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PROBABILITY ASSESSMENT OF THE KYIV RESERVOIR OVERFLOW

Abstract. *Reservoirs are an integral part of the world's hydraulic infrastructure and form the basis of modern water management in most countries including Ukraine. However, reservoirs are also sources of an essential danger to the environment, infrastructure, and population. The potential danger and risks to the population living near reservoirs especially downstream may be no less than to people living near nuclear facilities or chemical plants, with which experts and the public usually associate problems of technogenic safety. Moreover, statistics show that about a third of all accidents on dams and levees occurred due to overflow of reservoirs when upstream water levels exceeded allowable values.*

There are 1103 reservoirs in Ukraine with a total water volume of about 55,500 million m^3*. The Kyiv reservoir is the third one by volume and water surface area in the country. In addition, the reservoir is created by one of the longest dams in the world; the total dam length of the reservoir reaches 70 km.*

Admittedly, the overflow of a reservoir can be caused by an extreme flood with inflow parameters exceeding the capacity of hydraulic structures. The challenge is that the capacity of water passage structures may be insufficient both due to the inaccuracy of the hydrological forecast and because of faults, poor functioning, or failures of the hydraulic structures during a design flood. In particular, long-term forecasts of floodwater discharges maxima of the inflow into the Kyiv reservoir based on using various probability distribution functions show the essential divergence of the obtained results. As well, as practice shows, the unavailability of some water passage tracts of the reservoir can reach several months in a year. Sometimes repair works were performed even during floods.

The aim of the study consisted of probabilistic forecasting the emergency situation on the Kyiv reservoir as a result of its uncontrolled overflow through the possible inaccuracy of the hydrological forecast concerning an actual water inflow into the reservoir and due to failures of water passage hydraulic structures during floods. To achieve the study aim the following tasks were solved: (1) there was proposed a method of hydrological forecasting, which allows taking into account results of long-term forecasts of floodwater discharges maxima based on using various probability distribution functions and fuzzy modelling; (2) there was performed hydrological forecasting of floodwater discharges maxima of the Dnieper affecting the condition of the Kyiv reservoir based on the actual data collected the Vyshgorod water level gauge; (3) there was assessed the probability of the Kyiv reservoir overflow taking into account the occurrence possibility of a shortage of the capacity of water passage structures with using the failure and fault tree method. Totally, six incompatible hypothetical emergency situations at the Kyiv reservoir were considered. The calculations showed the total probability of the Kyiv reservoir overflow equal to $3.84{\cdot}10^{-4}$ *(*$year^{-1}$*), which is acceptable to guarantee the hydrological safety of infrastructure and the population.*

Keywords: *annual exeedance probability; failure and fault tree method; floods; forecasting; fuzzy modelling; hydrological safety; Kyiv reservoir overflow*

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1. Introduction

Reservoirs are an integral part of the world's hydraulic infrastructure and form the basis of modern water management in most countries [1]. They provide reliable managing and controlling water resources of rivers for various purposes that may include flood control, water conveyance by canals, irrigation, navigation, power generation, municipal and industrial water supply, fishing, environmental protection, water tourism and recreation, and others [1, 2]. Admittedly, overall, hydraulic infrastructure including reservoirs has delivered substantial social and economic benefits [1]. In particular, it is argued (e.g. by Muller et al. [3]) that socio-economic development is curtailed in countries that have insufficient infrastructure to manage water, as a result of which many developing countries are held hostage to their hydrology.

Reservoirs and ponds (a pond is a reservoir with a capacity not exceeding 1.0 million m^3) are the most common water management facilities in Ukraine too. There are 1103 reservoirs in Ukraine with a total water volume of about 55,500 million m^3 and 50,793 artificial ponds with a total water volume of 3,969.4 million m^3 [4, 5]. They are present in various sectors of the national infrastructure providing its reliable and safe operation, and safety of the population life activity.

However, past experience shows that artificial reservoirs are sources of potential danger to the environment, socio-economic infrastructure, and population especially downstream of large dams. The World Commission on Dams report (2000, [6]) concluded that inadequate valuation potential danger from reservoirs was a significant factor in the poor or negative performance of many large dams as water-retaining structures. In many cases, as the report states, actual social and environmental costs of reservoirs building turned out to be unreasonable; many of them were built without comprehensive analysis and evaluation of the technical, financial, and economic criteria applicable at the time, much less the social and environmental criteria that apply in today's context.

The most serious consequences of the construction and operation of reservoirs are associated with accidents of dams and other water-retaining hydraulic structures [7]. These accidents can lead to occurrences of dam-break floods [8, 9]. The peak discharges of the flow caused by a dam-breach flood can greatly exceed previous natural floods, and the response time available for warning the populace is much shorter than for usual precipitation-runoff floods [9, 10]. In general, quantification of the dam-break flood hazard is quite a complex task [11–14]. The potential danger and risks to the population living downstream reservoirs may be no less than to people living near nuclear facilities or chemical plants, with which experts and the public usually associate problems of man-made safety [15]. There have been many cases of destructive accidents on reservoirs and water-retaining hydraulic structures including ones with numerous human victims [7, 11, 15, 16].

Accidents on water-retaining hydraulic structures occur for various reasons [15]. Often, it is extremely difficult to establish all possible causes of dam accidents, as well as to identify the principal factors determining them [7, 16]. However, statistics show that about a third of all accidents on dams and levees occurred due to overflow of reservoirs when upstream water levels exceeded design or allowable values [15–17]. Reservoir overflows are especially dangerous in the case of uncompleted or damaged water-retaining hydraulic structures. More than 80 per cent of dam accidents due to reservoir overflows occurred on such hydraulic structures [15]. Reservoir overflows can lead to flooding of areas and facilities situated upstream, threaten the loss of stability of riverbank slopes, cause overloading of water-retaining hydraulic structures and become triggers for the development of various emergency processes. In particular, reservoir overflows lead to serious problems to manoeuvre gates. An uncontrolled reservoir overflow often has an utterly adverse psychological impact on staff. Eventually, reservoir overflow can lead to dam crest water overtopping; for embankment dams and levees, such events usually end in catastrophic accidents [7, 15, 18, 19].

2. The case study

The Kyiv reservoir is the uppermost reservoir of the Dnieper cascade consisting of the six largest Ukrainian reservoirs (Fig. 1). The reservoir was created north of Kyiv city in the 1960s after the dam of the Kyiv hydropower plant was built near Vyshhorod town [20]. It is the third reservoir by volume and water surface area among the Dnieper reservoirs. Originally, at the normal (full) storage level of 103.0 m, the reservoir volume was 3.73 km^3, the water surface area was 922 km^2, and the usable volume was 1.17 km^3 [20, 21]. As a result of the reservoir sedimentation and overgrowing, especially in the backwater decrement part, the current reservoir area has probably decreased to 824 km^2 and its usable volume to 1.05 km^3 [22].

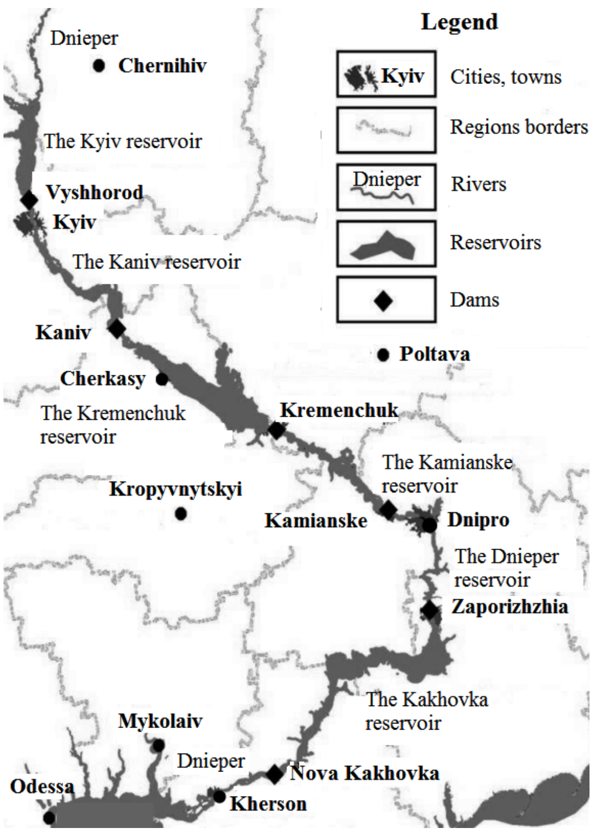


Fig. 1 – The map-scheme of the Dnieper cascade of reservoirs

The Kyiv reservoir does the seasonal Dnieper flow control. Operational water level fluctuations in the reservoir are within 1.5 m, up to the dead storage level of 101.5 m. During a flood having the 0.1-per cent annual exceedance probability (AEP), the water level in the reservoir is admitted to rising by 1.1 m from full storage level (FSL = 103.0 m) to the mark of 104.1 m. The volume of the forcing water prism from the FSL to the highest water level (HWL) of 104.1 m can reach 1.15 km^3. Then, the reservoir water surface area can increase to 1,166 km^2.

