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Modeling the water regime of the Kura cascade of reservoirs in the Republic of Azerbaijan

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Abstract. This study was conducted in connection with the recent increasing attention to saving water resources in Azerbaijan and to studying the condition of the largest cascade of reservoirs on the Kura River. The article highlights some aspects of hydrological modeling of this cascade. Modeling occurs in several stages: an orographic scheme is created, a system of differential equations compiled on the basis of this scheme is solved, and the results are displayed. To carry out the simulation, a program was developed in the MATLAB environment. The program works in 2 modes – design and working. In the design mode, an orographic diagram is created, including the main objects of the cascade (reservoirs, rivers, canals) and their parameters are set (volume, water transfer, geodata about location). The program allows you to edit and add objects. When switching to the operating mode, according to the selected model, a system of differential equations is created corresponding to the current orographic scheme. The number of equations is equal to the number of reservoirs in the cascade. The equations are solved using MATLAB. The solution is carried out sequentially, starting from the first equation of the system. Then the results found are substituted into the 2nd equation. With each subsequent equation its complexity increases. The results are displayed in the form of obtained formulas and in the form of graphs reflecting the state of the cascade. Thus, the developed program has the ability to carry out visual design, and can also be successfully used to model similar reservoir cascades.

1 Introduction

One of the most significant challenges facing humanity at present is the problem of the lack of water resources on the planet. Water resources play an important role in solving the country’s food and energy programs [1]. In Azerbaijan, this problem, first of all, lies in the uneven distribution of water, both geographically and seasonally. Most mountain rivers originating on the southern slopes of the Lesser Caucasus overflow in the spring and turn into mudflows, and dry up at other times of the year [2-3].

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Fig. 1. Location of the cascade of reservoirs on the Kura river.

The creation of reservoirs makes it possible to achieve certain targets, but also entails a number of negative changes in the surrounding area. Their impact on the environment can manifest itself in different ways: directly and indirectly; permanently and temporarily; increasing, constantly over the years or fading.

Modeling of processes occurring both in the reservoir itself and outside it in some area close to it is a type of hydrological modeling. According to Vinogradov, the study of hydrological objects, phenomena and processes is truly effective only within the framework of mathematical modeling methodology. A variety of approaches to hydrological modeling can and should lead to the creation of more reliable models that reliably describe hydrological processes taking place, including in reservoirs. Every hydrological process can be described using mathematical formulas. Therefore, in a broad sense, the term "mathematical modeling of hydrological systems" can be understood as the use of mathematics to describe the characteristic features of hydrological systems or processes [5]. The mathematical model only approximately reflects the behavior of real objects. On the other hand, the construction of more accurate models leads to quite complex problems, the analytical solution of which cannot be obtained. Therefore, at the first stage of studying any process, a relatively simple model is used. Thus, the formation of a mathematical model depends on which aspects of a particular phenomenon are considered main and which are secondary. The model reproduces those parameters of the object of interest that are considered important for the study being conducted.

Details of the actual object may be ignored because they are not important in a particular case or because they are too complex and therefore create difficulties. To create a mathematical model of a phenomenon, it is necessary to express the laws governing this phenomenon in mathematical form. Often, models of various mechanical phenomena, electrical and magnetic phenomena, etc. are expressed in the form of differential equations. To find their particular solutions, the initial and boundary conditions of the phenomena under consideration are also necessary.

2 Materials and methods

Monitoring tools and hydrological modeling are used to check the condition of reservoirs. The structure of river basin monitoring is determined by the peculiarities of the geographical location of each basin, the types of its landscapes, morphometric characteristics, intensity and diversity of economic use. Hydrological modeling is a simplified conceptual representation of part of the hydrological cycle. The use of modeling has both positive properties and disadvantages. The first include the possibility of studying various scenarios for the development of the situation, as well as processes and phenomena that are inaccessible to experiments, or those that are theoretically possible, but not currently occurring; the second is the complexity of the mathematical expression of the model and the need to develop specialized software. Hydrological processes are a description of some phenomenon that occurs, constantly changing, often depending on time. The hydrograph itself is expressed by a graph of changes in runoff versus time [6].

An accurate mathematical model of a cascade of reservoirs requires taking into account all water losses, including due to evaporation from the water surface, due to leakage into groundwater through direct penetration, direct pumping and other factors.

The purpose of a reservoir simulator is to conduct research on a real reservoir without the expense of testing a real facility, or to test different scenarios to find the optimal one before putting the reservoir into operation. In this case, the most studied factors and well-known boundary conditions are taken into account in order to obtain the least uncertainty.

