Integrated water resources management in large river basins based on simulation modeling and optimization methods

Real-time water resource management using optimization methods and multi-criteria analysis, “Lake Baikal – Irkutsk Reservoir” case study

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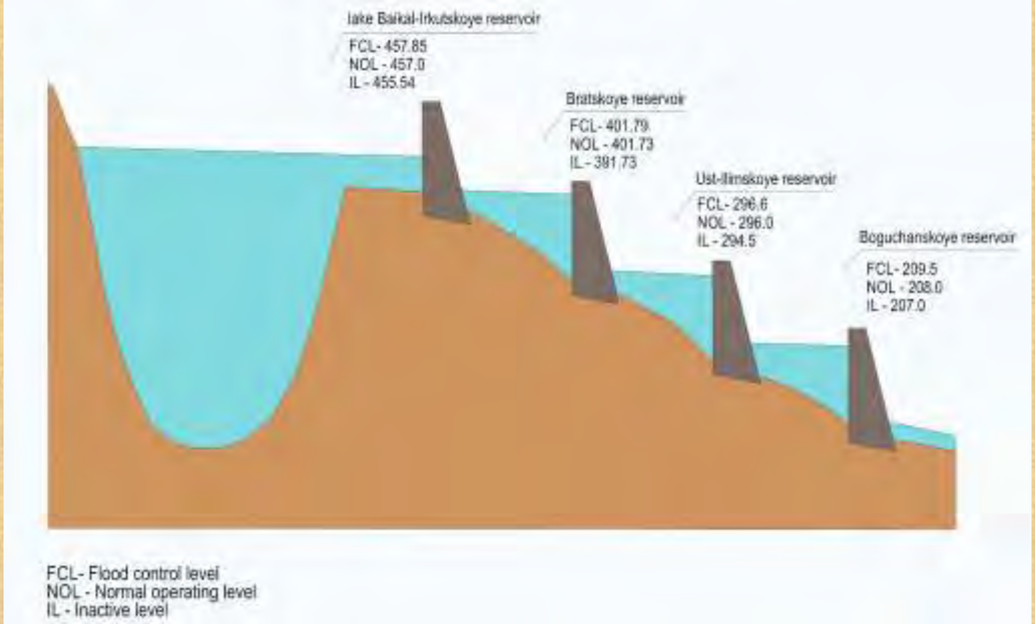
4. Integral indicators of reliability are proposed.
5. Development of release rules for managing water resources in real time based on optimization methods.
6. Practical justification of the proposed release rules based on optimization methods.

The Angara River Cascade of reservoirs



Baikal: the total volume - 23600 cubic km, depth - 1642 m, average annual inflow - 60 cubic кm

Reliability standards for normal water consumption by the number of not violation years, percent:

97 - 99	Sanitary releases
95 - 99	Water supply (drinking, household, industrial)
85 - 95	Hydropower
85 - 90	Navigation (to maintain depths)
75 - 90	Irrigation and agricultural flooding
75 - 90	Fisheries

Lake Baikal - Irkutsk reservoir

$$W^{t+1} = W^t + Q^t - R^t$$

Balance equations

$$\nabla H^t = F(W^t)$$

Bathygraphic function "Baikal lake level - the volume of water"

