\ &\frac{dV_3}{dt} = Q_2(t) + P_3(t) - Q_3(t) - \Lambda_3(t) - \beta_3\ (t),\\ &\frac{dV_4}{dt} = Q_3(t) + P_4(t) - Q_4(t) - \Lambda_4(t) - \beta_4\ (t),\end{aligned} \tag{3}$$

where functions $\beta_i(t)$ determine the total consumptive water withdrawal by water users at the relevant macro area with constraints $\beta_i(t) \le \beta_i^{\max}$.

The main water management constraints are:

$q_{ij}(t) \geq q_{ij}^{\min}$ – flow rates for all water withdrawals of macro area i and area j should be larger than the minimum permissible ones for the area;

$h_{ij}(t) \geq h_{ij}^{\min}$ – similarly, the levels of the river by area for the open water in the zone of water withdrawal should be higher than the minimum permissible ones.

For the normal (failure-free) operation of water diversion points in the lower reach of Irkutsk hydropower plant at present the required flow rates through the hydrosystem should be no less than 1300 m3/s (1250 m3/s when the hard ice cover is formed).

For the Bratsk reservoir, the level of the upper reach should not be below 392.73 m of the Baltic Elevation System (BS) (according to the operating conditions of the diversion facility in Svirsk). Indices of consumptive water use by water consumers are taken into account in water balance equations.

Normal navigation conditions in the lower reach of the Irkutsk hydropower plant require the flow rate through the hydrosystem to be no less than 1500 m3/s during the period from May to October. For the Bratsk reservoir, the navigation level according to the current rules [3] should be at least 394.73 m BS during the period from June to October. For the Ust-Ilimsk and Boguchany reservoirs, the normal navigation levels correspond to 295.5 and 207.5 m BS, respectively. The level of pre-flood drawdown for each reservoir as of May 1 should not exceed 456.15 m of Pacific Altitude System (PS) for Lake Baikal; 400.23 m BS for Bratsk reservoir; 295.19 m BS for Ust-Ilimsk reservoir, and 207.20 m BS for the Boguchany reservoir.

For all reservoirs in the cascade, the maximum permissible level of the upper reach is limited to the normal water surface (NWS), except for periods of extremely high floods.

The most severe limitation in the summer-autumn period (from May to October) is the maintenance of the Lower Angara and Yenisei levels not lower than the minimum permissible levels for the three control sites (Boguchany – not lower than 0 cm; Tatarka – not lower than 180 cm; Yeniseisk – not lower than 300 cm relative to the base marks of the corresponding water points), providing navigation on the Yenisei.

Water withdrawal constraints (limits and norms of permissible impacts) are taken into account for each section of the Angara river basin.

The hydraulic model is used to estimate the flooding zones in the lower reach of the Irkutsk hydropower plant, as well as in the unregulated areas of the Lower Angara for the current calculation of the Angara river levels at the control cross-sections of Boguchany and Tatarka.

The calculations for the steady-state flow are based on the Chezy equation [30] used to calculate the average flow velocity in an arbitrary cross-section:

$$\upsilon = C\sqrt{R \cdot I} \qquad (4)$$

$$\begin{gathered} P = \sum\nolimits_{(i)} l_i,\ S = \sum\nolimits_{(i)} s_i,\ B = \sum\nolimits_{(i)} b_i, \\ l_i = \sqrt{h_i^2 + b_i^2},\ s_i = (h_{i-1} + h_i) \cdot b_i / 2,\ i = \overline{1, N}, \\ R = S / P,\ Q = \upsilon \cdot S,\ K = C \cdot S \cdot \sqrt{R}, \\ C = R^y / n_i,\ y = 1/6, \end{gathered} \qquad (5)$$

where *P* – wetted perimeter; *S* – area; *B* – width; *Q* – flow rate; *K* – flow rate characteristic; h_i, b_i, l_i, s_i, n_i – depth, width, length, area, and roughness of the *i*-th section of the cross-section.

For the case of a small change in the river level, the iteration method is used to calculate these indices with a given error based on given and calculated flow rates.

For a given flow rate, the morphometric characteristics are calculated for each of the cross-sections, starting with the last one located downstream, for which the level is determined by the Chezy equation. The roughness coefficients for the initial calculations are divided into two parts: the riverbed one in a range of 0.02–0.05 and the floodplain one in a range of 0.05–0.07. The roughness coefficients are specified through verification of levels for several hydrological points (the Irkutsk hydropower plant dam, the Yunost Island, the bridge, the river port, the village of Bokovo, and the town of Angarsk) according to the available statistical indices of daily levels of the Angara river in the high water years (1971, 1973, 1985, 1988, 1994, 1995, 1998, and others).

