Modern Civil Engineering (ISSN 2470-4180)
December 2023, Volume 3, No. 9-12, pp. 141-153
Doi:10.15341/mese(2470-4180)/09-12.03.2023/001
Academic Star Publishing Company, 2023
www.academicstar.us

Real-time Water Resource Management Using Optimization Methods and Multi-Criteria Analysis: "Lake Baikal - Irkutsk Reservoir" Case Study

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Abstract: The study presents mathematical methods, algorithms and computational technologies that make it possible to form operational modes of the reservoirs in various hydrological conditions, taking into account the hierarchy of priorities of water users' requirements based on dispatch schedules and optimization methods. In the proposed computing technology, a statistical forecast is carried out for several years (tens of years) based on the last years of the historical inflow, which reflect the ongoing climatic changes, and on this series the optimization task of the releases formation is solved, starting from a given initial reservoir volume. The optimization task is obtained with a dimension more than 1000 variables, solved by special methods developed by the authors in a classical deeply nonlinear setting. The water management system "Lake Baikal-Irkutsk Reservoir" was used as an object of research. Operations are carried out using dispatch schedules (DS), developed in 1988 (and currently in use) on the basis of long-term hydrological series of the observed inflow and statistical analysis methods. Changing climatic conditions are impacting the effectiveness of the schedules. Water resourcet calculations were performed for various inflow series scenarios according to dispatch schedules and optimization methods for the modern requirements of water users. Multi-criteria analysis by statistical summaries of performance criteria (reliability, resilience, vulnerability) showed that the operating DS does not provide control with normative reliability in recent years and in the low-water period, but the optimization approach does. The results indicate that it is necessary to 1) develop DS on historical hydrological series over the past 20-30 years, and not on the entire series, 2) update DS every 10 years, 3) Create tools that allow you to manage in real time using the optimization approach suggested in this case study. The study also proposed methods for creating a long-term multi-year inflow forecast for performing optimization calculations. The calculations were carried out using a specially developed software using the Visual Basic language in the Excel with a built-in Solver optimizer.

Key words: water resource calculation, dispatch schedule, inflow time series, release rules, optimization methods, multi-criteria analysis

1. Introduction

In the basins of large rivers with a large number of the river hydropower reservoirs, it is necessary, on the one hand, to make operating decisions on the interconnected passage of flood through waterworks, on the other hand, to ensure guaranteed water supply to all water consumers and users during the low water period. At the same time, considering the forecast and actual inflow to the reservoirs cascade, it is necessary to meet the following water management system participant's requirements to the discharges and water levels:

- Not to allow levels in reservoirs forced above the Flood control level until the capacity of the spillways is completely exhausted;
- When carrying out different activities, to maintain the limiting levels of water filling in reservoirs.

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- To prevent releases into the downstream reservoir, leading to damage from flooding of developed floodplain lands.
- Ensure energy release in volumes determined by the rules;
- Meet the requirements of water users: energy, navigation, municipal engineering, ecology, agriculture, and fisheries and others — in the amounts determined by the rules;
- Maintain fishery releases during the spawning period, while preventing even short-term drops in reservoirs water levels;
- Maintain agricultural releases during the growing season (April-September);
- Provide water users with guaranteed reliability.

A typical example of an object requiring the solution of such a problem is the Angarsk cascade of reservoirs, including: lake Baikal, Irkutskoye, Bratskoye, Ust-Ilimskoye and Boguchanskoye reservoirs. The Angarsk cascade of reservoirs was constructed for producing renewable hydroelectric energy, transportation through the Angara and Yenisei Rivers, and for avoiding floods. As an example, we will use a water management system that includes Lake Baikal and the Irkutskoye reservoir. The upper reservoir (Irkutsk Dam) is used to regulate the level of Baikal Lake. Baikal is the largest freshwater lake in the world, containing more than 20% of the world's fresh surface water. The total volume is more than 23,000 cubic kilometers, the average inflow per year is 60 cubic km. Baikal contains more water than all the North American Great Lakes together. With a maximum depth of 1642 m Baikal is the world's deepest and cleanest lake. Baikal is home to thousands of species of plants and animals, many of which exist nowhere else in the world. Baikal was declared a UNESCO world heritage site in 1996.

The operational management of reservoir operation modes in Russia is carried out using dispatch schedules (DS), developed on the basis of long-term hydrological series of the observed inflow, water user demands and statistical analysis methods. The "Lake Baikal–Irkutsk Reservoir" schedules were developed in 1988. Changing climatic conditions are reducing the effectiveness of the DS. Therefore, DS must be developed on the basis of the hydrological series of recent years, and not on the entire historical series of observed inflows, which distorts the flow parameters. In addition, it is necessary to use the tools to find the optimal DS configuration, providing the best reliability of the release rules. Studies of operating methods, based on the dispatch schedule's parameters optimization, are described in [1].

In the article [2] provides methods for improving dispatcher schedules, taking into account the forecast for the next 2 periods (a decade, a month). Alternative approaches to constructing the optimal configuration and dispatch schedules based on genetic algorithms are described in articles [3, 4].

However, as practice shows, the use of optimization methods when performing water resources calculations for long-term series of inflows gives significantly better indicators of the release rules reliability than DS.

The purpose of the research presented here is a multi-criteria analysis of the Irkutsk reservoir operating modes under different hydrological conditions, based on dispatch schedules and optimization methods. The article presents mathematical methods, algorithms and computational technologies for the formation of reservoir operation modes, allowing one to consider the long-term interval hydrological inflow series observations and the water users' requirements priorities hierarchy. The research was carried out on the basis of the stochastic hydrology method use, optimization methods and the theory of making trade-offs decisions, set out in Chapter 9 of Loucks and van Beek, 2017 [5].