$$\nabla \overline{H^t} = F(\nabla H^t, R^t)$$

Dependence of the USL on the Baikal level and Irkutsk release

$$\nabla \underline{H^t} = F(R^t)$$

Dependence of the Downstream level on the Irkutsk reservoir release

$$N^t = F(\nabla \overline{H^t}, \nabla \underline{H^t}, R^t)$$

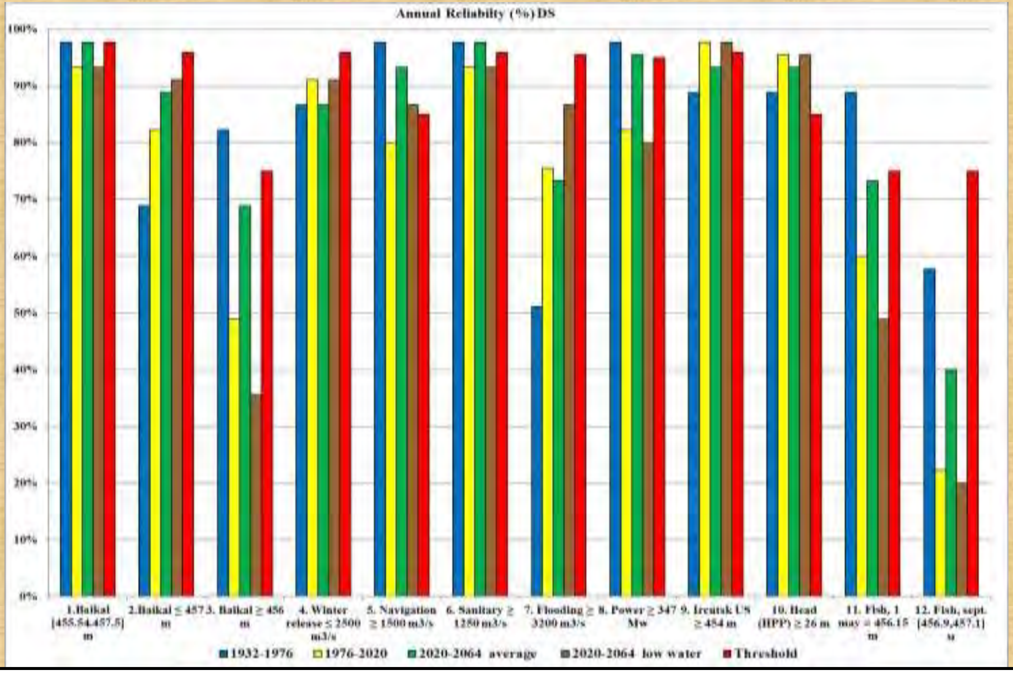
Hydropower

Here: t - time interval, W -the volume of the Baikal, Q - the inflow, R - release

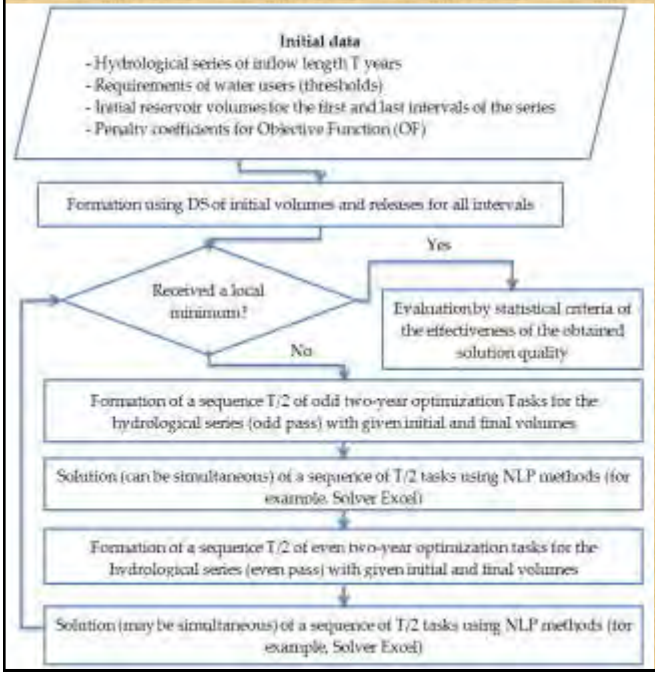
Water users' requirements form 12 criteria

1. The Lake Baikal level should be in range (455.54, 457.5) m;
2. The Lake Baikal level should be ≥456 m, [25];
3. The Lake Baikal level should be ≤457 m, [25];
4. The maximum release in winter should be less than 2500 m^3/s;
5. The transport release during navigation should be more than 1500 m^3/s;
6. The release for water supply should be in range of (1250, 1300) m^3/s;
7. Flood control release should be less than 3200 m^3/s;
8. Guaranteed winter power should be more than 347 MW;
9. The Irkutsk reservoir upstream level for water intakes operation should be more than 454 m;
10. The pressure on the dam for HPP operation should be more than 26 m;
11. The Lake Baikal level on May 1 for normal fish spawning should be 456.15 m;
12. The Lake Baikal level during September for normal fish spawning should be 457 m.