The length of the Kyiv reservoir full water storage front (FSL = 103.0 m) reaches 42.3 km [20]. The reservoir has one of the longest dams in the world. In particular, only the Kyiv left-bank earthen dam has a length of 17.2 km. The left-bank earthen dam abuts further upon the 52 km-long left-bank earth dike protecting the floodplain between the Dnieper and Desna rivers. With the 285 m long hydropower plant building, which is combined with spillway, the navigable lock, and the right-bank earth dam, the total length of the water-retaining hydraulic structures of the Kyiv reservoir reaches almost 70 km [20].

The Kyiv reservoir provides operation of the Kyiv hydropower plant (HPP), the current installed capacity of which is 440 MW. In addition, the Kyiv reservoir serves as the lower reservoir for the Kyiv pumping-storage power plant (PSPP), with an installed capacity of 235.5 MW in the turbine mode and 135 MW in the pumping mode [20]. As well, the reservoir and the Kyiv navigable lock are considered to be an integral part of the International Waterway E40 [23]. The reservoir is also used for industrial and public water supply purposes, irrigation, fisheries, and water recreation.

However, the Kyiv reservoir poses also an essential potential threat of break-dam flood occurrence, if one of the water-retaining structures is destroyed. Moreover, the reservoir contains the additional major threat connected with the consequences of the Chernobyl Nuclear Disaster in 1986. The threat is likely because of radionuclides in the reservoir bottom sediments [24, 25]. The possible accident and the reservoir descent might threaten radioactive contamination of Kyiv and others cities, territories, and water bodies downstream [26].

3. The problem formulation, aim, and objectives of the study

Admittedly, the overflow of a reservoir can be caused by an extreme flood, inflow parameters of which exceed the capacity of hydraulic structures.

The challenge is that the water passage capacity of hydraulic structures may be insufficient both due to the inaccuracy of the hydrological forecast concerning a possible water inflow into the reservoir and due to faults, poor functioning, or failures of the hydraulic structures during a design flood.

The capacity of spillways and outlets can be significantly reduced, for example, due to their blocking by floating bodies (garbage, forest, etc.), as well sediments, ice, etc. Two examples of such blocking are shown in Fig. 2.

Fig. 2 – Overtopping of Palagnedra dam in Switzerland due to plugging of spillway by floating debris in 1978 (left) [27]; the similar plugging of the spillway of Kerckhoff dam in California, USA, in 1997 (right) [28]

Spillways and outlets may lose their capacity due to malfunctions or failures of mechanical equipment: jamming of gates, faults of lifting mechanisms serving the gates including lack of power. For example, those reasons provoked a disaster to occur on the Tous dam in Spain in 1982 during a heavy rainstorm. The dam gates were not managed to rise in time due to damaged communications and power supply failure [29]. A special accident also occurred on the Taum Sauk PSPP in the U. S. in 2005. The cause of the overflow of the PSPP's upper basin was the failure of a computer program in the system of automatic regulation of water levels [31].

One of reasons for the decrease in the capacity of water passage structures may also be the unavailability of some of them to perform water escape functions due to incompleteness of the necessary repair and maintenance work in inter-flood periods. The condition of unavailability of some water passage tracts, which in general form water passage fronts on reservoirs (spillways, outlets, outfalls, culverts, weirs, sluices, pressure conduits of HPPs, locks, etc.) is quite common situation for a long period of time. According to S. Potashnik, the unavailability of some water passage tracts of the Kyiv HPP reached several months in a year [32]. Sometimes repair works were performed even during floods.

Cavitation erosion, abrasion, riverbed downstream erosion, underwashing, and hydrodynamics loads are usually recognized the main causes of damage to water passage structures in need of repair and restoration. However, as the example of the accident at the Oroville reservoir gated service spillway in 2017 (Fig. 3) shows, the failure causes can be very diverse [33, 34]. In general, incidents and accidents on water passage hydraulic structures occur much more often than on dams. Structures can be repeatedly damaged by floods and recovered after each subsequent flood. So, from 1977 until 2017, when the dangerous accident occurred, there were five (in 1977, 1985, 1997, 2009, and 2013) repeated slab repairs of the Oroville service spillway [33]. Usually, a majority of water passage structures on reservoirs can be either in standby mode or being repaired. Especially it concerns emergency spillways. Eventually, it was the emergency spillway overflow weir that prevented the Oroville reservoir from overflowing and the tallest dam in the U.S., 235 m high, from collapsing, despite a quite critical situation downstream of the dam.

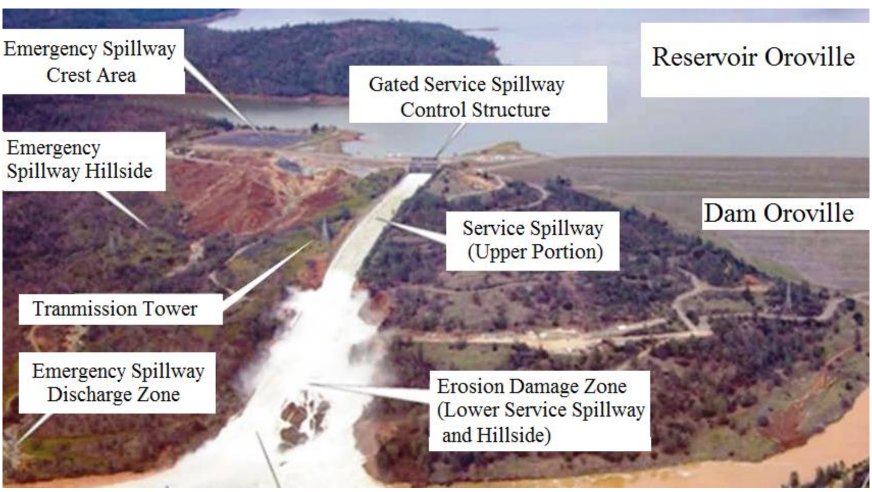


Fig. 3 – Oroville site during the 2017 incident [33]

As an entire probabilistic indicator of the reliability of spillways and outlets, in terms of their ability to perform specified functions of passing excess water from upstream to downstream, it is convenient to use the availability A or unavailability U coefficients, which complement each other as follow [15]:

$$A + U = 1, \text{ or } A + U = 100 \text{ (in per cent).} \tag{1}$$

The coefficient U can be expressed as the ratio of the total time during which a water passage structure may not be fully used, in spite of being necessary, because doing repair and maintenance works or through other technological reasons, to its design service life. According to estimates shown by various authors, an average coefficient of unavailability of an individual spillway structure, regardless of its type, design, causes of possible incidents, is about 10 per cent, that is U = 0.1 [35–37]. A similar integrated estimate of an average unavailability coefficient (U = 0.1, or 10 per cent) for an individual hydraulic power unit taking into account failures of its control system was given by J. Lecornu [38]. The above values of unavailability coefficients of various water passage hydraulic structures to perform required functions can be specifically clarified with additional data [39]. Eventually, if the must-have additional data are not available, the above-mentioned values can be considered as first approximations for unavailability coefficients of individual spillways, outlets, etc to assess the reliability of a reservoir spillway front as an entire system consisting of separate spillways and outlets as structural and functional units of the system [39–41]. In any case, the reliability of a spillway front of a reservoir may depend on a set of spillways and outlets, and an order of their use while escaping floods including design floods [39–41].

However, it is floods that generate main challenges for engineers making decisions on the safety of reservoirs. The most essential one among them is probably through the complexities, biases, and errors of hydrological forecasting. It is because the reasons, phenomena, factors, and events that cause floods are diverse, multifaceted, interrelated, and unsolved in a sufficient way, which not only complicates the task of hydrological forecasting but also creates a number of uncertainties while estimating design hydrological characteristics [42, 43].

The task of hydrological forecasting, in particular regarding the maximum water discharges of floods, is somewhat simplified for gauged rivers, but in the presence of data of uninterrupted hydrological observations within time intervals of at least 30-40 years. The basic mathematical model used to forecast design hydrological characteristics (water levels and discharges, etc.) according to hydrological observations is a probability distribution function [44, 45]. This model to assess design values of water levels and discharges having extremely small AEPs is accepted all over the world [46–52] including Ukraine [53].

Below, there are four examples of standardization of AEP values of maximum design water discharges depending on dam classes, categories or other criteria in accordance with the Ukraine's standard [55] (Table 1), as well the standards of Spain (Table 2), of Finland (Table 3), and France (Table 4). The parentheses show the average return periods (in years) of the corresponding estimated maximum discharges. It should be noted that the recurrence intervals of design floods may significantly exceed the periods of uninterrupted hydrological observations.