In the proposed computing technology, a statistical forecast is carried out for several years (tens of years) using the last years of the historical inflow, which reflect the ongoing climatic changes, and on this series the optimization task of the releases formation is solved, starting from a given initial reservoir volume. The optimization task with a dimension of about 1000 variables is formulated, which is solved by special methods developed by the authors in a classical deeply nonlinear setting. It should be noted that in all publications, optimization is generally used only as a means of strategic planning and as a tool for building "good" release rules.

The studies have assessed climate changes in recent years and how these changes affect the management of the reservoir, according to the accepted release rules (DS). For different inflow series, water resource calculations were carried out according to the current rules, and with the help of optimization with the modern requirements of water users. Calculations have shown the genesis of climate change. On the basis of multi-criteria analysis by statistical criteria, it was shown that the operating DS does not provide control with normative reliability in recent years and in the low-water period, but the optimization approach does. To solve the problems of water resources management, special optimization algorithms were developed and used for calculations. Also, an algorithm for constructing a long-term multi-year hydrological forecast was developed, which is necessary when generating releases in real time. In practical work, 11-year series of recurrence were used, based on 11-year cycles of solar activity by Schwabe.

Experimental confirmation of the correctness of the developed optimization approach was carried out for the historical series from 1914 to 1924. Unfortunately, it is impossible to rigorously prove mathematically that the proposed algorithm gives better management than for DS for any reservoirs. The calculations were carried out using a program specially developed in the Visual Basic language with the Solver optimizer built into the Excel.

2. Material and Methods

In Russia, requirements documents have been adopted on the development of reservoirs water resources use rules, which define the requirements for the construction of release rules based on dispatch schedules, formulate the procedure for regulating reservoirs according to dispatch schedules, and provide criteria for assessing their reliability.

The dispatch schedule establishes the flow regulating rules for the reservoir, allowing to determine the releases from the reservoir depending on the water level, inflow forecast and the period of the year (decade, month).

In the general case, the dispatch schedule is a set of piecewise linear functions (interruption lines), sorted in descending order, and defined on a discrete set of time periods (decade, month). For each zone between two adjacent interruption lines, the range of levels and releases allowed for that zone in the given period is set. Fig. 1 shows the DS of "Lake Baikal – Irkutsk Reservoir" in graphical form, and Fig. 2 in tabular form.

The following two principles for managing of the reservoir operation according to Dispatch schedules (direct and reverse) have been adopted:

1) The water level at the dam at the end of the estimated time period is determined by the level at the beginning of the period, the forecast inflow and the range of acceptable releases, for the zone in which the level was located at the beginning of the period.

2) The water level at the dam at the end of the estimated time period is determined by the level at the beginning of the period, the forecast inflow and the range of allowable releases, for the zone in which the level will be at the end of the period.

The Fig. 3 shows two operation mode control options: in the first one, the reset range is taken for zone m + 1, in the second for zone m. You can see this ranges on the Fig. 3 for m+1 and m zone.

In the Excel environment on the Visual Basic language, a software for performing water resource calculations of the "Lake Baikal – Irkutsk Reservoir" was developed using long-term inflow series based on the specified coordinates of dispatch schedules (Fig. 4).

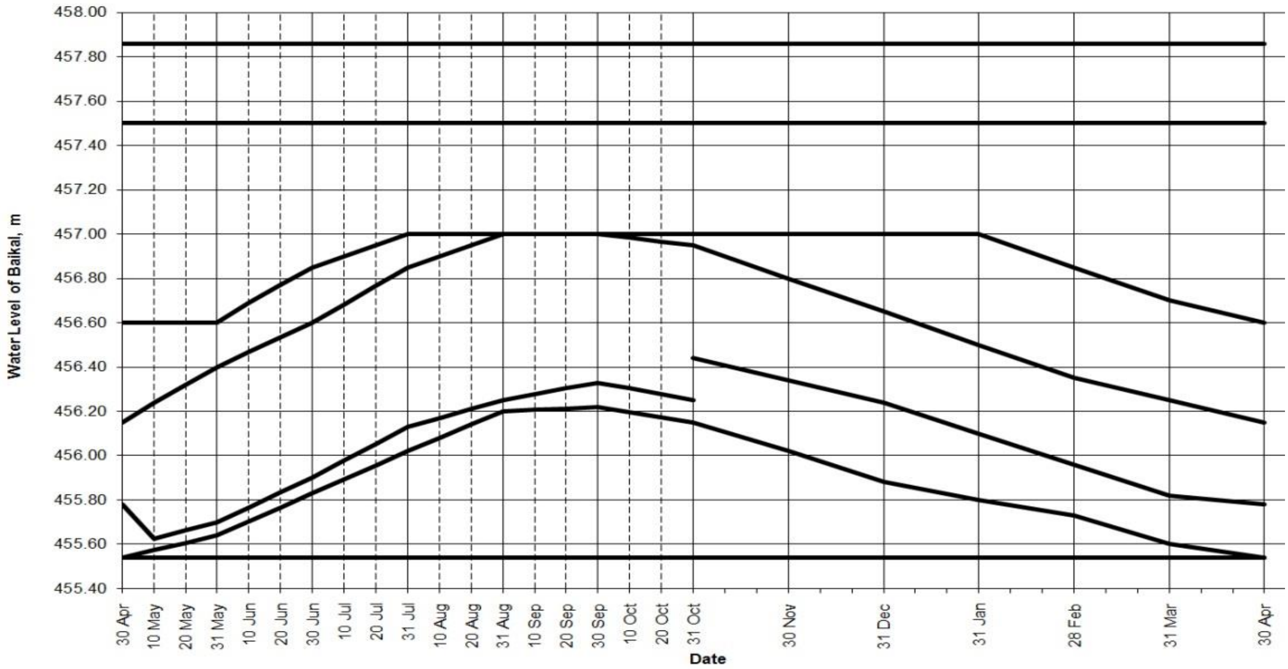

Fig. 1 Dispatch schedule of "Lake Baikal – Irkutsk Reservoir" (release curves).