After the iterative procedures of the level refinement in each basic cross-section, the structure of their characteristics is formed. These characteristics are used to determine the parameters of intermediate cross-sections with a water surface level change uniform in length and refinement of hydraulic parameters.

For the *unsteady flow* associated with unregulated lateral inflows, the difference scheme of calculations based on the Saint-Venant equations is applied. Estimation of an average ten-day flow at point *X*, situated at distance *L* from the initial one, can be defined as follows:

$$\begin{gathered} Q^X = \frac{1}{T} \cdot [Q^- \Delta t + Q^+ (T - \Delta t) + \\ q^- \tau + q^+ (T - \tau)], \end{gathered} \qquad (6)$$

where Q^-, Q^+ – flow rates in the initial cross-section for the previous and current ten days; q^-, q^+ – similar average ten-day lateral inflows in the section; Δt, τ – the lag time of the main and lateral inflow to point *X; T* – ten days (c).

Since the lateral inflows are, as a rule, much less than the main inflow and the lag time is much less than Δt, equation (6) can be simplified as follows:

$$Q^X \approx \frac{1}{T} \cdot [Q^- \Delta t + Q^+ (T - \Delta t)] + q^+. \qquad (7)$$

The lag time of the changed flow can be determined by the average current velocity in the section according to the Chezy equation: $\Delta t = L / \upsilon$, where *L* is a distance between the cross-sections.

Models for complex management of the Angara cascade hydroelectric plants operation include many simulation and optimization models. The main components of the metamodel designed to study the HPP operation management are shown in Fig. 5. To consider the HPP cascade it is necessary to develop the metamodels for each HPP and for the entire cascade.

Simulation models determine all the necessary parameters, criteria and constraints for water-energy calculations based on hydrological, water-management and energy models. They make it possible to carry out end-to-end calculations for the entire period of the statistics collection (since 1899) or for individual studied periods (for low-water and high-water periods, since the beginning of HPP operation, since the year of introduction/changes in the Rules for Water Resource Management (RWRM), etc.), as well as to calculate model inflows. Water flows through the HPP cross-sections are determined not only by reservoir operating curves but also by special algorithms taking into account prognostic water availability indices.

The construction of simulation models to study different HPP operating conditions requires that the flow rate through the HPP cross-sections at each considered period be uniquely determined. When modeling the natural regimes of the Irkutsk hydropower plant, we determine the flow rate by the family of correlation curves between the level of Lake Baikal and the level of the upper reach of the dam. When modeling the winter operation of the Bratsk HPP, it is necessary to set its flow rate so that the total capacity of all HPPs of the Angara-Yenisei cascade has a certain guaranteed value. The summer operation of the Bratsk HPP should provide the flow rate for navigation in the Lower Angara, as well as the filling of the Ust-Ilimsk and Boguchany reservoirs and subsequent maintenance of their levels.

Multi-criteria optimization models include several models ranked by priority of optimization criteria for the use of water resources by different water users, provided their requirements are met with given normative reliability. The main modeling parameters are a set of several reservoir operating curves that take into account the specifics of individual water users. Their internal parameters can vary. The formal description of the models and the notations they contain are given below:

$t=(y,d)$ – discrete time, y – year,

d – ten days (month);

P_t – actual inflow into the reservoir at time t;

P_t^* – predicted inflow;

q_t – the flow rate through the HPP cross-sections;

h_t^+ – level of the upper reach at the end of the period $[t, t+\tau]$;

h_t^- – level of the lower reach;

Δh_t – head;

N_t – HPP power;

E_t – electricity output over the period $[t, t+\tau]$, where τ is period duration;

$\omega_t(k,\theta_k)=\{q_t, h_t^+, h_t^-, \Delta h_t, N_t, E_t, \theta_t^\omega\}$ is a set of basic calculated parameters that are determined by the function $\omega_t(k,\theta_k)=F^\omega(D_k(\theta_k), P_t, P_t^*, h_{t-1})$ over the time interval $[t, t+\tau]$; θ_t^ω are additional parameters considering detailed operating parameters (for example, efficiency, total and effective heads, loading of hydro-power units, etc.); $D_k(\theta_k)$ is the k-th reservoir operating

