Economic losses from floods have become catastrophic due to the increase in the number and scale of their propagation. Existing procedures for passing floods and pre-preparing reservoirs for flood water acceptance are ineffective and need to be improved. Therefore, the task to devise a methodology that would eliminate these shortcomings was urgent.

This paper has proposed a procedure for calculating the passage of floods based on the forecasts of water inflow, taking into consideration the characteristics of the flood wave and the mode of reservoir filling, which makes it possible to bring down (reduce) the maximum flow rate through a waterworks by accumulating floodwaters in the reservoir.

The software package Mike 11 (Danish Institute, Denmark) was employed to build a hydrodynamic model of floodwater movement along the examined river section from a hydrological station to a waterworks, which makes it possible to determine the levels of water and the flow rate in a reservoir at any time in the form of free surface curves when passing floods of various range.

Based on the devised methodology, recommendations have been compiled for the forced discharges of water through hydroelectric turbines (in m^3/s) when passing floods of various probabilities (which is especially important for floods whose probability is 0.01 %). The constructed hydrodynamic model of floodwater movement through a reservoir has allowed the verification of the devised procedure.

The procedure was devised in order to effectively pass floodwaters and bring down the maximum flow rate through a waterworks.

The introduction of the methodology for calculating the passage of floods could make it possible to avoid idle water discharge through the water drains of waterworks to the lower pool and provide for the most efficient utilization of floodwater resources

Keywords: fluctuations in water levels, unsteady mode, water flow rate, efficient use of water resources, implicit boundary-difference flow scheme, MIKE 11

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A PROCEDURE TO FORECAST AND MANAGE WATER RESOURCES AND TO REDISTRIBUTE RUNOFF WATER FLOW WHEN PASSING FLOODS

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1. Introduction

The increase in the number of floods over recent years in different parts of the world that flooded large surrounding areas along rivers has led to a significant increase in economic losses. This is a concern that makes the global community think about forming effective mechanisms for predicting and regulating run-off during floods.

Abnormal volumes of precipitation and the frequency of their occurrence lead to the formation of either too large or too little volumes of water resources, the observed result being, respectively, floods or droughts. In general, climate change in the world affects both the environment and the socio-economic situation.

The frequency of flood formation is subject to certain patterns that are manifested in the alternation of periods of high and low water content. It is during the period of increased water content that floods become threatening, even catastrophic. Therefore, devising effective measures to protect the territory from the harmful effects of water has become the most important task of state importance.

Considering the European experience, almost all countries of the world undergo a gradual transition from passive flood protection to the active phase, which is based on the construction of anti-flood volumes and reservoirs within hydroelectric power stations. That could reduce the levels of high floods to the floods with a probability of 10 %, and pass them within riverbeds without unregulated flooding of the adjacent territories.

The extent of influence exerted by hydro energetics on flood management is quite high. For example, the construction of the Dniester reservoir made it possible to reduce losses from flooding the territories adjacent to the Dniester river by managing spring floods. To that end, a special anti-flood capacity of 570 million m^3 is provided in the reservoir to manage floods. It is in the prism of forcing between the marks of the normal retaining level (NRL), 121.00 m, and the forced retaining level (FRL), 125.00 m. This anti-flood complex makes it possible to reduce the impact of periods of high floods by redistributing the runoff through accumulating excess water in anti-flood facilities. Water levels of the Dniester river in high floods would be reduced by two meters.

Successful fight against floods on rivers requires improvement of existing procedures for passing floods and early preparation of reservoirs for the acceptance and management of large volumes of water. Therefore, it is necessary to improve available techniques for calculating flood passage. Verification of improved procedures should be carried out by constructing a computerized mathematical (hydrodynamic) model that would make it possible to predict flood behavior and prepare reservoirs in advance. In addition, an opportunity could be created to analyze various flood passage scenarios.

The requirement to build automated systems is associated with a growing need to solve numerous tasks related to improving the efficiency of operational management of water resources. Some problems are not mathematically stated yet. These are problems without which effective systems of accounting, design, operation of water management systems cannot be built; solving them affects the efficiency of utilization and saving of water resources.

2. Literature review and problem statement

Existing procedures to forecast floods based on hydrological models of varying complexity are characterized by both strengths and constraints that do not make it possible to obtain reliable results. According to the results of studies reported in [1, 2], there is a tendency to consider issues related to improving existing flood forecasting techniques on the basis of hydrological models using variable and constant initial data.

When considering the potential of the process to improve existing flood forecasting procedures based on hydrological models, it is important to note that discussions usually culminate in the concept of uncertainty. Most studies related to flood modeling report that there are uncertainties in existing flood models [3].

Uncertainty analysis includes an assessment of the completeness of the model's source data and their impact on calculation results [4]. Sensitivity analysis helps understand the characteristics of a flood model according to various parameters, for example, topography and a Manning friction coefficient [5].

Over the past decade, attempts to improve existing flood forecasting techniques based on hydrological models have been widely discussed in the flood modeling literature [6] but it is still claimed that existing flood models have not yet reached an acceptable calibration limit [7]. This is due to the limited availability of the relevant source data, which are crucial in the modeling of floods.

There are many software systems in the world for modeling floodwaters, one of which is MIKE 11 [8]. This software package makes it possible to simulate floods, work out evacuation routes, and calculate dam breakouts. There are a large number of techniques for solving numerically the equations of flow continuity in branched riverbeds, some of which are described in [9]. However, it is necessary to take into consideration that each river has its hydrological characteristics and features, so existing procedures need to be adapted to the appropriate conditions or the use of research on analog rivers with a similar hydrological situation [10]. Climate change is also an important factor, and this must also be taken into consideration in calculations [11].

Thus, given the urgent need to improve the existing techniques of forecasting floods based on hydrological models, the logical alternative is to devise a special model involving the unsteady flood wave movement through a reservoir with the help of the software MIKE 11. Underlying the procedure is the implicit boundary-difference flow scheme based on a 2D Saint-Venant equation. The estimation scheme employs water flow forecasts in a reservoir based on the actual data from hydrological stations located above the reservoir. This approach could minimize the amount of uncertain initial data and elucidate the sensitivity of a model to different characteristics in order to adapt the model to the specific hydrological characteristics of a river.