Table 1 – AEPs (per cent) of maximum design water discharges (design floods) and their average return periods (years) according to the current Ukraine's standard [55]

Estimated cases	The classes (subclasses) of consequences (responsibility) of structures			
	CC3	CC2		CC1
		CC2-1	CC2-2	
Main	0.1 (1,000)	1.0 (100)	3.0 (33)	5.0 (20)
Test	0.01* (10,000)	0.1 (1,000)	0.5 (200)	1.0 (100)

* Taking into account the warranty correction to the corresponding water discharge

Table 2 – AEPs (per cent) of design floods and their average return periods (years) according to the Spanish standards [56]

Dam categories	Cases	
	Design	Extreme
A	0.1 (1,000)	0.02÷0.01 (5,000÷10,000)
B	0.2 (500)	0.1÷0.02 (1,000÷5,000)
C	1.0 (100)	1.0÷0.2 (100÷500)

Table 3 – AEPs (per cent) of design floods and their average return periods (years) according to the Finnish standards [57]

Dam categories	Values
P	0.02÷0.01 (5,000÷10,000)
N	0.2÷0.1 (500÷1,000)
O	1.0÷0.2 (100÷500)

Table 4 – AEPs (per cent) of maximum design floods and their average return periods (years) for a reservoir with an embankment dam without consideration of vulnerability downstream according to the standards of France [58]

Index C *				
< 5	5 to 30	30 to 100	100 to 700	> 700
1.0 (100)	0.2 (500)	0.1 (1,000)	0.02 (5,000)	0.01 (10,000)

* The index C is calculated as $C = H^2\sqrt{V}$, where H is the height of the dam above ground level in metres, and V is the normal volume of the reservoir in hm^3

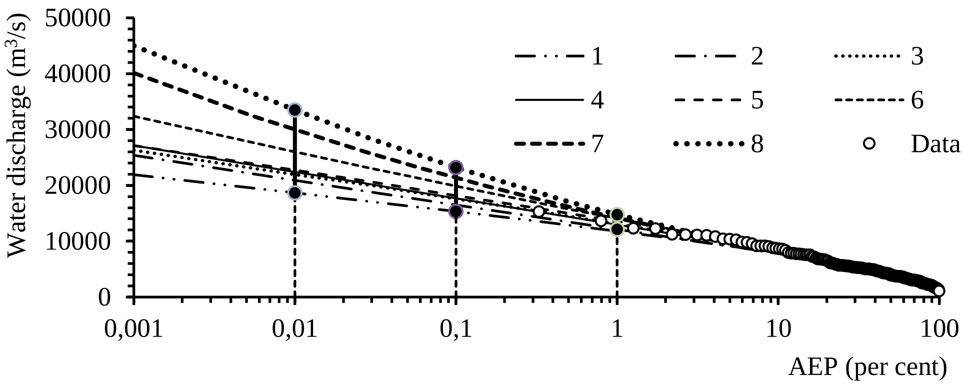
Usually, the hydrological maxima distributions have an essential positive asymmetry. In addition, they exceed zero, or some other lower limit, although, in theory, they are not limited to the upper limit. There is a great deal of analytical probability distributions that meet above conditions and might be used to forecast values of maximum hydrological characteristics not formerly observed yet. These are, for example, such distributions as follows: the log-normal (two- and three-parameter) distributions, the gamma family and related distributions (exponential, two-parameter distributions, the three-parameter Kritsky-Menkel distribution and the Pearson type III distribution, etc.), and the extreme value distributions, which were developed within the extreme value theory [47, 48].

It is noteworthy that in own national standards regulating hydrological calculations, different countries in the world may recommend to use various probability distribution functions. Some of the most known standardized probability distribution function types adopted for frequency analysis of design floods in different countries using AEPs of design floods or their return periods as the main indexes in design flood classification are showed in Table 5.

Table 5 – Standardized probability distribution function types adopted for frequency analysis of design floods in different countries [59]

Recommended probability distribution function types	Country
Pearson type III distribution (P-III)	China, Switzerland
Logarithmic Pearson type III distribution (LP-III)	The US, Canada, India
Generalized extreme value distribution (GEV)	Great Britain, France
Extreme Value type I, type III distribution (EVI, EV3)	Great Britain, France
Two/Three parameters logarithmic-normal distribution	Japan
Extreme value type I distribution	Germany, Sweden, Norway
Kritsky-Menkel distribution (K-M)	Ukraine, Russia

In general, there is no theoretical or another acceptable justification for choosing an appropriate probability distribution function to forecast hydrological characteristics based on observed data [53]. Therefore, any of them might be considered as a working hypothesis, if it meets adopted statistical criteria and other considerations regarding the adequacy of simulation are taken into account [60]. However, the main problem is that different function types including standardized ones can give different prognosis results especially regarding future floods having very long recurrence intervals (See an example in Fig. 4).



Probability distribution types: 1 – K-M distribution, C_V = 0.5, $C_S = 2C_V$, where C_V is the coefficient of variation, C_S is the coefficient of asymmetry; 2 – K-M, C_V = 0.5, $C_S = 2.5C_V$; 3 – P-III; 4 – EVI (Gumbel I); 5 – K-M, C_V = 0.6, $C_S = 2C_V$; 6 – K-M, C_V = 0.6, $C_S = 2.5C_V$; 7 – two-parameter lognormal distribution; 8 – LP-III

Fig. 4 – Forecasting of water discharges maxima of the Dnieper based on the Vyshgorod water level gauge data [53, 54]

Fig. 4 shows the essential divergence (uncertainty) of long-term forecasting results of flood water discharges maxima inflowing into the Kyiv reservoir based on using various probability distribution functions. In particular, the estimated limits (“sup” and “inf”) of maximal water discharges having the 1.0-per cent AEP obtained with using different probability distributions differ by more than 1.2 times; for the 0.1-per cent AEP the discharges differ more than 1.5 times; and for the 0.01-per cent AEP the difference between the “sup” and “inf” estimates of water discharges reaches almost 1.8 times. Note that the statistical testing of the hypotheses by the Pearson criterion χ^2 according to the significance level of 0.1 per cent showed all proposed distributions to be the hypotheses that agreed well with empirical frequencies of observed data [53, 54].

Based on the above, the following aim of the study was formulated. This aim consists of probabilistic forecasting the emergency situation on the Kyiv reservoir as a result of its uncontrolled overflow through the possible inaccuracy of the hydrological forecast concerning an actual water inflow into the reservoir and due to faults, poor functioning, or failures of various hydraulic structures of the reservoir during floods. To achieve the aim, the following objectives were set:

(1) to propose a method of hydrological forecasting, which allows taking into account results of long-term forecasts of flood water discharges maxima based on using various probability distribution functions;

(2) to perform hydrological forecasting of flood water discharges maxima affecting the condition of the Kyiv reservoir based on the actual hydrological observations data collected the Vyshgorod water level gauge;

(3) to assess the probability of the Kyiv reservoir overflow taking into account the occurrence possibility of shortage of the capacity of various hydraulic structures forming its water passage front;

(4) to assess the actual safety of the Kyiv reservoir against its uncontrolled overflow and reveal possible challenges if they are.

4. Materials and methods

Starting from the right bank, the Kyiv reservoir water passage front includes two hydraulic structures. These are the Kyiv navigable single-lift lock and the Kyiv HPP building combined with bottom spillway outlets [20].

At present, the Kyiv navigable lock is not enough reliable as a waterway structure. The lock requires repair the upstream maintenance gate hoist system and replace the upstream maintenance miter gates, replace and repair the lock lift drainage pump system, and repair the guideways along with replacement of the service gates for the lock emptying system [61]. Formerly, in emergency mode, the lock was able to pass a flow discharge 300 m^3/s. Today it is rather questionable.

The Kyiv HPP building combined with bottom spillway outlets is the main water passage hydraulic structure of the Kyiv reservoir. It consists of 5 separate sections, in each of which there are four capsule hydraulic units and four bottom outlets. Estimated flow discharge through one hydraulic turbine is 305 m^3/s. Estimated flow discharge through one bottom outlet at full storage level (FSL = 103.0 m) is 305 m^3/s too. Estimated flow discharge through one bottom spillway at the highest water level (HWL = 104.1 m) is 400 m^3/s. Thus, the total capacity of the Kyiv reservoir water passage front is 12,500 m^3/s at FSL = 103.0 m; at the HWL = 104.1 m its water throughput taking into account the transformation of the test flood (the 0.1-per cent AEP) by the reservoir is 14,400 m^3/s. The peak discharge of the test flood having the 0.1-per cent AEP without the flood transformation by the reservoir is estimated at 17,580 m^3/s.

The gates of bottom spillway outlets are serviced by two lifting cranes. The design time for opening one bottom spillway hole is 30 minutes; the opening time of all bottom spillway holes is 20 hours.

On average, within flood seasons, 1-2 hydraulic units are repaired at the Kyiv HPP [20]. However, with a risk margin, the probability of a hydraulic unit being unavailable for the passage of water will hardly exceed 0.25.

To forecast of water discharges maxima of the inflow into the Kyiv reservoir, there was considered a time series of observations at the Vyshgorod water level gauge from 1787 to 1999 (Fig. 5). It covers 212 years. The time series has the following statistical parameters [53, 54]: the mean value $\bar{x}$ = 4,692 m^3/s; the standard deviation σ = 2,632 m^3/s; the coefficient of variation C_V = 0.56; the coefficient of asymmetry C_S = 1.26. The accuracy indexes of calculations of these statistical characteristics are shown in Table 6.