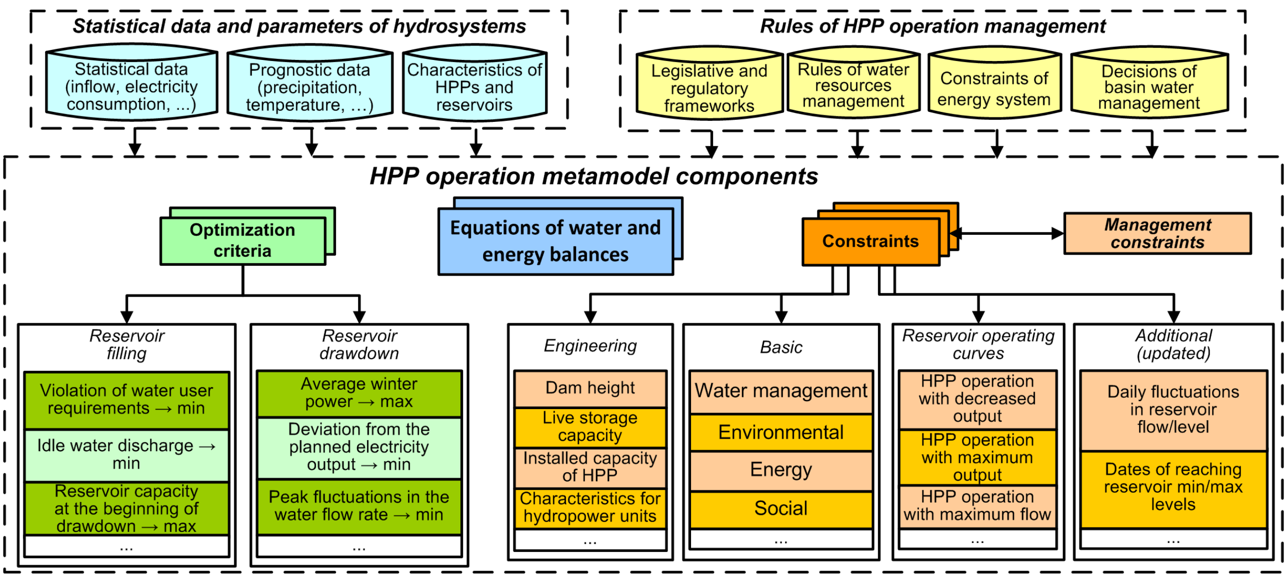

Fig. 5. The structure of the main components of the HPP operation metamodel

curve with a set of internal parameters θ_k from a set of the studied $\overline{D} = \{D_k(\theta_k) : k = \overline{1,K}; \theta_k \subset \overline{\theta}_k\}$;

$\Omega_{t_1 \to t_2}(k, \theta_k) = \left(\{\omega_t(k, \theta_k), (P_t, P_t^*) : t \in [t_1, t_2]\}\right)$ – end-to-end calculations of operating conditions for the period $[t_1, t_2]$;

$\overline{\Omega}_{t_1 \to t_2} = \{\Omega_{t_1 \to t_2}(k, \theta_k) : k = \overline{1,K}; \theta_k \subset \overline{\theta}_k\}$ – matrix of solution options for all the reservoir operating curves and variation in the internal parameters from the set $\overline{\theta}_k$;

$\Lambda = (\lambda^A, \lambda^B, \lambda^E, \lambda^T, \lambda^R, \lambda^S)$ – vector of availabilities after meeting: A – operational and technical constraints, B – water withdrawal requirements, E – energy requirements; T – water transport requirements; R – fisheries requirements; S – territory non-flooding requirements;

$\Lambda\ (k, \theta_k) = F^{\Lambda}(\Omega_{t_1 \to t_2}(k, \theta_k))$ – function for determining the availability at a time interval $[t_1, t_2]$ and in the reservoir operating curve $D_k(\theta_k)$.

The main objective is to simultaneously maximize the vector of criteria:

$$(\lambda^A, \lambda^B, \lambda^E, \lambda^T, \lambda^R, \lambda^S) \to \max(\overline{\Omega}_{t_1 \to t_2}) \quad (8)$$

$$\Lambda_i \geq \Lambda_i^{\min} : i = \overline{1, K^{\Lambda}}, \quad (9)$$

where the magnitude $\Lambda_i^{\min}$ depends on the selected water user, for example, according to normative indices, the normal water consumption by the number of uninterrupted years is $\Lambda_1 \geq 95$ for water supply, $\Lambda_4 \geq 85$ for water transport, and $\Lambda_5 \geq 75$ for fishery.

The sequences of ranking the criteria by water user determine different options of HPP water resources management.

The specific feature of the calculation of the Bratsk HPP operating conditions is simultaneous consideration of the basic parameters of three (Bratsk, Ust-Ilimsk, and Boguchany) HPPs. Moreover, when calculating the average winter power of the Angara-Yenisei cascade, it is necessary to take into account the Yenisei cascade operation.

When solving problem (8)–(9), a subset of the matrix (corresponds to the Pareto set) is formed, from which the most acceptable solutions are selected.

