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FORECASTING THE DESIGN MAXIMA WATER DISCHARGES OF FLOODS ON THE LATORICA RIVER ACCORDING TO THE DATA OF THE MUKACHEVO GAUGING STATION USING PLOTTING POSITION FORMULAS

Abstract. *This article presents the results of forecasting design maxima discharges on the Latorica River within Mukachevo town based on hydrological observation data at the "Mukachevo" gauging station using plotting position formulas. While solving the task, a novel non-parametric method of forecasting using observation data is applied. The method includes extrapolating the discrepancy (divergence, disagreement) between the estimates of the statistical annual probabilities of exceedance obtained by different plotting position formulas. The task is considered in the frame of the stationarity hypothesis of the maximum river flow employing a time series of maximal discharges of the Latorica River observed at the "Mukachevo" gauging station from 1947 to 1999.*

We involved the thirteen plotting position formulas. There was no specific criterion for choosing them to solve the task. All applied formulas were considered admissible options, and results obtained after using them – expert judgments reflecting decision-makers' predisposition to more cautious or less expensive decision options in flood management strategies.

The epistemic uncertainty of the different plotting positions was reduced by employing the Fishburn rule. According to this rule, the significance of various plotting positions was given by arranging their estimates in descending order of importance of their values under decision-making. Depending on the selected significance option assignment of the different plotting position formulas, such rank-weighted estimates of the design peak discharges (each of them for annual exceedance probability 1%, 0.5%, and 0.2%) were computed: (1) the rank-weighted upper bound estimate (sup-estimate) corresponding to the predisposition to more cautious decision options; (2) the rank-weighted lower bound estimate (inf-estimate) corresponding to the predisposition to less expensive decision options. As possible control theoretical alternatives for forecasting design maximal discharges considered were five parametric probability distributions: 1) the Kritskyi-Menkel three-parameter gamma distribution; 2) Pearson's type III distribution; 3) the Extreme value type I distribution (Gumbell's type I distribution); 4) the Logarithmic Pearson type III distribution; and 5) the Two-parameters logarithmic-normal distribution. The population statistical parameters for these parametric probability distributions were estimated from the sample statistics by the method of moments.

Keywords: *Annual exceedance probability, design maxima discharge, epistemic uncertainty, extrapolation, flood, forecasting, observation data, parametric probability distributions, plotting position formulas, rank-weighted estimates.*

https://doi.org/10.32347/2411-4049.2024.3.123-140

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1. Introduction

Riverine floods are among the essential natural hazards threatening human life and activity in Ukraine. In terms of frequency, area of distribution, and losses, they outweigh any natural disasters, including storms, earthquakes, heat waves, landslides, droughts, forest fires, etc. According to national natural hazard statistics for 1980-2020, floods caused more than 34% of annual natural hazard occurrences in the country [1]. Floods threaten more than 27 per cent of the country's territory and about a third of Ukraine's population lives in flood-prone areas [1-3].

Most often, disastrous floods occur in the western regions of Ukraine. Namely, the basins of the Ukrainian Carpathian Rivers form one of the most flood-prone regions in Europe and the world [4, 5], and disastrous floods in the Tisza, Dniester, Prut, and Siret Rivers' basins seem to be common natural phenomena [6].

The region that especially suffers from river floods in Ukraine is Transcarpathia. The region is located within the south-western slopes and foothills of the Ukrainian Carpathian Mountains (Fig. 1), which cover around 80% of its area. Transcarpathia has the densest river network in Ukraine. According to [4, 7-9], the region has the highest risk of catastrophic floods in Ukraine.

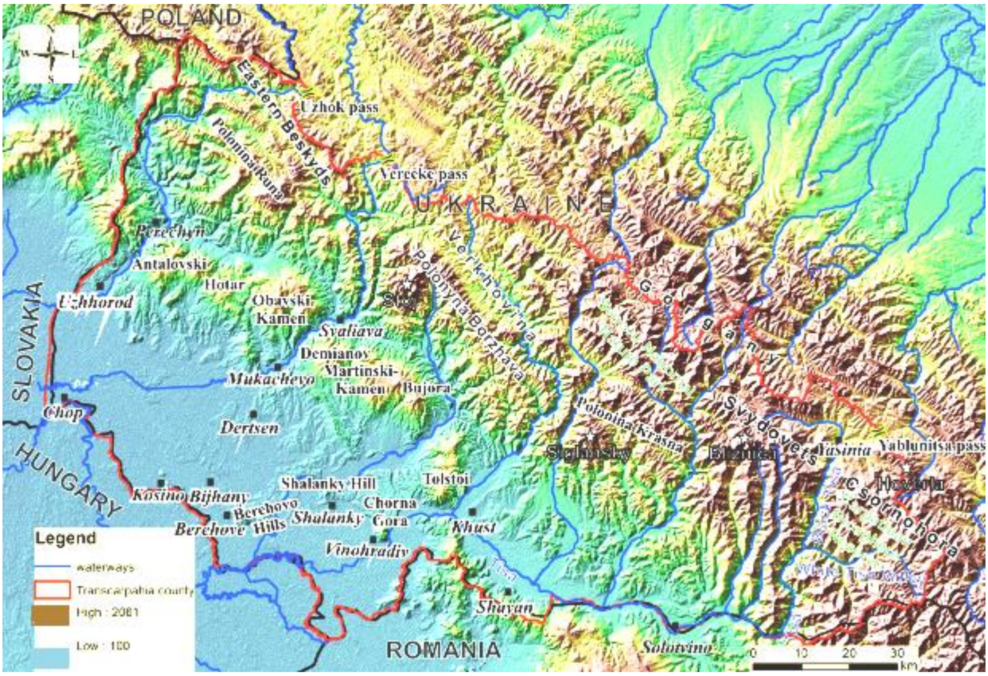

Fig. 1. Topographical sketch of Transcarpathia Digital Elevation model: SRTM 1 arc sec (https://lta.cr.usgs.gov/SRTM1Arc) (Taken from [10])

