Environmental and hydrological risks in the Lake Baikal basin water resources management

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Abstract. For optimal water resources management of the Angara reservoirs cascade (a complex "Lake Baikal – Irkutsk, Bratsk, Ust-Ilimsk and Boguchansk reservoirs") and water users provision in the MIKE 11 software a quasi-two-dimensional simulation hydrodynamic model of the Angara hydroelectric power stations (HPS) cascade from Lake Baikal to the Boguchansk HPS downstream, which is a tool for reproducing the features of the water flow hydrodynamic structure, was developed. A hydrodynamic computer model using the built-in module "Regulating structures" module makes it possible to form reasonable operating modes of the Angarsk cascade of reservoirs that meet the most significant requirements of water users: ecology, fisheries and utilities, transport and energy. Hydrodynamic calculations and the flood zones obtained in the GIS project of the territory showed that catastrophic phenomena in the floodplain and coastal zone of Irkutsk occur even when releases into the lower pool of the Irkutsk reservoir exceed 3200 m³/s. The developed hydrodynamic model of the Angarsk cascade of reservoirs makes it possible to determine the objects and floodplain areas most susceptible to flooding in the downstream of the Irkutsk HPS for further development of scientifically based measures to protect them, prevent flooding and develop evacuation plans in an emergency.

1. Introduction

Anthropogenic impacts are serious factors affecting ecosystems in the zone of intensive economic activity. This is facilitated by natural and anthropogenic climate changes. As the result, there is a partial deflation of the soil cover, degradation of landscapes and pollution of the adjacent territory and water bodies [1, 2, 3].

Environmental requirements for the use of Lake Baikal water resources should be developed with reference to restrictions on runoff in the downstream, to Lake Baikal levels and reservoirs of the hydroelectric power station (HPS) cascade on the Angara river. Since a special Federal law regulates Lake Baikal conservation, consideration of environmental requirements should be as complete as possible and should be based on the following provisions:

1) The parameters of the regulated flow and level fluctuations should be as close as possible to the characteristics of the natural water regime.
2) The created quasi-natural water regime should be controlled by the following parameters that have an acceptable range of the specified probability:
- date of the minimum level;
- date of the maximum level;
- the rate of increase in the water level (should not be significantly higher than it would be in natural conditions);
- interannual level variability (should remain equal to its values until the flow is regulated).

All these parameters are probabilistic in nature, the possibility of their implementation is determined both by the accepted management rules in combination with the reservoir regulatory capacity, and by the hydrometeorological conditions of a particular year. Accounting for such requirements as, for example, the preservation of interannual variability is provided at the stage of dispatching rules development, and is not controlled during operational management due to the lack of a long-term large advance inflow forecast. Another part of the parameters that characterize lake recharge in specific hydrometeorological conditions is largely determined by the conditions of the estimated period of regulation and is maintained with a certain confidence level. These parameters (dates of maxima and minima and the recharge rate) is also taken as criteria in the formulation of the optimal dispatch rules. The method of accounting for the formulated environmental requirements is that water balance calculations are based on the possibility of meeting the average values of hydrological parameters that determine the functioning of the ecosystem, and if they cannot be "maintained", a deviation is allowed within the obtained confidence intervals determined (set) using histograms of their distributions [4, 5].

The distribution form of the used hydrological regime characteristic, as well as the distribution parameters that are considered when assigning discharge, are set as follows: when developing dispatching rules for water resources management, the boundaries position of the zones with different parameters of return is assigned based on the possibility of providing such filling modes that maximally correspond to the conditions of the natural regime of water level fluctuations in the lake and its flow. It is clear that it is impossible to maintain an absolutely natural regime, since the use of water resources involves the runoff redistribution between seasons and years in order to guarantee the provision of water resources to various water users, and even with conflicting interests. Therefore, when assigning the values of reservoir discharge (filling) for the calculated time interval, considering environmental restrictions, it is necessary to proceed from those parameters of the mode that can be implemented in this dispatching scheme. Recommendations boil down to the fact that if there is a range of returns within the actual zone of the dispatching schedule, a specific amount of returns should be assigned considering the optimal rate of reservoir filling in a sensitive period for the water ecosystem functioning.

All of the above referred to the case of so-called eustatic level fluctuations, levels that characterize the filling of the control tank and are functionally related to the water supply (volume) in the reservoir (Lake Baikal). These levels are used when assigning reservoir management modes. However, the actual surface of the water in the lake is very complex, since it is distorted by wind denivelations, seiche fluctuations, and distortions due to the distributed inflow and different atmospheric pressure in different parts of the water area. The functioning of water and near-water systems depends very much on these high-frequency fluctuations in levels that vary significantly across the lake's water area. We cannot control the level regime of the lake based on the high-frequency fluctuations (local denivelations) formation features, but we need to get an idea of the real level fluctuations, first of all, in order to understand how environmentally friendly the management is implemented.