Annual Reliability: Water resource calculated (WRC) by Dispatch schedule (DS)



The algorithm flowchart of optimal releases for solving a reservoir task



Initial data
- Hydrological series of inflow length T years
- Requirements of water users (thresholds)
- Initial reservoir volumes for the first and last intervals of the series
- Penalty coefficients for Objective Function (OF)

Formation using DS of initial volumes and releases for all intervals

Received a local minimum?

Yes

Evaluation by statistical criteria of the effectiveness of the obtained solution quality

No

Formation of a sequence T/2 of odd two-year optimization Tasks for the hydrological series (odd pass) with given initial and final volumes

Solution (can be simultaneous) of a sequence of T/2 tasks using NLP methods (for example, Solver Excel)

Formation of a sequence T/2 of even two-year optimization tasks for the hydrological series (even pass) with given initial and final volumes

Solution (may be simultaneous) of a sequence of T/2 tasks using NLP methods (for example, Solver Excel)

The mathematical setting of the ith two-year task: minimize objective function (OF):

$$F_{2i-1,2i}(W,R) = \sum_{k\in[1,K]} C_k \times \left(\sum_{m\in[1,M]} \Delta^2_{2i-1,m,k}(W_{2i-1,m},R_{2i-1,m},W_{2i-1,m+1}) + \sum_{m\in[1,M]} \Delta^2_{2i,m,k}(W_{2i,m},R_{2i,m},W_{2i,m+1})\right)$$

Under the following constraints on the variables W and R:

$$W_{2i-1,1} + P_{2i-1,1} - R_{2i-1,1} = W_{2i-1,2};$$

……………………………

$$W_{2i-1,m} + P_{2i-1,m} - R_{2i-1,m} = W_{2i-1,m+1};$$

……………………………

$$W_{2i-1,M} + P_{2i-1,M} - R_{2i-1,M} = W_{2i,1};$$

$$W_{2i,1} + P_{2i,1} - R_{2i,1} = W_{2i,2};$$

……………………………

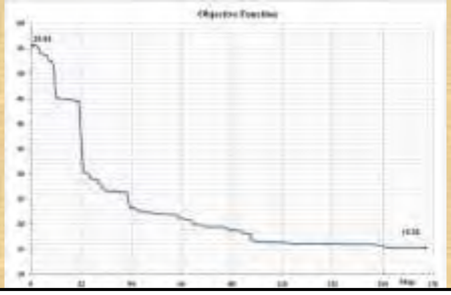
$$W_{2i,m} + P_{2i,m} - R_{2i,m} = W_{2i,m+1};$$

……………………………

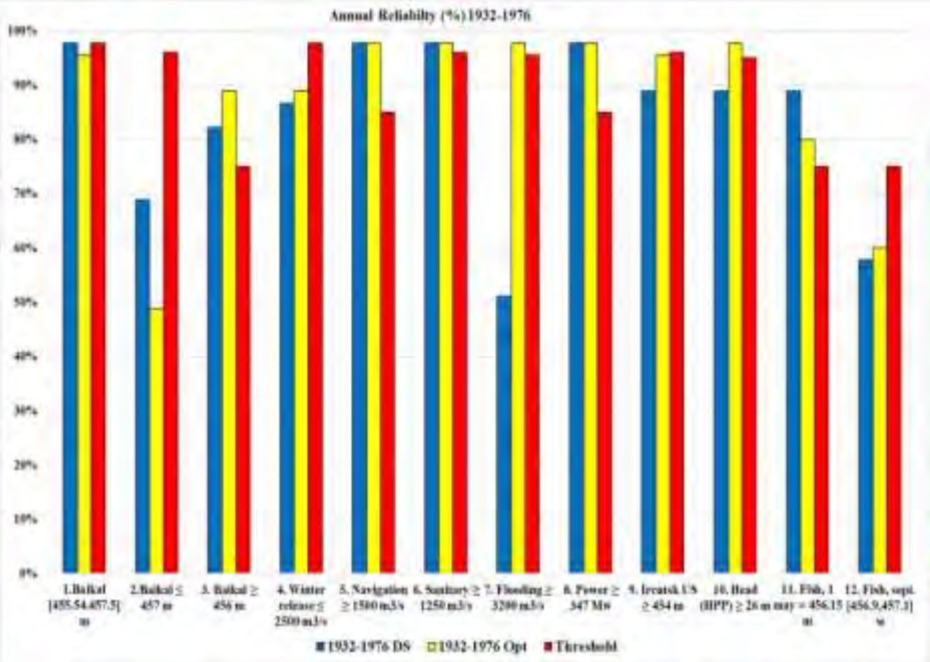
$$W_{2i,M} + P_{2i,M} - R_{2i,M} = W_{2i+1,1};$$