It is necessary to emphasize that at present it is not possible to control the level of floodwater and improve forecasting techniques without the use of mathematical modeling.

Flood water level forecasting is based on the following methods:

– an algorithm that categorizes an image into "dry land"/"water" classes. This algorithm is based on the concept of fuzzy sets and the use of a measure of coherence, calculated on the basis of Interferometric Synthetic Aperture Radar. The disadvantage of the method is the need to use several images to implement the InSAR methodology, as well as the complexity of the procedure [12, 13];

– a neural network method of mapping floods based on satellite images (the neural networks by Kohonen are used to segment and categorize radar images, providing an intelligent approach to data analysis) [12, 14];

– fuzzy forecasting of expected flood losses based on the extrapolation method (in the form of several trends built for different sample dynamics series, which differ by the count origin, and the use of fuzzy sets) [15];

– a method for solving the tasks related to prompt forecasting of floods according to ground-based and radar measurements of precipitation. The use of radar for measuring precipitation makes it possible to simultaneously cover large areas and acquire a significant amount of information that needs to be processed in real time [12, 16]. Existing methods of processing radar images have the following disadvantages: the need to manually adjust threshold values and parameters for image segmentation, the need to use multiple images, the absence of a spatial relationship between image pixels.

There are other methods for predicting flood water levels as well.

Some systems for forecasting floods are under development, such as the information and measurement system "Prykarpattya" [17]; INTERREG IIIB CADSES/TACIS "Improvement of flood management system – MOSES" [18]; the automated information and measuring system (AIMS) "Tisa" [19].

Therefore, there is reason to believe that it is necessary to devise a procedure that, on the one hand, would not require expensive and long-term measures, and, on the other hand, could provide proposals for actions when passing floods of various levels at maximum accuracy.

3. The aim and objectives of the study

The aim of this work is to improve procedures for calculating the passage of floods through a waterworks based on water inflow forecasts, taking into consideration the characteristics of the flood wave and the mode of reservoir filling. That could make it possible to operate the reservoir in advance, thereby preparing it for the acceptance of large volumes of water and warranting a reduction in the maximum flow rate to the lower pool of a waterworks.

To achieve the set aim, the following tasks have been solved:

– to build a hydrodynamic model that reproduces the characteristics of the studied section of a river close to actual conditions and adequately describes the impact of floodwaters on raising levels at any cross-section of the studied section of the river;

– to develop an algorithm for regulating floods in the Dniester reservoir based on water inflow forecasts;

– to calculate the transformation of floods for a reservoir at various levels.

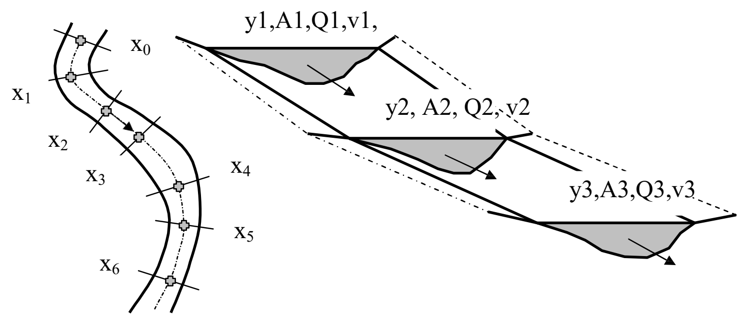

Fig. 1. Cross-sections shown in the plan of the Dniester river section and a 3D image of the flow with parameters calculated depending on the water level *h*: *A* – cross-sectional area; *Q* – water flow rate; *v* – flow velocity

4. The study materials and methods

To build a hydrodynamic model and perform further calculations, the methods of hydrodynamic modeling of hydraulic parameters were used. The research was carried out in the software package MIKE 11, which makes it possible to calculate the unsteady flow mode using an implicit boundary-difference estimation scheme for different flow modes. Underlying the calculations is the solution to complete nonlinear **Saint-Venant** equations for flows in the open branched riverbeds.

The main provisions on the **Saint-Venant** equations are set forth in [20].

The **Saint-Venant** equations are partial differential equations with two unknown variables *x* and *t*. Speed u, water level y, (depth h), and flow rate Q (dependent variables) depend on them. Speed *u*, water level *y*, (depth *h*), and flow rate *Q* (dependent variables) depend on them. Such a differential equation has no analytical solution.

The basic idea for a numerical solution to these equations was proposed by the Courant, Friedrichs, and Levi by using the theory of boundary differences [20]. We solved this problem in the software package MIKE 11 based on sampling.

The sampling was performed by substituting the derivatives of the boundary differences, and the coefficients for the polynomials used for interpolation between the points at which the flow parameters were determined were assigned.

When using this method, a transition is executed from the continuous domain of equation existence in the plane of independent variables (*x*, *t*) to the discrete grid. That is why this method is termed the method of boundary differences.

The studied section of the Dniester river from the hydrological station Zalishchyky to the Dniester hydroelectric power station dam site with a length of 257.30 km (along the water flow axis) is divided into sections using calculation points; the time is divided by time steps (Fig. 1).

Discrete equations are solved for each point (cross-section) in order to derive dependent variables.