To determine the given above criteria (parameters) possible differences from the observed water levels characteristics in the Lake Baikal waters local areas, the level measuring observations data were processed, empirical probability distribution functions were constructed and discussed above parameters of Lake Baikal water level growth probability distribution function during the nesting period in natural and modern conditions were calculated.

The obtained results allow to conclude that the real picture of the lake level impact, considering the entire spectrum of fluctuations on the biotic component, is characterized by greater variability. Of course, the longer the averaging time interval, the smaller the differences, but the choice of indicators
of the current level that most objectively reflect the mentioned impact on the ecosystem is not a closed issue, especially when assessing the admissibility of management modes.

The Irkutsk region is one of the main flood-dangerous regions of Russia. The formation of the hydrosystems operation modes in the period of floods is carried out according to: The Basic Water Resources Use Rules of Angara Hydroelectric Power Stations Cascade Reservoirs (Irkutsk, Bratsk and Ust-Ilimsk) (1988), Regulations of Boguchansky Reservoir Water Use (2015), Project Rules of Water Resources Use in Irkutsk, Bratsk and Ust-Ilimsk Reservoirs (2013). The main documents regulating the lake level regime in years of different probability are: the Federal Law from 01.05.1999 № 94 (ed. from 31.07.2020) “About the Lake Baikal Protection”, the Government Decree of March 26, 2001 № 234 “The Water Level Limit Values in Lake Baikal in the Implementation of Agricultural and Other Activities (until 01.01.2021)” and the Temporary Government Decree of the Russian Federation № 1667 “About the Water Level Maximum and Minimum Values in Lake Baikal in 2018-2020”, which the range of permissible fluctuations in the level is 2.31 m (455.54-457.85 m).

The total discharge capacity of the Irkutsk HPS with the normal operating level and full opening of all outlets is 7040 m³/s, but Irkutsk floodplain part flooding occurs when the total flow rate of the Irkut river and the Irkutsk HPS exceeds the value of 3600 m³/s.

2. Materials and methods
The regulation of the Angara reservoirs cascade is carried out for the number of water user’s needs: public utilities and fisheries, ecology, energy, industrial production and water transport. Flooding of the Irkutsk HPS downstream with water discharge more than 3200 m³/s is also a threat.

For optimal water resources management of cascade and water users provision under the Grant of Russian Foundation for Basic Research on the topic: “Development of optimization approaches to water resources management in reservoirs of the Angara cascade of hydroelectric facilities and justification of Lake Baikal level fluctuations range” in the MIKE 11 software (Danish Hydraulic Institute), a quasi-two-dimensional simulation hydrodynamic model of the Angara HPS cascade from Lake Baikal to the Boguchansk HPS downstream, which is a tool for reproducing the features of the water flow hydrodynamic structure, was developed. The model implements the managing principles of hydroelectric facilities according to the priority’s hierarchy of water users hydraulic requirements using the built-in module "Regulating structures", which is based on a PID controller that supports a set water level value (h) in the upstream (US) of the HPS by changing the amount of releases (Q) [6].

The MIKE 11 software is actively used in the Russian Federation and abroad, for example, to build a hydrodynamic model of the Wan river (India) and determining the performance of the canal system (main and distribution), which allowed the research to decide to revise irrigation schedules [7].

To estimate the water supply of the Xiaoling river in Northern China, a compilation of MIKE SHE with MIKE 11 was used. The model demonstrated good accuracy in calculating the daily flow simulation in the overmoistened zone [8]. The hydrodynamic model of Kanhan river in India allows to assess the impact of diffuse and point sources of pollution on the water quality in the river [9].

In the Russian Federation, hydrodynamic models of the Amur, Don, Kuban, Middle and Lower Volga rivers, etc. were developed on the MIKE 11 software.

The hydrodynamic model of the Angara cascade is a complex "Lake Baikal – Irkutsk, Bratsk, Ust-Ilimsk and Boguchansk reservoirs". Maps of the General Staff scale 1:100,000 and 1:50,000 were used to build the river network. Cross-sections were put on the Angara river route in the "Cross-section" editor with 5 km step, based on a Digital terrain model combined with horizontal maps of various scales and sailing directions. The main hydraulic characteristics were formed for cross-sections in the software (cross-section area, hydraulic radius, water cut width, etc.). Reservoirs volumes in the Angara cascade were set by bathygraphic functions during the modeling. The volume discrepancy was eliminated when calibrating the model by setting additional tanks in cross-sections at the end sections of the reservoirs water area. In the "Boundary data" editor, boundary conditions were set: the level or inflow to Lake Baikal, a function depending on the level of water consumption Q(h) to downstream (DS) of the Boguchansk HPS, the lateral inflow to the Bratsk reservoir (the Irkut, Kitoy, Oka, Iya
rivers), lateral inflow to the Ust-Ilimsk reservoir (the Ilim river) and lateral inflow to the Boguchansk reservoir [10].

