ISSN 0097-8078, Water Resources, 2018, Vol. 45, No. 5, pp. 819–826. © Pleiades Publishing, Ltd., 2018.
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WATER RESOURCES DEVELOPMENT: ECONOMIC AND LEGAL ASPECTS

Searching for Compromise Solution in the Planning and Managing of Releases into the Lower Pool of the Volgograd Hydropower System.

1. Strategic Planning

M. V. Bolgov[a, *], A. L. Buber[b], A. A. Komarovskii[b], and A. V. Lotov[c]
[a] *Water Problems Institute, Russian Academy of Sciences, Moscow, 119333 Russia*
[b] *Kostyakov All-Russian Research Institute of Hydraulic Engineering and Amelioration, Moscow, 127550 Russia*
[c] *Dorodnicyn Computing Center, Russian Academy of Sciences, Moscow, 119333 Russia*
**e-mail: bolgovmv@mail.ru*

Received April 4, 2016; accepted for publication December 29, 2016

Abstract—The article presents a new information technology for the analysis of problems and the support of decision making regarding the availability of water resources for the users of the water management complex of the Lower Volga and the entire Volga–Kama chain of HPPs. A procedure is proposed to search for compromise decisions in water resources management in the interests of various water users (hydropower engineering, transport, ecology, agriculture, fishery, etc.). Modern methods of multicriteria analysis and the theory of compromises a used. The issues considered in the study include the determination of the potentially possible levels of meeting the requirements of the water users mentioned above and the effect produced on these levels by possible changes in the Management Rules of the Volga–Kama Chain of Reservoirs.

Keywords: Volga–Kama chain of reservoirs, management, water resources, allowable targets, compromises, releases

DOI: 10.1134/S0097807818050044

INTRODUCTION

Nine large hydroengineering structures are in operation in the Volga Basin to form the Volga–Kama Chain of Reservoirs (VKC), with a total active storage capacity of 78 km^3. VKC operation is aimed to meet the requirements of power engineering, transport, agriculture, fishery, industry, municipal services, etc., in the periods of spring flood, as well as summer–autumn and winter dry seasons. The operation regime of the reservoirs is governed by the Regulation for the Use of Water Resources of Reservoirs [12–14].

The construction of VKC has caused a decrease in spring flood runoff and drying of the Volga–Akhtuba floodplain (VAF), Volga Delta, and Western Substeppe Il’mens (WSI), which affected the composition of the fauna and flora of the Lower Volga. The total production of floodplain lands dropped abruptly, and the inundation areas decreased appreciably. Considerable changes in spring flood parameters shifted fish spawning and feeding periods. Because of the unfavorable hydrological regime, fish productivity of the delta and floodplain decreased by 35–60%.

To reduce the damage inflicted to the aquatic ecosystem and to ensure the optimal use of water resources in the Volga basin, an approach is proposed, which will meet the contradictory requirements of water users. The methodological basis of the proposed approach is the concept of holistic treatment of environmental and economic problems [7, 11, 15], including the construction of an integral model of the study object and the use of the method of attainable goals/dialog decision maps (MAG/DDM) [6]—a method of multicriteria optimization based on the visualization of unimprovable boundary (also referred to as Edgeworth–Pareto boundary and compromise surface).

The objective of this study is to develop a mathematical model, describing VKC functioning, and a method for solving the problem of its management and to create a convenient computational technology (CT), supporting the activities of a wide range of users, i.e., experts in water resources management [1, 2].

To attain the goal, the process of decision making is divided into two phases:

(1) Strategic planning, which, at the intersectoral level, has to solve the problem of the choice of a long-term goal, i.e., the preferable attainable (realizable) set of the values of water availability for its users and the key parameters of the functioning of VAF and VKC as a whole;

(2) Tactical (annual) planning with decisions made at the level of Interdepartmental Working Group with the aim to take into account the specific hydrological and water-management conditions of the current year.

The first part of the study considers the issues of strategic planning.

DECISION MAKING IN THE CASE OF CONFLICTING INTERESTS

For each possible (allowable) management decision, we can calculate the reliability of the meeting of water user requirements or the exceedance probability in terms of faultless years in the long-term aspect (the percent proportions of the number of the requirements that have been met to the total number of years in the series). The value of each this variable should be maximized. The exceedance probabilities of various water users form a set of decision-making criteria. In making a decision, a preferable achievable combination of criterion values is to be chosen, i.e., the one that can be realized with the use of an admissible decision.