The software package MIKE 11 employs the Abbott-Ionescu scheme (Fig. 2). In this scheme, there are two dependent variables, for example, flow rate *Q* and depth *h*, which are determined at different points of the grid (Fig. 3). The flow equations are:

$$b_{st}\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0, \qquad (1)$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+gA\frac{Q|Q|}{K^2}=0. \qquad (2)$$

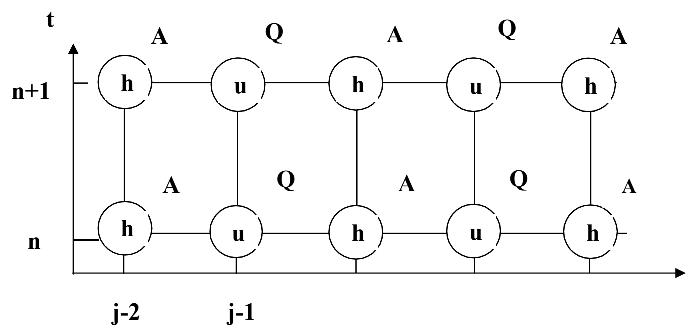

Fig. 2. Estimation grid under the Abbott-Ionescu method

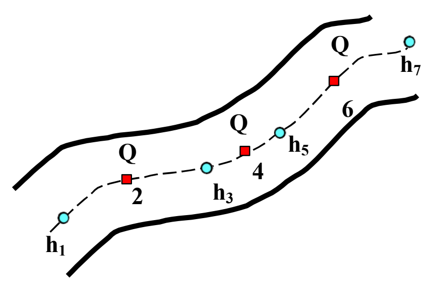

Fig. 3. Riverbed area with an estimation grid

In the Dniester reservoir, 58 sites were highlighted, from the hydrological station of Zalishchyky to the Dniester Hydroelectric Station dam site. The profiles of the cross-sections of the riverbed and floodplain in the estimation dam sites were determined by the topographic maps of scale 1:25000 – only on tributaries, and, along the riverbed, based on photographs taken in 1982, 1992, and 2014 [21]. The boundary conditions are set in the form of hydrographs of the inflow and discharges of the actual flood on July 24–31, 2008.

We also used the following as the initial data for the construction of a hydrodynamic model:

– cross-sections with distances between them;

– hydraulic parameters and morphometric characteristics of the estimation sections;

– the curves of the volumes and areas of the reservoir mirror;

– parameters of the initial water regime, which are set in the form of marks of water levels and flow rate at the beginning of a flood;

– roughness coefficients [21, 22];

– the characteristic of the throughput capacity of a waterworks;

– the boundary conditions, which are set in the form of hydrographs of inflow and discharge.

The basic morphometric characteristics and design levels of the reservoir are given in Table 1.

Table 1

Characteristic design levels and morphometric characteristics of the Dniester reservoir

Indicator	Indicator value
1. Waterworks structure	Drainage type hydroelectric power plant, stone-earth dam
2. Run-off control by a reservoir	Seasonal, with the transition to perennial
3. Reservoir purpose	Hydropower, water supply, irrigation, flood protection
4. Characteristic design levels in the reservoir:	
– normal retaining level (NRL);	121.00
– dead volume level (DVL);	102.50
– forced retaining level (FRL) when discharging flood with a probability of 0.01 %	125.00
5. Reservoir morphometric characteristics: 5. 1. Mirror area, km^2:	
– at NRL;	136
– at DVL	67.9
5. 2. Static volume, mln.m^3: – at FRL;	3,227
– at NRL;	2,657
– at DVL;	750
– anti-flood volume (between FRL and NRL);	570
– usable volume (between NRL and DVL)	1,907
6. Length, km	194 (along fairway at NRL=121.0 m)
7. Mean width, m	701
8. Depth, m:	
– maximal;	54
– mean	19.5
9. Designed flow rate 9. 1. Discharge regulated flow rate of rain floods, m^3/s, with a probability of:	
– 0.01 %;	13,260
– 0.1 %;	8,320
– 1 %;	2,600
– 10 %	2,600
9. 2. Hydropower plant maximal flow rate, m^3/s	1,970

The data given in Table 1 are the initial conditions for calculations in the software package MIKE 11.

5. Results of studying a procedure of forecasting and planning water resources and redistributing of run-off flow rate when passing floods

5. 1. Construction of a hydrodynamic model

The estimation model in mathematical notation is shown in Fig. 4.

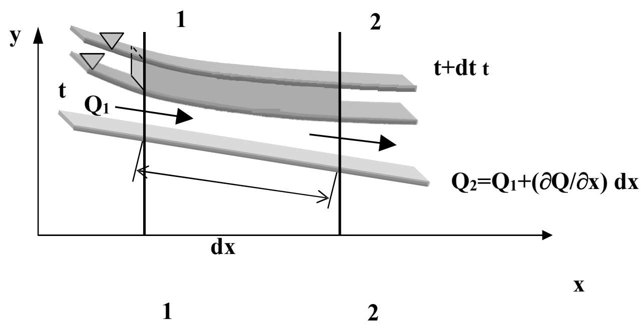

Fig. 4. Estimation model in mathematical notation

Boundary conditions for solving equations of unsteady flow movement determine the distribution of flow parameters in boundary areas. They are set in the starting (inlet) dam site and in the outlet dam site.

In the inlet dam site (the hydrological station Zalishchyky), in this case, a hydrograph of the discharge flow rate $Q(0, t)$ is set (Tables 2, 3, tributary).

In the inlet dam site (the dam site of the Dniester hydroelectric power plant), a hydrograph of the discharge flow rate $Q(0, t)$ is assigned (Tables 2, 3, discharge flow rate).

The side inflow (positive) or negative (outflow) is set concentrated in the form of water flow rate per unit length at the point of entry into the main riverbed.

Initial conditions are set in the form of water level marks along the entire length of the studied section of the river (Table 5, level marks at the beginning of the flood).

The result of our calculations is the derived values of the water levels and flow rate in each of the 58 estimation cross-sections at each hour (numerical values are given in Table 2).

Fig. 5 shows the curves of the free surface of the Dniester reservoir during the flood of 2008 with a probability of 1 %. Comparing the curve, acquired from calculations in the MIKE 11 software package, and the one built according to the actual operational data, we can state the following: the maximum discrepancy in the levels is 0.05 m. This discrepancy was registered at the time of maximum levels in the Dniester Reservoir near the Dniester HPP dam site.