$$W_{2i-1,1} = W^{0}_{2i-1,1};\ W_{2i+1,1} = W^{0}_{2i+1,1};$$

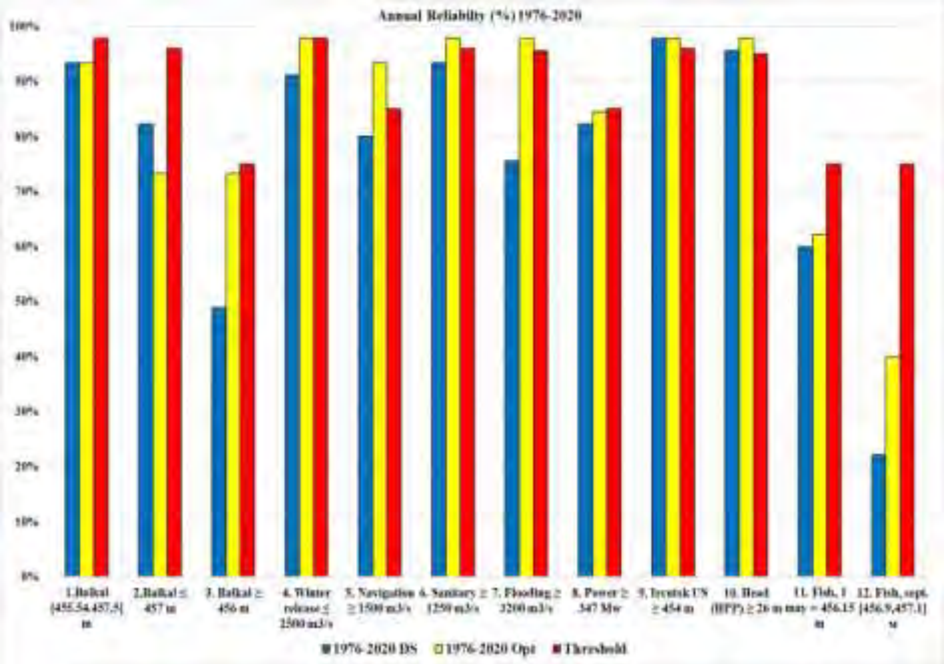
$$W_{2i-1,m} \ge 0,\ W_{2i,m} \ge 0,\ R_{2i-1,m} \ge 0\ R_{2i,m} \ge 0,\ \forall m = [1,M]$$



Annual Reliability: WRC by DS and using optimization (1932-1976)



Annual Reliability: WRC by DS and using optimization (1976-2020)



Statistical analysis of the water resources management quality

The integrated normalized reliability index (INRI) is defined as the sum of failure for all criteria, divided by the number of years in the time series. It is determined by the formula:

$$\mathbf{INRI} = \Sigma_{k=[1,K]} (1 - \mathbf{Reliability}^{k}[X])$$

Reliabilty^k[X] is the reliabilty (in fractions) for the kth criterion, K is the number of criteria.