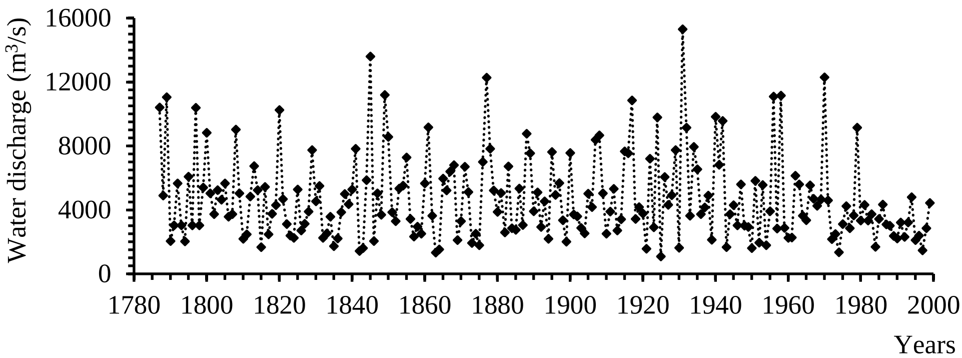


Fig. 5 – The time series of water discharges maxima of the Dnieper from 1787 to 1999 according to the Vyshgorod water level gauge data [53, 54]

Table 6 – The accuracy of calculations of the statistical characteristics for water discharges maxima of the Dnieper, the Vyshgorod water level gauge data

Parameter	Estimation	Standard error	Relative error, per cent
Mean value $\bar{x}$ (m^3/s)	4,692	180	3.8
Standard deviation σ (m^3/s)	2,632	128	4.9
Coefficient of variation C_V	0.56	0.06	11.0
Coefficient of asymmetry C_S	1.26	0.17	13.2

Two main methods were used to assess the probability of the Kyiv reservoir overflow. To take into account the possibility of shortage of the capacity of various hydraulic structures forming the reservoir water spillway front, the failure and fault tree method was used. This method allows implementing the scenario approach practically [11]. The computational model of this method is a circuit-free tree graph, the vertex of which presents a resulting emergency event, the probability of which is to be calculated. In our case, this resulting emergency event is the Kyiv reservoir overflow. The model includes the set of graph-analytical elements, which outline a limited set of possible events being able to cause the expected emergency event, and the set of correspondences modelling logic-probabilistic relations between various events. When modelling, special structural elements such as event symbols and logical operators are used [11, 15, 41, 62]. Logical operators display the logic of causal relationships between possible events and enable calculating the probabilities of consequence events (Table 7).

Table 7 – Formulas for calculating the probabilities of consequence events depending on logical operators

Logical operator	Formulas for estimating the probabilities of consequence events
"OR"	$P(A) = 1 - \prod_{i=1}^{n} \left(1 - P(B_i)\right)$, (2) B_i, $i = \overline{1,n}$, are compatible cause events;
"XOR"	$P(A) = \sum_{i=1}^{n} P(B_i)$, (3) B_i, $i = \overline{1,n}$, are incompatible cause events;
"AND"	$P(A) = \prod_{i=1}^{n} P(B_i)$, (4) B_i, $i = \overline{1,n}$, are compatible cause events;
"PROHIBITION"	$P(A) = P(B) \cdot P(C)$, (5) B, C are compatible cause events;
"M of N"	$P(A) = P(A)_m + P(A)_{m+1} + ... + P(A)_n$, (6) if $P(B_i) = P(B)$, $i = \overline{1,n}$, $m < n$: $P(A)_m = \left(1 - (1 - P(B))^n\right) \cdot \left(1 - (1 - P(B))^{n-1}\right) \cdot ... \cdot \left(1 - (1 - P(B))^{n-m+1}\right)$; $P(A)_{m+1} = P(A)_m \cdot \left(1 - (1 - P(B))^{n-m}\right)$, …, $P(A)_n = P(B)^n$; (7)
where n is a total number of random cause events B_i, $i = \overline{1,n}$; $P(A)$, $P(B_i)$, $P(C)$ are the probabilities of a consequence event A, a cause event B_i, a condition event C.	

The probability of failures of the mechanical equipment servicing bottom spillway outlets was estimated by the formula [15, 41]:

$$P(_{t+t_r}) = 1 - \exp\{-\lambda \cdot t \cdot \exp(-\rho \cdot t_r)\}, \quad (8)$$

where λ is the failure rate of the facility before the first failure; t is the service life of mechanical equipment (ME) during which at least one work operation is expected; ρ is the repair rate of ME; t_r is the additional time to repair the facility.

The failure rate λ of a "gate – lifting crane" system and the repair rate ρ of ME was taken according to statistical data [15, 3638]: λ = 2·10^{-3}, year^{-1}; ρ = 10, year^{-1}. The additional time the "gate – lifting crane" system to repair was taken t_r = 0.00228 year (20 hours) [20]. The expected service life of mechanical equipment for the bottom spillway facilities was taken t = 10 years.

Finally, to overcome the essential non-stochastic uncertainty of results of long-term forecasting of discharges maxima based on using various probability distribution functions (Fig. 4) the following method was used. According to this method, results obtained by using different versions of probability distribution functions are considered as expert estimates, which further are processed by methods of fuzzy set theory and fuzzy logic [63].

When fuzzy modelling, the following fuzzy variables are used:

1) "a value of the parameter x will be greater… (not less)…"; the fuzzy variable is modelled using the Z - shaped membership function;

2) "a value of the parameter x will be less than… (not greater)…"; the fuzzy variable is modelled using the S - shaped membership function.

Membership functions $\mu_Z(x)$, $\mu_S(x)$ are given graphically based on their empirical estimates $\hat{\mu}_Z(x)$, $\hat{\mu}_S(x)$, $\hat{\mu}_Z(x)+\hat{\mu}_S(x)=1$, which are established after the statistical hypotheses testing by the Pearson criterion χ^2 on alternative probability distribution functions by values of the hypotheses validities $v(\chi_i^2)$.

The following fuzzification algorithm based on simulation of S-shaped and Z-shaped membership functions of fuzzy variables is considered [63].

1. With an increase in predicted values X_i of the parameter x and a simultaneous increase in values $v(\chi_i^2)$ with increasing indexes of i-th models, empirical estimates for the S-shaped membership function of the fuzzy linguistic variable "a value of the parameter x will be less than…" follows as:

$$\hat{\mu}_S(x_i) = \frac{v(\chi_i^2)}{v(\chi_i^2)_{\max}}, \tag{9}$$

where $v(\chi_i^2)$ is an i-th hypothesis validity; $v(\chi_i^2)_{\max}$ is the maximum value among validities $v(\chi_i^2)$ of alternative probability distributions considered as separate expert assumptions on a more suitable distribution.

2. Then, for the fuzzy variable "a value of the parameter x will be greater than…" empirical estimates for the Z - shaped membership function follows as:

$$\hat{\mu}_Z(x_i) = 1 - \hat{\mu}_S(x_i). \tag{10}$$

3. With a decrease in predicted values X_i of the parameter x but an increase in values $v(\chi_i^2)$ with increasing indexes of i-th models, empirical estimates for the Z-shaped membership function of the fuzzy linguistic variable "a value of the parameter x will be greater than…" follows as:

$$\hat{\mu}_Z(x_i) = \frac{v(\chi_i^2)}{v(\chi_i^2)_{\max}}. \tag{11}$$

4. Then, for the fuzzy variable "a value of the parameter x will be less than…" empirical estimates for the S - shaped membership function follows as:

$$\hat{\mu}_S(x_i) = 1 - \hat{\mu}_Z(x_i). \tag{12}$$

Finally, membership functions of fuzzy sets for values of linguistic variables of the type of "a value of the parameter x will be in an interval…" can be found as: $\tilde{A} = \tilde{Z} \cap \tilde{S}$, $\tilde{B} = \tilde{Z} \cap \tilde{S}$, and $\tilde{C} = \tilde{A} \cap \tilde{B}$.

5. Results

Table 8 shows results of forecasting of the maximum water discharges inflowing into the Kyiv reservoir having annual exceedance probabilities (AEPs) ranging from 0.001 to 5.0 (per cent). When forecasting, the Vyshgorod water level gauge data and eight model probability distribution functions were used.

Table 8 – Results of forecasting of maximum water discharges inflowing into the Kyiv reservoir

Hypothesis number and probability distribution type		Calculated maximum water discharge values (m^3/s) according to their AEP (per cent)					
		0.001	0.01	0.1	0.5	1.0	5.0
1	Kritsky-Menkel (K-M) (C_V = 0.5, C_S = 2C_V)	21,911	18,674	15,343	12,856	11,777	9,103
2	K-M (C_V = 0.5, C_S = 2.5 C_V)	25,384	20,880	16,469	13,466	12,152	9,149
3	Pearson type III	26,020	21,936	17,580	14,463	13,080	9,735
4	Extreme value type I (Gumbel I)	27,120	22,415	17,687	14,379	12,951	9,605
5	K-M (C_V = 0.6, C_S = 2C_V)	27,120	22,756	18,158	15,014	13,560	10,088
6	K-M (C_V = 0.6, C_S = 2.5 C_V)	32,375	25,994	19,894	15,765	14,076	10,088
7	Two-parameter lognormal	40,100	29,930	21,356	16,203	14,172	9,830
8	Logarithmic Pearson type III	45,000	33,500	23,200	17,043	14,744	10,000

After the statistical hypotheses testing by the Pearson's criterion χ^2, the probability distributions used in forecasting were divided into two groups of expert models. The first group included the distributions 1-3, the second – the distributions 4-8. When grouping the distributions, it was taken into account that their validities

$v(\chi_i^2)$ increase monotonically within each of the groups: from the distribution (hypothesis) 1 to the distribution (hypothesis) 3, from the distribution (hypothesis) 4 to the distribution (hypothesis) 8. The results of calculating empirical values of membership functions of forecasted values of the Dnieper water discharge maxima to appropriate fuzzy sets are given in Table 9.

