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Search of trade-off solutions at the water resources management in the interests of the Kuban river basin irrigation systems[1]

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Abstract

Introduction: The basin of the Lower Kuban is experiencing an acute shortage of water resources during the growing season. Every third year is low water year. Water Intake in the complex layout of rice irrigation systems requires reliable forecasting and skilful management. The Report presents the results of research and developed methods for finding the optimal operating modes for the water-resource system of the Lower Kuban based on hydrodynamic solutions and the trade-offs theory that ensure the reliable operation of rice irrigation systems, considering the conflicting requirements of water users.

Materials and Methods: The methodology is based on multi-criteria analysis and hydrodynamic modelling with application of the 'Operating Structures' module, which, according to a given hierarchy of priorities, allows fulfilling the water users' requirements to discharges and water levels during determined time period (water intakes and outlets points on the river network). The developed computational technology allows to reach

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reasonable compromise decision in the process of negotiations between water users and water basin authorities.

Results: the results of calculating the simulation model of two alternative scenarios for 2013. Blue scenario - the choice is made in favor of CHIS, black is made in favor of PAIS. On the lower graph, you can see that blue (CHIS) is above black, and on the top black (PAIS) is above blue (red - requirements). The given results show how well MIKE 11 abides by the hierarchy of water users' requirements priorities. To convert the results obtained during the simulation in MIKE 11 into Excel format, and to calculate the deficits for water users and the drawdown for the Krasnodar reservoir, a calculation scheme was developed. To drawdown the Krasnodar reservoir no more than 40% due to the small private fleet, to increase the water supply to PAIS-1, PAIS-2 by slight decrease in the total deficit and deficit for CHIS-1, CHIS-2 water users. The results of this research show the Sc69 scenario, in which the drawdown of the Krasnodar reservoir is 40%, the average deficit is 29%, and the total deficit is 20%. Deficits for other water users are respectively: 0%, 0%, 9%, 0%, 94%, 96%. This compromise scenario is agreed with the majority of interested water users and approved by the Decision Maker.

Conclusions: Developed are the principles of water management in the cascade of the Lower Kuban reservoirs considering the forecast of the hydrological situation and the requirements of water users (rice irrigation systems). A hydrodynamic computer model of the Lower Kuban was created based on the use of the “Operating Structures” module, which allows to consider the hierarchy of priority of irrigation systems requirements during the vegetative period. Different scenarios for hydrodynamic calculations with a possible hierarchy of priorities were formed, scenario calculations were made, and a decision matrix was formed. A multi-criteria analysis of the decision matrix was made; a formulated and demonstrated was the computational technology that supports the negotiation process when choosing the “optimal” compromise solution for the operating modes of the Lower Kuban Water Management System in the dry year (2013).

Keywords: Water resources management, Hydrodynamic modeling, Operating structures, Multi-criteria analysis, Trade-off solution, Irrigation.

1. Introduction

Water resource systems have to provide reliable operation of water users: agriculture and fisheries, ecology, navigation, drinking water supply, flood protection, recreation, etc. To assess the effectiveness of the system, various criteria are used that determine the quantitative assessment of the reliability of the operation of the WRS. Some of these criteria may contradict each other. In these cases, trade-offs between the conflicting criteria should be considered when searching for the 'best' solution. Set of multiple found probable solutions are discussed with the participation of all stakeholders and the "optimal" compromise decision is taken in the negotiation process solution (Lotov *et al*., 2004; Lotov *et al*., 1999; Loucks & van Beek, 2017; Lotov *et al*., 2013).

The aim of the research was the development of mathematical methods and creation of Computational Technology (CT) for the formation "optimal" operation modes of the multi-purpose reservoirs waterworks located in the Lower Kuban and intended water supply for agricultural users. To develop the computational technology two modern computing platforms were used, which allow performing:

● hydrodynamic modelling of the river network and management of installed hydraulic structures;

● multi-criteria analysis and search for compromise solutions.

As a computational platform for hydrodynamic modelling, the MIKE 11 software complex of the Danish Hydraulic Institute was used (Abbott, 1979; Abbott & Basco, 1989; Murota & Tada, 1989; Rungø *et al*., 1989; Madsen *et al*., 2003). Multi-criterial analysis was performed on the basis of the toolkit "Pareto Front Viewer" developed at the Computing Centre named after A.A. Dorodnicyn (Lotov *et al.*, 2013). This software allows to build Interactive Decision Maps and to visualize all non-dominated solutions from the Solution Matrix.