апрель	01-10 май	11-20 май	21-31 май	01-10июнь	11-20июнь	21-30июнь	01-10июль	11-20июль	21-31 июль	01-10 авг	11-20 авг	21-31 авг	01-10 сен	11-20 сен	21-30 сен	01-10 октн	11-20 окт	21-31 окт	ноябрь	декабрь	январь	февраль	март	апрель
7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200	7 200
457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86	457.86
6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50	457.50
6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000	4 000
456.60	456.60	456.60	456.60	456.69	456.77	456.85	456.90	456.95	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	457.00	456.85	456.70	456.60
3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200	3 200
2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900	2 900
456.15	456.24	456.32	456.40	456.47	456.53	456.60	456.68	456.77	456.85	456.90	456.95	457.00	457.00	457.00	457.00	456.98	456.97	456.95	456.80	456.65	456.50	456.35	456.25	456.15
3 100	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	1 800	3 100
1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500
455.78	455.63	455.66	455.70	455.77	455.83	455.90	455.98	456.05	456.13	456.17	456.21	456.25	456.28	456.30	456.33	456.30	456.28	456.25	456.34	456.24	456.10	455.96	455.82	455.78
1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400
1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400	1 400
455.54	455.57	455.61	455.64	455.70	455.77	455.83	455.89	455.96	456.02	456.08	456.14	456.20	456.21	456.21	456.22	456.20	456.17	456.15	456.02	455.88	455.80	455.73	455.60	455.54
1 500	1 300	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500
1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300	1 300
455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54	455.54
1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050	1 050

Fig. 2 Dispatch schedule of "Lake Baikal – Irkutsk Reservoir" (tabular form).

The software uses Balance equation for t+1 period

$$W^*t+1 = W^*t + Pt+1 - Rt+1 \quad (1)$$

where $\mathbf{W^*_t}$, $\mathbf{W^*_{t+1}}$ are initial and final reservoir volumes, $\mathbf{P_{t+1}}$ inflow, $\mathbf{R_{t+1}}$ release for t+1 period (reservoir volume in the next time interval is equal to reservoir volume in the current interval plus inflow and minus release).

When performing water resource calculations, the following data are formed and used:

- Start dates of periods;
- Volumes in the lake Baikal at the beginning of the period;
- Useful volume of inflow to Lake Baikal - by periods;

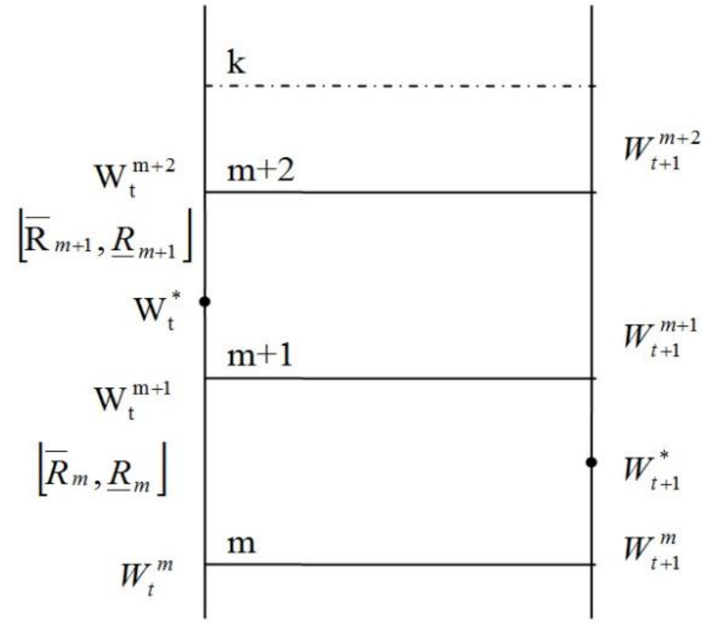

Fig. 3 Principles of reservoir operation mode control (direct and reverse).