Table 9 – Empirical values of membership functions of forecasted values of the Dnieper water discharge maxima depending on the probability distributions

Hypothesis number and probability distribution type		$v(\chi_i^2)$	Empirical values of membership functions	
			$\hat{\mu}_Z(x)$	$\hat{\mu}_S(x)$
1	Kritsky-Menkel (K-M) (C_V = 0.5, C_S = 2C_V)	0.0418	0.7196	0.2804
2	K-M (C_V = 0.5, C_S = 2.5 C_V)	0.0865	0.4195	0.5805
3	Pearson type III	0.1491	0	1
4	Extreme value type I (Gumbel I)	0.0425	0.9062	0.0938
5	K-M (C_V = 0.6, C_S = 2C_V)	0.1256	0.7227	0.2773
6	K-M (C_V = 0.6, C_S = 2.5 C_V)	0.2874	0.3655	0.6345
7	Two-parameter lognormal	0.3752	0.1718	0.8282
8	Logarithmic Pearson type III	0.4530	0	1

Below, Fig. 6-11 show geometric illustrations of the computed membership functions.

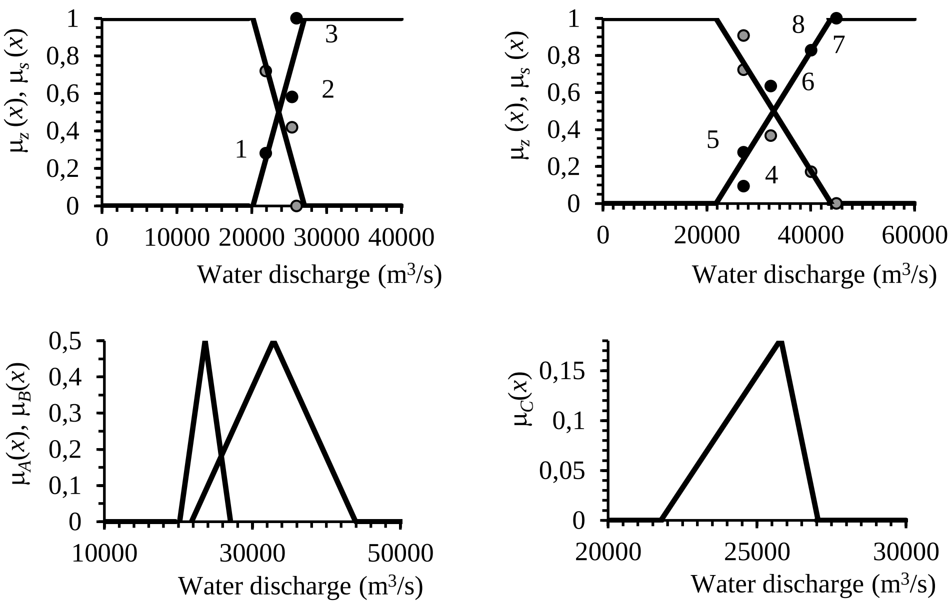


Fig. 6 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 0.001-per cent AEP

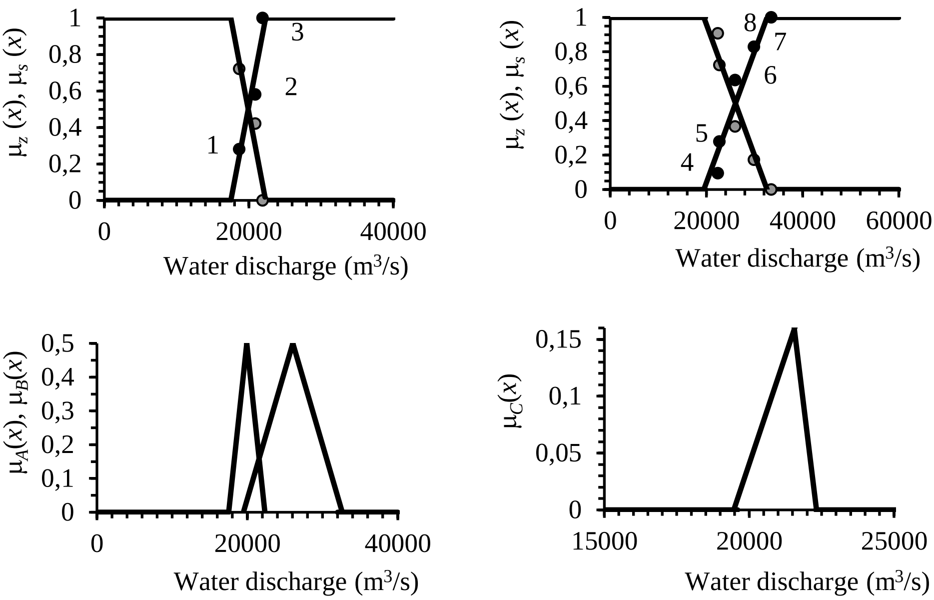


Fig. 7 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 0.01-per cent AEP

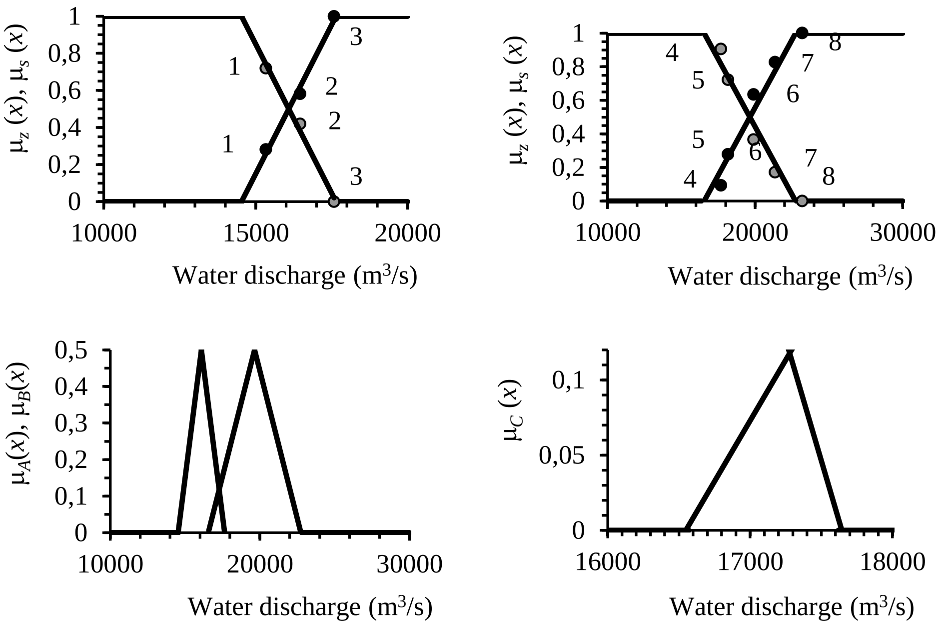


Fig. 8 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 0.1-per cent AEP

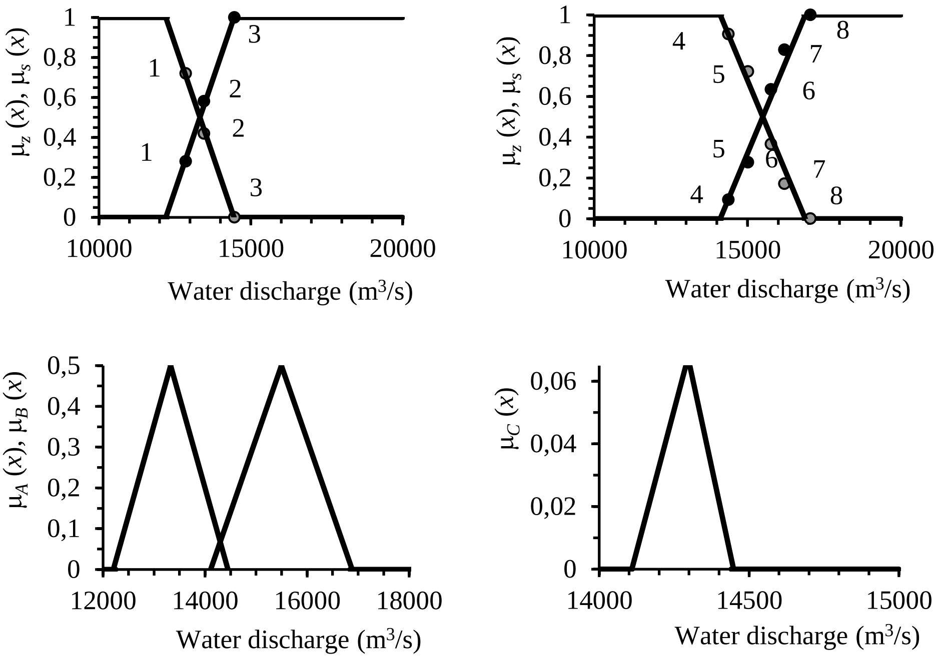


Fig. 9 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 0.5-per cent AEP

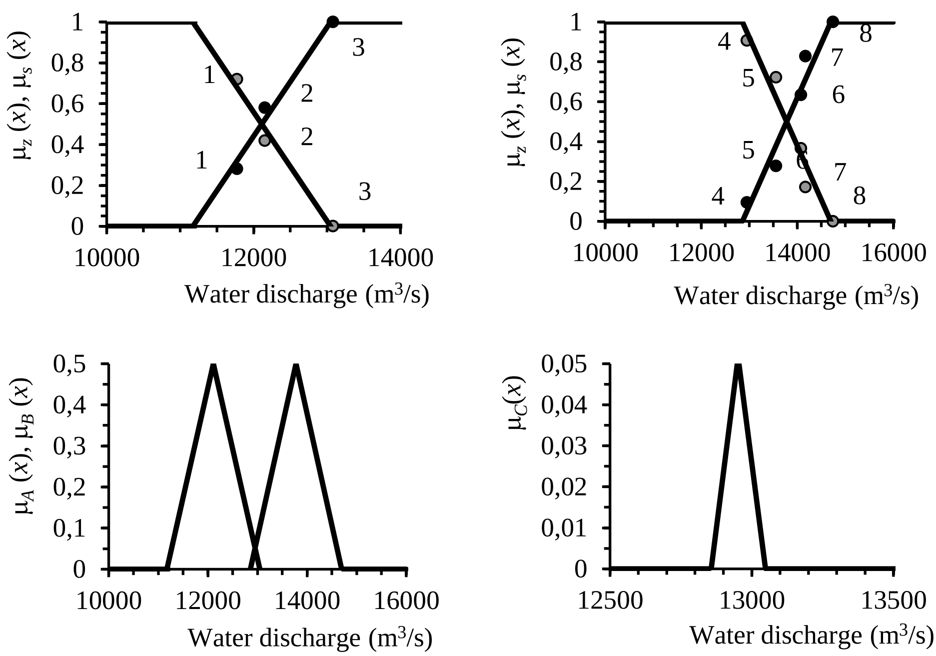


Fig. 10 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 1.0-per cent AEP

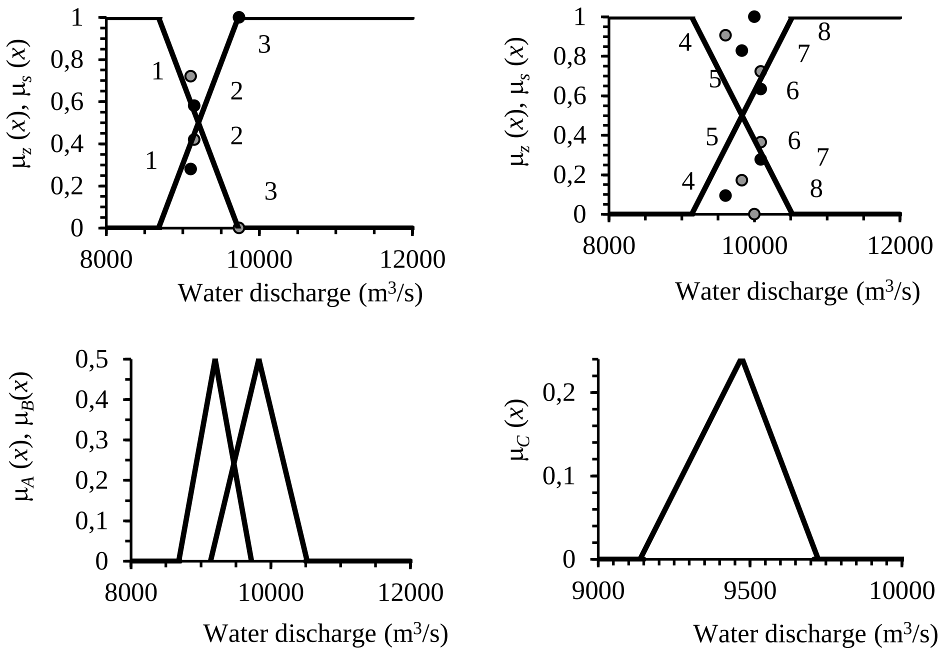


Fig. 11 – Membership functions characterizing forecasted values of the Dnieper water discharge maxima having the 5.0-per cent AEP

The membership functions of fuzzy sets for the values of linguistic variables of the type of "a maximum water discharge having an annual exceedance probability (AEP) (per cent) will be in an interval…" $\tilde{A} = \tilde{Z} \cap \tilde{S}$ were computed on the results of forecasting by means of probability distributions with indices $i = \overline{1,3}$; in turn, the membership functions $\tilde{B} = \tilde{Z} \cap \tilde{S}$ were computed on the results of forecasting by means of probability distributions with indices $i = \overline{4,8}$.