For the energy option, the sequence of priorities of criteria (9) will have the form:

$$(\lambda^A, \lambda^B, \lambda^E, \lambda^T) \to \max(\overline{\Omega}_{t_1 \to t_2}), \quad (10)$$

For the transport option, this sequence will have the form:

$$(\lambda^A, \lambda^B, \lambda^T, \lambda^E) \to \max(\overline{\Omega}_{t_1 \to t_2}), \quad (11)$$

In the considered statements, the priorities of the first level are strict compliance with technical and operational constraints and water intake requirements. As a rule, these constraints can be included in each considered reservoir operating curve. Then, generally, the maximization of the availability criteria (11) can be written as follows:

$$(\lambda^E, \lambda^T, \lambda^R, \lambda^S) \to \max(\overline{\Omega}_{t_1 \to t_2}) \quad (12)$$

Some regulation options can be of priority only in certain periods. For example, the priority of reducing the risks of inundation of Irkutsk during periods of increased flow through the hydrosystem or the priority of permissible fluctuations in reservoir water levels under daily and weekly regulation during the periods of fish spawning. These priorities and limitations can be taken into account in problem (8)–(12), the solution to which forms a sustainable option for water resources management in the Angara river basin. A specific feature of the model is the possibility of studying the operating conditions not only throughout the full retrospective period but also at any randomly given time.

In practice, problems (10)–(12) are solved by specialized methods designed to optimize the cascade HPP operating conditions, which are formed based on the long-term reservoir operating curves. The standards established to meet the requirements of water users are determined by the Methodological Instructions on the Development of Reservoir Management Rules.

IV. Formation of long-term scenarios of water inflows into the HPP reservoirs

The reservoir operating curves currently used to manage the HPP operation are based on the statistical characteristics of inflows and allow reservoir levels to be managed according to the current total inflows and achieved water levels in each reservoir. They, however, do not allow long-term planning of water users and consumers' operation. In this regard, an important condition for planning is the development of future water inflow scenarios.

At present, the practice of the HPP operation involves along with the reservoir operating curves, the series of statistical hydrological indices and water availability forecasts provided by the Meteorological Office for a period of up to 1–3 months. As already noted, this does not meet the current needs of water and energy organizations that carry out long-term management and planning of the operation. Furthermore, due to global and regional climate change, the use of meteorological statistics alone for predictive water availability assessments becomes inefficient. Given the significant advances in the development and use of global climate models over the past decades, it seems appropriate to use them for long-term water availability assessments for a period of up to one year. One such model is the global climate model CFS-2 (Climate Forecast System) developed by the Environmental Modeling Center (EMC), a member of the international organization National Centers for Environmental Prediction (NCEP) [31]. This model is used daily to update an ensemble (set) of forecasts of the state of the atmosphere and the ocean with a time interval from several hours to 9 months for the entire globe. The ensemble approach used in the global