The difference between the NRL and DVL of the Dniester reservoir is 18.50 m. Given this, the resulting calculation error is 0.27 %. This indicates that the estimated section of the Dniester River is reproduced quite accurately to natural conditions, and the built hydrodynamic model can be used in further calculations of the passage of floods at various levels.

Table 2

The basic indicators of the levels and flow rate of the actual flood of 2008 and those obtained from our calculations

Date	Hour	Zalishchyky station inflow, m^3/s	Discharge at the Dniester HPP dam site	Water level near the Dniester HPP dam site	
				H, m, upstream (actual)	H, m, upstream (MIKE 11)
24.07.08	8	467	532	120.62	120.64
	12	705	1,672	120.54	120.58
	16	924	1,402	120.45	120.49
	20	1,180	1,113	120.39	120.43
25.07.08	0	1,670	1,114	120.36	120.32
	4	1,570	538	120.43	120.40
	8	1,650	811	120.44	120.41
	12	1,760	1,688	120.45	120.42
	16	1,900	1,695	120.44	120.43
	20	2,060	1,695	120.44	120.48
26.07.08	0	2,250	1,690	120.46	120.49
	4	2,490	1,690	120.52	120.56
	8	2,980	1,900	120.62	120.66
	12	3,590	2,320	120.62	120.65
	16	4,210	2,530	120.64	120.67
	20	4,680	2,730	120.70	120.74
27.07.08	0	4,930	2,725	120.77	120.81
	4	5,060	2,730	120.86	120.89
	8	5,180	2,930	120.98	121.01
	12	5,360	3,150	121.09	121.10
	16	**5,410**	**3,780**	121.16	121.20
	20	**5,410**	3,380	121.23	121.28
28.07.08	0	5,340	3,360	121.33	121.35
	4	5,160	3,385	121.40	121.42
	8	5,060	3,400	121.54	121.57
	12	4,900	3,400	121.61	121.64
	16	4,840	3,420	121.70	121.74
	20	4,690	3,200	121.74	121.76
29.07.08	0	4,540	2,980	121.88	121.90
	4	4,210	2,980	121.97	121.99
	8	4,150	2,980	122.06	122.08
	12	4,070	2,760	122.15	122.17
	16	4,050	2,760	122.26	122.28
	20	3,780	2,760	122.34	122.36
30.07.08	0	3,690	2,760	122.42	122.44
	4	3,450	2,980	122.43	122.47
	8	3,300	2,980	122.50	122.53
	12	3,110	2,990	**122.53**	**122.54**
	16	2,860	2,990	**122.53**	**122.58**
	20	2,610	2,990	**122.53**	**122.58**
31.07.08	0	2,370	2,990	122.52	122.57
	4	2,130	2,990	122.49	122.51
	8	1,850	2,990	122.46	122.49
	12	1,560	2,300	122.41	122.43
	16	1,310	2,530	122.35	122.31
	20	1,150	2,300	122.31	122.28

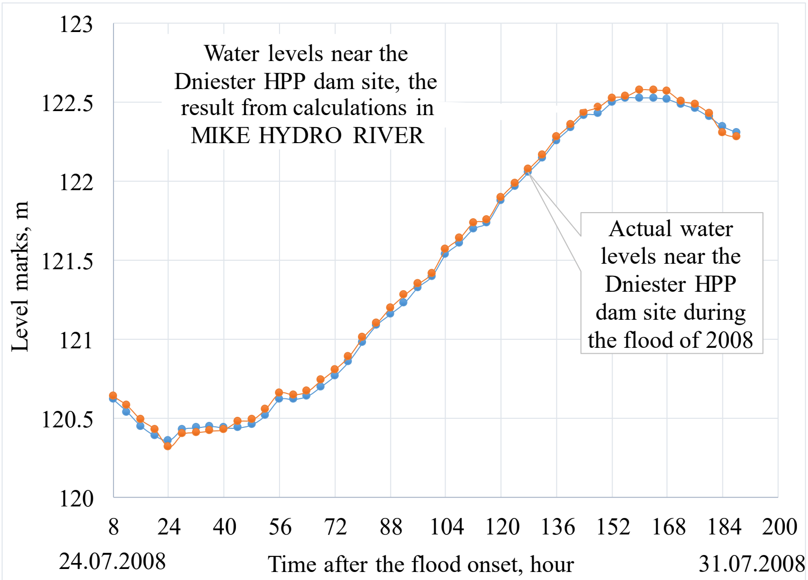

Fig. 5. The course of water levels (actual and obtained from calculations in the MIKE 11 software package) during the flood period of July 24–31, 2008

5. 2. An algorithm for managing floods in the Dniester reservoir based on water inflow forecasts

The main scheme to manage floods and spring watershed, adopted in the approved project of the Dniester waterworks is a scheme disregarding forecasts [23–33], which warrants bringing down (reducing) the maximum flood flow rate with a probability of 1–10 % to 2,600 m^3/s. This scheme uses information on an hourly water flow rate in the Zalishchyky hydrological station dam site (the main water inflow to the Dniester reservoir).

When managing floods under the scheme that disregards forecasts, the maximum flow rate of floods with a probability of 0.5–10 % is cut only, and, most of all, the flood is cut with a probability of 1 % – by 2,540 m^3/s, or by 49.4 %.

The flow rate less than 0.5 % is not cut off as the anti-flood capacity is filled at the stage of flood rise.

The disadvantage of the methodology that disregards forecasts is that flood flow rate at the probability exceeding 1 % are either cut off little or not cut off at all. This disadvantage can be eliminated using the forecasts of water inflow to the Dniester reservoir.

To this end, it is proposed to manage floods in the Dniester reservoir based on the use of the forecast of a water flow rate of the Dniester River near the hydrological station Zalishchyky (the nearest station to the Dniester HPP dam site) on a daily advance basis.