After modelling of fuzzy sets $\tilde{C}$ for linguistic variables of the type of "a maximum water discharge having an AEP (per cent) will be in an interval…", the corresponding fuzzy intervals $Su_C = \{Q_{\max} : \mu_C(Q_{\max}) > 0\}$ with searched cores $Co_C = \{Q_{\max} : \mu_C(Q_{\max}) = \max\}$ of fuzzy sets were obtained. Defuzzification was performed by the centroid method [64]. Analytical modelling of membership functions was performed in MS Excel. The computed generalized water discharge maxima values of the inflow into the Kyiv reservoir (the Vyshgorod water level gauge) having annual exceedance probabilities (AEPs) ranging from 0.001 to 5.0 (per cent) are given in Table 10 and Fig. 12.

Table 10 – Generalized values of maximal water discharges inflowing into the Kyiv reservoir (the Vyshgorod water level gauge)

Annual exceedance probability (AEP) (per cent)	0.001	0.01	0.1	0.5	1.0	5.0
Maximum water discharge (m^3/s)	25,000	21,215	17,170	14,285	12,954	9,450

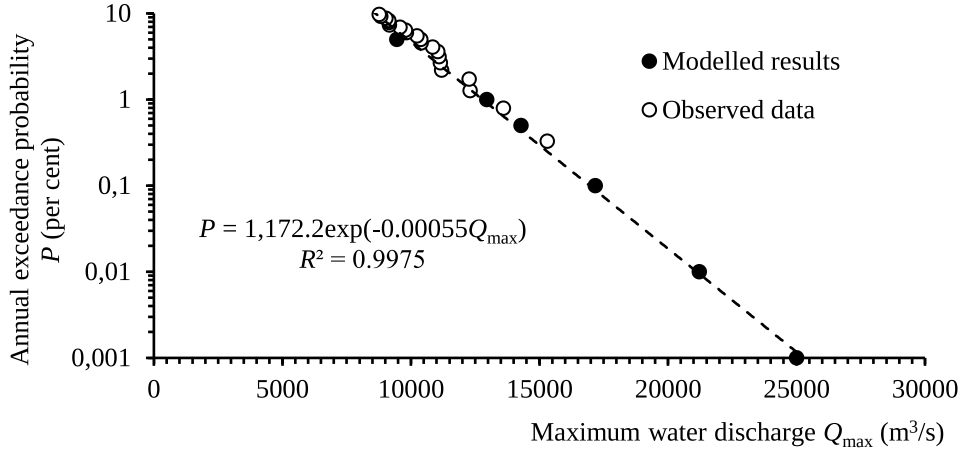


Fig. 12 – The computed curve of the generalized exceedance probability function of water discharge maxima Q_{max} ranging from the 5.0-per cent AEP to the 0.001-percent AEP (the Vyshgorod water level gauge)

Accordingly, the annual exceedance probability (AEP) P (per cent) of calculated values of water discharge maxima Q_{max} (m^3/s) ranging from the 5.0-per cent AEP to the 0.001-percent AEP are well described by the function

$$P = 1172.2 \exp(-0.00055 Q_{max}) . \tag{12}$$

To measure the quality of the prediction performing with the function (12) for maximum discharges having AEPs less than 10.0 per cent the appropriate verification was carried out. To verify whether forecast results could adequately represent observed data, the estimators of standard error and relative standard error and the Nash-Sutcliff model efficiency criterion [65] were used. The Nash-Sutcliff model efficiency criterion (NSE) [65] is widely used for assessment of the predictive power of hydrological models. In particular, it is accepted that hydrological predictions with the NSE above 0.8 can be considered as being very good. Fig. 13 shows the graphical illustration of the NSE assessment.