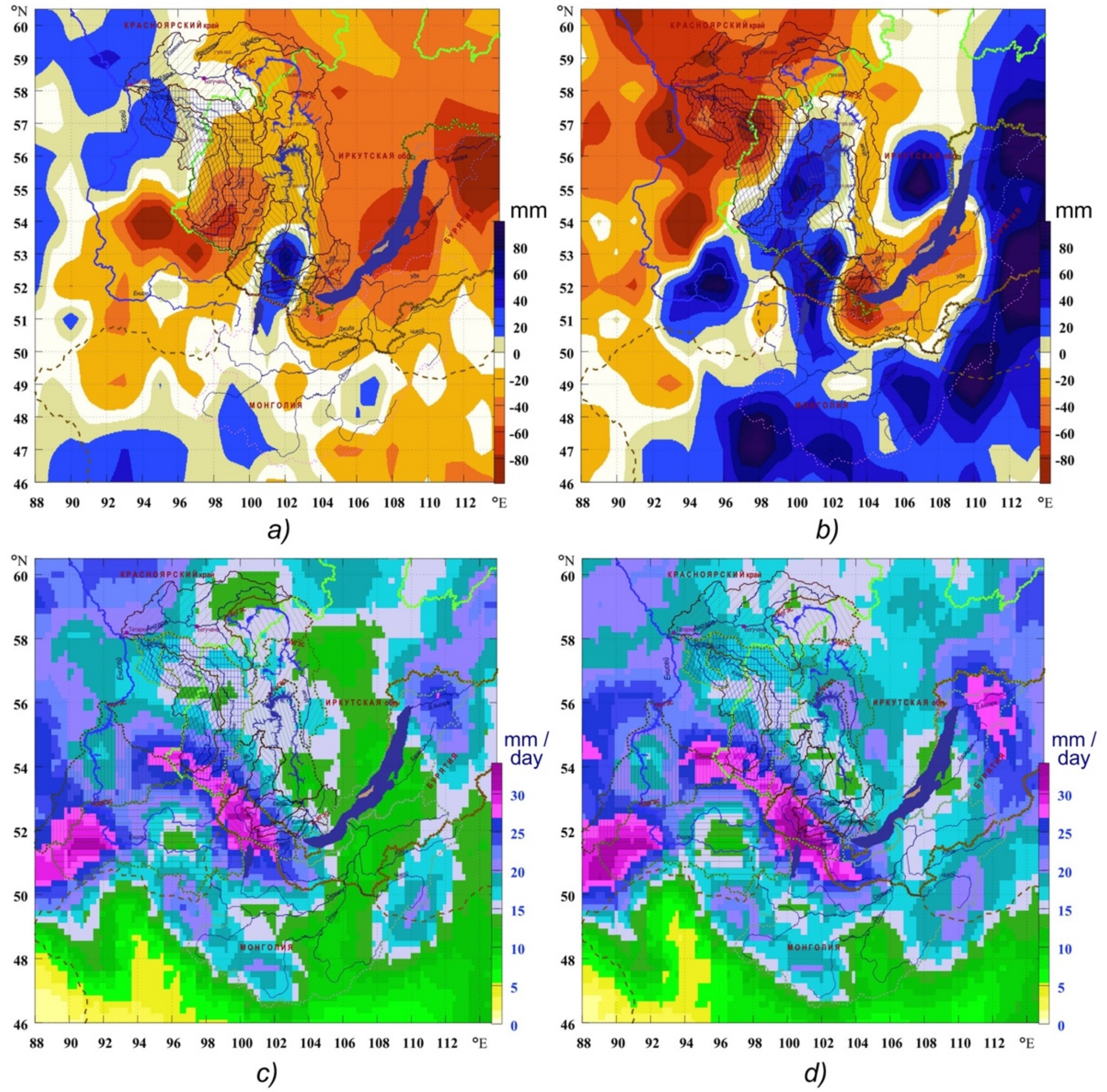

Fig. 6. Examples of anomalies in the Angara reservoir catchment basins: deviation of average summer precipitation in 2014–2017 compared to those in 1996–2013 (a); summer precipitation anomalies in 2018 (b); prognostic indices of precipitation intensities in June (c) and July (d) in 2019 (based on the 10 forecast ensembles of the CFS-2 model).

climatic model allows the probabilistic estimations of the atmosphere state to be formed for a long term.

A research team of the Melentiev Energy Systems Institute SB RAS has developed special components in the GeoGIPSAR system for monitoring, collection, and processing of modeling results. These components make it possible to quickly generate long-term estimates of precipitation, temperatures, pressure, and geopotential in the basins of Lake Baikal, the Angara and Yenisei rivers and periodically update them (weekly, every ten days, monthly, quarterly). Examples of an analysis of the climatic situation in the basins of Lake Baikal and Angara reservoirs in the past period and estimated data of the global models are shown in Fig. 6. The Figures show the estimated data of the global climatic model CFS-2 for the considered region on the anomalies of precipitation and temperature for the period from May to August 2019. The map of temperature anomalies in July-August shows a high probability of increased water for the basins of Lake Baikal and the Angara river and average water in the Yenisei basin.

The processed data of the forecast ensembles of meteorological parameters are used to make estimations of

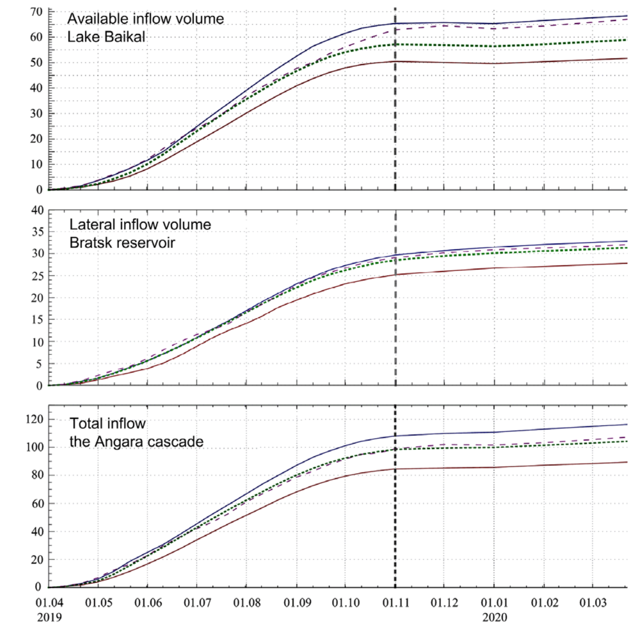

Fig. 7. An example of three forecast scenarios of available water inflow into Lake Baikal (a), lateral inflow into the Bratsk reservoir (b) and total inflow into the Angara HPP cascade (c) for the 2019–2020 water year.