One of the most destructive floods in Ukrainian Transcarpathia, which caused significant damage to the region, occurred in November 1998 [4, 11]. The snowmelt and rain by origin flood exceeded all previous floods in this region in water level height rise and consequences of flooding. Because of the snow-melting and intensive rains, the Tisza, Tereblya, Teresva, Uzh, Borzhava, Latorica and other rivers burst their banks, flooding almost 120 settlements. Nearly 350,000 people, around a third of the region's population, were in the disaster zone. In particular, the town of Mukachevo (Fig. 2), through which the Latorica River flows (Fig. 3), was seriously affected too. Almost 80 per cent of the town territory was submerged. As you can see below in the photo, Fig. 4(a), the water level rose to the bridge in the town centre. The level continued to grow. In a matter of hours, Latorica, which divides the town into two halves, left its banks.

Fig. 2. View the Mukachevo town and Latorica River from the Palanok Castle, May 2012 (Author's photo)

Fig. 3. River Latorica, May 2012. Right – Monument to victims of the flood "1998. Year of trouble and trials" (Author's photo)

Heavy floods on Latorica, which threaten the town of Mukachevo, with more than 85,000 inhabitants, occur almost annually (See, for example, Fig. 4(b)) [8, 9, 12]. The Latorica and Uzh Rivers form the so-called Transcarpathian Sub-river Basin Area characterised by heavy floods. Around 1.2 million people live within this area, where climate-soil conditions of the lowland favour the development of agriculture [13]. They live under constant flood threat. Today, the region's only physical protection against floods is provided with dikes and levees [14], not all of which stand in condition to correspond to realities and modern requirements. In particular, in [14], there is no information on design discharges for many of these structures, for example, for the dikes on Latorica within Mukachevo (See Table 1).

(a) (b)

Fig. 4. Flooding cases in Mukachevo: (a) November 1998 (https://www.mukachevo.net/ua/news/view/186143); (b) May 2019 (https://www.rbc.ua/ukr/styler/zhutkoe-navodnenie-zakarpate-pokazali-vyso-ty-1558682813.html)

Table 1. Dikes within Ukraine in the Latorica River (Taken from [14])

No.	Dike name	Locality name	Length (m)	YFO[1]	AEP[2]	CCS[3]
1	Right bank dike Latorica river	Vinkovo	27,840	1939	5%	M
2	Left bank dike Latorica river	Solomonovo	21,900	1967	1%	B
3	Left bank dike Latorica river	Chomonyn	20,900	1939	5%	M
4	Right bank dike Latorica river	Palad Komarivtsi	17,600	1967	1%	B
5	Left bank dike Latorica river (from the Sadova-Monastery Bridge to railway bridge)	Mukachevo	6,855	?	?	M
6	Left bank dike Latorica river (from the railway bridge to the road bridge)	Mukachevo	6,855	?	?	M
7	Right bank dike Latorica river (from the Sadova-Monastery Bridge)	Mukachevo	5,013	?	?	M
8	Left bank dike Latorica river	Bystrytsa	2,450	1948	5%	M
9	Right bank dike Latorica river	Kolchyno	1,600	1936	5%	M

[1] YFO – Year of function into operation

[2] AEP – Annual Exceedance Probability (year^{-1}, %) of design peak discharge of flood

[3] CCS – Current Condition Status: G – good, M – moderate, B – bad

As of 2010, there were eight hydrological gauging stations (HS) in the Latorica basin [15], four of them – on the Latorica River: in Pidpolozzia, Svaliava, Mukachevo, and Chop. In the HS “Pidpolozzia” and “Mukachevo”, hydrological observations of peak discharges of floods have been carried out since 1947; in the HS “Chop” – since 1957, and in the HS “Svaliava” – since 1962. However, the hydrological risks relating to floods on the Latorica River have not been explored enough within Ukraine.

2. The case study and the purpose of this paper

Latorica is a river belonging to the watershed of the Danube. It is one of the longest rivers in the Transcarpathians. The Latorica River flows from Ukraine into Slovakia, confluences with the Ondava River in Zemplín, within Slovakia, and gives rise to the Bodrog River, itself a tributary of the Tisza River, which flows into the Danube River. The total length of the Latorica River is around 190 km. The river flows about 156 km within Ukrainian territory, the rest – in Slovakia. Its source is in the Ukrainian Carpathians (Eastern Carpathian Mountains), near the Latirka village, at an altitude of about 800 m. The total river drop is 703 m, and the average slope is 3.7‰ [15, 16]. It flows the Svaliava, Mukachevo, Solomonovo, and Chop towns in Ukraine, and the Veľké Kapušany town – in Slovakia. Its basin size is around 7,740 km^2.