Underlying the procedure for calculating the passage of floods through the Dniester waterworks based on forecasts of water inflow is the following algorithm for managing floods in the Dniester reservoir (Fig. 6):

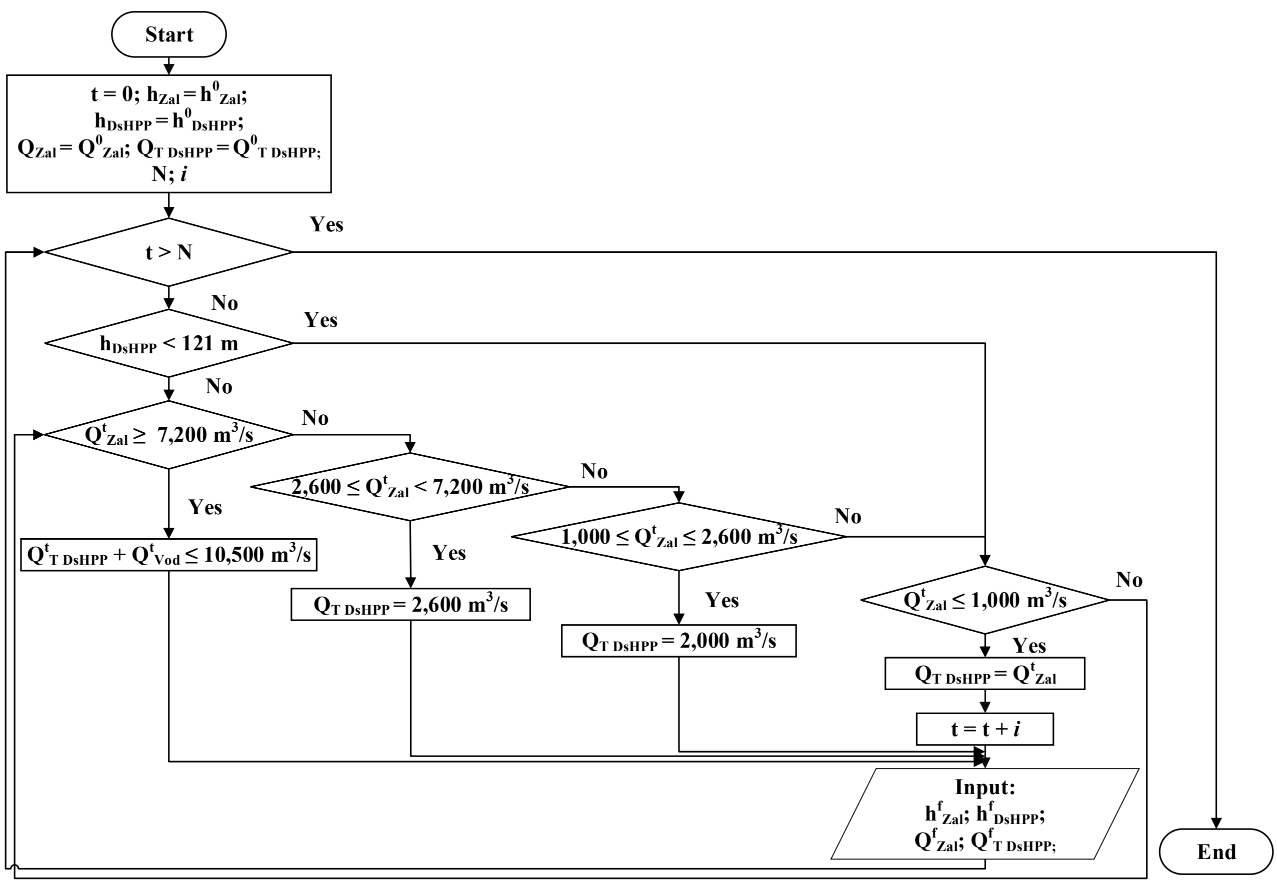

Fig. 6. Algorithm for managing floods in the Dniester reservoir based on water inflow forecasts, taking into consideration the characteristics of the flood wave and the mode of reservoir filling

The throughput flow rate through the Dniester waterworks is determined on the basis of the forecast of water flow rate near the hydrological station Zalishchyky 24 hours in advance. The calculation took into consideration the fact that the forecast comes during the flood period at least 3 times a day every 8 hours.

Following the flood, the forcing capacity is freed; the water level in the reservoir is reduced to the NRL mark of 121.00 m.

5. 3. Flood transformation calculation

Calculations of flood transformation with a probability of 0.01 % were performed to check the proposed flood pass method using forecasts. The maximum flow rate was 13,260 m^3/s.

The result of calculating the passage of flood through the Dniester waterworks according to the procedure that we proposed is the derived values of water levels and flow rate in each of the 58 estimated cross-sections. In a numerical form, the results are given in Tables 3, 4. We analyzed a change in the curve of the free surface of the Dniester reservoir during flood (Fig. 7). And it can be argued that during the period of rising floods, significant amounts of water accumulate in the tail section of the reservoir, which are gradually moving towards the dam.

Table 3

Hydrographs of hourly flow rate near the hydrological station Zalishchyky (inflow) and the outflow to the lower pool of the Dniester waterworks (discharge) during a flood with a probability of 0.01 % in the Dniester reservoir

Total hours	Hour	Inflow to the station Zalishchyky, m^3/s	Discharge flow rate through the Dniester hydroelectric power plant, m^3/s, according to the proposed procedure
0	8	100	1,000
12	12	250	1,000
16	16	450	1,000
20	20	1,100	1,960
24	0	1,530	1,960
28	4	1,960	1,960
36	8	2,400	2,600
40	12	3,570	2,600
44	16	4,740	2,600
48	20	5,900	2,600
52	0	7,435	10,500
56	4	8,970	10,500
60	8	10,500	10,500
64	12	11,270	10,500
68	16	12,035	10,500
72	20	12,800	10,500
76	0	12,955	10,500
80	4	13,107	10,500
84	8	13,260	10,500
88	12	13,140	10,500
92	16	13,020	10,500
96	20	12,900	10,500
100	0	12,735	10,500
104	4	12,570	10,500
108	8	12,400	10,500
112	12	12,170	10,500
116	16	11,935	10,500
120	20	11,700	10,500
124	0	10,970	10,500
128	4	10,235	10,500
132	8	9,500	105,00
136	12	8,770	10,500
140	16	8,035	10,500
144	20	7,300	10,500
148	8	6,800	6,800
152	12	6,300	6,300
156	16	5,800	5,800
160	20	5,600	5,600
164	0	5,400	5,400
168	4	5,200	5,200
172	8	5,000	5,000
176	12	4,800	4,800
180	16	4,600	4,600
184	20	4,450	4,450
188	0	4,250	4,250
192	4	4,050	4,050