Time intervals			Lake Baikal						Irkutsk reservoir (HPP)				
years	Intervals	Beginning of interval	Volume mln.m3	Level m	Inflow for an interval		Release for an interval		US Level (av.) m	DS Level m	Turbine flow m3/s	Power MW	Electricity generation billion kWh
					m^3/s	$mln.m^3$	m^3/s	$mln.m^3$					
	Initial volume		20 709	455.66									
2016 - 2017	V 1-10	01.05.2016	16 622	455.53	2 123	1 834	1 300	1 123	454.42	425.83	1 296	313.0	75.1
	V 11-20	11.05.2016	17 333	455.55	2 123	1 834	1 300	1 123	454.50	425.83	1 296	313.9	75.3
	V 21-31	21.05.2016	18 044	455.57	2 123	2 018	1 300	1 236	454.59	425.83	1 296	314.8	83.1
	VI 1-10	01.06.2016	18 826	455.60	3 990	3 447	1 300	1 123	454.75	425.83	1 296	316.7	76.0
	VI 11-20	11.06.2016	21 151	455.67	3 990	3 447	1 300	1 123	454.98	425.83	1 296	319.1	76.6
	VI 21-30	21.06.2016	23 475	455.75	3 990	3 447	1 300	1 123	455.15	425.83	1 296	321.1	77.1
	VII 1-10	01.07.2016	25 799	455.82	2 947	2 546	1 300	1 123	455.27	425.83	1 296	322.4	77.4
	VII 11-20	11.07.2016	27 222	455.86	2 947	2 546	1 300	1 123	455.37	425.83	1 296	323.4	77.6
	VII 21-31	21.07.2016	28 645	455.91	2 947	2 801	1 300	1 236	455.46	425.83	1 296	324.5	85.7
	VIII 1-10	01.08.2016	30 210	455.96	4 123	3 562	1 300	1 123	455.57	425.83	1 296	325.7	78.2
	VIII 11-20	11.08.2016	32 649	456.04	4 123	3 562	1 300	1 123	455.70	425.83	1 296	327.1	78.5
	VIII 21-31	21.08.2016	35 088	456.11	4 123	3 918	1 300	1 236	455.83	425.83	1 296	328.6	86.7
	IX 1-10	01.09.2016	37 771	456.20	2 290	1 979	1 400	1 210	455.87	426.01	1 396	352.2	84.5
	IX 11-20	11.09.2016	38 540	456.22	2 290	1 979	1 400	1 210	455.91	426.01	1 396	352.7	84.6
	IX 21-30	21.09.2016	39 309	456.25	2 290	1 979	1 400	1 210	455.95	426.01	1 396	353.2	84.8
	X 1-10	01.10.2016	40 078	456.27	242	209	1 400	1 210	455.94	426.01	1 396	353.1	84.7
	X 11-20	11.10.2016	39 078	456.24	242	209	1 400	1 210	455.89	426.01	1 396	352.5	84.6
	X 21-31	21.10.2016	38 077	456.21	242	230	1 400	1 331	455.84	426.01	1 396	351.8	92.9
	XI	01.11.2016	36 977	456.17	-30	-78	1 400	3 629	455.71	426.01	1 396	350.3	252.2
	XII	01.12.2016	33 270	456.06	-111	-297	1 400	3 750	455.49	426.01	1 396	347.8	258.7
	I	01.01.2017	29 223	455.93	359	962	1 400	3 750	455.28	426.01	1 396	345.2	256.8
	II	01.02.2017	26 435	455.84	469	1 135	1 400	3 387	455.11	426.01	1 396	343.1	230.6
	III	01.03.2017	24 182	455.77	316	846	1 400	3 750	454.87	426.01	1 396	340.3	253.2
	IV	01.04.2017	21 279	455.68	1 180	3 059	1 400	3 629	454.67	426.01	1 396	338.0	243.4

Fig. 4 Water resource calculations in the Excel.

- Dispatch schedule of the complex "Lake Baikal - Irkutskoye Reservoir";
- Releases from the Irkutskoye reservoir — by periods;
- The Irkutskroye reservoir level (depends on the level of the Lake Baikal and the release according to the corresponding dispatch schedule);
- Downstream level of the Irkutskoye reservoir (is calculated based on the level/release curve).

For the Irkutskaya HPP the head is calculated as the difference between upstream and downstream level. Turbine discharge and power are determined by the operational characteristics of the HPP.

The main indicator of the reliability is probability of providing the consumer with water. The reliability is determined on the basis of statistical processing of water resource calculations results performed for long-term series of observed inflows. The reliability is calculated by the formula on the slide:

$$P = 100*M/(N+1) \quad (2)$$

where M is the number of calculation periods in which the water user requirements was not violated, N is the total number of calculation periods in the long-term hydrological series.

When developing release rules, it is necessary to determine such a configuration of the dispatching schedule, which will provide for each water user the following standard reliability:

- sanitary releases — 97-99 percent;
- water supply (drinking, household, industrial) — 95-99 percent;
- hydropower — 85-95 percent;
- navigation with maintaining water levels by releases from reservoirs - 85-90 percent;
- irrigation and agricultural watering — 75-90 percent;
- fisheries — 75-90 percent.

Designing a dispatch schedule is a complex process. If all water users' requirements are satisfied with the normative reliability, then the DS can be put into operation. However, if the Water Resource Calculation (WRC) does not give normative reliability, then the DS developer has four problems:

(1) Are the DS coordinates well chosen, i.e., a valid solution exists, but developer has not found it.

(2) How severely are reliability standards violated? Is it possible to use such a DS in real-time control?

(3) Does the reservoir "water capacity" of the catchment area allow it to satisfy the water users' requirements?

(4) Is the DS management optimal or is it possible to achieve better results using other management tools?

The first two problems are solved on the basis of methods for finding the optimal coordinates of the DS. Although a complex, nonlinear, discrete (piecewise-continuous) optimization problem of small dimension (in our case, 168 independent variables) arises, its solution requires great skill and special optimization methods (the authors used special methods of local optimization and genetic algorithms [4]). These methods do not give a global optimum, but they significantly improve the reliability indicators of water supply to users.

The third and fourth problems is related to the solution of a rather complex optimization problem of large dimension (in our case, 24 * 44 = 1056 independent variables), which requires the development of special optimization methods, since it is almost impossible to solve an optimization task of such dimension in a reasonable time using nonlinear programming (NLP) methods. However, only its solution gives (or refutes) confidence in the quality release rules.

The meaningful formulation of the optimization task is as follows: it is necessary to determine the releases (independent variables) from the reservoir for the entire calculation period, which minimize a certain Objective Function (OF), under constraints associated with the fulfillment of balance equations. The OF is calculated depending on water users requirements and should decrease with decrease failure events (when required releases violate the threshold). Water users' requirements priorities hierarchy is reflected in the OF by means of penalty coefficients (the higher priority, the higher penalty for requirements violation). The initial data for the optimization task is the interval inflow series, initial and final reservoir volumes.