Latorica forms a unique landscape of oxbow lakes, soft and hardwood floodplain forests, grasslands, and meadows. The river valley is an important migration corridor supporting the natural biodiversity, a habitat for rare and threatened bird species, including other endemic species' biodiversity hotspots, particularly, indigenous fish species [10, 17]. The Latorica River is also applied to meet different water needs – in drinking and industrial water supply, irrigation, recreation, fish farming etc [16].

The nature of Latorica along its flow is very variable. From its source to the town of Svalyava, the river is a mountainous character. In Mukachevo, Latorica turns into a slow-flowing river. They say Mukachevo owes its origins to the river. In ancient times, there was a big mill on Latorica. Initially, the town was mainly developing on the left bank of the river. Today, Latorica divides Mukachevo on the right bank part (the central part) and the left bank part. The town is protected by three dikes, totalling 18,723 m (See above Table 1). However, we do not know how reliable these structures are and against which floods they can protect the town’s residents. Also, we are unaware of what design discharges of floods should be discussed to reconstruct the dikes.

This study's purpose was to discover the epistemic uncertainty in forecasting design maxima discharges of the Latorica River using observation data to open the discussion regarding the reconstruction of the flood-protected dikes in Muchachevo. The article presents the preliminary results of forecasting design maxima discharges in the Latorica River within Mukachevo town based on hydrological observation data at the “Mukachevo” gauging station using plotting position formulas. Considered were thirteen plotting position formulas. In order to minimise the epistemic uncertainty of the plotting positions’ options, the Fishburn rule was used. Depending on the selected significance option assignment of the different plotting position formulas, such rank-weighted estimates of the design peak discharges (each of them for annual exceedance probability 1%, 0.5%, and 0.2%) were computed:

(1) the rank-weighted upper bound estimate (sup-estimate) corresponding to the predisposition to more cautious decision options; (2) the rank-weighted lower bound estimate (inf-estimate) corresponding to the predisposition to less expensive decision options.

3. Data, materials, assumptions, and techniques used in the study

The study employs a fragment of the time series of maximal discharges of the Latorica River, which were observed at the hydrological station (HS) “Mukachevo” from 1947 to 1999 (Fig. 5). The data were taken from the Hydrological Yearbooks [18].

The data sample length is 53 years. The maximum observed peak discharge value within the data sample is 1630 m^3/s (in 1980), and the minimum value is 114 m^3/s (in 1961). Four outliers of peak discharges that exceeded 827 m^3/s (in 1968) were observed: 1480 m^3/s in 1957, 1630 m^3/s in 1980, 1300 m^3/s in 1981, and 1310 m^3/s in 1998. The mean peak discharge within the data sample is 525 m^3/s; the sample standard deviation – of 326 m^3/s. The coefficient of variation of the time series C_V is 0.62, the skewness C_S is 1.62, and the C_S / C_V is 2.60.

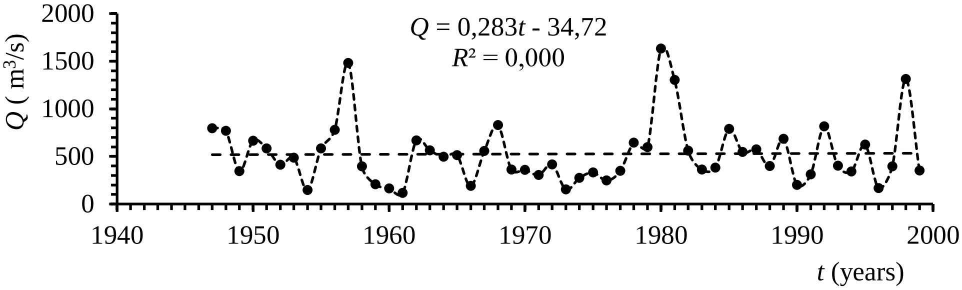

Fig. 5. Time series of annual maximum water discharges, the Latorica River, the “Mukachevo” gauging station, the data sample of 1947-1999

We used two well-known flood frequency analysis techniques to discover the epistemic uncertainty in forecasting design water discharges based on observational data. The first technique is parametric by applying probability distribution functions. The second technique is non-parametric by using plotting position formulas. Two assumptions were applied. The first was a true (the best, an optimal etc) discharge maxima probability distribution would remain unknown [19]. The second was that choosing a plotting position formula among possible options to examine the adequacy of alternative parametric probability distributions can be arbitrary [20].

Admittedly, various parametric probability distributions, independently of techniques of assessing their parameters, can fit observed annual maximum discharges practically equally [19, 21-23]. Correspondingly, any of them might be considered a permissible hypothesis for design peak discharge forecasting [22]. In confirmation of this, let us mention that the national standards of different countries in the world propose for frequency analysis of maximum peak discharges of floods to use various probability distribution function types [24, 25]. However, as practice shows, they can forecast nonsimilar peak discharges with a chosen annual exceedance probability. The same forecasted discharge can have different values of exceedance probabilities depending on the distributions used [21-23]. In turn, similar to forecasting results using different probability distributions, the results of calculating empirical probabilities of exceedance observed maxima water discharges show an increase in the disagreement between the estimates obtained using the different plotting position formulas in case of more extreme events. So, we have to consider both a family of parametric distributions and a family plotting position formulas to shed light on possible estimates and check how substantive the forecasting uncertainty could be.