3 Results and Discussion

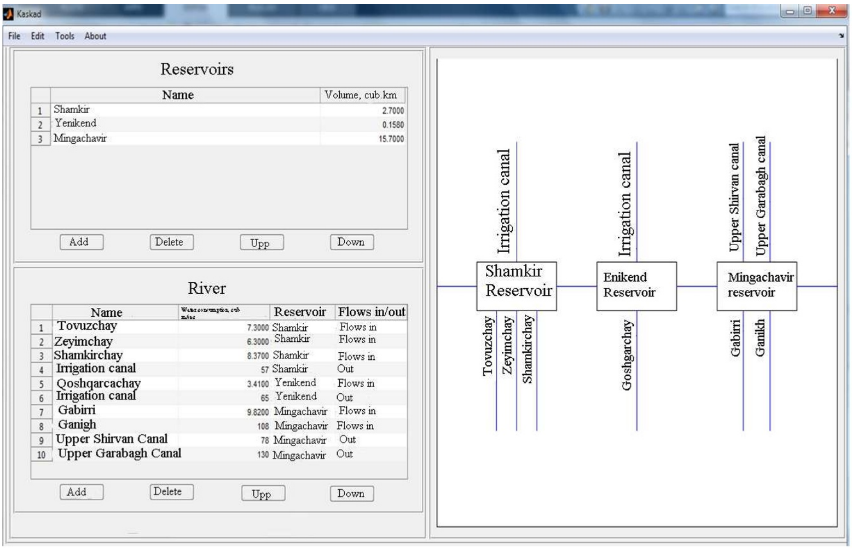
Temporal and spatial derivatives of hydrological processes are equally important, especially in a changing climate [8]. In the process of working on the article, a simulation model was created to study the joint influence of these factors. However, some other influencing factors were not taken into account in the calculations. Thus, the purpose of this model was to study some specific scenarios such as:

- Violation of the basic hydrological operating regime.
- Destruction of the reservoir.

At the first stage, to generate a map of the region, an archive of geodata was downloaded from the site gis-lab.info. The archive contains an extensive library of vector geodata in shapefile format, numbering about 50 different layers, including state boundaries, administrative divisions, infrastructure, hydrological and other objects, including the contours and attributes of reservoirs and rivers [9]. Loading geodata and creating a project database was carried out using the Mapping Toolbox package included in the MATLAB program. For the best study of the operating modes of the cascade, complexes are being developed, including: a hydrological model in the form of a computer program; database; as well as the user interface. This enables data management, visualization and reporting capabilities. In particular, this is how almost all open source modeling platforms work [10]. For modeling in the MATLAB programming environment, the “Kaskad” program was developed, which has a graphical user interface [11]. The program operates in two modes: design and working. Design mode is intended for editing a project. In this mode, it is possible to add or delete water objects, as well as edit their parameters: volume, flow and other values. In Fig.2 shows the program in design mode.

On the left in Figure 2 there are panels with tables containing the parameters of all water bodies of the project. On the right is an orographic diagram of the cascade, corresponding to the data from the tables. On the orographic diagram, reservoirs are shown as rectangles. The lines entering them from below show the rivers flowing into the reservoirs, and from above - the canals flowing out of them. In design mode, the program has the ability to create and edit basic program objects. These objects include:

- Reservoirs of the Kura cascade.
- Rivers and canals that are part of the basins of individual reservoirs.



Reservoirs

	Name	Volume, cub.km
1	Shamkir	2.7000
2	Yenikend	0.1580
3	Mingachavir	15.7000

River

	Name	Water consumption, cub m/sec	Reservoir	Flows in/out
1	Tovuzchay	7.3000	Shamkir	Flows in
2	Zeyimchay	6.3000	Shamkir	Flows in
3	Shamkirchay	8.3700	Shamkir	Flows in
4	Irrigation canal	57	Shamkir	Out
5	Qoshqarcachay	3.4100	Yenikend	Flows in
6	Irrigation canal	65	Yenikend	Out
7	Gabirri	9.8200	Mingachavir	Flows in
8	Ganigh	108	Mingachavir	Flows in
9	Upper Shirvan Canal	78	Mingachavir	Out
10	Upper Garabagh Canal	130	Mingachavir	Out

Fig. 2. Appearance of the program in design mode.