The main dependent variables of the WRC are calculated using the known functions for the "Lake Baikal-Irkutsk reservoir" complex:

$Z_i = F_B(W_i)$ — bathymetric dependence function of the Lake Baikal level $\mathbf{Z_i}$ on the Lake Baikal volume; (3)

$H^u{}_i = F_u(Z_i,R_i)$ — dependence function of the Irkutsk reservoir upstream level, $\mathbf{H^u{}_i}$ on the lake Baikal level and releases from the Irkutsk reservoir to downstream; (4)

$H^d{}_i = F_d(R_i)$—dependence function of downstream level $\mathbf{H^d{}_i}$ on the Irkutsk reservoir release into the downstream (5)

$N_i = N(H^u{}_i, H^d{}_i, R_i)$—hydroelectric power dependence function on headwater level, tailwater and release from the Irkutsk reservoir to downstream (difference on the head—$H^u{}_i - H^d{}_i$) (6)

Water users' requirements form 12 criteria:

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

To find the optimal DS coordinates, we used two types of optimization algorithms developed by us. The first one — "vertical" or V algorithm, the second — "horizontal" or H algorithm.

"Vertical" — the calculation of the nodal points optimal coordinates is performed sequentially for all intervals boundaries — at each border simultaneously for all lines. Thus, the nodal points for two adjacent interval boundaries can be shifted in different directions. The self-similarity of the dispatcher's lines may not be preserved.

"Horizontal" — the calculation of the nodal points optimal coordinates is performed sequentially for all lines — at each line simultaneously for all points. All nodal points of the same line are shifting in the same direction. The self-similarity of the dispatcher's lines is preserved.

In both cases, the nodal points coordinates of the first (upper) and last (lower) lines remain unchanged. These lines hold their positions.

The combined optimization algorithm involves the alternate use of vertical and horizontal algorithms. Both can be applied an arbitrary number of times in an arbitrary order. In this case, the results of the calculations at the previous step are transmitted as source data for the subsequent calculation. Fig. 5 shows the movement of nodal points during horizontal and vertical optimization.

In order to formulate reservoir management rules based on optimization, it was necessary to solve the task of water resource calculation for a long-term inflow series and specified water users requirements.

The formulation of the optimization task is as follows: it is necessary to determine the releases from the reservoir for the entire calculation period, which minimizes a certain objective function, under constraints associated with the fulfillment of balance equations. To solve optimization task, a special algorithm called "Pulsating Spring method" was developed. The iterative algorithm for finding the optimal solution is as follows:

1) The initial decision is determined by the dispatch schedule.

2) Odd pass. The volume values in the first and last interval of an odd two-year (1, 3, 5, etc.) are fixed, and Solver-Excel solves the task of minimizing the objective function of the corresponding two-year.
3) Even pass. The volume values in the first and last interval of an even two-year (2, 4, 6, etc.) are fixed, and Solver-Excel solves the task of minimizing the objective function of the corresponding two-year.
4) The second and third iterations are repeated until the convergence of the objective function is achieved.

Thus, the original large-dimensionality optimization task is split into optimization of two-year subtasks that can be solved independently of each other. This decomposition makes it possible to use multitasking and multiprocessor computer modes. Such an algorithm was implemented in Excel using the Visual Basic. Fig. 6 shows the step-by-step change of objective function as a result of calculating the fourth cycles of even and odd passes.

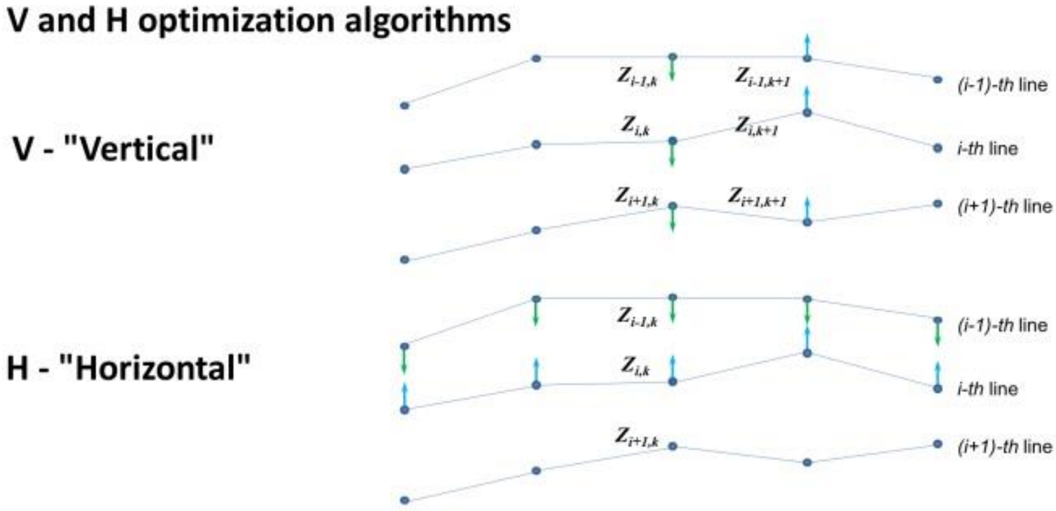

Fig. 5 Search optimal DS coordinates.