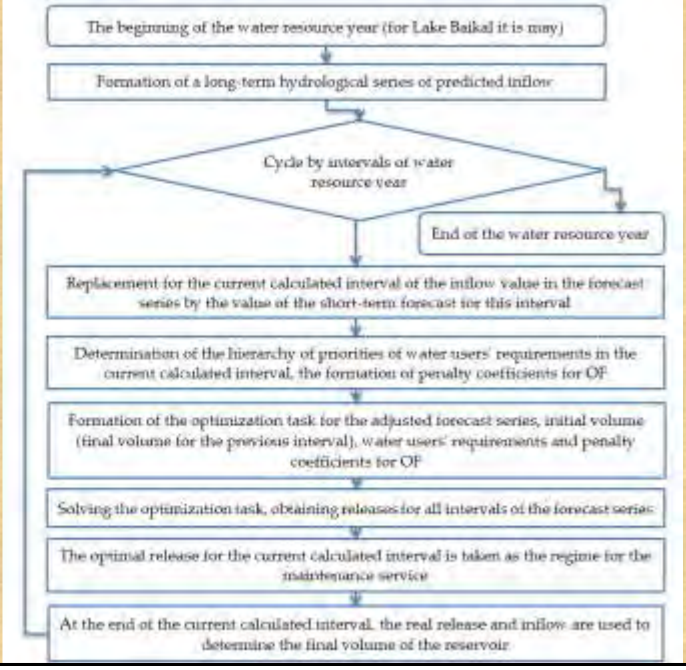
Normative reliability **T_{INRI}** is threshold for **INRI** :

$$T_{INRI} = \Sigma_{k=[1,K]} (1 - T^{k})$$

T^k is the normative security for the kth criterion expressed in fractions

Time Series of Inflow	WRC Using DS	WRC Using Optimization	Improvement%
1932–1976	1.96	1.53	22%
1976–2020	2.78	1.91	31%
2020–2064 average	1.98	1.33	33%
2020–2064 low water	2.80	1.47	48%
T_{INRI}	1.33	1.33	

The flowchart of the reservoir release rule algorithm in real time



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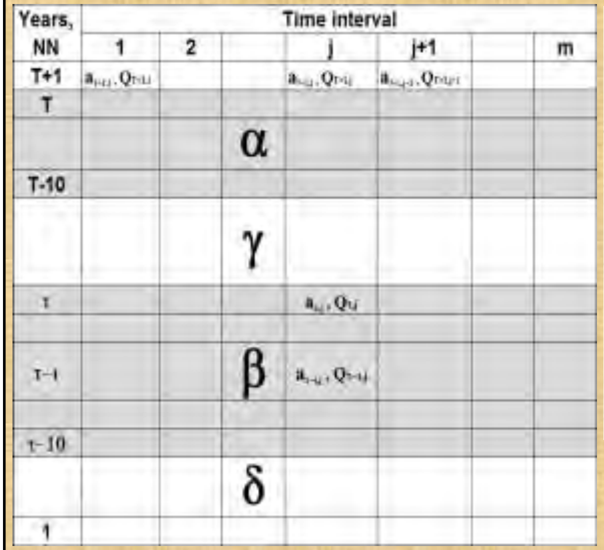
The long-term forecast hydrological series for optimization calculations



Years, NN	Time interval 1	2		j	j+1		m
T+1	$a_{T+1,1}, Q_{T+1,1}$			$a_{T+1,j}, Q_{T+1,j}$	$a_{T+1,j+1}, Q_{T+1,j+1}$		
T							
			α				
T-10							
			γ				
τ				$a_{\tau,j}, Q_{\tau,j}$			
τ-1			β	$a_{\tau-1,j}, Q_{\tau-1,j}$			
τ-10							
			δ				
1							

1. An 11-year array **α** in the initial hydrological series **P** is allocated, the final year of which is the year **T** of the **P** series, and the initial year is the year **T-10**, respectively.