Figure 1 shows the flowchart of the computational technology algorithm for the formation of reservoir operating modes in real time.

Based on the data of the interval (decade, month and quarter) hydrological forecast of the Hydrometeorological Center, a daily hydrological series of inflows are formed.

During the growing season, each water user submits irrigation schedule which are the basis for forming out requirements for discharge and water levels. Requirements are set in time series for the upstream and downstream of reservoirs, water intakes and outlets points and, etc.

Further, a set of various probable priorities (scenarios) of water users' requirements is formed. The hierarchy of priorities, hydrological series and the requirements of water users allows us to formulate and solve the task of hydrodynamic modeling using the module "Operating Structures". As a result, the modes of operation of all waterworks, water intakes and outlets are determined.

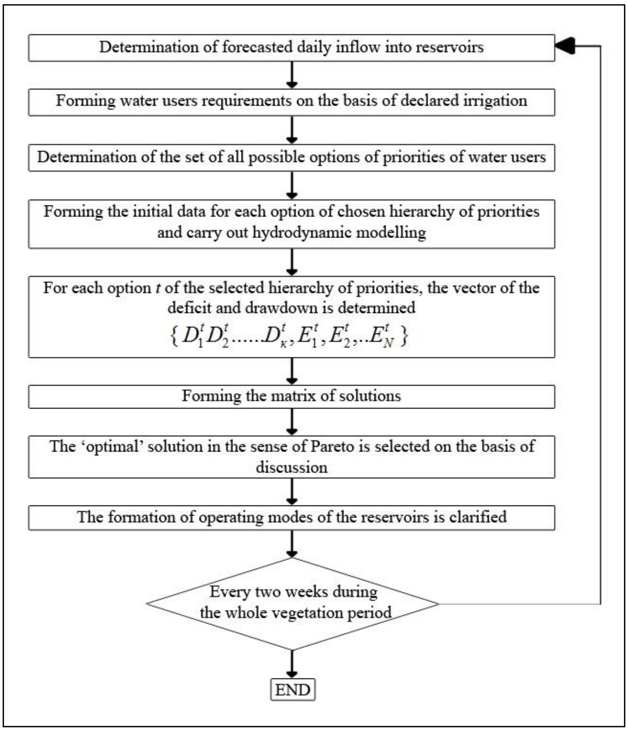

Figure 1. The flowchart of the computational technology algorithm

2. Hydrodynamic model of the Lower Kuban

For the creation of the hydrodynamic model, a calculation scheme was developed in MIKE 11 that included the hydrographic/water source network of the Lower Kuban River (Figure 1). The basin of the Lower Kuban includes the following water bodies: Krasnodarskoe, Shapsugskoe, Kryukovskoe, Varnavinskoe reservoirs, Fedorovsky and Tikhovsky waterworks, the Kuban River and the branch Protoka, which flow into the Azov Sea.

The rice irrigation complex in the hydrodynamic model is described by the points of the outlets and intakes of the pumping stations within the Fedorovskaya (FIS-R_1) Kubanskay (KIS-R_2), Ponuro-Kalininskaya (PKIS-R_2), Maryano-Cheburgolskaya (MCIS-R_2), Petrovsko-Anstasievskaya (PAIS-R_3-R_4), Temriykskaya (TIS-R_5), Chernoerkovskaya (CHIS-R_6-R_7) and irrigation systems.