Table 4

Coordinates of the free surface curves during a flood with a probability of 0.01 % using the forecast of inflow (Fig. 7)

No. of entry	Title		Level marks, m			
	dam site	Distance from Dniester HPP	flood onset	the time point of min. level near the dam	the time point of max. level near the station Zalishchyky	the time point of max. level near the dam
1	2	3	4	5	6	7
DHPP	**Dniester HPP dam**	0.00	121.00	115.70	117.40	122.60
1	Cross sections 1	0.58	121.00	115.80	117.40	122.60
2	**w/p Novodnistrovs′k**	0.70	121.00	115.90	117.40	122.60
3	678.1 km	2.00	121.00	116.00	117.40	122.60
4	Cross sections 2	8.85	121.00	116.00	117.40	122.60
5	Kalyus village	9.90	121.00	116.00	117.40	122.60
	w/p Nepovorotove	13.60	121.00	116.00	117.40	122.60
6	Nepovorotove village	16.90	121.00	116.00	117.40	122.60
7	Cross sections 3	17.95	121.00	116.00	117.40	122.60
8	Loyevtsi village	28.00	121.00	116.00	117.40	122.60
9	Cross sections 4	29.19	121.00	116.00	117.40	122.60
10	Cross sections 5	33.59	121.00	116.00	117.40	122.70
	w/p Ushytsya	37.60	121.00	116.00	117.40	122.80
11	Stara Ushytsya village	40.00	121.00	116.00	117.40	122.80
12	Cross sections 6	48.53	121.00	116.00	117.40	122.80
13	Komarovo village	50.40	121.00	116.00	117.40	122.95
14	Studenytsya village	55.70	121.00	116.00	117.40	122.95
15	Cross sections 7	56.30	121.00	116.00	117.40	123.00
16	Vil′yamivka (Rohozaniv)	62.80	121.00	116.10	117.40	123.00
	w/p Hrushevtsi	64.60	121.00	116.10	117.40	123.00
17	Cross sections 8	65.49	121.00	116.15	117.40	123.00
18	Mar″yanivka village	75.70	121.00	116.15	117.55	123.00
19	Luka Vrublevets′ka village	83.10	121.00	116.17	117.60	123.00
20	Cross sections 9	84.03	121.00	116.17	117.70	123.00
21	V. Slobodivka	93.40	121.00	116.17	117.71	123.00
22	Cross sections 10	93.61	121.00	116.18	117.72	123.00
23	Cross sections 11	97.33	121.00	116.24	117.75	123.00
	w/p Ustya	103.60	121.00	116.25	117.77	123.10
24	Cross sections 12	104.73	121.00	116.38	117.96	123.10
25	Sokil	111.40	121.00	116.48	118.50	123.15
26	Cross sections 13	120.84	121.00	117.75	119.51	123.16
	w/p Zhvanets′	125.60	121.00	117.80	119.53	123.17
27	Malynivtsi	131.20	121.00	118.82	121.20	123.20
28	Cross sections 14	135.13	121.00	119.82	122.10	123.60
29	Cross sections 15	143.23	121.00	121.90	124.00	125.00
30	Khotyn town	149.70	121.00	123.50	125.60	126.00
31	Cross sections 16	151.03	121.00	123.75	126.00	126.20
32	Cross sections 16 a	151.29	121.00	123.90	126.01	126.30
33	Zhvanets′ village	152.60	121.00	124.20	126.40	126.40
34	Cross sections 17	157.84	121.00	125.60	127.80	127.60
35	Bilevtsi	162.80	121.00	127.00	129.20	128.60
36	Cross sections 18	166.37	121.00	127.80	130.10	129.75
37	Volkovtsi village	175.40	121.40	130.30	132.60	131.93
	w/p Ruhotyn	176.60	121.60	130.60	132.80	132.10
38	Cross sections 19	177.12	121.63	130.75	132.95	132.20
39	Cross sections 20	186.23	122.60	132.50	134.51	133.75
40	Cross sections 21	190.17	123.60	133.20	135.45	134.45
41	Khudykovtsi village	190.80	123.80	133.40	135.50	134.65
42	873.6 km	196.20	125.40	134.40	136.51	135.60
43	Goroshevo village	202.10	127.40	137.25	139.10	137.90
44	Goroshevo village	203.10	127.80	138.60	140.50	139.45
45	Cross sections 22	203.27	127.83	138.75	140.60	139.50
46	Onut village	206.80	129.00	139.73	141.80	140.60
47	Samushin village	211.80	130.20	140.72	142.65	141.45
48	Ustya village, ferry	216.30	131.30	141.45	143.25	142.20
49	Ustya village	216.50	131.40	141.51	143.35	142.30
50	Kolobrodka village	221.50	132.90	143.25	144.75	143.60

Continuation of Table 4

1	2	3	4	5	6	7
51	Brodok village	227.80	134.60	145.80	147.25	146.10
52	Zozulyntsi village	234.60	136.40	148.70	149.80	148.47
53	Vasyliv village	240.80	137.80	150.50	151.80	150.25
54	Kulevtsi village	244.60	139.00	151.60	153.00	151.50
55	Dobrovlyany village	251.70	142.20	153.70	155.00	153.50
56	Zalishchyky town, dam site	256.10	144.20	154.80	155.95	154.50
57	Zalishchyky town, motor bridge	257.30	146.60	155.70	156.80	155.20
58	**Zalishchyky town**	258.00	146.70	155.80	156.90	155.30