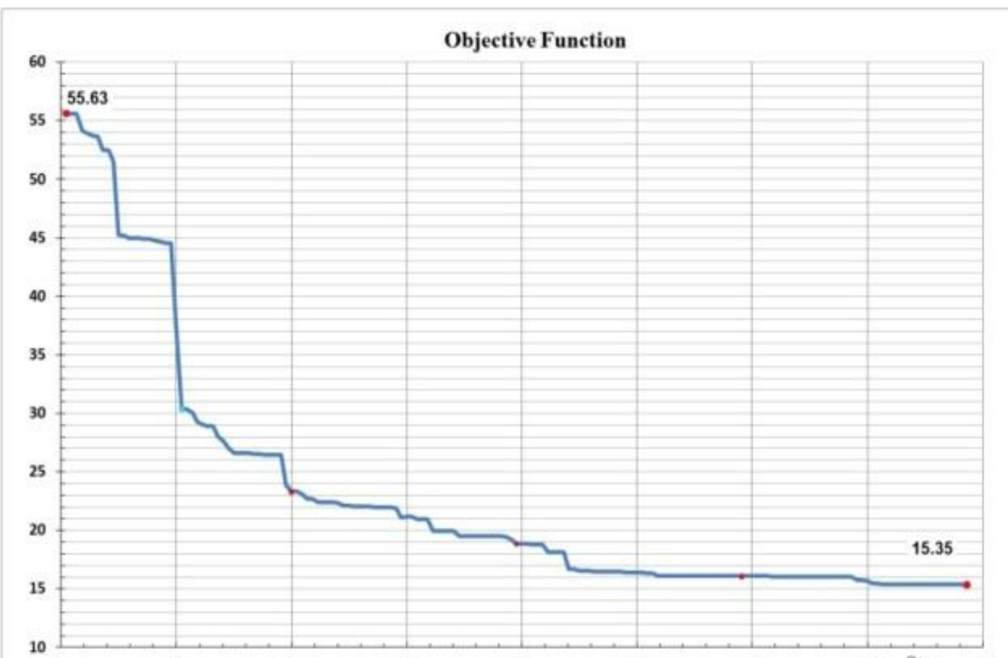

Fig. 6 Result of calculating the fourth cycles of even and odd passes.

The authors have developed the computational technology that would make it possible to manage the reservoir water resources in an operational mode on the basis of optimization methods and inflow forecast. It implemented in the Excel using the optimizer described above.

This technology forms releases for the next time interval depending on the reservoir volume at the interval beginning; hydrological inflow forecast for this interval; Historical inflow series; and the actual water users' requirement for this period. The algorithm is the following:

1) At the beginning of the year formation of the long-term forecast inflow.
2) Replacement of forecast inflow for the current interval by the value of the short-term forecast.
3) Determination actual water users' requirements.
4) Formation and Solving of the optimization task.
5) The optimal release for the current calculated interval is taken as the regime for the maintenance service.
6) At the end of the current calculated interval, the real release and inflow are used to determine the final volume of the reservoir,

Both optimization algorithms are mathematically rigorously formulated in Ref. [6].

For a long-term multi-year forecast, we recommend using the last 11 years of inflow, as precipitation correlates quite well with the 11-year Schwabe solar cycle. The algorithm for generating the forecast inflow series is as follows:

Let **R** is the historical inflow series with a length duration of **T** years. It is necessary to make a decision on the reservoir operating modes in the current **(T+1)**-th year.

The variability of climate is controlled by natural processes, such as ocean cycles, changes in solar activity, volcanic activity and anthropogenic factors. The largest contribution comes from solar activity, which has been documented by a large body of published case studies [7]. The algorithm for generating the forecast inflow series is as follows:

1) Last 11-year array α in the initial hydrological series **R** is allocated.
2) We find below α the 11-year array β in the initial hydrological series **P** close to α in the accepted measure. The proximity measure can be determined as the sum of the absolute values difference elements of the arrays α and β (Fig. 7).

$$||\alpha - \beta|| = \Sigma_{i=[0,10]} \Sigma_{j=[1,m]} abs(a_{T-i,j} - a_{\tau-i,j}) \qquad (7)$$

Let γ be the array separating α and β. The series $\mathbf{R_1} = \{\gamma+\alpha\}$ will be used for calculating releases by optimization method (Fig. 8).

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				$a_{\tau,j}$, $Q_{\tau,j}$			
$\tau-\iota$			β	$a_{\tau-\iota,j}$, $Q_{\tau-\iota,j}$			
$\tau-10$							
			δ				
1							

Fig. 7 The initial long-term hydrological row of the inflow R.

	Years, NN	Time interval						
		1	2		j	j+1		m
				α				
R1				γ				
	T+1	$a_{T+1,1}$, $Q_{T+1,1}$			$a_{T+1,j}$, $Q_{T+1,j}$	$a_{T+1,j+1}$, $Q_{T+1,j+1}$		

Fig. 8 Model hydrological series R_1 for optimization calculations.

3. Results and Discussion

3.1 Search for the Optimal Coordinates of Dispatcher Schedules

Using the above algorithm and software in Excel, calculations were made of the optimal coordinates of dispatch schedules for the complex “Lake Baikal-Irkutsk Reservoir” for modern hierarchically ordered requirements (criteria) of water users. The operating DS was taken as the initial configuration (Figs. 1, 2). The objective function was calculated as the sum of the squared deviations from the requirements in case of their violation with weighting coefficients that determine the hierarchy of requirements priorities. Two approaches were applied: only horizontal optimization and combined application of horizontal and vertical optimization. As a result, two corresponding dispatch schedules were obtained, shown in Figs. 9 and 10. At the same time, the annual and interval reliability for both options increased, and for the second option they increased significantly. For the second option, the depth of failures for almost all criteria also significantly decreased.

Although the second DS (Fig. 10) gives the best reliability indicators, it is impossible to control according to such a DS.

Therefore, in order to apply combined optimization (horizontal and vertical), it is necessary to further restrict the type of interrupt lines. For example, to imagine them as a set of nested hats (Fig. 1). This is achieved by exponential functions with different hydrological parameters.