Thus, in addition to editing the composition of the cascade, it is possible to create a new project from scratch by filling out the "Reservoirs" and "Rivers" tables. If these tables are filled out correctly, it becomes possible to create a new orographic scheme and a corresponding mathematical model. If these tables are filled out correctly, it becomes possible to create a new orographic scheme and a corresponding mathematical model. Editing capabilities include adding new objects, deleting and editing existing ones. It is also possible to move objects to the top or bottom of tables. All of the above actions entail corresponding changes in the orographic scheme. Table 1 summarizes the values of object parameters and their designations, which will later be used in the differential equations of the model. After editing is completed, the program has the ability to switch from design to production mode. At the same time, based on the created orographic scheme, MATLAB automatically creates a system of differential equations. The system includes equations (2) – (4).

Table 1. Summary table of water body parameter.

No.	**Name**	**Designation**	**Options**	
			Volume,km^3	**Stock, m^3 in s**
1	Shamkir reservoir	w_{11}	2.7	-
2	Yenikendskoye reservoir	w_{12}	0.158	-
3	Mingachevir reservoir	w_{13}	15.7	-
4	Tovuzchay river	x_1	-	7.3
5	Zeyimchay river	x_2	-	6.3
6	Shemkirchay river	x_3	-	8.37
7	Goshgarchay river	x_4	-	3.41
8	Gabyrry river	x_5	-	9.82
9	Ganikh river	x_6	-	10.8
10	Irrigation conduit	E_1	-	57
11	Irrigation conduit	E_2	-	65
12	Upper Shirvan conduit	E_3	-	78
13	Upper Karabakh conduit	E_4	-	130

$$\frac{dw_1}{dt} = A_1 - k_1 w_1 \tag{1}$$

$$\frac{dw_2}{dt} = A_2 + k_1 w_1 - k_2 w_2 \tag{2}$$

$$\frac{dw_3}{dt} = A_3 + k_2 w_2 - k_3 w_3 \tag{3}$$

Where:

$$A_1 = x_1 + x_2 + x_3 - E_1 \tag{4}$$

$$A_2 = x_4 - E_2 \tag{5}$$

$$A_3 = x_5 + x_6 - E_3 - E_4 \tag{6}$$

w_1, w_2, w_3 – sought variables, output values of reservoirs; k_1, k_2, k_3 – parameters of discharge modes of individual reservoirs.

The equations are solved using the function MATLAB dsolve(eq, cnd), where eq – differential equation formula, a cnd – initial condition [14, 15].

As an example, we give the form of this function for solving the equation (1): dsolve(‘Dw1 = A1-k1*w1’, ‘w1(t1)=w11’)

Time constants *t1, t2, t3* – delays in the propagation of water flow to the exit of the 1st, 2nd and 3rd reservoirs, respectively.

The equations are solved sequentially, starting from the first reservoir. The found solution to the first equation is inserted. The found solution to the first equation is inserted into the second equation, and so on, until the last one. Below are the solutions to the equations (2) and (3).

z1 = (A1 - exp(k1*t1)*exp(-k1*t)*(A1 - k1*w11))/k1 (7)

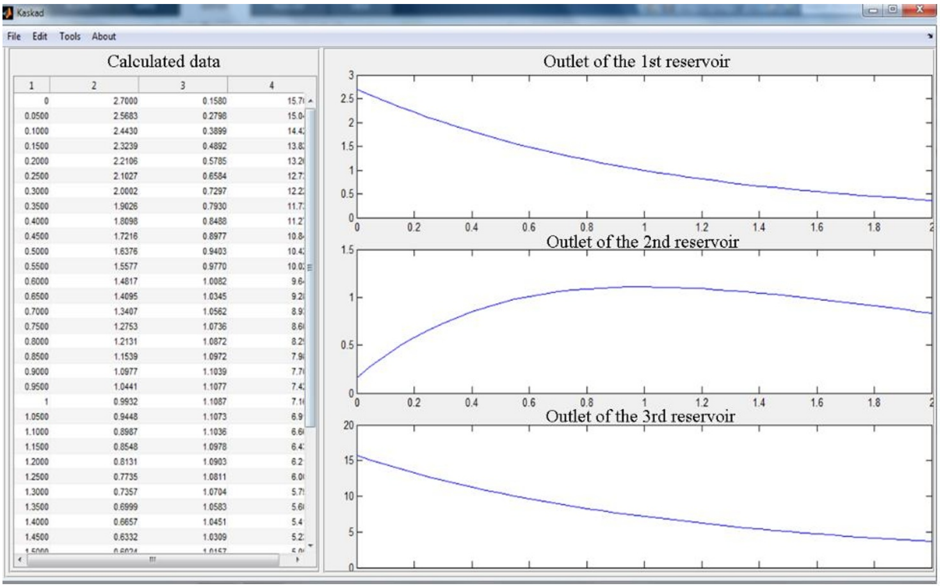
Here z1 – solution to the equation (1) in symbolic form. This expression is substituted for w1 into the equation (2). Solving the equation (2) looks like that:

z2 = exp(-k2*t)*((exp(k2*t - k1*t)*(A1*exp(k1*t1) - k1*w11*exp(k1*t1)))/(k1 - k2) + (exp(k2*t)*(A1 + A2))/k2) + exp(-k2*t)*exp(k2*t2)*(w12 - exp(-k2*t2)*((exp(k2*t2 - k1*t2)*(A1*exp(k1*t1) - k1*w11*exp(k1*t1)))/(k1 - k2) + (exp(k2*t2)*(A1 + A2))/k2)) (8)

Accordingly, this value is substituted instead w2 into the equation (3).

The solution to the 4th equation is not given for reasons of compactness, since in symbolic form it occupies 21 lines.

In operating mode, to present simulation results in tabular and graphical form, the program sets the time quantization step and starts the solution process. Figure 3 shows the program in operating mode. The abscissa axis values are expressed in hours, and the ordinate axis values are expressed in km^3.



Calculated data

1	2	3	4
0	2.7000	0.1580	15.7
0.0500	2.5683	0.2798	15.0
0.1000	2.4430	0.3899	14.4
0.1500	2.3239	0.4892	13.8
0.2000	2.2106	0.5785	13.2
0.2500	2.1027	0.6584	12.7
0.3000	2.0002	0.7297	12.2
0.3500	1.9026	0.7930	11.7
0.4000	1.8098	0.8488	11.2
0.4500	1.7216	0.8977	10.8
0.5000	1.6376	0.9403	10.4
0.5500	1.5577	0.9770	10.0
0.6000	1.4817	1.0082	9.6
0.6500	1.4095	1.0345	9.2
0.7000	1.3407	1.0562	8.9
0.7500	1.2753	1.0736	8.6
0.8000	1.2131	1.0872	8.2
0.8500	1.1539	1.0972	7.9
0.9000	1.0977	1.1039	7.7
0.9500	1.0441	1.1077	7.4
1	0.9932	1.1087	7.1
1.0500	0.9448	1.1073	6.9
1.1000	0.8987	1.1036	6.6
1.1500	0.8548	1.0978	6.4
1.2000	0.8131	1.0903	6.2
1.2500	0.7735	1.0811	6.0
1.3000	0.7357	1.0704	5.7
1.3500	0.6999	1.0583	5.6
1.4000	0.6657	1.0451	5.4
1.4500	0.6332	1.0309	5.2
1.5000	0.6024	1.0157	5.0

Fig. 3. Appearance of the program in operating mode.

Summarizing all of the above, the block diagram of the simulation program can be presented in the following form (Figure 4).

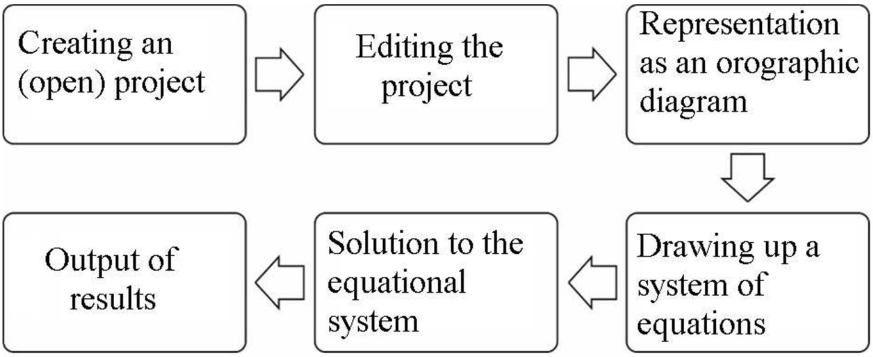


Fig. 4. Block diagram of the reservoir cascade modeling program.

4 Conclusion

A new program has been developed for calculating the mathematical model of the Shamkir, Yenikend, Mingachevir cascade reservoirs (Kursk cascades), located on the territory of the Republic of Azerbaijan. The program allows you to edit the parameters of objects (reservoirs and rivers), as well as add new ones and delete existing ones. Based on this program, after editing, you can automatically build a mathematical model in the form of an orographic diagram and a system of differential equations based on it. The solution of the system is carried out using the built-in tools of the MATLAB program. The solution results are presented in tabular and graphical form. Thus, the development of this simulation model allows us to study the behavior of real objects in selected situations.

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