The strategic planning uses the up-to-date approach to the analysis of the results of multicriteria optimization based on MAG/DDM method [9]. This method allows one to construct explicitly and to analyze the set of attainable goals (in this problem, the combinations of exceedance probabilities for different water users) and to choose the preferable attainable goal (i.e., the preferable attainable combination of exceedance probabilities of different water users) at the Pareto boundary of this set.

The computation scheme is based on water management calculations for long-term hydrological series of the values of lateral inflow to VKC reservoirs. The variables in the model are the releases from the reservoirs in each design time interval; these releases are determined by optimization methods, depending on the technical characteristics of reservoirs and water user demands.

A set of all attainable values of exceedance probabilities is constructed based on the set of all allowable solutions with the use of MAG/DDM computation algorithms. Unimprovable solutions (i.e., we cannot improve the value of one exceedance probability without deteriorating the value of some other) correspond to an unimprovable (Pareto, undominated, compromise) boundary (of exceedance probabilities).

The final compromise solution is found from studying Pareto boundary of the set of attainable exceedance probabilities in the process of negotiations between the water users concerned.

The criteria for the choice of solution were taken to be the exceedance probabilities of the demands of the four major water users in the VKC:

(1) All reservoirs in the chain are to be filled up to the normal operating level (NOL) by the end of spring flood; this is an integral characteristic, the meeting of which will ensure the safe functioning of almost all water users (power engineering, transport, industry, municipal services, etc.) in the summer–autumn and winter low-water seasons all over the chain of reservoirs;

(2) Season-averaged winter (from December to March) firm capacity of VKC HPPs; in accordance with the project it is 2945 MW;

(3) Transport release in the lower pool (LP) of the Volgograd Hydroengineering Structure (HES) (not less than 5000 m^3/s in the navigation period);

(4) Ecological release into the LP of the Volgograd HES during the spring flood; this release meets the agricultural, fishery, transport, and sanitary demands; in accordance with the requirements of fishery and agriculture, it is to be 120 km^3 with an exceedance probability of 50% (i.e., it is to occur once in every two years), 110 km^3 with the exceedance probability of 75%, and 90 km^3 with the exceedance probability of 95%.

For these criteria, a set of attainable exceedance probabilities was constructed. Studying the unimprovable boundary of this set showed that VKC water users are not provided with water simultaneously with sufficient reliability; therefore, in any year with low or medium water abundance, a conflict of interests will appear.

Below, we consider a mathematical model of WMC underlying the solution of strategic planning problems.

DENOTATIONS AND DEFINITIONS

To describe model structure, we introduce the following denotations:

i	is the number of VKC HPP reservoir ((1) Rybinsk, (2) Gorky, (3) Cheboksary, (4) Kama, (5) Votkinsk, (6) Nizhnekamskoe, (7) Kuibyshev, (8) Saratov, and (9) Volgograd)
t	is the number of a year in the long-term water-management (from April 1 to March 31) hydrological series, $t = 1, T$
j	are characteristic design intervals within a year (spring flood, summer–autumn dry season, winter dry season), $j = 1, 2, 3$ ((1) from April 1 to June 30, (2) from July 1 to October 31; (3) from November 1 to March 31), τ_1, τ_2, τ_3 are the numbers of days in the characteristic intervals, respectively ($\tau_1 = 91$, $\tau_2 = 123$, $\tau_3 = 151$)
$W^i_{j,t}$	is water volume in the ith reservoir at the beginning of the characteristic interval j in the design year of the long-term series t