Optimal trade-offs with geometry similar to the current 1988

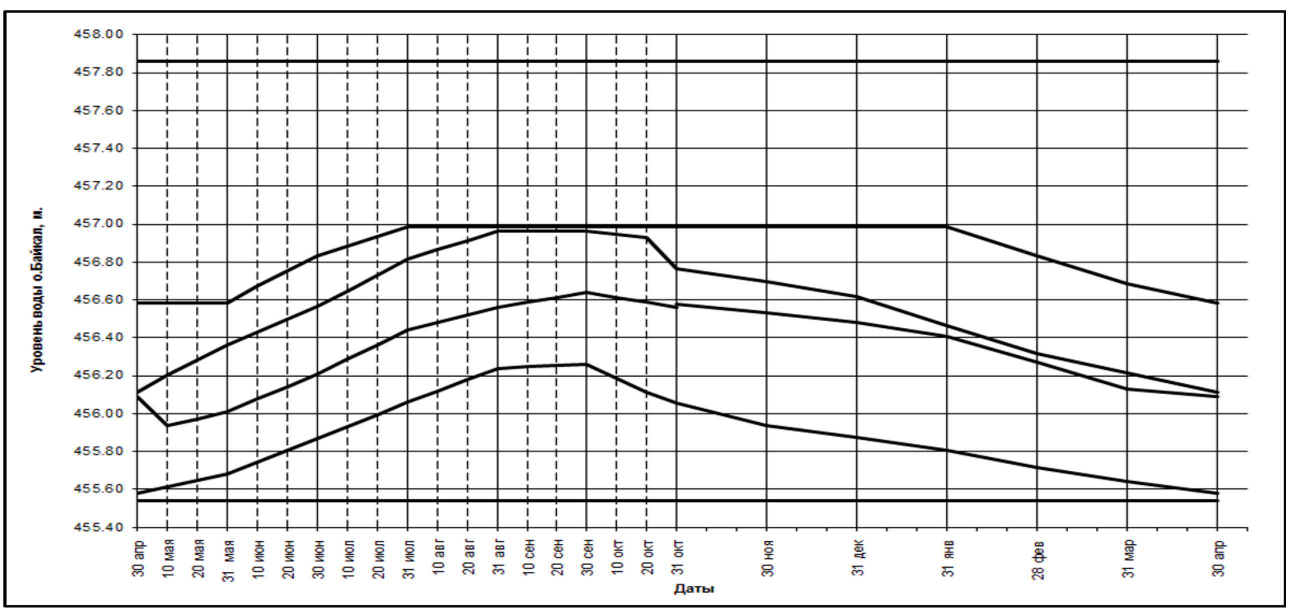

Fig. 9 DS obtained by only horizontal optimization.

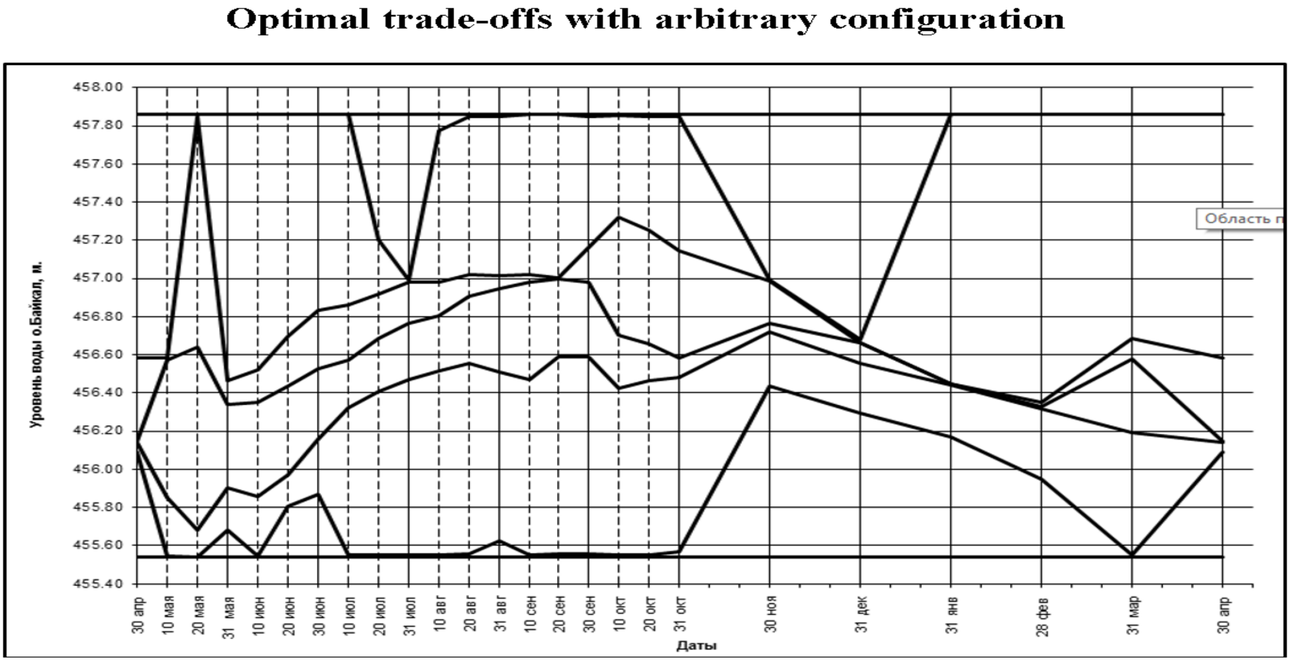

Fig. 10 DS obtained by both horizontal and vertical optimization.

3.2 Water Resource Calculation Analysis of Climate Change

To assess climate change, two periods of 44 years of the historical time series of the Inflow were taken: from 1932 to 1976, on which the Dispatch Schedule were built, and modern - from 1976 to 2020. For these two series, water resource calculations (WRC) were performed using the current dispatch schedule 1988 and based on the optimization methods outlined in Section 2.

Water resource calculations showed [6]:

- DS works well for the series on which it was created, and practically does not work on the modern series;
- Optimization gives good reliability for both series.

The conclusions are as follows:

- The genesis of the climate has changed a lot;
- Dispatch schedules should be developed only using a series for the last 20-30 years;
- Dispatch schedules need to be updated every 10-15 years;
- It is possible to manage with regulatory reliability even in the dry season if release rules are built close to optimal.