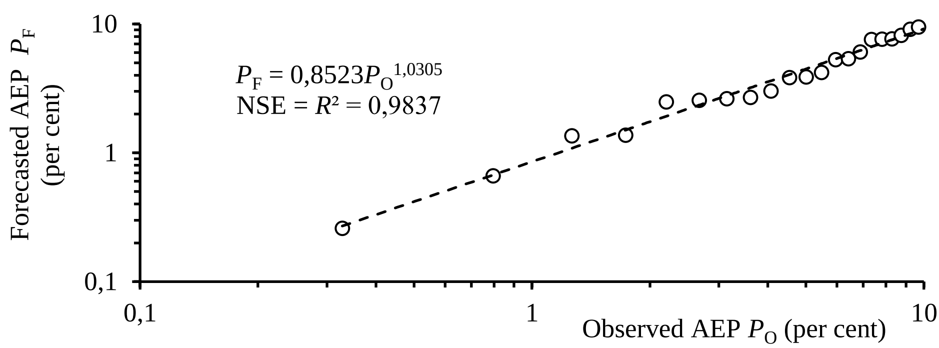


Fig. 13 – The Nash-Sutcliff model efficiency criterion (NSE) assessment

As well, the standard error for AEPs ranging from 10.0 to 0.33 (per cent) turned out to be equal 0.03 per cent. It is 0.0003 ($year^{-1}$) in the interval of probability values from 0.1 to 0.0033 ($year^{-1}$). The relative standard error does not exceed 6.6 per cent. According to all applied criteria the predictive power of the generalized distribution function (12) of water discharge maxima inflowing into the Kyiv reservoir can be considered as being acceptable in the interval of AEP values from 10.0 to 0.001 (per cent).

The failure and fault tree diagram used in assessing the Kyiv reservoir overflow probability is presented below in Fig. 14. Six incompatible hypothetical emergency situations at the Kyiv reservoir were considered:

S_1 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 17,580 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m; there occurs a failure at the spillway facilities of the reservoir when one hydro unit fails or one bottom outlet stays unavailable though the mechanical equipment failure, etc.;

S_2 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 16,475 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m because of a failure at the spillway facilities occurs when one hydro unit fails, and simultaneously two bottom outlets stay unavailable though the mechanical equipment failure, etc.;

S_3 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 16,170 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m because of a failure at the spillway facilities occurs when two hydro units fail, and simultaneously two bottom outlets stay unavailable though the mechanical equipment failure, etc.;

S_4 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 15,770 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m because of a failure at the spillway facilities occurs when two hydro units fail, and simultaneously three bottom outlets stay unavailable though the mechanical equipment failure, etc.;

S_5 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 15,465 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m because of a failure at the spillway facilities occurs when three hydro units fail, and simultaneously three bottom outlets stay unavailable though the mechanical equipment failure, etc.;

S_6 – the maximum water discharge of the inflow into the Kyiv reservoir reaches 15,065 m^3/s; the water level in the reservoir rises to the highest water level (HWL) of 104.1 m because of a failure at the spillway facilities occurs when three hydro units fail, and simultaneously four bottom outlets stay unavailable though the mechanical equipment failure, etc.

The annual probability of failure of any of the 20 hydro units of the Kyiv HPP taking into account data of S. Potashnik [32] and the current Ukrhydroenergo information on repair and maintenance works [20] was set at 0.25. Then, the expected probability of a hydro unit failure will be $P_u = 1 - (1 - 0.25)^{1/20} = 0.0143$ ($year^{-1}$). The probability of the failure of a bottom outlet P_b was calculated by the formula (7) according to statistical data [15, 36-38] including the current Ukrhydroenergo information [20] and amounted to $P_b = 0.0194$ ($year^{-1}$).

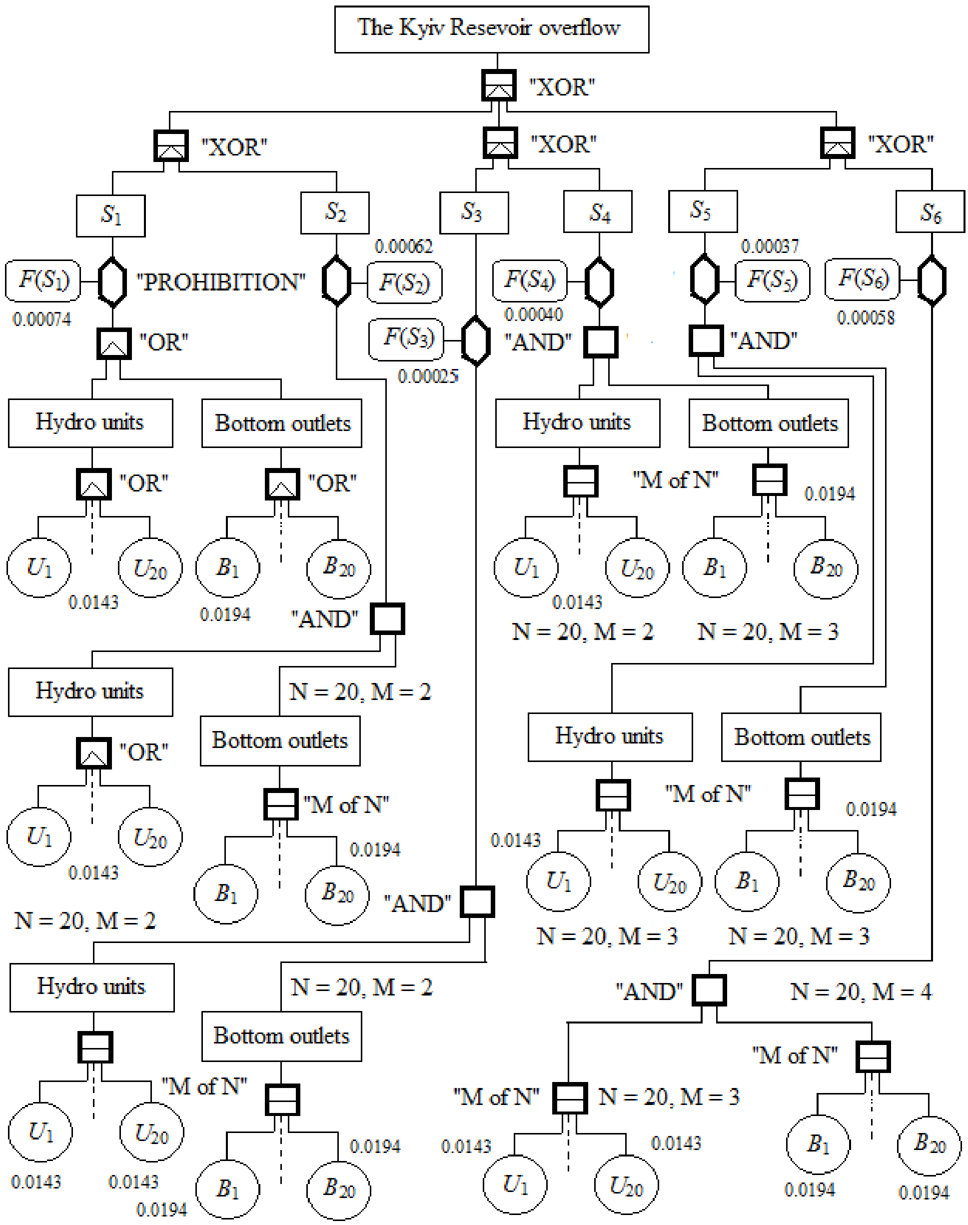


Fig. 14 – The failure and fault tree diagram to assess the Kyiv reservoir overflow probability

Table 11 shows annual exceedance probabilities (AEP_i) (per cent) of flood conditions $F(S_i)$ triggering the hypothetical emergency situations S_i, $i=\overline{1,6}$, and the annual probabilities $pF(S_i)$ of these condition occurrence (year^{-1}) in a full group of events. To form the full group of events, the annual probabilities $pF(S_i)$ (year^{-1}) were estimated as: $pF(S_1)$ = $0.01AEP_1$, $pF(S_2)$ = $0.01(AEP_2 - AEP_1)$, … , $pF(S_6)$ = $0.01(AEP_6 - AEP_5)$.

Table 11 – Parameters of the flood conditions $F(S_i)$ triggering the hypothetical emergency situations S_i, $i = \overline{1,6}$

Parameters	Flood conditions					
	$F(S_1)$	$F(S_2)$	$F(S_3)$	$F(S_4)$	$F(S_5)$	$F(S_6)$
Maximum water discharge (m^3/s)	17,580	16,475	16,170	15,770	15,465	15,465
AEP (per cent)	0.074	0.136	0.161	0.201	0.237	0.295
The flood condition occurrence annual probability ($year^{-1}$) in the full group of events	0.00074	0.00062	0.00025	0.00040	0.00037	0.00058

The calculation of the failure and fault tree (Fig. 14) showed the total probability of the Kyiv reservoir overflow equal to $3.84 \cdot 10^{-4}$ ($year^{-1}$). This is about four emergency cases per 10,000 years, or one such case per 2,500 years.

6. Discussion

The study showed that the forecasted test maximum water discharge value having 0.1-per cent AEP generalized on the eight model probability distributions calculated according to data of the Vyshgorod water level gauge is 17,170 m^3/s. This forecasted discharge value is less than the value of the design discharge of 17,580 m^3/s of the 0.1-per cent flood, to which the hydraulic structures of the Kyiv reservoir were calculated. The forecasted AEP of the design water discharge of 17580 m^3/s is 0.074 (per cent) or $7.4 \cdot 10^{-4}$ ($year^{-1}$). It is almost 15 per cent less than the 0.1-per cent AEP design value set by current national standards [55]. The last may indicate that the hydrological safety of the Kyiv reservoir hydraulic structures meets the current national standards [55] with a 15 per cent risk margin.