In this study, we applied thirteen plotting position formulas (Table 2). They appear in the hydrological literature most commonly. We arranged them from the least plot position (Hazen's formula) for the most observed peak discharge to the most plot position (according to the Weibull formula).

Table 2. Plotting position formulas used in the study

No	Author (year)	Formula to calculate P_m (1/year)*	References
1	Hazen (1914)	$\frac{m-0.5}{n}$	[20, 26, 27, 29, 30]
2	Gringorten (1963)	$\frac{m-0.44}{n+0.12}$	[20, 26, 28, 27, 29, 30]
3	Nguyen et al. (1989)	$\frac{m-0.42}{n+0.3C_S+0.05}$, C_S is skewness	[28, 30]
4	Cunnane (1978)	$\frac{m-0.4}{n+0.2}$	[27, 28, 29, 30]
5	Blom (1954)	$\frac{m-3/8}{n+1/4}$	[20, 27, 29, 30]
6	Hosking (1990)	$\frac{m-0.35}{n}$	[28, 30]
7	Tukey (1962)	$\frac{m-1/3}{n+1/3}$	[27, 29, 30]
8	Goel (1993)	$\frac{m-0.02C_S-0.32}{n-0.04C_S+0.36}$	[28, 30]
9	Beard (1945)	$\frac{m-0.3175}{n+0.365}$	[20, 26, 27, 29, 30]
10	Kim et al. (2012)	$\frac{m-0.32}{n+0.0149C_S{}^2-0.1364C_S+0.3225}$	[28, 30]
11	Chegodaev (1965)	$\frac{m-0.3}{n+0.4}$	[27, 30]
12	Adamowski (1985)	$\frac{m-0.25}{n+0.5}$	[27, 29, 30]
13	Weibull (1939)	$\frac{m}{n+1}$	[20, 26, 27, 28, 29, 30]

[*] P_m is the empirical exceedance probability of the *m*-th order observed value, *m* is the rank of the value, where the highest one being "1", and *n* is the number of observed statistics.

As possible theoretical alternatives for forecasting design peak discharges of 1%, 0.5%, and 0.2% annual exceedance probabilities considered were five parametric probability distributions: 1) the Kritskyi-Menkel three-parameter gamma distribution (KM3) ($C_V = 0.62$, $C_S = 3C_V$); 2) Pearson's type III distribution (P3) ($C_S = 1.62$); 3) the Extreme value type I (Gumbell's type I) distribution (EV1); 4) the Logarithmic Pearson type III distribution (LP3) ($C_S = –0.11$); and 5) the Two-parameters log-normal distribution (LN2). Results of forecasting are shown below in Fig. 6 and Table 3. Fig. 6 also shows Weibull's and Hazen's plot positions for observed peak discharges.

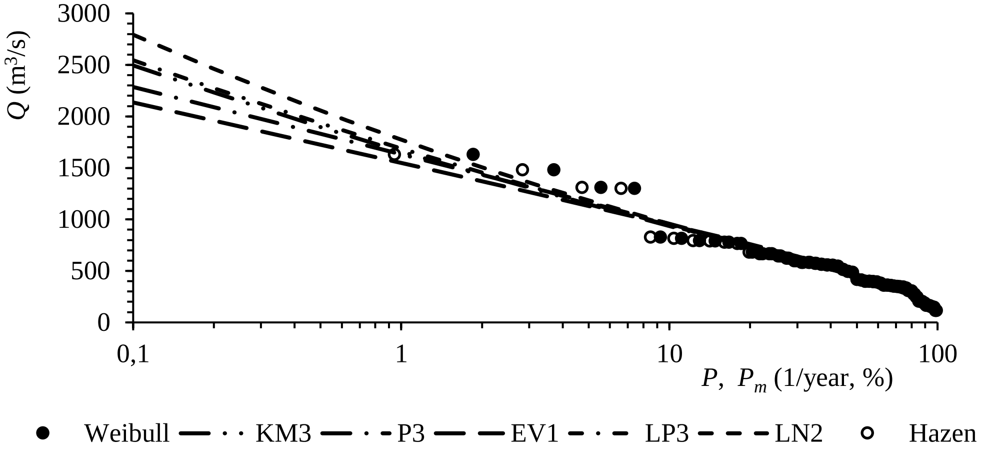

Fig. 6. Alternative parametric probability distributions of annual maxima discharges of the Latorica River, the HS "Mukachevo", the data sample of 1947-1999; P and P_m are forecasted and empirical annual exceedance probabilities

Table 3. Results of alternative forecasting the design maxima discharges of 1%, 0.5%, and 0.2% annual exceedance probabilities for the Latorica River, the HS "Mukachevo", using parametric probability distributions

Probability distribution	P (1/year, %)		
	0.2	0.5	1.0
Two-parameters log-normal distribution (LN2)	2462	2056	1772
Logarithmic Pearson type III distribution (LP3)	2274	1933	1688
Kritskyi-Menkel's three-parameter gamma distribution (KM3)	2232	1897	1657
Pearson's type III distribution (P3)	2091	1831	1634
Gumbell's type I distribution (EV1)	1959	1725	1548

The population statistical parameters for the alternative parametric probability distributions KM3, P3, EV1, LP3, and LN2 (Fig. 6) were estimated from the sample statistics by the moments' method by equating the sample characteristics to the population parameters.