Statistical performance criteria (reliability, resilience, vulnerability) make it possible to quantify the reliability of using the adopted release rule for each individual water users requirements. Unfortunately, the objective function also gives a poor representation of the quality and total impact of the release rule on the comprehensive fulfillment of water users’ requirements.

For a multi-criteria analysis of a criteria set, an integrated normalized reliability index (INRI) is proposed [6]. It 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:

$$\mathbf{INRI} = \boldsymbol{\Sigma}_{\boldsymbol{k}\,=\,[1,K]}\,(1 - \text{Reliability}^{\boldsymbol{k}}[\mathbf{X}]) \qquad (8)$$

where reliabilty^{k}[**X**] is the reliabilty (in fractions) for the ***k***th criterion, K is the number of criteria.

The normative reliability can be used as an estimated $\mathbf{T}_{\mathbf{INRI}}$ threshold for **INRI** by defining it as follows:

$$\mathbf{T}_{\mathbf{INRI}} = \boldsymbol{\Sigma}_{\boldsymbol{k}\,=\,[1,K]}\,(1 - \mathbf{T}^{\boldsymbol{k}}) \qquad (9)$$

where $\mathbf{T}^{k}$ is the normative riliability for the ***k***th criterion expressed in fractions.

The Table 1 shows how the optimization improves reliability in comparison with Dispatch schedules and with normative reliability (last row).

Table 1 INRI indicator values for the eight performed WRCs.

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%**
T_{INRI}	**1.33**	**1.33**	

3.3 Real-time of Reservoir Water Resources Management of Reservoir Based on Optimization

An experimental proof of the effectiveness of the approach described in Section 2 was carried out for the 11-year historical series 1914-1924. The calculations were carried out according to the Dispatch Schedule, optimization for the entire series and optimization according to the proposed algorithm. The expected result is obtained: the reliability according to the proposed algorithm is higher than Dispatch schedules, but, of course, worse than optimizing for the entire series (Fig. 11). Statistical analysis of the results by Integrated Normalized Reliability Index confirmed the quality of the proposed Computational Technology (**INRI = 3.08, 1.67, 2.33** for relevant calculations).

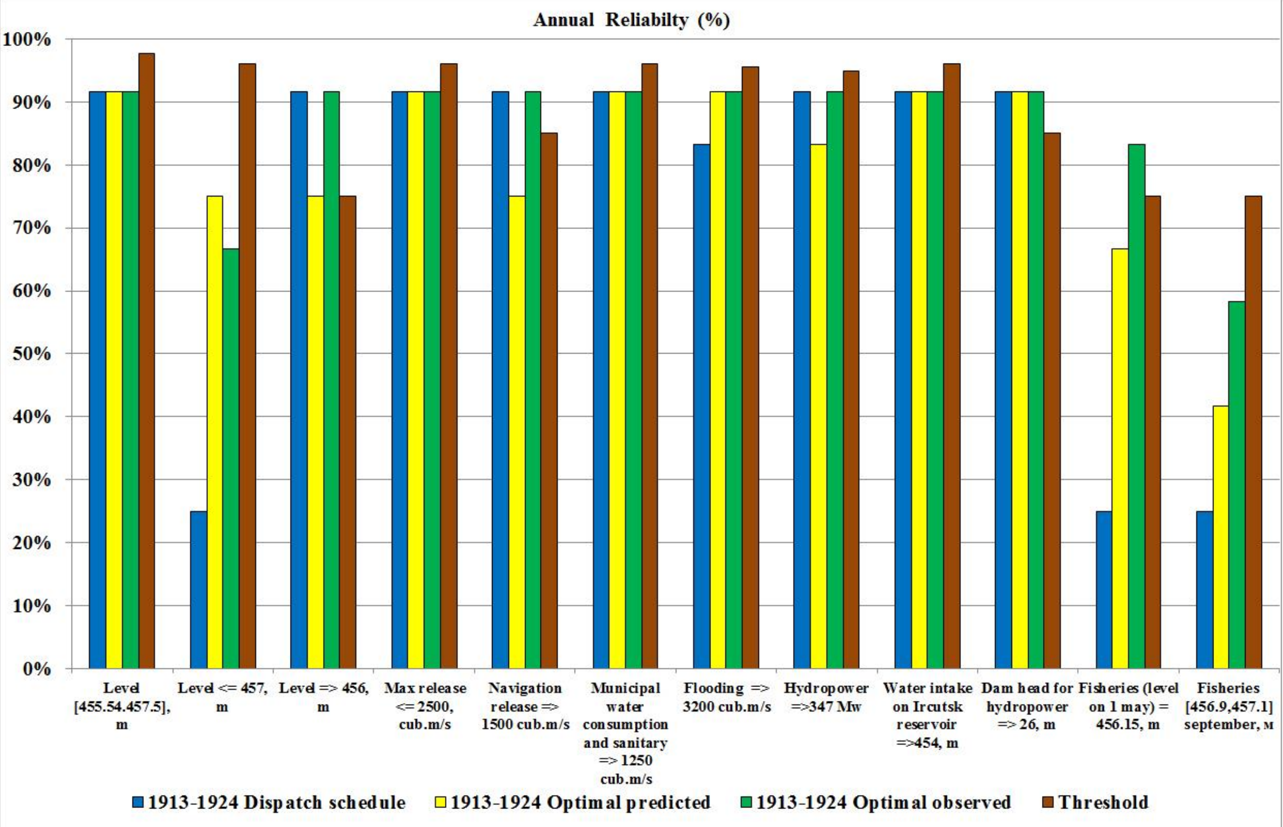

Fig. 11 Annual Reliability: WRC by DS and using optimization (1913-1924).

Unfortunately, it is impossible to rigorously prove mathematically that the proposed algorithm gives better control than Dispatch schedules for any reservoirs.

4. 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.

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