The assignment of roughness coefficients along the Angara riverbed was based on the model basic calibration when the flow rate of 1000 m$^3$/s was released into the Irkutsk HPS downstream. Then a vertical calibration was performed directly in the cross sections at a flow rate of 2000 and 4000 m$^3$/s. The initial data for calibration were the curves of $Q = f(h)$ for the hydrosystem upstream and downstream, as well as data obtained from the posts of hydrological observations - Irkutsk, bridge; Irkutsk, river port; Angarsk.

3. Results and discussion

Figure 1 shows the longitudinal profile of the hydrodynamic model obtained in the MIKE 11 software when the flow rate of 1000 m$^3$/s is passed at all hydroelectric units of the cascade.

![Longitudinal profile of the Angara river from Lake Baikal to Boguchansk HPS downstream.](image)

Based on the basic calibration results, the error was no more than 4 cm. After determining the horizontal roughness, a vertical roughness was assigned within each cross-section. As the calculation result, the levels were obtained for characteristic sections, the error during vertical calibration of the model in comparison with the observed data was no more than 5 cm, which may indicate the adequate functioning of the model at the specified discharges. The calibration results are presented in the Table 1.

At the end of July 2019, the increase in the water level in rivers was recorded in the Irkutsk region, which is associated with prolonged heavy rains, occurred in the region. The most intense flood was observed on the Iya river in the Tulunskiy district. From June 25 to 27, 2019, there was a record amount of precipitation, more than the monthly norm by 3.7 times. As the result, there was a large-scale flood with human casualties, automobile infrastructure was partially destroyed, dozens of settlements and more than 6700 residential buildings were flooded.
Table 1. Comparison of calibration results with observed data on Lake Baikal and hydrosystems.

| Section, km | Lake Baikal | US Irkutsk HPS | DS Irkutsk HPS | DS Bratsk HPS | US Ust-Ilimsk HPS | DS Ust-Ilimsk HPS | US Boguchansk HPS | DS Boguchansk HPS |
|-------------|-------------|----------------|---------------|---------------|------------------|------------------|------------------|------------------|
|             |             | Discharge 1000 m$^3$/s (basic calibration) |               |               |                  |                  |                  |                  |
| Observations| 457.09      | 457            | 425.49        | 295.27        | 295.04           | 208.08           | 208.04           | 136.99           |
| Calculation | 457.09      | 457            | 425.49        | 295.27        | 295.04           | 208.08           | 208.04           | 136.99           |
| Error, cm   | 0.00        | 0.00           | -0.01         | 0.02          | 0.04             | -0.02            | 0.04             | -0.01            |
|             |             | Discharge 2000 m$^3$/s |               |               |                  |                  |                  |                  |
| Observations| 457.25      | 457            | 426.83        | 295.7         | 295.03           | 208.19           | 208.04           | 137.7            |
| Calculation | 457.3       | 456.97         | 426.86        | 295.74        | 295.03           | 208.19           | 208.04           | 137.65           |
| Error, cm   | 0.05        | -0.03          | 0.03          | 0.04          | 0.03             | -0.01            | 0.04             | -0.05            |
|             |             | Discharge 4000 m$^3$/s |               |               |                  |                  |                  |                  |
| Observations| 457.9       | 457            | 428.35        | 296.8         | 295              | 208.55           | 208.04           | 138.6            |
| Calculation | 457.85      | 457.03         | 428.32        | 296.76        | 294.97           | 208.51           | 207.96           | 138.65           |
| Error, cm   | -0.05       | 0.03           | -0.03         | -0.04         | -0.03            | 0.01             | -0.04            | 0.05             |

Due to the development of rain flooding in the Barguzin and Selenga rivers in September 2020 (according to the Federal hydrometeorological service), the inflow to Lake Baikal was predicted up to 130% of the norm. To pass the flood, it was necessary to increase the discharge from the Irkutsk HPS to 2700 m$^3$/s, such releases are set for non-flooding of Irkutsk and suburban areas, but the increase in the release may lead to flooding of the coastal part of the city. From September 14 to 30, the level of the Irkutsk reservoir exceeded 457.05 m, and on September 30, it was 457.11 m of Pacific height system (PHS).