4. The forecasting method used in the study

4.1. Some preliminary remarks about the method being used

While solving the task, a novel non-parametric method of forecasting based on observation data was applied, which was the author's development [30, 31]. This method includes extrapolating the discrepancy (divergence, disagreement) between the estimates of the statistical annual probabilities of exceedance obtained using different plotting position formulas.

Previous research [30, 31] discovered that different plotting position formulas provide similar results for high probable events with return periods $T_{r,m}$ of 5 years and less or the annual exceedance probabilities P_m of 20% and more, where $T_{r,m} = 1/P_m$, or $T_{r,m} = 100/P_m$ if P_m is calculated as percentages. However, the disagreement between probabilities tends to increase while enlarging the modelling horizon towards low probable (more extreme) events. The same conclusion relates to alternative parametric probability distributions (See above Fig. 6).

As a disagreement metric between empirical probabilities obtained using different plotting position formulas, proposed indicator d_m, namely:

$$d_m = \frac{P_{m,i}}{P_{m,j}}, \text{ or } d_m = \frac{T_{r,m,j}}{T_{r,m,i}}, i \neq j, \qquad (1)$$

where $P_{m,i}$ and $P_{m,j}$ are the empirical annual exceedance probabilities (plot positions), and $T_{r,m,i}$, $T_{r,m,j}$ are return periods of the observed maximal discharges, calculated using the i-th and j-th counterparty plotting position formulas, which provide $P_{m,i} > P_{m,j}$, $T_{r,m,i} < T_{r,m,j}$, and $d_m > 1$, m is a rank of a maxima water discharge value where the highest one has the rank $m = 1$.

In the next step [30, 31], we have studied the possibility of modelling such kind of regression dependencies relating to the disagreement indicator d_m: (1) between the return periods $T_{r,m,i}$, $T_{r,m,j}$ calculated using i-th and j-th counterparty plotting position formulas and the indicator d_m, $d_{m,i} = f(T_{r,m,i})$, $d_{m,j} = f(T_{r,m,j})$; (2) between the observed peak discharges Q_m and the indicator d_m, $d_m = f(Q_m)$. Thus, by estimating the indicator d_m and building the before-mentioned regressions, we can make forecasting by applying extrapolation.

4.2. Applying the Fishburn rule to reduce the epistemic uncertainty of using various plotting position formulas

In the study, the results of using different plotting position formulas are considered expert judgments, which may have different importance in decision-making [30, 31]. For instance, Weibull's plotting positions may contribute to choosing more cautious decision options among alternative flood management strategies. However, such options can be associated with increasing capital costs. Hazen's plotting position estimates may contribute to choosing cheaper decision options, but the risk of flood losses increases.

Thus, when making decisions, we can consider different plotting position formulas as indicators of the predisposition to more cautious or less expensive decision options. In other words, various plotting position estimates obtained using different plotting position formulas can acquire their weight level in a system of indicators' importance under the decision-making process [30, 31].

In the method, the corresponding "weights" w_i for the i-th plotting position estimates $P_{m,i}$ $i=\overline{1,k}$ according to the Fishburn rule [32, 33] will be:

$$w_i = \frac{2(k-i+1)}{(k+1)\cdot k}, \tag{2}$$

where i is the rank of the i-th plotting position estimate obtained using the i-th formula taking into account the level of the formula importance; the highest estimate gets the rank i = 1 when there is a predisposition to more cautious options, and vice-versa, when there is a predisposition to options with lower capital costs, the smallest one has the rank i = 1; k is the total number of the ranked-set plotting position estimates (formulas) (k = 13, See Table 2).

Accordingly, depending on the selected significance option of the different plotting position formulas the rank-weighted estimate of the plotting position probability

$$P_{m,w} = \sum_{i=1}^{k} P_{m,i} \cdot w_i \, , \tag{3}$$

where m is the rank of the observed peak water discharge Q_m.

5. Results of the study

For the total number of the used expert estimates (formulas) k = 13, the following weights of the i-th different plotting position estimates (formulas) were obtained depending on their rank of importance: (i = 1, w_1 = 0.143); (2, 0.132); (3, 0.121); (4, 0.110); (5, 0.099); (6, 0.088); (7, 0.077); (8, 0.066); (9, 0.055); (10, 0.044); (11, 0.033); (12, 0.022); (i = 13, w_{13} = 0.011). Depending on the selected significance option of the different plotting position formulas, the Fishburn rule enabled us to get two rank-weighted estimates for the considered annual plotting position probabilities $P_{m,w}$: the rank-weighted upper bound estimates (sup) $P_{m,w}^{\text{sup}}$; the rank-weighted lower bound estimates (inf) $P_{m,w}^{\text{inf}}$. Accordingly, for the Latorica River, the HS "Mukachevo", two grades for each possible rank-weighted estimate of the maxima discharges of 1%, 0.5%, and 0.2% annual exceedance probability using the non-parametric method have been forecasted: the lower bound ("inf") and the upper bound ("sup") estimates of design peak discharges. The results are presented in Tables 4-6 and Figures 7, 8.