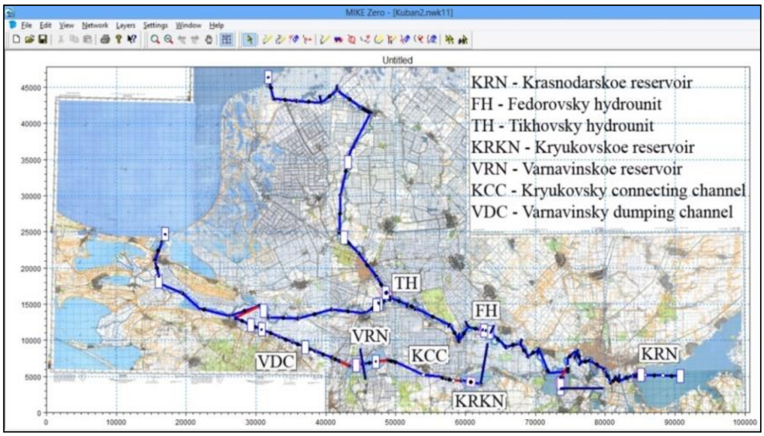

Figure 2. The scheme of the Lower Kuban River network in MIKE 11

Figure 3 shows the longitudinal profile of the Kuban River from the Krasnodar reservoir to Temryuk with one of the calibration options (discharge 500 and 200 m^3/sec in the Kuban, 300 m^3/sec in the Protoka).

As a result of calibration, bed roughness and correction coefficients for the vertical component of the stream flow along the cross-sections were obtained adequate to observations.

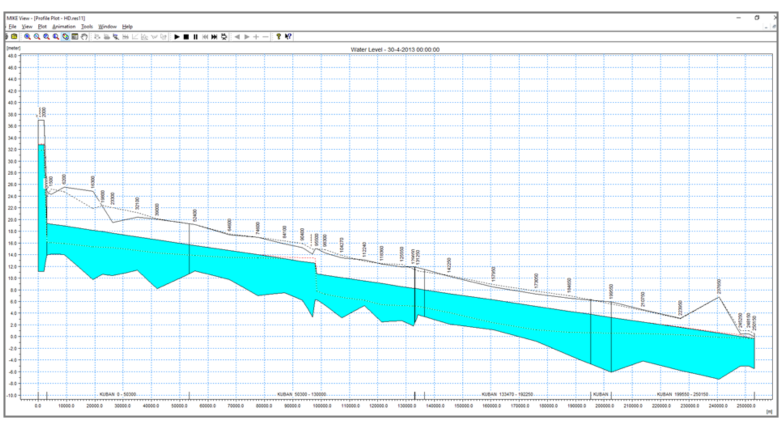

Figure 3. The surface curve of the Kuban River from the Krasnodar reservoir to Temryuk

3. Scenarios

Operation mode of releases from the Krasnodar Reservoir (KR - R_0), Fedorovskaya Waterworks (FW) and Tihovsky Water Divider (TWD) was carried out according to various lexicographically ordered scenarios with prioritization of requirements in favor of various water users to maintain the required water consumption level modes (normal water intakes for pumping stations - PS).

The requirements of water users are as follows:

R_1–PS FIS (water intake - 32m^3/s, level - 13,4m on DS FW);

R_2–PS KIS, PKIS, MCIS (water intake-143m^3/s, level-13,4m). The systems water intake is carried out from the main channel above FW;

R_3–PS PAIS (water intake - 32m^3/s, level - 6,1m). The systems water intake is carried out from the main channel located in TWD

R_4–PS 9, 10 PAIS (water intake - 6m^3/s, level - 5,5m);

R_5–PS TIS (water intake - 4m^3/s, level - 1,8m);

R_6–PS CHIS (water intake - 10m^3/s, level - 3,6m);

R_7–PS CHIS (water intake - 29m^3/s, level - 2,8m).

Operation of The Krasnodar reservoir was aimed at maintaining the specified water discharges and levels in Kuban and Protoka branches by means of necessary releases from the Krasnodar reservoir.

Operation of the Fedorovsky Waterworks was carried out to maintain the required headwater level FH (13.4m) providing normal water consumption intake for a group of water users KIS, PKIS, MCIS, FIS.

Operation of the Tikhovsky Waterworks (Tikhovsky water Divider) was to distribute the water flow between the Kuban and Protoka branches in the required proportions to meet the requirements of water users CHIS, PAIS.

Calculation water supply scheme and water users' requirements for water management system of the Lower Kuban are shown on Figure 4.