In connection with the current hydrological situation on the instructions of the Federal Agency for water resources of Russia (Rosvodresursy) and the Ministry of civil defense, emergencies and disaster relief of the Russian Federation (EMERCOM of Russia) based on the observed data for September 2020, the calculation was made on the Angara reservoirs cascade hydrodynamic model to increase the releases to the downstream of the Irkutsk HPS from 2700 m$^3$/s to 3200 m$^3$/s and to determine the zones of possible flooding in accordance with the rules for using Angara reservoirs. Table 2 shows the comparison of water levels in the DS Irkutsk HPS at the discharge of 2700 and 3200 m$^3$/s. Figure 2 below shows the flood zones based on the developed digital elevation model (DEM).

Table 2. Water levels in the releases from Irkutsk HPS.

| № section | Level in the DS releases from Irkutsk HPS of 2700 m$^3$/s, m PHS | Level in the DS releases from Irkutsk HPS of 3200 m$^3$/s, m PHS |
|-----------|---------------------------------------------------------------|---------------------------------------------------------------|
| 1         | 427.53                                                       | 427.9                                                        |
| 2         | 427.19                                                       | 427.54                                                       |
| 3         | 426.16                                                       | 426.48                                                       |
| 4         | 423.87                                                       | 424.26                                                       |
| 5         | 422.75                                                       | 423.22                                                       |
| 6         | 421.5                                                        | 422.1                                                        |
Figure 2. The flood zones for the calculated levels in Irkutsk HPS DS at discharges 2700 m$^3$/s and 3200 m$^3$/s.

It should be noted that the flood zones obtained from the used DEM and actually observed do not coincide in area. Therefore, it is necessary to make a DEM development and refinement, using remote sensing methods.

Also, on the instructions of the Federal water resources Agency and the EMERCOM calculations were performed to determine the time of the wave's arrival to the possible flooding sections in Irkutsk HPS downstream (determining the time of arrival of the maximum water levels for 6 sections in the city and the suburban areas). The Figure 3 and the Table 3 show the calculations results.
**Figure 3.** Dynamics of wave arrival along the lines from the Irkutsk HPS downstream.

**Table 3.** The maximum wave arrival along the lines from the Irkutsk HPS downstream.

| № section | Distance from Lake Baikal, km | maximum level arrival time | Level, m | maximum discharge arrival time | discharge m³/s |
|-----------|------------------------------|----------------------------|---------|-------------------------------|---------------|
| 1         | 55.6                         | 12:00                      | 427.86  | 12:00                         | 3200          |
| 2         | 59.5                         | 12:15                      | 427.5   | 12:10                         | 3180          |
| 3         | 64.9                         | 13:20                      | 426.43  | 12:40                         | 3160          |
| 4         | 70.1                         | 15:15                      | 424.14  | 14:20                         | 3130          |
| 5         | 75.3                         | 18:15                      | 423.02  | 16:05                         | 3090          |
| 6         | 79.3                         | 20:15                      | 421.86  | 17:20                         | 3060          |

In order to protect the unique ecological system of Lake Baikal, a special regime is established for agricultural and other activities carried out in accordance with the following principles (the Federal Law from 01.05.1999 № 94 “About the Lake Baikal Protection”):
- Priority of activities that do not lead to violation of the unique ecological system of Lake Baikal and the natural landscapes of its water protection zone;
- Registration of the agricultural and other activities complexity impact on the unique ecological system of Lake Baikal;
- Balanced solution of socio-economic problems and protection of the Lake Baikal unique ecological system based on the sustainable development principles; mandatory state environmental expertise.

There is a ban on raising the water level in Lake Baikal above the maximum values of 457 m and lowering the water level in Lake Baikal below the minimum values of 456 m. When maintaining the Lake Baikal level at maximum levels, negative consequences were noted: destruction of feeding reservoirs, coastal erosion, erosion of island ridges.

The operating mode of the Irkutsk HPS was formed, which makes it possible to meet the requirements of the fisheries to maintain the control mark of the minimum drawdown of Lake Baikal level in April 456.03 m (Explanatory note to the draft Rules for the use of water resources of the
Irkutsk reservoir and Lake Baikal, 2013). In this case, the regulation of the lake is carried out in the range of 1 m, as shown in the Figure 4.

![Figure 4. Results of modeling the scenario to meet the requirements of ecology and fisheries.](image)

4. Conclusion

1) A hydrodynamic computer model using the "Regulatory Structures" module makes it possible to form reasonable operating modes of the Angarsk cascade of reservoirs that meet the most significant requirements of water users: ecology, fisheries and utilities, transport and energy.

2) Hydrodynamic calculations and the flood zones obtained in the GIS project of the territory showed that catastrophic phenomena in the floodplain and coastal zone of Irkutsk occur even when releases into the lower pool of the Irkutsk reservoir exceed 3200 m³/s.

3) The developed hydrodynamic model of the Angarsk cascade of reservoirs makes it possible to determine the objects and floodplain areas most susceptible to flooding in the downstream of the Irkutsk HPS for further development of scientifically based measures to protect them, prevent flooding and develop evacuation plans in an emergency.

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