Table 4 presents empirical exceedance probabilities P_m of the m-th order observed peak discharges of the Latorica River, the HS “Mukachevo”, the data sample of 1947-1999, $m=\overline{1{,}8}$, depending on the different plotting position formulas. Table 5 shows estimates $P_{m,w}^{\sup}$, $P_{m,w}^{\inf}$ of $P_{m,w}$, the indicator d_m = $P_{m,w}^{\sup}$/ $P_{m,w}^{\inf}$, and the return periods $T_{r,m}^{\sup}$ = 100/ $P_{m,w}^{\sup}$, $T_{r,m}^{\inf}$ = 100/ $P_{m,w}^{\inf}$.

Table 4. Exceedance probabilities P_m for the observed peak discharges with ranks $m=\overline{1{,}8}$ depending on the different plotting position formulas

No	Plotting position formula (author)	P_m (1/year, %), $m=\overline{1{,}8}$, Q_m (m³/s)							
		1	2	3	4	5	6	7	8
		1630	1480	1310	1300	827	813	794	788
1	Hazen	0,94	2.83	4.72	6.60	8.49	10.38	12.26	14.15
2	Gringorten	1.05	2.94	4.82	6.70	8.58	10.47	12.35	14.23
3	Nguyen et al.	1.08	2.95	4.82	6.69	8.56	10.42	12.29	14.16
4	Cunnane	1.13	3.01	4.89	6.77	8.65	10.53	12.41	14.29
5	Blom	1.17	3.05	4.93	6.81	8.69	10.56	12.44	14.32
6	Hosking	1.23	3.11	5.00	6.89	8.77	10.66	12.55	14.43
7	Tukey	1.25	3.13	5.00	6.88	8.75	10.63	12.50	14.38
8	Goel	1.22	3.09	4.97	6.84	8.72	10.60	12.47	14.35
9	Beard	1.28	3.15	5.03	6.90	8.77	10.65	12.52	14.40
10	Kim et al.	1.28	3.16	5.04	6.92	8.81	10.69	12.57	14.45
11	Chegodaev	1.31	3.18	5.06	6.93	8.80	10.67	12.55	14.42
12	Adamowski	1.40	3.27	5.14	7.01	8.88	10.75	12.62	14.49
13	Weibull	1.85	3.70	5.56	7.41	9.26	11.11	12.96	14.81

Table 5. The estimates $P_{m,w}^{\sup}$, $P_{m,w}^{\inf}$, d_m, $T_{r,m}^{\sup}$, $T_{r,m}^{\inf}$ depending on the m-th order’s peak discharges

Parameters	Observed peak discharge Q (m³/s)							
	1630	1480	1310	1300	827	813	794	788
m	1	2	3	4	5	6	7	8
$P_{m,w}^{\sup}$ (%)	1,34	3,22	5,09	6,96	8,83	10,71	12,58	14,45
$P_{m,w}^{\inf}$ (%)	1,15	3,03	4,91	6,78	8,66	10,54	12,42	14,30
d_m	1,168	1,062	1,037	1,026	1,020	1,016	1,013	1,011
$T_{r,m}^{\sup}$ (years)	74	31	20	14	11	9	8	7
$T_{r,m}^{\inf}$ (years)	87	33	20	15	12	9	8	7

Fig. 7 and Table 6 present the results of forecasting the peak discharges of 1%, 0.5%, and 0.2% annual exceedance probability for the Latorica River, the HS "Mukachevo", carried out according to the data shown in Table 5.