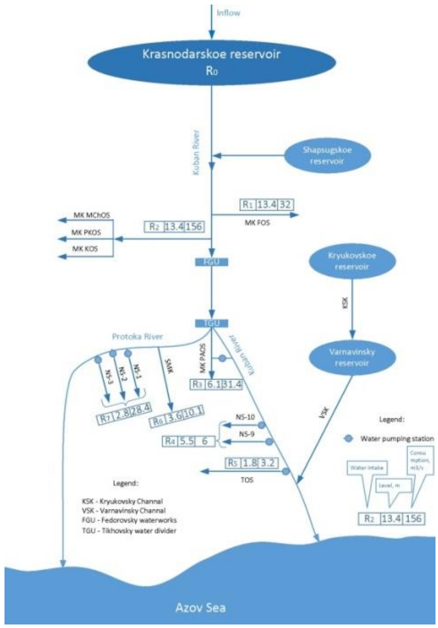

Figure 4. Calculation water supply scheme and water users' requirements

Depending on the method of releases management at waterworks, the calculations made can be divided into three groups.

In the first group of calculations, the Krasnodar Reservoir ($У_{KR}$) was managed to maintain the required level at which normal water intake for water users is carried out – R_1-R_7.

The management of the Fedorovsky water work ($У_{FWW}$) was carried out to maintain the required upstream level, at which normal water intake is carried out for water users R_1 and R_2, with flow rates of 32m^3/s and 143m^3/s.

The releases management of the Tikhovsky water work ($У_{TWD}$) was carried out on the basis of meeting the requirements of water users located either on the Kuban branch or on the Protoka branch. The management was determined by the distribution of water flow between the Kuban and the Protoka branches in the required proportions (54% - the Protoka, 46% - the Kuban; 40% - the Protoka, 60% - the Kuban; 60% - the Protoka, 40% - the Kuban).

The scenarios also considered options where the discharges of three water users – R_1 - R_3 were cut by 50% in different variations, based on the reducing water supply by reducing acreage in farms (Sc-01 – Sc-56).

In the second group of calculations, the Krasnodar Reservoir ($У_{KR}$) was managed to maintain the specified discharges (405, 340, 220, 175 and 90 m^3/s) due to the releases required for this from the Krasnodar reservoir.

The management of the Fedorovsky waterwork ($У_{FWW}$) was carried out to maintain the required upstream level (13.4 m), at which normal water intake is carried out for water users R_1 and R_2, with discharges of 32 m^3/s and 143 m^3/s.

The management of the releases of the Tikhovsky hydroelectric power plant ($У_{TWD}$) was carried out to fulfill the discharges distribution ratio between the Kuban and the Protoka in the required proportions: 54% - Protoka, 46% - Kuban; 50% - Protoka, 50% - Kuban; 40% - Protoka, 60% - Kuban; 60% - Protoka, 40% - Kuban. The required distribution proportions were set for each discharge from the series (405, 340, 220, 175 and 90 m^3/s).

For each discharge from the series (405, 340, 220, 175 and 90 m^3/s) and different proportions of the distribution of Kuban water between the Kuban and the Protoka branches water intakes of three water users – R_1 - R_3 were also cut by 50% in different variations, basing on reducing acreage in farms.

In the third group of calculations, the Krasnodar Reservoir ($У_{KR}$) was managed to meet the required level of water user R_6.

The management of the Fedorovsky water work ($У_{FWW}$) is carried out to maintain the required upstream level of -13.4 m, at which normal water intake is carried out for water users R_1 and R_2, with flow rates of 32 m^3/s and 143 m^3/s.

Management of the Tikhovsky hydroelectric complex ($У_{TWD}$) was carried out in the interests of fulfilling the requirements of the water user R_6.

Table 1 shows a fragment of a coded description of scenarios for possible water supply to rice irrigation systems, considering their priorities.

Table 1. Fragment of computational group scenarios in coded form

Sc-01	[$У_{KR}$-R_1-R_2]_[$У_{FWW}$-R_1-R_2]_[$У_{TWD}$-54]_[R_3-R_7 leftover principle]
Sc-57	[$У_{KR}$-405]_[$У_{FWW}$-R_1-R_2]_[$У_{TWD}$-54]_[R_3-R_7 leftover principle]
Sc-150	[$У_{KR}$-R_6]_[$У_{FWW}$-((R_1-R_2)/2)]_[$У_{TWD}$-46]_factor-4.5_[R_3-R_5, R_7 leftover principle]

Scenario encoding examples:

Sc-01: [$У_{KR}$-R_1-R_2]_[$У_{FWW}$-R_1-R_2]_[$У_{TWD}$-54]_[R_3-R_7 leftover principle]**.**

KR control for the implementation of the required discharges from KR, maintaining the required level of MMC, ensuring normal operation on R_1 and R_2; $У_{FWW}$-R_1-R_2 – FWW control so that the required level is performed on R_1 and R_2; $У_{TWD}$-54 – TWD control so that the ratio of discharge distribution between the Kuban and the Protoka branches is fulfilled in the following proportions: 54% - the Protoka, 46% - the Kuban. The requirements of the remaining water users R_3-R_7 are satisfied according to the leftover principle.

Sc-57: [$У_{KR}$-405]_[$У_{FWW}$-R_1-R_2]_[$У_{TWD}$-54]_[R_3-R_7 leftover principle].

defines KR control so that the flow rate in the controlled section is greater than or equal to 405 m^3/s; $У_{FWW}$ - R_1-R_2 – FWW control so that the required level is provided on R_1 and R_2; $У_{TWD}$-54 – TWD control so that the ratio of flow distribution between the Kuban and the Protoka branches is carried out in the following proportions: 54% - the Protoka, 46% - the Kuban. The requirements of the remaining water users R_3-R_7 are satisfied according to the leftover principle.

Sc-150: [$У_{KR}$-R_6]_[$У_{FWW}$-((R_1-R_2)/2)]_[$У_{TWD}$-46]_factor-4.5_[R_3-R_5, R_7 leftover principle]**.**

$У_{KR}$-R_6 – KR control so that the required level is provided on R_6; $У_{FWW}$-((R_1-R_2)/2) – FWW control so that the required level is performed on R_1 and R_2, the flow rate on R_1 and R_2 is supplied half as much as required; $У_{TWD}$-46 – TWD control so that the required level is provided on R_6, and, if possible, the proportion between the Protoka and Kuban branches was maintained in relation to: 46% and 54%, respectively. The requirements of the remaining water users R_3-R_5, R_7 are satisfied according to the leftover principle.

4. Calculation Results and Solutions matrix

The “Operating Structures” module allows you to define a management strategy depending on the specified requirements of water users and their hierarchy of priorities. The control strategy describes the function of releases dependence on the value at the controlled point. Using the if operator, you can make a choice between management strategies. For each operator (string), you can define the required number of conditions that are evaluated as working if the if operator is "true". Thus, it is possible to use a different management policy (strategy) depending on the actual discharges, time, etc.

The management strategy is determined by the relationship between the independent variable (the value at the control point) and the dependent variable (the value at the target point).

The concept of using a "target point", which indirectly affects releases, is implemented in MIKE11 by using various computational modes. For example, obtaining the required water level depending on release is realized by choosing the calculation mode solution by iterations. Especially effective is the use of the Proportional Integral Derivative (PID) regulator mode.

Figure 5 compares the results of calculations in the MIKE 11 environment for two scenarios.

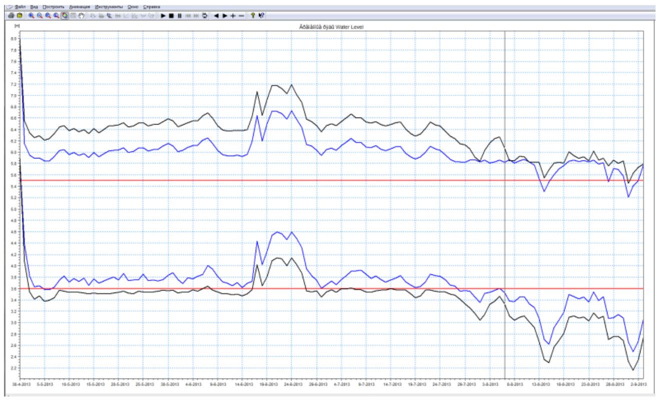

Figure 5. Comparison of calculation results in the MIKE 11 for two scenarios

The Figure 5 shows the results of calculating the simulation model of two alternative scenarios for 2013. Blue scenario - the choice is made in favor of CHIS, black is made in favor of PAIS. On the lower graph, you can see that blue (CHIS) is above black, and on the top black (PAIS) is above blue (red - requirements). The given results show how well MIKE 11 abides by the hierarchy of water users' requirements priorities.