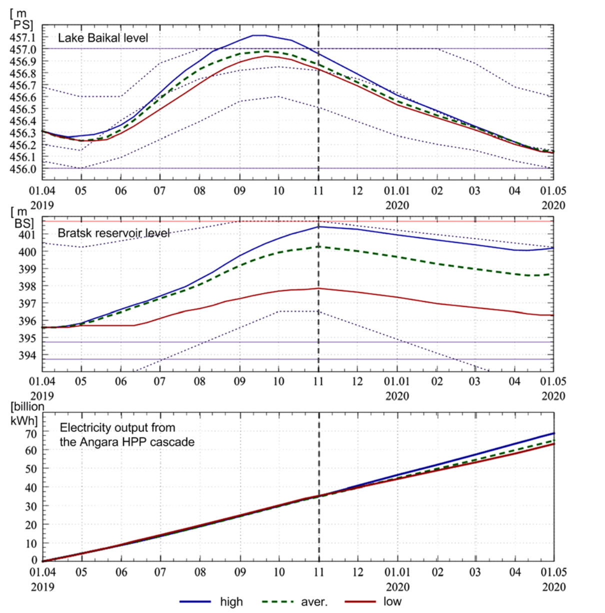

Fig. 8. Modeling of the levels of Lake Baikal, the Bratsk reservoir, and electricity output from the Angara cascade of hydropower plants for the 2019–2020 water year under different inflow scenarios.

the inflows into the cascade reservoirs in the form of ranges of probability distributions. The final prognostic scenarios are determined by an automated procedure including components of a search for analog years, rejection of low-probability events, processing of regression relationships between the meteorological indices and flows in rivers, and refinement of their boundaries using the experts' estimations made with other models [32–35]. Due to the considerable global changes in the regional climate, the study does not consider the technique for the selection of optimal prognostic models based on the machine learning methods, which is related to the need to verify their efficiency based on both retrospective and forecast samples.

Figure 7 shows an example of three scenarios of water inflow into Lake Baikal, the Bratsk reservoir, and the entire Angara HPP cascade for the coming water year, which determines the boundaries of their changes by the total indices.

V. Modeling results

Based on the long-term forecast scenarios of inflows

Table 1. Operating conditions of the Irkutsk HPP (Lake Baikal) – average water availability scenario.

Date	Availablei nflow, m^3/s	Flow through HPP, m^3/s	**Level of Lake Baikal, m PS**	Water level near dam, m PS	Level of the lower reach, m PS	**Live capacity of reserv., km^3**	Gross head, m	Capac. utilizat. factor, %	Availab. power, MW	**Calc. average power, MW**	**Calc. electricity output, mil. kWh**
01.05.2019	2900	1800	**456.23**	455.61	426.31	**21.9**	29	72	662.4	**478**	**355**
01.06.2019	4900	1800	**456.32**	456.01	426.04	**24.6**	30	65	662.4	**430**	**310**
01.07.2019	4800	1900	**456.58**	456.27	426.24	**32.9**	30	72	662.4	**475**	**354**
01.08.2019	4100	2600	**456.83**	456.20	426.95	**40.6**	29	97	662.4	**643**	**479**
01.09.2019	2900	2700	**456.96**	456.30	427.01	**44.6**	29	99	662.4	**657**	**473**
01.10.2019	1200	2400	**456.97**	456.40	426.74	**45.0**	30	89	662.4	**592**	**440**
01.11.2019	-120	1700	**456.87**	456.57	426.03	**41.8**	31	65	662.4	**433**	**311**
01.12.2019	-180	1700	**456.72**	456.39	426.03	**37.1**	30	66	662.4	**435**	**324**
01.01.2020	300	1700	**456.56**	456.20	426.03	**32.0**	30	65	662.4	**433**	**322**
01.02.2020	390	1700	**456.44**	456.06	426.03	**28.3**	30	65	662.4	**433**	**291**
01.03.2020	380	1800	**456.34**	455.85	426.15	**25.1**	30	68	662.4	**452**	**336**
01.04.2020	900	1900	**456.22**	455.53	426.23	**21.3**	29	70	662.4	**462**	**333**
01.05.2020	–	–	**456.14**	–	–	**18.8**	–	–	–	–	–
Average indices by season											
Summer	3470	2200	**456.65**	456.13	426.55	**34.9**	29.5	82	662	**545**	**2410***
Winter	280	1750	**456.53**	456.10	426.08	**30.9**	30.0	67	662	**440**	**1920***
Yearly	1870	1980	**456.59**	456.12	426.32	**32.9**	29.8	74	662	**490**	**4330***

* – total indices

Table 2. Operating conditions of Bratsk HPP – average water availability scenario.