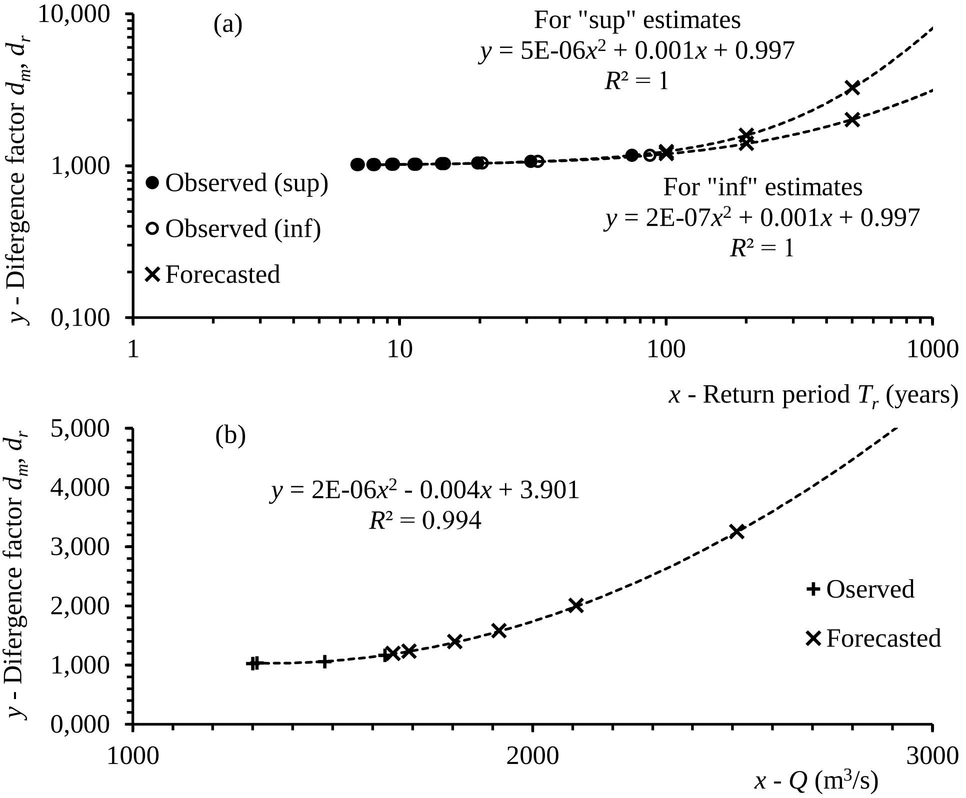

Fig. 7. Forecasting the peak discharges of 1%, 0.5%, and 0.2% annual exceedance probability for the Latorica River, the HS "Mukachevo", by extrapolating the regressions $d_{m,i} = f(T_{r,m,i})$, $d_{m,j} = f(T_{r,m,j})$ (a), and the regression $d_m = f(Q_m)$ (b)

Table 6. The results of forecasting the peak discharges of 1%, 0.5%, and 0.2% annual exceedance probability for the Latorica River, the HS "Mukachevo"

P (1/year, %)	$T_r = 100 \cdot P^{-1}$ (years)	Design maxima discharge Q (m^3/s) :	
		estimate "inf"	estimate "sup"
1	100	1650	1690
0.5	200	1805	1915
0.2	500	2108	2510

Finally, Fig. 8 shows the visualisation of the forecasted peak discharges (Table 6) obtained using the discussed non-parametric method in comparison with the plots giving the chosen alternative parametric probability distributions.

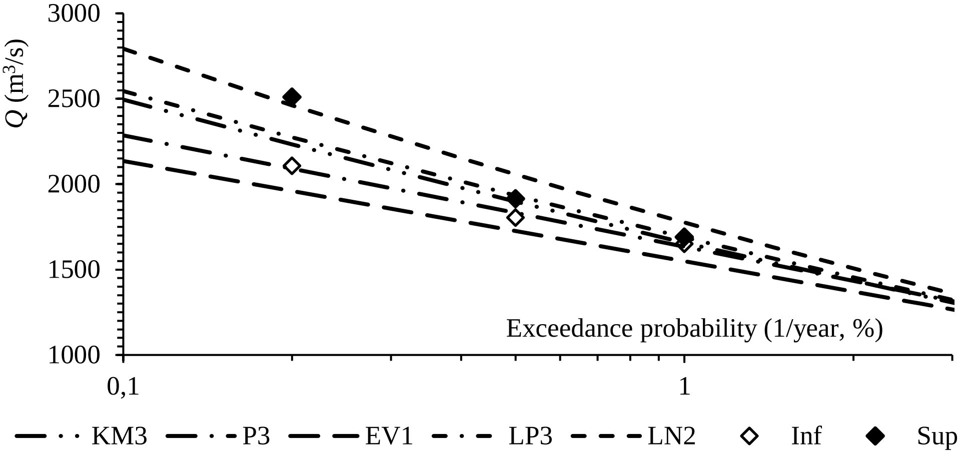

Fig. 8. The visualisation of the forecasted peak discharges (estimates “inf” and “sup”) of 1%, 0.5%, and 0.2% annual exceedance probability for the Latorica River, the HS “Mukachevo”, obtained using the discussed method in comparison with plots of the chosen alternative parametric probability distributions

In the considered case (the Latorica River, the HS “Mukachevo”), it should be noted the nice goodness of fit of the lower bound (“inf”) estimates of the forecasted peak discharges of 1%, 0.5%, and 0.2% annual exceedance probability obtained by applying the non-parametric method to the proper forecasts by the Pearson type III distribution (P3). We have 1650 m^3/s, 1805, and 2108 m^3/s (See Table 6) opposite to 1634 m^3/s, 1831, and 2091 m^3/s (See Table 3). The estimates differ by 1.0, 1.45, and 0.82%. The upper bound (“sup”) estimates of the 1%, 0.5% exceedance probability peak discharges forecasted by applying the non-parametric method correspond better to the Logarithmic Pearson type III distribution (LP3). We have 1690 opposite 1688 m^3/s and 1915 opposite 1933 m^3/s. The estimates differ by 0.14 and 0.94%. However, the upper bound (“sup”) estimate of the 0.2% exceedance probability peak discharge forecasted by applying the non-parametric method corresponds better to the Two-parameters logarithmic-normal distribution (LN2). We have 2510 opposite 2462 m^3/s. The estimates differ by 1.95%.

6. Some discussion remarks

There are a lot of parametric probability distributions to forecast peak discharges of floods based on observation data [19, 24, 25], including proper techniques to assess the distribution parameters [23]. As practice shows, different probability distributions can forecast various peak discharges of a chosen annual exceedance probability [19, 21-25]. Accordingly, depending on the chosen distributions, the same forecasted peak discharge can have different exceedance probabilities.