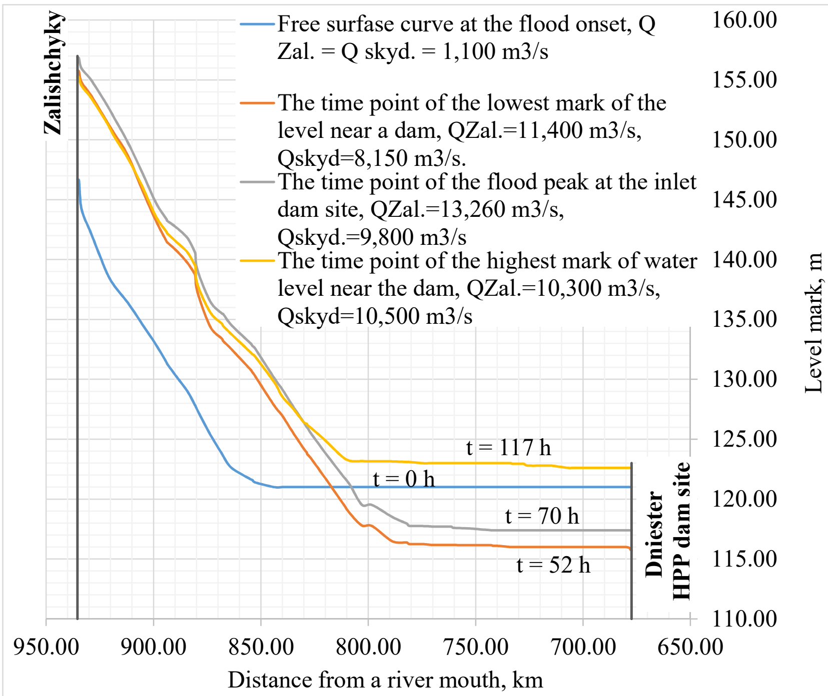

Fig. 7. Free surface curves in the Dniester reservoir during a flood with a probability of 0.01 %

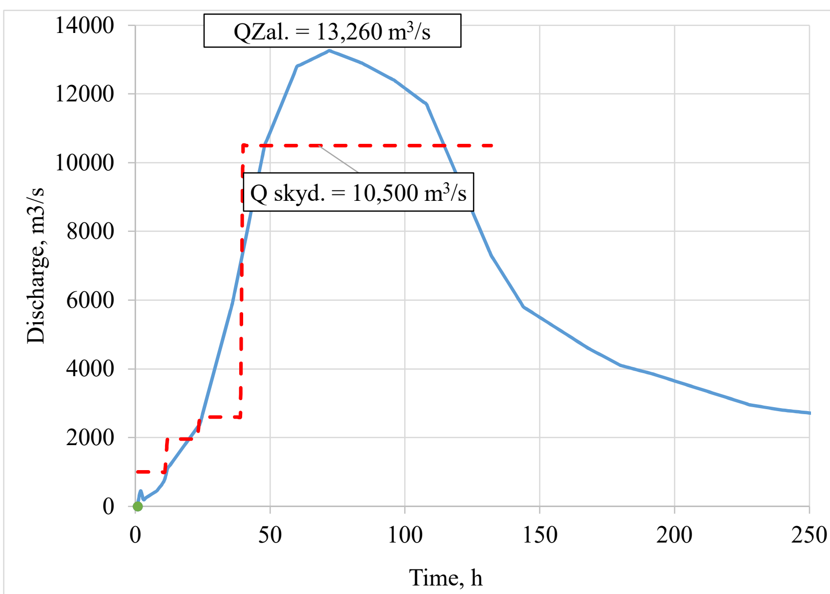

Fig. 8. The scheme of passing a flood with a probability of 0.01 % according to the proposed procedure taking a forecast into consideration

At the very descent of the flood, although the discharge flow rate exceeds the inflow rate, there was a rise in the water levels near the dam. This increase in the level is explained by the movement of dynamic volumes that accumulated during the rise of the flood from the tail section to the dam-adjacent section of the reservoir. The highest level of forcing reached the mark of 122.60 m at the time when the water flow rate at the hydrological station Zalishchyky was equal to 10,300 m^3/s, and the discharge rate was 10,500 m^3/s.

And for floods with a probability of 1 %, with a maximum flow rate of 5,410 m^3/s, the proposed procedure warrants a decrease of up to 2,600 m^3/s (Fig. 9).

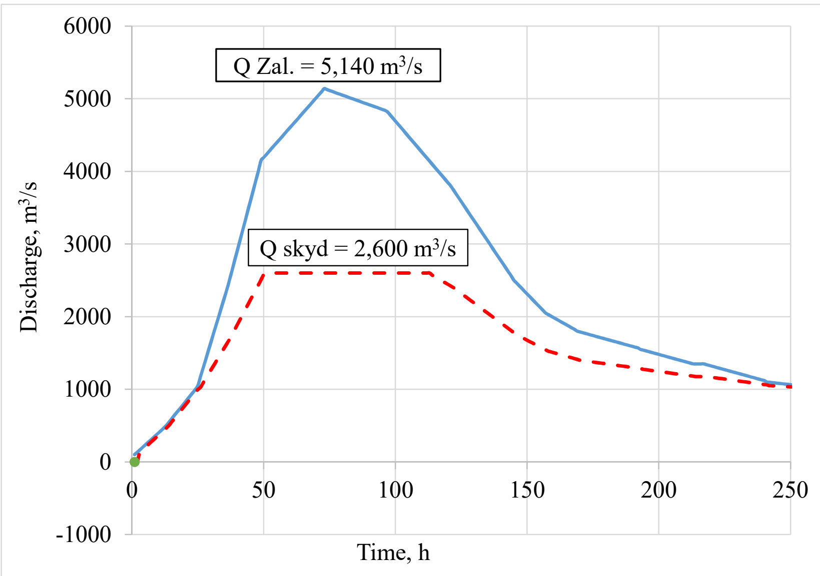

Fig. 9. The scheme of passing a flood with a probability of 0.01 % according to the proposed procedure taking a forecast for Zalishchyky into consideration

6. Discussion of results of studying the passage of floodwaters through a waterworks

Our results in improving the calculation methodology related to the construction of a new hydrodynamic model and a new algorithm for managing floods in a reservoir make it possible to resolve the following issues that are relevant when using the specialized software package MIKE 11:

– to define a set of initial data to describe the studied section of the river with its hydrological features and a series of unknowns;

– the way to describe the roughness of the riverbed in order to get as close as possible to the natural conditions of the object under study;

– the way to take into consideration a series of right tributaries [21], which fall into the main riverbed;

– the way to divide each explored area into a riverbed and a floodplain since, with a significant rise in water levels, the outflow at significant volumes reaches the floodplain and only after the flood is over, it flows into the reservoir over a long time.