In addition, the hydraulic structures reduce the probability of the reservoir overflow to the value of $3.84 \cdot 10^{-4}$ ($year^{-1}$). It is near 1.9 times less compared to the forecasted AEP of $7.4 \cdot 10^{-4}$ ($year^{-1}$) of the design discharge of 17580 m^3/s, and it also confirm a high guarantee the hydrological safety of downstream territories.

Table 12 shows the occurrence probabilities of six incompatible hypothetical emergency situations at the Kyiv reservoir and their contributions to the total probability of the reservoir overflow. The obtained results indicate that the most probable dangerous event is the hypothetical emergency situation S_1. This situation can occur when the maximum water discharge of the inflow into the Kyiv reservoir reaches 17,580 m^3/s, the water level in the reservoir rises to the highest water level (HWL) of 104.1 m, and there occurs a failure at the spillway facilities when one hydro unit fails or one bottom outlet stays unavailable though the mechanical equipment failure, etc. In general, the study results may indicate that the water spillway front of the Kyiv reservoir is designed with significant reserves for the passage of floods that are less than the design 0.1-per cent flood. As well, calculations showed that floods having AEPs of more than 0.136 per cent give in a sum less than 5 per cent of the total Kyiv reservoir overflow probability.

Table 12 – Analysis of probabilities of the six incompatible hypothetical emergency situations at the Kyiv reservoir

Parameter	Hypothetical emergency situations						Total
	S_1	S_2	S_3	S_4	S_5	S_6	
Probability	$3.66{\cdot}10^{-4}$	$1{,}56{\cdot}10^{-5}$	$1{,}5{\cdot}10^{-6}$	$7{,}1{\cdot}10^{-7}$	$1{,}5{\cdot}10^{-7}$	$7{\cdot}10^{-8}$	$3.84{\cdot}10^{-4}$
Share (per cent)	95.29	4.07	0.39	0.19	0.04	0.02	100

Fig. 15 shows the curve of the reservoir overflow probability depending on the floods that are considered as triggers of the six examined hypothetical emergency situations. This curve can be used as a model curve of hydrological risk of the Kyiv reservoir overflow in consequence of floods having annual exceedance probabilities ranging from 0.295 per cent to 0.074 per cent.

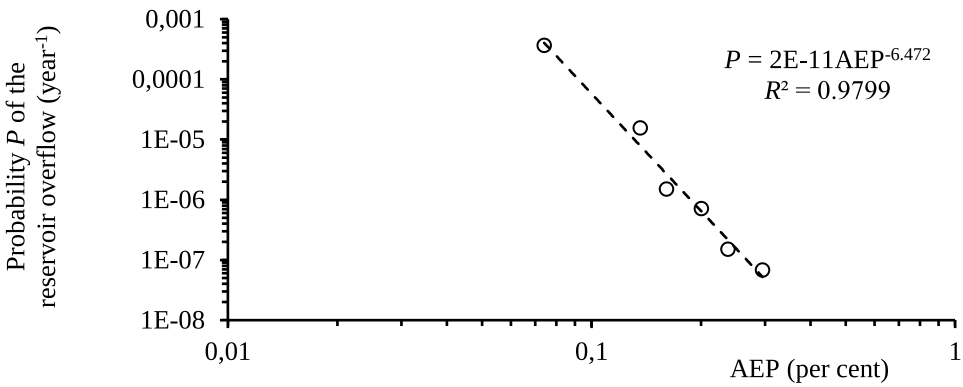


Fig. 15 – The curve of the probability of the Kyiv reservoir overflow depending on annual exceedance probabilities of floods

Eventually, it can be concluded that the risk of the Kyiv reservoir overflow through floods, the AEPs of which are greater than 0.3 per cent, is utterly low.

7. Conclusions

The probabilistic forecast the emergency situation occurrence on the Kyiv reservoir as a result of its uncontrolled overflow was performed. The forecast was carried out taking into account the possible inaccuracy of the hydrological forecast concerning water inflow into the reservoir and possible failures of the reservoir water passage hydraulic structures during floods.

A method of hydrological forecasting, which allows taking into account results of long-term forecasts of flood water discharges maxima based on using various probability distributions, was proposed. According to this method, results obtained by using different versions of distributions are considered as expert estimates, which further are processed by methods of fuzzy set theory and fuzzy logic.

To forecast water discharges maxima of the inflow into the Kyiv reservoir, there was taken the time series of observations data collected the Vyshgorod water level gauge from 1787 to 1999. A total of eight model probability distributions were considered. The fuzzy modelling showed that the forecasted value of the maximum water discharge of 17,170 m^3/s having the 0.1-per cent annual exceedance probability (AEP) generalized on eight model probability distributions is less than the value of the design discharge of 17,580 m^3/s of the 0.1-per cent flood for which the spillway structures of the Kyiv reservoir were calculated. This indicates that the hydrological safety of the Kyiv reservoir water passage structures meets the current standards [55] with a 15 per cent risk margin.

To assess the probability of the Kyiv reservoir overflow taking into account the occurrence possibility of the capacity shortage of various hydraulic structures to water passage, the failure and fault tree method was used. Totally, six incompatible hypothetical emergency situations at the Kyiv reservoir were considered. The calculation of the failure and fault tree (Fig. 14) showed the total probability of the Kyiv reservoir overflow equal to $3.84 \cdot 10^{-4}$ ($year^{-1}$). It is near 1.9 times less compared to the forecasted AEP that is $7.4 \cdot 10^{-4}$ ($year^{-1}$) for the design discharge of 17580 m^3/s, that gives quite a high guarantee of the hydrological safety of the infrastructure and population downstream of the reservoir.

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ОЦІНКА ЙМОВІРНОСТІ ПЕРЕПОВНЕННЯ КИЇВСЬКОГО ВОДОСХОВИЩА

Анотація. *Водосховища є невід'ємною частиною світової гідротехнічної інфраструктури і формують основу сучасного управління водними ресурсами в більшості країн. Однак водосховища також є джерелами потенційної небезпеки для навколишнього середовища, інфраструктури та населення, особливо в нижніх б'єфах великих гребель. Потенційна небезпека та ризики для населення, що проживає поблизу водосховищ, особливо нижче за течією, можуть бути не меншими, ніж для людей, які проживають поблизу ядерних установок або хімічних підприємств, з чим експерти та громадськість зазвичай пов'язують проблеми техногенної безпеки. Причому, статистика показує, що близько третини всіх аварій на греблях і дамбах сталося через переповнення водосховищ, коли рівень води у верхньому б'єфі перевищував проектні або допустимі значення.*

В Україні налічується 1103 водосховища загальним об'ємом води близько 55 500 млн м^3. Київське водосховище – третє за обсягом та площею поверхні води в країні. Крім того, це водосховище утворюється однією з найдовших гребель у світі. Загальна довжина гідротехнічних споруд Київського водосховища сягає 70 км.

Загальновизнано, що неконтрольоване переповнення водосховища може викликатися надзвичайним паводком з параметрами припливу, що перевищують пропускну здатність гідротехнічних споруд. Проблемою є те, що пропускна здатність гідротехнічних споруд може бути недостатньою як через неточність гідрологічного прогнозу, так і через несправності, погане функціонування або відмови гідроспоруд під час проектного паводку. Зокрема, довгострокові прогнози максимальних витрат паводкових вод Дніпра в створі Київського водосховища на основі використання різних функцій розподілу ймовірностей показують істотну розбіжність їх результатів. Також, як показує практика, неготовність деяких водопропускних трактів Київського водосховища може досягати кількох місяців на рік. Іноді ремонтні роботи на цих спорудах проводилися навіть під час паводків.

Метою дослідження було ймовірнісне прогнозування надзвичайної ситуації на Київському водосховищі внаслідок його неконтрольованого переповнення внаслідок можливої неточності гідрологічного прогнозу щодо фактичного притоку води у водойму та через відмови водопропускних споруд під час паводку.

Для досягнення мети були вирішені наступні завдання: (1) запропоновано метод гідрологічного прогнозування, який дозволяє враховувати результати довгострокових прогнозів максимальних витрат паводкових вод на основі використання різних функцій розподілу ймовірностей та нечіткого моделювання; (2) проведено гідрологічне прогнозування максимальних витрат Дніпра, що впливають на стан Київського водосховища, на основі фактичних даних, зібраних на гідрологічному посту «Вишгород»; (3) оцінено ймовірність переповнення Київського водосховища з урахуванням можливості виникнення дефіциту пропускної здатності гідротехнічних споруд з використанням методу дерева відмов та несправностей. Всього було розглянуто шість несумісних гіпотетичних надзвичайних ситуацій на Київському водосховищі. Розрахунки показали, що ймовірність переповнення Київського водосховища не перевищує 3,84·10^{-4} (рік$^{-1}$), що є прийнятним в контексті гарантування гідрологічної безпеки інфраструктури та населення.

Ключові слова: *щорічна ймовірність перевищення; метод дерева відмов та несправностей; паводки; прогнозування; нечітке моделювання; гідрологічна безпека; переповнення Київського водосховища*

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