W^i	is the volume of the *i*th reservoir, km^3
W^i_{MOL}, W^i_{NOL}, W^i_{PDL}, W^i_{DSL}	are the volumes of the *i*th reservoir at the maximal operating level (MOL), at NOL, at a variable level of obligatory preflood drawdown (PDL), and at dead-storage level (DSL), km^3, respectively
$\hat{W}^i_{\text{PDL}}$	is the maximal volume of the *i*th reservoir at PDL with a variable level of preflood drawdown, km^3
W	is the volume of an equivalent reservoir (the sum of the volumes of all reservoirs), km^3, $W = \Sigma_i W^i$
W_{MOL}, W_{NOL}, W_{PDL}, W_{DSL}	are the volumes of an equivalent reservoir at the respective characteristic levels ($W_{\text{MOL}} = \Sigma_i W^i_{\text{MOL}}$ etc.), km^3
Z^i	is water level in the upper pool (UP) *i*th reservoir, m
Z^i_{MOL}, Z^i_{NOL}, Z^i_{PDL}, Z^i_{DSL}	are water levels in the UP of the *i*th reservoir at MOL, NOL, PDL, and DSL, m, respectively
Q^i	is water discharge rate into the LP of the *i*th reservoir, m^3/s
R^i	are the volumes of water discharge into the LP of the *i*th reservoir, km^3
B^i	is lateral inflow volume into the *i*th reservoir (for the 1st and 4th reservoirs, the inflow from the upper reaches), km^3
N^i	is the nominal installed capacity of the HPP of the *i*th hydroengineering structure, MW
N^i_{Firm}	is the season-averaged winter (from November to March) firm capacity with 90% exceedance probability of the HPP at the *i*th hydroengineering structure, MW
K^i	are weight coefficients, characterizing the proportion of the volume of the *i*th reservoir in the volume of an equivalent reservoir W ($K^i = W^i_{\text{NOL}} / W_{\text{NOL}}$ or $K^i = N^i/\Sigma_i N^i$)
m^i	is the proportionality factor in the calculation of capacity by the head and the discharge through the turbines ($N^i = m^i H^i Q^i$) for the hydropower units of the *i*th reservoir
dh^i	are head losses on the grids for the *i*th reservoir
$R_{\text{san rel}}$	is the volume of sanitary release into the LP of the Volgograd HPP during spring flood (25 km^3)
$Q_{\text{san sum}}$	is the sanitary release from the Volgograd Reservoir during summer dry season (not less than 3000 m^3/s)
$Q_{\text{san win}}$	is the sanitary release from the Volgograd Reservoir in winter dry season (the minimal value is 1000 m^3/s)

The input data for WMC included

$B^i_{j,t}$	is the lateral inflow into the *i*th reservoir in the characteristic interval *j* in each design year in the long-term series *t* (for the 1st and 4th reservoirs, this is the inflow from upstream reaches)
$B_{j,t}$	is the total lateral inflow to an equivalent reservoir in the *j*th characteristic interval *j* ($j = 1, 2$) in each design year of the long-term series *t* (for the 1st and 4th reservoirs, this is the inflow from the upstream reaches), $B_{j,t} = \Sigma_i B^i_{j,t}$
W^i_0	is the volume of the *i*th reservoir at the beginning of the first design year of the long-term hydrological series ($W^i_{\text{PDL}} \le W^i_0 \le \hat{W}^i_{\text{PDL}}$)
$Z^i = z_i(W^i)$	is the bathimetric curve or the dependence of the level in the UP of the *i*th reservoir on water volume W^i (z_i^{-1} is the inverse function)
$H^i = h_i(Q^i, Z^{i+1})$	is the function of the level in the LP of the *i*th reservoir on water discharge rate and the level in the UP of the ($i + 1$)th reservoir
$R_{j,t}$	are the volumes of water discharged into the LP of the equivalent reservoir (releases from the Volgograd HPP) in the characteristic interval *j* ($j = 1, 2$) in each design year of the long-term series *t*
$R^i_{j,t}$	are the volumes of water discharge into the LP of the *i*th reservoir in the characteristic interval *j* ($j = 3$) in each design year of the long-term series *t*
$W_{1,t}W_{2,t}W^i_{3,t}$	are water volumes in the equivalent and the *i*th reservoirs at the beginning of characteristic intervals in each design interval of the long-term series *t*

$Z^i_{3,t}$, $Z^i_{1,t+1}$	is the level in the UP of the *i*th reservoir at the beginning and end of the 3rd characteristic interval in each design year in the long-term series *t*
$H^i_{3,t}$	is the level in the LP of the *i*th reservoir within the 3rd characteristic interval
$N^i_{3,t} N^i_{1,t+1}$	is the capacity of the HPP at the *i*th reservoir in the beginning and end of the 3rd characteristic interval