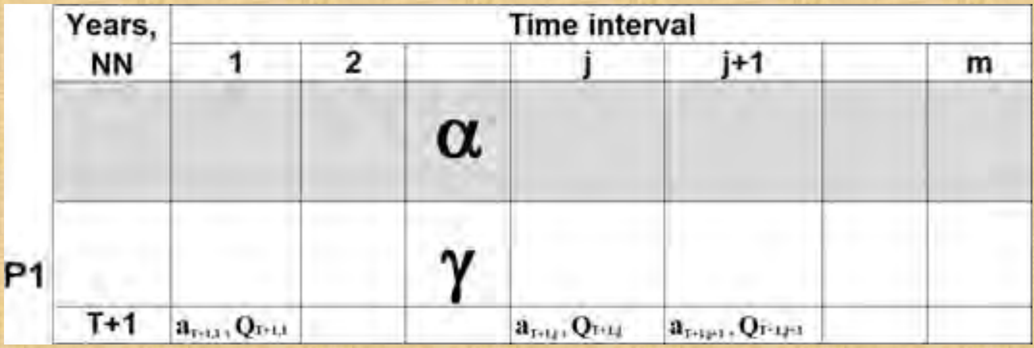
2. We find the 11-year array **β** in the initial hydrological series **P** close to the 11-year-old array **α** ($\alpha \cong \beta$) in the accepted measure. At the same time, the last year **τ** in the array **β** must satisfy the condition **T-10> τ** (the arrays **α** and **β** are assumed to be disjoint). The proximity measure can be determined by the formula:

$$\|\alpha - \beta\| = \Sigma_{i\in[0,10]} \Sigma_{j\in[1,m]} \mathrm{abs}(a_{T-i,j} - a_{\tau-i,j});$$

where $a_{\tau,j}$ is the inflow in the year **τ** and the interval **j** (Figure 1).

3. Let **γ** be the array the array separating **α** and **β** (see figure 1). The number of years T_γ in the array **γ** obviously satisfies the condition $T_\gamma \geq 0$ due to the disjointness of **α** and **β**. Thus, the hydrological series **P** is divided into 4 arrays: **P = {α+γ+β+δ}** (Figure 1), where the array **δ** is the set of remaining years below **τ-10**.

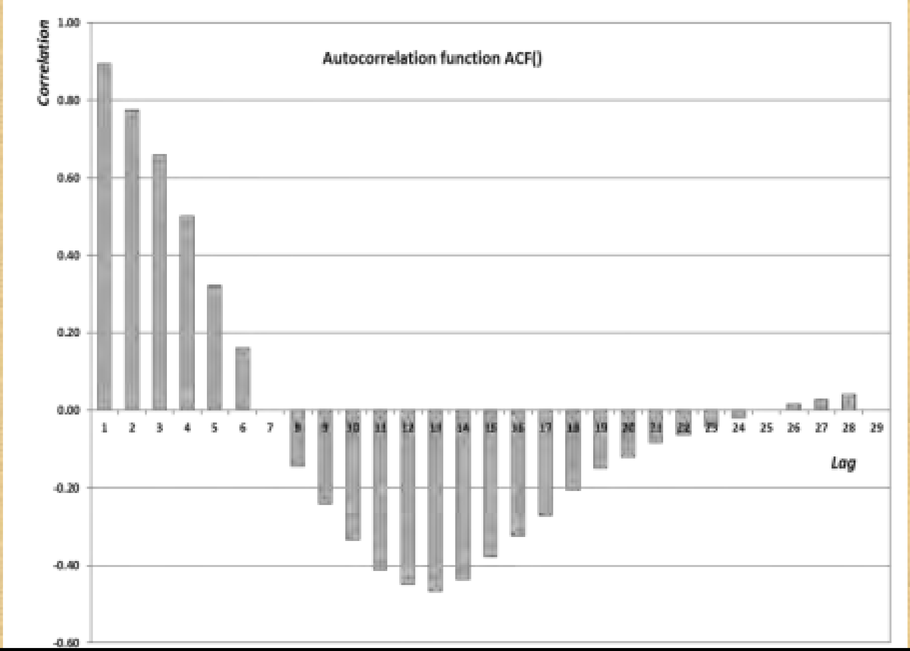
The long-term forecast hydrological series for optimization calculations