Date	Total inflow, m^3/s	Lateral inflow, m^3/s	Flow through HPP, m^3/s	**Levels of reserv., m BS**	Level of the lower reach, m BS	**Live capacity of reserv., km^3**	Gross head, m	Capac. utilizat. factor, %	Availab. power, MW	**Calc. average power, MW**	**Calc. electricity output, mil. kWh**
01.05.2019	3400	1500	2200	**395.78**	295.87	**18.0**	101	45	4226	**2018**	**1503**
01.06.2019	3700	2000	2200	**396.46**	296.24	**21.2**	101	45	4249	**2045**	**1473**
01.07.2019	4100	2200	2600	**397.24**	296.39	**25.0**	102	53	4290	**2383**	**1774**
01.08.2019	4800	2100	2700	**398.06**	296.43	**29.0**	103	55	4363	**2491**	**1854**
01.09.2019	4200	1500	2700	**399.16**	296.44	**34.6**	103	56	4494	**2536**	**1826**
01.10.2019	3200	900	2600	**399.92**	296.38	**38.5**	104	53	4500	**2406**	**1781**
01.11.2019	2060	360	2600	**400.27**	296.39	**40.4**	104	54	4500	**2445**	**1761**
01.12.2019	1950	250	2600	**400.01**	296.41	**39.0**	103	55	4500	**2475**	**1841**
01.01.2020	1890	190	2600	**399.67**	296.43	**37.2**	103	56	4430	**2512**	**1869**
01.02.2020	1860	160	2500	**399.26**	296.34	**35.1**	103	51	4381	**2304**	**1549**
01.03.2020	1960	160	2500	**398.97**	296.19	**33.6**	102	52	4364	**2362**	**1757**
01.04.2020	2500	600	2500	**398.67**	295.94	**32.1**	103	51	4397	**2297**	**1654**
01.05.2020	–	–	–	**398.68**	–	**32.2**	–	–	–	–	–
Average indices by season											
Summer	3900	1700	2500	**397.77**	296.29	**27.7**	101.8	51	4354	**2310**	**10210***
Winter	2040	290	2550	**399.48**	296.28	**36.2**	103.2	53	4429	**2400**	**10430***
Yearly	2970	990	2530	**398.62**	296.29	**32.0**	102.5	52	4391	**2360**	**20640***

* – total indices

into reservoirs, using the above system of models, the long-term operating conditions of individual hydropower plants and the entire Angara cascade were modeled.

The study on the long-term HPP operation involved the determination of average monthly discharges through the hydrosystems, levels of upper and lower reaches, and live capacities of reservoirs at the beginning of each month. This provides more informed planning of operation of power generating companies and the System Operator in the coming water year, including summer and winter seasons. Depending on the long-term scenario of water availability, the calculated scenarios make it possible to assess the expected electricity output and the average used power from HPPs, other HPP operating parameters (head, capacity utilization factor), to form prospective energy balances in the energy system, and to determine the expected load of thermal power plants.

Tables 1, 2 and Fig. 8 present the results of modeling the long-term operation of the Irkutsk and Bratsk HPPs for the water management year 2019–2020 for the average water availability scenario characterized by the highest probability as of April 2019.

As can be seen from Fig. 8, under the high water availability scenario, for Lake Baikal there is a risk of

Table 3. Power (MW) and electricity output (million kWh) from the Angara HPP cascade under different inflow scenarios.

Inflow scenario	Average										High		Low	
HPP	Irkutsk HPP		Bratsk HPP		Ust-Ilimsk HPP		Boguchany HPP		**Angara Cascade**		Angara cascade		Angara cascade	
Value / Date	Average power (AP)	Electricity output (EO)	AP	EO	AP	EO	AP	EO	AP	EO	AP	EO	AP	EO
01.05.2019	478	**355**	2018	**1503**	1997	**1483**	1739	**1299**	6232	**4640**	5920	**4263**	5849	**4211**
01.06.2019	430	**310**	2045	**1473**	2112	**1521**	1931	**1389**	6518	**4693**	6094	**4533**	6462	**4818**
01.07.2019	475	**354**	2383	**1774**	2277	**1694**	1931	**1436**	7067	**5257**	6627	**4770**	7120	**5126**
01.08.2019	643	**479**	2491	**1854**	2302	**1713**	1931	**1436**	7368	**5482**	7193	**5354**	7068	**5259**
01.09.2019	657	**473**	2536	**1826**	2301	**1658**	1931	**1389**	7424	**5346**	7456	**5546**	7269	**5411**
01.10.2019	592	**440**	2406	**1781**	2153	**1594**	1791	**1325**	6942	**5141**	7510	**5405**	7404	**5330**
01.11.2019	433	**311**	2445	**1761**	2105	**1516**	1720	**1239**	6702	**4826**	7033	**5208**	6964	**5155**
01.12.2019	435	**324**	2475	**1841**	2132	**1587**	1735	**1291**	6777	**5043**	7693	**5539**	6065	**4366**
01.01.2020	433	**322**	2512	**1869**	2169	**1614**	1759	**1309**	6872	**5114**	7749	**5764**	6125	**4557**
01.02.2020	433	**291**	2304	**1549**	2241	**1506**	2005	**1347**	6982	**4693**	7448	**5542**	6223	**4628**
01.03.2020	452	**336**	2362	**1757**	2272	**1690**	2023	**1505**	7108	**5288**	7967	**5353**	6325	**4249**
01.04.2020	462	**333**	2297	**1654**	2283	**1644**	2049	**1475**	7091	**5105**	7944	**5911**	6443	**4793**
Average (MW) and total (million kWh) indices by season														
Summer	545	**2410**	2310	**10210**	2190	**9660**	1875	**8270**	6930	**30560**	6800	**29870**	6860	**30160**
Winter	440	**1920**	2400	**10430**	2200	**9560**	1880	**8170**	6920	**30070**	7640	**33320**	6360	**27750**
Yearly	490	**4330**	2360	**20640**	2190	**19220**	1880	**16440**	6920	**60630**	7220	**63190**	6610	**57900**