COMPUTATION SCHEME

The computation scheme of WMC is based on the successive calculations by formulas (1)–(19) from the first characteristic interval in the first design year to the last characteristic interval of the last design year (formula 1 holds only for the first year):

$$W^i_{1,1} = W^i_0, \quad W_{1,1} = \Sigma_i W^i_0, \tag{1}$$

$$W_{\text{DSL}} \le W_{2,t} = W_{1,t} + B_{1,t} - R_{1,t} \le W_{\text{NOL}}, \tag{2}$$

$$R_{\text{san rel}} \le R_{1,t}, \tag{3}$$

$$W_{\text{DSL}} \le W_{3,t} = W_{2,t} + B_{2,t} - R_{2,t} \le W_{\text{NOL}}, \tag{4}$$

$$Q_{\text{san sum}} \le Q_{2,t} = R_{2,t} / (86400\tau_2). \tag{5}$$

Calculations by formulas (6)–(18) are made for each *i*th reservoir:

$$W^i_{3,t} = K^i \times W_{3,t}, \tag{6}$$

$$Z^i_{3,t} = z_i(W^i_{3,t}), \tag{7}$$

where $Z^i_{3,t}$ is the level in the UP of the *i*th reservoir at the beginning of the 3rd characteristic interval;

$$\begin{gathered} W^i_{\text{PDL}} \le W^i_{1,t+1} = W^i_{3,t} + B^i_{3,t} \\ - R^i_{3,t} \le \hat{W}^i_{\text{PDL}} \le W^i_{\text{NOL}} \ (\text{for } i = 1, 4), \end{gathered} \tag{8}$$

$$\begin{gathered} W^i_{\text{PDL}} \le W^i_{1,t+1} = W^i_{3,t} + B^i_{3,t} + R^{i-1}_{3,t} \\ - R^i_{3,t} \le \hat{W}^i_{\text{PDL}} \le W^i_{\text{NOL}} \ (\text{for } i = 2,\ 3,\ 5,\ 6,\ 8,\ 9), \end{gathered} \tag{9}$$

$$\begin{gathered} W^i_{\text{PDL}} \le W^i_{1,t+1} = W^i_{3,t} + B^i_{3,t} + R^3_{3,t} \\ + R^6_{3,t} - R^i_{3,t} \le \hat{W}^i_{\text{PDL}} \le W^i_{\text{NOL}} \ (\text{for } i = 7), \end{gathered} \tag{10}$$

$$Z^i_{1,t+1} = z_i(W^i_{1,t+1}), \tag{11}$$

where $Z^i_{1,t+1}$ is the level in the UP of the *i*th reservoir at the end of the 3rd characteristic period (at the beginning of the 1st characteristic interval of the next year);

$$Q^i_{3,t} = R^i_{3,t} / (86400\tau_3), \tag{12}$$

$$Q_{\text{san win}} \le Q^9_{3,t}, \tag{13}$$

$$H^i_{3,t} = h_i(Q^i_{3,t}), \tag{14}$$

here, $H^i_{3,t}$ is the level in the LP of the *i*th reservoir in the 3rd characteristic interval for reservoirs with numbers 2, 5, 6, 7, 8, and 9 ($H^i_{1,t+1} = H^i_{3,t}$);

$$H^i_{3,t} = h_i(Q^i_{3,t}, Z^{i+1}_{3,t}), \tag{15}$$

here, $H^i_{3,t}$ is the level in the LP of the *i*th reservoir in the beginning of the 3rd characteristic interval for reservoirs with numbers 1, 3, 4 (for $i = 3$, $i + 1 = 7$);

$$H^i_{1,t+1} = h_i(Q^i_{3,t}, Z^{i+1}_{1,t+1}), \tag{16}$$

here, $H^i_{1,t+1}$ is the level in the LP of the *i*th reservoir at the end of the 3rd characteristic interval; for reservoirs with numbers 1, 3, and 4 (для $i = 3$, $i + 1 = 7$);

$$N^i_{3,t} = m^i(Z^i_{3,t} - H^i_{3,t} - dh^i)Q^i_{3,t}, \tag{17}$$

here, $N^i_{3,t}$ is the capacity of the HPP of the *i*th reservoir in the beginning of the 3rd characteristic interval;

$$N^i_{1,t+1} = m^i(Z^i_{1,t+1} - H^i_{1,t+1} - dh^i)Q^i_{3,t}, \tag{18}$$

here, $N^i_{1,t+1}$ is the capacity of the HPP of the *i*th reservoir at the end of the 3rd characteristic interval (the beginning of the first characteristic interval of the next year);

$$W_{1,t+1} = \Sigma_i W^i_{1,t+1}. \tag{19}$$

As mentioned above, the criteria for the choice of solutions are the exceedance probabilities of various users by the number of faultless years in a long-term interval, i.e., the percentage of the years in which the requirements were met in the total number of years in the series. Table 1 gives the characteristics of reliability (criteria) and the requirements of water users VKC HPPs, used in the search for the optimal compromise solutions.