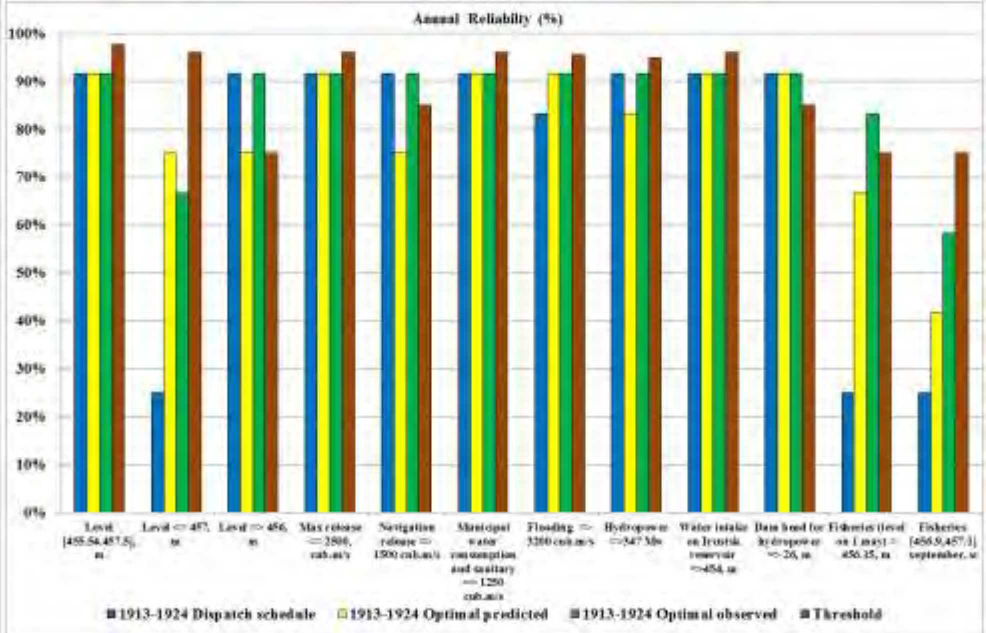
	Years, NN	Time interval 1	2		j	j+1		m
				α				
P1				γ				
	T+1	$a_{T+1,1}, Q_{T+1,1}$			$a_{T+1,j}, Q_{T+1,j}$	$a_{T+1,j+1}, Q_{T+1,j+1}$		

4. A new hydrological series $P_1=\{\gamma+\alpha\}$ is being formed, beginning in the current **(T+1)**-th year, which will be used as a model in the calculation of operating modes based on optimization methods.

Autocorrelation function for the relative difference curve



Practical evidence (verification) of the reservoir release rule algorithm proposed Annual Reliability: WRC by DS and using optimization (1913-1924)



Statistical analysis by INRI of the qualityof the reservoir release rule algorithm proposed

WRC type and Time Series of Inflow	Integrated normalized reliability index (INRI)
1913-1924 Dispatch schedule	3.08
1913-1924 Optimal by predicted	2.33
1913-1924 Optimal by observed	1.67
T_{INRI}	1.33

Conclusion

Based on the research carried out, the following conclusions can be drawn:

1. The dispatch schedule of 1988 does not give reliable results when performing water resource calculations on modern hydrological series, in comparison with the inflow series on the basis of which it is built.
2. The inflow genesis has changed (there was an intra-annual change in runoff), and the average annual inflow has decreased significantly over the past 44 years (by 13%).
3. For normal operation of the Irkutsk reservoir, it is necessary to develop a new dispatch schedule that would consider modern hydrology (last 20 – 30 years), modern requirements of water users and modern priorities.
4. Water resource calculations based on optimization methods give results in terms of reliability, resilience and vulnerability, much better than when using DS.
5. Developed a mathematical model, an algorithm and computer technique for the formation of the reservoir optimal trade-off operation modes in real-time (for the next time interval) based on optimization methods.
6. For the implementation of the computer technique, a unique optimization algorithm was developed that allows for quick solving of complex nonlinear tasks of large dimensions.
7. Methods for a comprehensive assessment of the developed rules for reservoir management (release rule) are proposed

Scheme of the “Lake Baikal – Irkutsk reservoir” complex and the location of gauging stations

Thanks for attention

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