exceeding the top of conservation pool (457 m PS) by 10 cm, accompanied by increased flows through the hydrosystem and idle discharges (up to 500 m3/s). The other HPPs of the Angara cascade will have quite favorable conditions for operation, which do not violate the current rules of regulation under all water availability scenarios in the considered period. Under average water availability, all reservoirs, except for the Bratsk one, can be filled up to the levels close to the top of the conservation pool. The available storage capacity of the Bratsk reservoir increases by 14–20 km3 (the last value – for the scenario of high water availability) and for the first time in recent years it is possible to provide the reserves of long-term cascade regulation which will increase the overall stability of the water and energy system operation.

Table 3 shows the estimated electricity and power output from the Angara cascade under different inflow scenarios. The average winter power of the cascade in the case of average water availability will be 6900 MW, under high – 7600 MW, and under low – 6300 MW. The estimated annual electricity output is 60600, 63200 and 57900 million kWh, respectively. Thus, depending on the expected water availability conditions in the coming period, the range of changes in the average winter power of the Angara HPP cascade in the considered period can amount to 1300 MW, and electricity output – to 5300 million kWh.

After updating the expected water availability indices in the first ten-day period of September, given the actual hydrological situation in the Angara and Lake Baikal basins, the achieved marks of reservoir filling, forecast of the Meteorological Office for September and the data of the global climate model, the most probable scenario of inflow for the upcoming autumn-winter and spring season (till May 1 of the next year) can be formed and, on its basis, proposals on efficient operating conditions of the Angara HPP cascade can be prepared. These proposals can be used by the System Operator to make up (specify) the prospective energy balances of power and electricity and to plan the load of thermal power plants in the electric power system of Siberia.

VI. Conclusion

The proposed system of models makes it possible to comprehensively study the efficient use of water resources of the Angara basin and to estimate long-term operating conditions of the Angara HPP cascade, given the water and energy requirements, as well as the impact of natural, climatic and socio-economic factors.

The disadvantage of the modeling methodology based on the long-term forecast water availability scenarios is the probabilistic nature of quantitative estimations. Since it is so far impossible to uniquely make the long-term water availability forecasts for more than 10 days ahead, it is additionally planned to develop a special method of "adaptive management" to improve the efficiency of decisions to be made. This method will be aimed at selecting the management of water flows through hydropower plants, minimizing the risks for each estimated period with periodic (monthly) adjustment of long-term scenarios in the case of significant changes in their probabilities.

The majority of modern methods designed to manage the long-term HPP operation (for the period of more than 3 months) are based on the statistical information of the previous period and do not use other prognostic inflow indices. This leads to a decrease in the efficiency of the HPP operation and an increase in the risk of violating the requirements of water users, especially in low-water and high-water periods. In this regard, given the global and regional climate change in the basins of the Angara river and Lake Baikal in the last two decades, it appears important to build the periodically updated hydrological statistics of various duration.

The developed structure of the HPP operation metamodel includes the knowledge base of the model components and the procedure for the synthesis of individual models. This allows a comprehensive study of the HPP cascade operation, taking into account different approaches, both traditional (based on the reservoir operating curves) and new ones (considering the data of global climate models), which improves the quality of decisions to be made.

The use of the system of models to assess the long-term operating conditions of the Angara cascade of hydropower plants makes it possible to identify possible risks in the operation of the water management system of the Angara basin and the electric power system of Siberia in advance.

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