The range of maximal allowable values of the exceedance probabilities of the appropriate requirements of water users is determined in the following manner [10]: sanitary releases: 97–99, hydropower engineering: 85–95, navigation: 85–90, irrigation and agricultural inundation: 75–90, fishery: 75–90%.

THE CONSTRUCTION AND ANALYSIS OF THE UNIMPROVABLE SET OF SOLUTIONS

The set of unimprovable solutions is constructed with the use of the decomposition method described in [3, 5, 8]. In the consideration of model (1)–(19), the decomposition method was applied under the assumption that, before the start of the spring flood, all reservoirs are to be drawn down to the PDL. Now the problem of constructing a set of unimprovable combinations of the exceedance probabilities for different water users can be solved by combinatorial methods. For this purpose, the problem is divided into

Table 1. Reliability characteristics (criteria) and the demands of water users of VKC HPPs (T are threshold (guideline) values: $T_{\text{en}1}$ is the total volume of VKC reservoirs at NOL, $T_{\text{en}2}$ is the total firm capacity of VKC HPPs in winter, T_{tr} is the necessary transport release in navigation period, T_{ec} are the demands of the ecology, fishery, and agriculture to the volumes of releases into the LP of the Volgograd HPP Reservoir during spring flood)

Reliability characteristics of VKC HPPs	T
Water volume in an equivalent reservoir by the end of spring flood $W_{2,t}$	$T_{\text{en}1} = 166.74$ km^3
Total firm capacity of VKC HPPs in winter $N_{\text{Firm},t} = (\Sigma_i N^i_{3,t} + \Sigma_i N^i_{1,t+1})/2$	$T_{\text{en}2} = 2945$ MW
Transport releases in summer–autumn dry season $Q_{2,t}$	$T_{\text{tr}} = 5000$ m^3/s
The volume of discharge into the LP of the Volgograd HPP during spring flood $R_{1,t}$	$T_{\text{ec}} = 120, 110, 90$ km^3

individual subproblems of constructing a set of achievable unimprovable combinations of the characteristics of meeting/not meeting the requirements for a single year, with which the unimprovable set is constructed for the entire long-term series.

The analysis of inflow series showed that all years can be divided into several classes:

the years when water was abundant enough to meet all users' demands simultaneously;

the years when water was not enough to fill all reservoirs up to NOL and to implement the required ecological release simultaneously, but all other needs could be fully met;

the years when water was not enough to fill all reservoirs up to NOL, but all other needs could be met;

dry years, corresponding to which were eight types of combinations of the characteristics of meeting/not meeting the needs.

Next, individual pairs were combined to form blocks of two years, followed by blocks of four years, etc. This process was described in detail in [8]. The result was an accurate description of the unimprovable set, which consisted of 3378 points.

The results of the search for the optimal solution shown below have been obtained with the use of software complex Pareto Front Viewer [9] developed in the Dorodnicyn Computing Center, Russian Academy of Sciences, with the aim to implement MDT.

A representation of MAG as a series of two-criterion sections at a release during spring flood 120 km^3 in volume is given in Fig. 1. Figures 1 and 2 show a computer display with the results of the search for a nondominated solution with the use of the developed computation technology. The horizontal axis in the figures gives the values of the first criterion, i.e., the exceedance probability of the filling of VKC reservoirs up to NOL in the end of flood (from 20 to 100%). The criterion is denoted by NPU. The vertical axis in the figures gives the values of the fourth ecological criterion, i.e., the exceedance probability of discharge into the LP of the Volgograd Hydropower Structure during spring flood (from 20 to 100%) 120 km^3 in volume. Denotation Fish is used. The second criterion (the total firm capacity of VKC HPPs in winter), denoted as Power is given by a color palette (top right corner of the figure). The third, navigation, criterion, denoted by Nav, is given by "scrolling" between two limiting values of exceedance probabilities shown in the panel under the horizontal axis. The instrument *scrolling* can be used to specify the admissible range of criterion values by moving two triangular sliders on the scroll bar.