To convert the results obtained during the simulation in MIKE 11 into Excel format, and to calculate the deficits for water users and the drawdown for the Krasnodar reservoir, a calculation scheme was developed.

Percentage of deficit and the drawdown was calculated by the difference between the required water intake and actually supplied for irrigation, correlated to the required nominal value (Buber *et al.*, 2019). As a result of calculations, a solution matrix (Table 2) with dimension 9 * 152 was obtained. The time for preparing data for one scenario, calculating and obtaining the deficit vector is 3 minutes.

Table 2. Fragment of the solutions matrix (deficit and drawdown in percent)

Scena-rios	R_0	R_1	R_2	R_3	R_4	R_5	R_6	Ave-rage	Sum-mary
Sc-01	8	0	0	64	37	87	86	49	23
Sc-02	27	0	0	48	18	87	87	43	20
***	***	***	***	***	***	***	***	***	***
Sc-69	40	0	0	9	0	94	96	29	20

Scena-rios	R_0	R_1	R_2	R_3	R_4	R_5	R_6	Ave-rage	Sum-mary
Sc-70	18	0	0	41	6	94	96	40	21
***	***	***	***	***	***	***	***	***	***
Sc-151	93	50	50	8	1	33	40	27	8
Sc-152	84	50	50	16	4	31	37	29	7

5. Multi-criteria analysis of the solutions matrix

Prepared Solutions Matrix and visualization software allows to form quickly an "optimal" compromise solution in the process of negotiations with stakeholders (irrigation systems management).

Visualization of the process of reaching "optimal" compromise solution is carried out by using the Pareto Front Viewer software package developed in the computer center named after A.A. Dorodnitsyna (author Lotov A.V.), allowing to do multi-criteria analysis using the Feasible Goals Method. The Feasible Goals Method allows to build Interactive Decision Maps and to visualize all non-dominated solutions from the Solution Matrix.

Negotiations in Russia are held at meetings of Interdepartmental Working Groups (IWG) of the Basin Water Authorities (BWA), where decisions upon operation modes of reservoirs on big rivers basins are discussed and made.

In the basin of the Lower Kuban, negotiations are conducted by the Decision-maker (Kuban BWA) with directorates of reservoirs and waterworks, the Kuban Meliovodhoz Administration, the Irrigation Systems Authority directly subordinated to it. The computer Expert support team (EST) also participates in the negotiations. EST prepares several initial compromise scenarios and accompanies the decision-making process.

The modes of operation of the Krasnodar Reservoir, Fedorovsky and Tikhovsky waterworks are formed until the end of the vegetation period on the basis of the chosen compromise "optimal" solution in the sense of Pareto using backward scrolling.

As follows is a possible option for such negotiations.

1. EST conducts scenario calculations on the developed hydrodynamic model and forms a decision matrix. For this matrix, the visualization parameters are determined and several compromise solutions are created using previous experience. The following visualization parameters are selected (in percent): the Krasnodar reservoir drawdown (KRN) is shown in colour, X axis is the average deficit (Average), Y axis is the Total deficit (Summery), other water users (FIS, KIS-MCIS-PKIS, PAIS-1, PAIS-2, CHIS-1, CHIS-2) are

represented by "sliders", limiting the range of values of variables. Figure 6 shows Interactive Decision Maps of Edgeworth-Pareto boundaries.

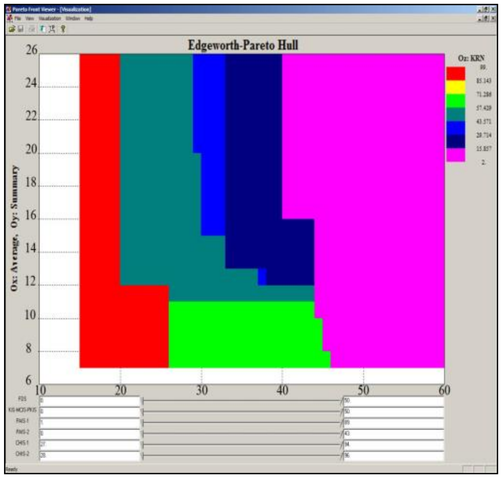

Figure 6. General map of Pareto boundaries (non-dominated solutions)

Figures 7 and 8 show two scenarios (Sc149, Sc150) proposed by the EST and distributed to stakeholders before the start of negotiations. For the Sc149 scenario, the drawdown of the Krasnodar reservoir is 65%, the average deficit is 26%, and the total deficit is 7% (the smallest). Deficit for other water users is respectively: 0%, 0%, 35%, 4%, 38%, 50%.