A special feature of the built hydrodynamic model is that it takes into consideration the conditions and characteristics of water outflow to the floodplain and runoff to the reservoir during the study period. A given hydrodynamic model makes it possible to determine the time of outflow running to the dam site of a hydroelectric power plant, as well as the very nature of the passage of a flood wave through the reservoir during floods of various probabilities.

A distinctive feature of the proposed new algorithm for managing floods in a reservoir is to take into consideration the forecast of water inflow to the reservoir based on the actual data from hydrological stations located above the reservoir.

The result of our calculations is the derived values of the levels and flow rate of water at each of the 58 estimated cross-sections per every hour (numerical values are given in Table 2).

Fig. 5 shows the curves of the free surface of the Dniester reservoir during the flood of 2008 with a probability of 1 %. Comparing the curve built from the calculations in the MIKE 11 software package and the one constructed according to the actual operational data, we can say the following: the maximum discrepancy in the levels is 0.05 m. This discrepancy was registered at the time of maximum levels in the Dniester reservoir near the Dniester HPP dam site.

The difference between the NRL and DVL in the Dniester reservoir is 18.50 m. Given this, the resulting calculation error is 0.27 %. This indicates that the estimated section of the Dniester river has been reproduced quite accurately to natural conditions, and the built hydrodynamic model can be used in further calculations of the passage of floods, as well as an integral part in devising a methodology for calculating flood passage, taking into consideration the forecast of inflow.

Thus, the hydrodynamic model calculates the time over which floodwaters from the inlet dam site reach the dam site of a waterworks, which makes it possible to predict the progress of levels through the reservoir and plan further actions for the successful passage of floods through waterworks, without flooding adjacent territories and avoiding idle discharges, enabling, therefore, the preservation of water resources.

The algorithm of flood management in a reservoir based on the forecasts of water inflow makes it possible to prepare the reservoir to manage large volumes of floodwater (by following the specified rules in the algorithm), on the one hand, and not to work to the limits, on the other hand. This warrants the cutting of floods of various probabilities. An example has been given by calculating catastrophic flooding with a probability of 0.01 %, which occurs every 100 years. The most complex conditions that have been encountered over the past 116 years of observations at the studied object were considered. We also calculated the passage of floods at a greater probability (0.1 %, 1 %, 5 %, 10 %); satisfactory results were obtained. For example, a flood with a probability of 1 % with a maximum flow rate of 5,410 m^3/s is cut to the flow rate of 2,600 m^3/s (Fig. 9). The results of the calculation using the proposed procedure indicate that the procedure is effective.

The methodology for calculating the passage of floods through the Dniester waterworks based on water inflow forecasts would help specialists to solve the following tasks:

– to compile short-term and long-term hydrological forecasts;

– to comprehensively analyze water supply in the Dniester river basin;

– to perform water-energy calculations and estimate optimal electricity generation;

– to calculate the time when water from the hydrological station of Zalishchyky reaches the Dniester HPP dam site;

– to build scenarios for the utilization of water resources and to perform calculations and comparative analysis for conditions of low water and flood.

The limitation of this study is that the data acquired from hydrological stations are not currently automated, so the construction and advancement of the hydrodynamic model takes a long time, and, when flood passes, it is necessary to quickly perform calculations. The use of a given procedure is possible at medium-pressure hydroelectric power plants and in analog rivers with similar hydrological conditions.

In the future, it is planned to build an automated information system: "A system to plan (forecast) and manage water resources and electricity generation at hydroelectric power plants and HSPP".

7. Conclusions

1. A hydrodynamic model has been constructed that reproduces the characteristics of the studied section of a river close to real conditions and adequately describes the impact of floodwaters on rising levels at any cross-section of the studied section of the river (the adequacy check of the built model was carried out by passing the actual flood that took place in 2008). Using the built hydrodynamic model makes it possible to take into consideration the conditions and characteristics of water outflow to the floodplain and its subsequent return to the reservoir after passing the maximum flood outflow and lowering the marks in the main riverbed over the study period. The hydrodynamic model determines the time when a flood flow from the inlet dam site reaches the dam site of a waterworks, which makes it possible to carry out dynamic calculations, and not on static containers.

2. The developed algorithm for managing floods in the Dniester reservoir takes into consideration the forecast of water inflow in the reservoir based on the actual data from hydrological stations located above the reservoir. This approach allows minimizing the amount of uncertain initial data in order to understand the sensitivity of the model to different characteristics for adapting the model to the specific hydrological features of the river under study.

3. We have calculated the transformation of floods in the reservoir at various probabilities (the example describes a flood with a probability of 0.01 % with the maximum flow rate of 13,260 m^3/s) using the proposed procedure for calculating the passage of floods through the waterworks based on water inflow forecasts, taking into consideration the characteristics of a flood wave and the mode of reservoir filling. Based on the obtained calculation results, it is clear that the proposed methodology warrants bringing down (reducing) the maximum flow rate from 13,260 m^3/s to 10,500 m^3/s in case of flood with a probability of 0.01 % (Fig. 8), and, for floods of a greater probability, for example, 1 %, whose flow rate is 5,410 m^3/s, it is guaranteed to cut the flow rate to 2,600 m^3/s.

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