The regulated release into the LP of the reservoir in the interests of an individual user is a variable, depending on to what extent the requirements of other water users are met. If a release is chosen to meet the requirements of only one user with a specified reliability, the interests of other water users will be met to a lesser extent. The regulated release into the LP of the Volgograd Hydropower Structure that meets the demands of some user with a specified reliability can affect the meeting of the demands of other water users.

According to fishery requirements, given in [4], the exceedance probability for releases with different volumes into the LP of the Volgograd Hydropower Structure during the spring flood (April–June) should be as follows (criterion Fish): a release 120 km^3 in volume should have the exceedance probability of 50% (once in two years); that of 110 km^3, 75%; and that of 90 km^3, 95%. The exceedance probability by NPU criterion is to be 85–95%; that by Power criterion, 90%; and that by Nav criterion, 85–90%.

We choose a point on the unimprovable Pareto boundary in Fig. 1 at a release during spring flood 120 km^3 in volume with exceedance probability 50% by Fish criterion. Now, other criteria will give the following values of exceedance probabilities (Fig. 1, the

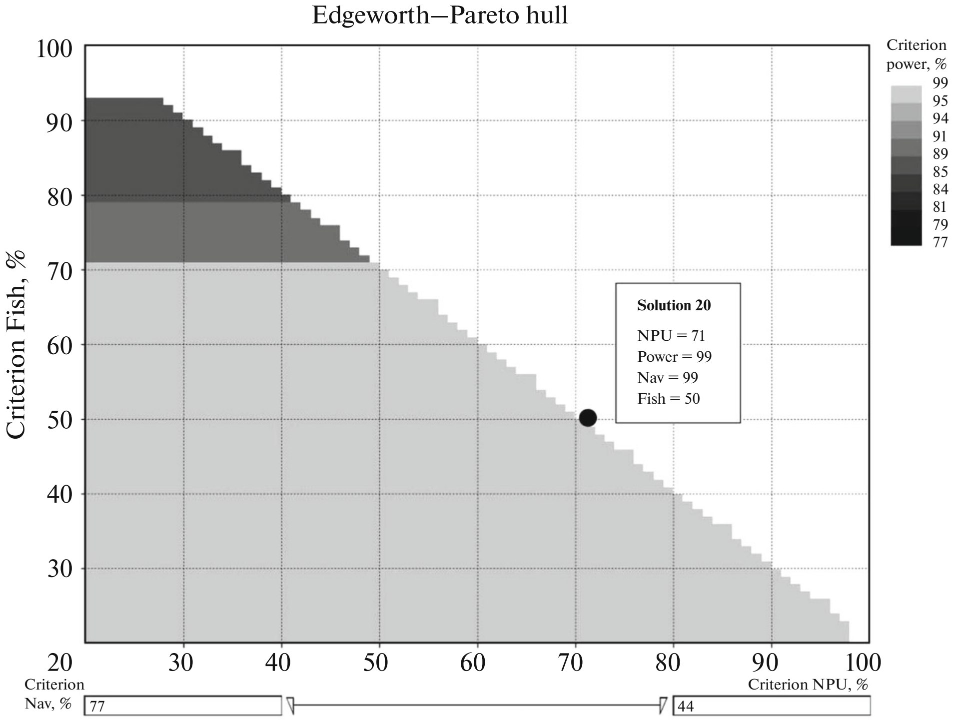

Fig. 1. Section of the unimprovable boundary at 120-km^3 release during spring flood

frame against the background of cross-section): 71 for NPU, 99 for Power, and 99% for Nav.

We choose the point on the unimprovable Pareto boundary (Fig. 2) that has an exceedance probability of 75% by Fish criterion at a 110-km^3 release during spring flood. Now, we will have the following values of exceedance probabilities (Fig. 2, the frame against the background of cross-section): 47 for NPU, 91 for Power, and 91% for Nav.

Similarly, for the section of the unimprovable Pareto boundary at a 90-km^3 release during spring flood with exceedance probability of 95% by Fish criterion will give the following values of exceedance probabilities: 44 for NPU, 91 for Power, and 80% for Nav.

Thus, while the exceedance probability by Fish criterion is determined with a specified reliability (50, 75, and 95%), NPU criterion shows considerable deviations (for NPU—71, 47, 44% as compared with the required 85–95%).