For the Sc150 scenario, the drawdown of the Krasnodar reservoir is 96% (maximum, close to inactive zone lIZL), the average deficit is 15% (the least), and the total deficit is 7% (the smallest). Deficit for other water users is respectively: 0%, 0%, 22%, 4%, 27%, 28%.

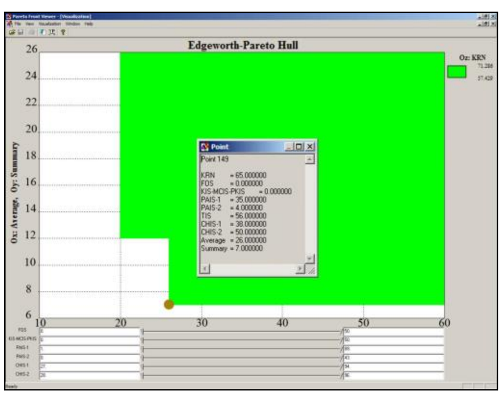

Figure 7. The compromise scenario Sc149

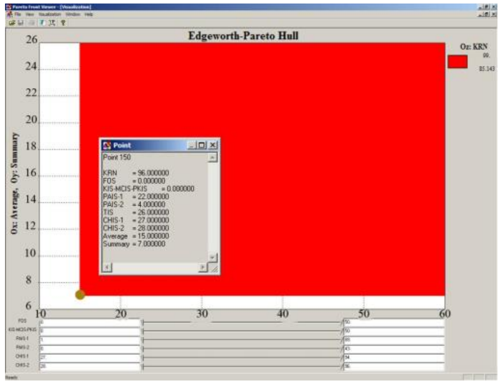

Figure 8. The compromise scenario Sc150

2. Decision maker (Kuban BWA) is negotiating with stakeholders, where the following decision is taken: to drawdown the Krasnodar reservoir no more than 40% due to the small private fleet, to increase the water supply to PAIS-1, PAIS-2 by slight decrease in the total deficit and deficit for CHIS-1, CHIS-2 water users.

Figure 9 shows the Sc69 scenario, in which the drawdown of the Krasnodar reservoir is 40%, the average deficit is 29%, and the total deficit is 20%. Deficits for other water users are respectively: 0%, 0%, 9%, 0%, 94%, 96%.

This compromise scenario is agreed with the majority of interested water users and approved by the Decision Maker.

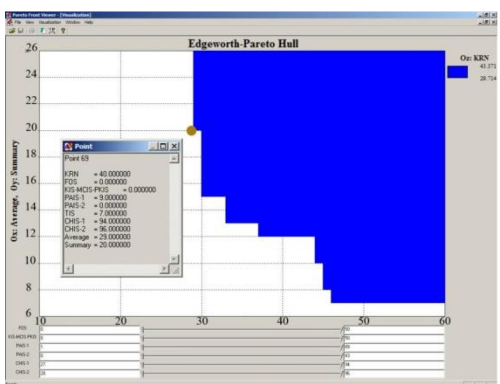

Figure 9 . The compromise scenario Sc69.

6. Conclusions

Developed are the principles of water management in the cascade of the Lower Kuban reservoirs considering the forecast of the hydrological situation and the requirements of water users (rice irrigation systems). A hydrodynamic computer model of the Lower Kuban was created based on the use of the "Operating Structures" module, which allows to consider the hierarchy of priority of irrigation systems requirements during the vegetative period. Different scenarios for hydrodynamic calculations with a possible hierarchy of priorities were formed, scenario calculations were made, and a decision matrix was formed. A multi-criteria analysis of the decision matrix was made, a formulated and demonstrated was the computational technology that supports the negotiation process when choosing the "optimal" compromise solution for the operating modes of the Lower Kuban Water Management System in the dry year (2013).

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