We use BT to solve the inverse problem. Suppose that the standard exceedance probability by PPU is specified at 85%; then, the exceedance probability by Fish criterion at a release into the PL of the Volgograd HPP during spring floods with volumes 120, 110, and 90 km^3 will be 36, 38, and 53% at the standard values of 50, 75, and 95%, respectively. Thus, we face an irrepressible conflict of interests between water users.

The obtained results suggest a conclusion that the current state of VKC under the existing Regulations on the Use of Reservoir Water Resources with Forced pre-Spring Flood to PDL and at the strict requirements to fish releases (Fish) fails to ensure meeting the 1st criterion (NPU) with the necessary reliability, a situation that is absolutely inadmissible. An action to improve the reliability of VKC functioning and to mitigate the conflict of interests is the change from the obligatory pre-spring flood drawdown to a variable one, depending on the forecasted inflow during the spring flood.

CONCLUSIONS

The developed CT enables effectively assessing the reliability of meeting the demands of VKC water users (exceedance probability) under current conditions. CT also can be used to evaluate the exceedance probabilities for water users during various actions aimed to improve the ecological conditions and the functioning of water management complex in the basins of the Volga and Kama in the future.

The present-day state of VKC under the approved Regulations of Reservoir Water Resources Development and under the strict requirements to the implementation of fishery releases (Fish) fails to ensure the meeting of the 1st criterion (NPU) with the required reliability.

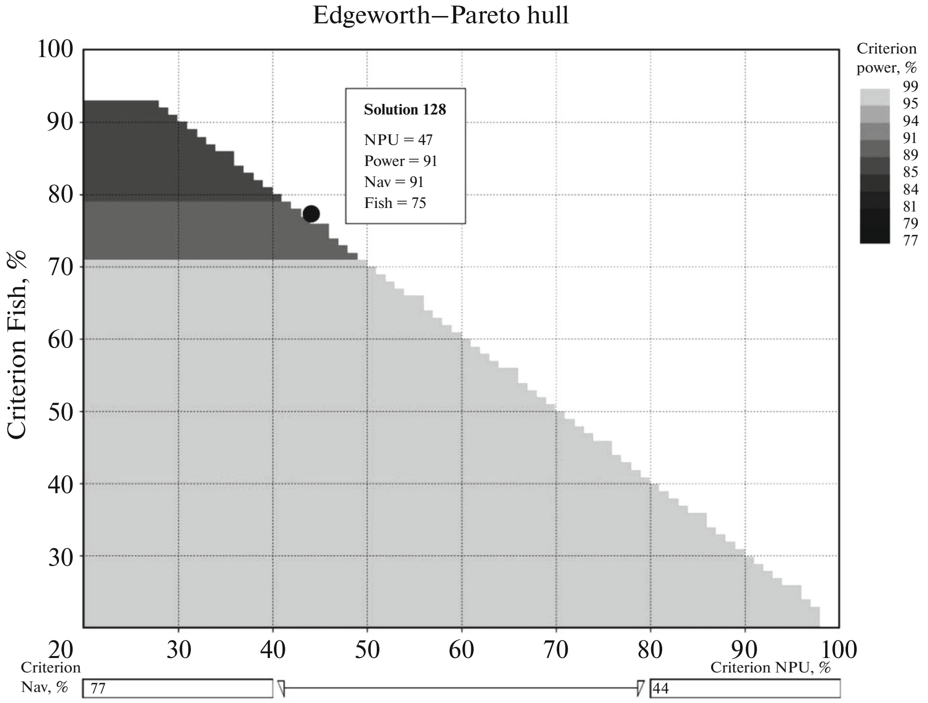

Fig. 2. Section of the unimprovable boundary at 110-km^3 release during spring flood.

The obligatory pre-spring flood drawdown is to be abolished to give place to a variable drawdown, depending on the forecasted inflow during the spring flood. To implement this proposal will require the improvement of the quality of hydrological forecasts of spring flood runoff (II quarter).

The filling of the reservoirs to NOL by July 1 will be enough for navigation in the summer–autumn dry period (93%) and for ensuring the total firm capacity of VKC HPPs in winter (90%).

ACKNOWLEDGMENTS

This study was partially supported by the Russian Foundation for Basic Research, project no. 17-29-05108.

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Translated by G. Krichevets