Moreover, we can apply different plotting position formulas to fit parametric probability distributions with the observed data (Table 2). The issue is the choice of an unbiased empirical formula to plot the observed data [20]. Any plotting position formula can be an option for fitting parametric probability distributions.

This is because there are two basic kinds of uncertainty relating to hydrological forecasting: natural (or stochastic) and epistemic (non-stochastic or model) uncertainty. The stochastic uncertainty relates to the issue that available data are always insufficient to define the probabilities of extreme events more precisely, independently of the forecasting way – parametric one by applying probability distributions or non-parametric one – based on plotting position formulas. In addition, the epistemic uncertainty related to the incomplete knowledge about the river runoff phenomenon [19] will remain a serious challenge despite the data volumes, their variety, veracity and monitoring scopes [32].

Possibly, just the multi-model approach to forecasting by applying alternative techniques and probabilistic models will promote revealing epistemic uncertainty of peak discharges' forecasts. At least, considering both a family of parametric distributions and a family of plotting position formulas can shed light on the spread of estimates to check how substantive the forecasting uncertainty could be in various cases. Based on a multi-model approach, the non-parametric, numerically analytical method, which is based on extrapolating the discrepancy (divergence, disagreement) between the estimates of the statistical annual exceedance probabilities obtained by applying different plotting position formulas, might improve forecasting of peak discharges of floods using observed data. It is also worth noting, in terms of forecast quality and accuracy, the estimates of the design peak discharges of the Latorica River, the HS “Mukachevo”, obtained by applying the non-parametric technique, do not principally differ from similar estimates obtained using the selected parametric probability distributions.

Conclusions

1. Some preliminary results of forecasting design peak discharges of floods of the Latorica River, the “Mukachevo” gauging station are presented. While solving the task, a novel non-parametric technique of forecasting based on observation data was applied, which is based on extrapolating the discrepancy (divergence, disagreement) between the statistical annual exceedance probabilities obtained using plotting position formulas. The task was considered in the frame of the stationarity hypothesis of the maximum river flow employing a time series of maximal discharges of the Latorica River observed at the “Mukachevo” gauging station from 1947 to 1999.

2. The main purpose of this study was to discover the epistemic uncertainty in forecasting design discharges of the Latorica River using observation data to open the discussion relating to the reconstruction of the flood-protected dikes in Muchachevo, the Transcarpathia region. Depending on the selected significance option of the applying plotting position formulas, two rank-weighted estimates of the design peak discharges (each of them for annual exceedance probability 1%, 0.5%, and 0.2%) were computed: (1) the rank-weighted upper bound estimates (sup-estimates) corresponding to the predisposition to more cautious decision options; (2) the rank-weighted lower bound estimates (inf-estimates) corresponding to the predisposition to less expensive decision options. As possible control theoretical alternatives for forecasting design maximal discharges considered were five parametric probability distributions: 1) the Kritskyi-Menkel three-parameter gamma distribution; 2) Pearson’s type III distribution; 3) the Extreme value type I distribution (Gumbell’s type I distribution); 4) the Logarithmic Pearson type III distribution; and 5) the Two-parameters logarithmic-normal distribution.

3. Among the practically significant results of the study, the following ones should be highlighted. There was revealed nice goodness of fit of the lower bound (“inf”) estimates of the forecasted peak discharges of 1%, 0.5%, and 0.2% annual

exceedance probability obtained by applying the non-parametric method to the proper forecasts by the Pearson type III distribution (P3), namely: the discharges of 1650 m^3/s, 1805, and 2108 m^3/s opposite to the discharges of 1634 m^3/s, 1831, and 2091 m^3/s. The estimates differ by 1.0, 1.45, and 0.82%. The upper bound ("sup") estimates of the 1%, 0.5% exceedance probability peak discharges forecasted by applying the non-parametric method correspond better to the Logarithmic Pearson type III distribution (LP3). The estimates are 1690 m^3/s opposite 1688 m^3/s and 1915 m^3/s opposite 1933 m^3/s and differ by 0.14, 0.94%, correspondingly. Finally, the upper bound ("sup") estimate of the 0.2% exceedance probability peak discharge forecasted by applying the non-parametric method corresponds better to the Two-parameters logarithmic-normal distribution (LN2): 2510 m^3/s opposite 2462 m^3/s. The estimates differ by 1.95%.

REFERENCES

1. Ukraine – Vulnerability. Climate Change Knowledge Portal. Available from https://climateknowledgeportal.worldbank.org/country/ukraine/vulnerability.
2. Flood protection of territories. United Nations Development Programme. UNDP in Ukraine. Available from https://www1.undp.org/content/dam/ukraine/docs/EE/Flood.
3. Stefanyshyn, D.V. (2022). What could we have learnt from the previous flood data to predict losses caused by the 1980, 1986, and 1998 catastrophic floods in Ukrainian Transcarpathian? Environmental safety and natural resources, 43(3), 81–109; https://doi.org/10.32347/2411-4049.2022.3.81-109.
4. Stoyko, S.M. (2002). The causes of catastrophic floods in the Transcarpathian region and the system of ecological prophylactic measures for their prevention. TISCIA monograph series, 6, 17–28.
5. Lukianets, O., Malytska, L., and Moskalenko, S. (2020). Maximum Riverine Runoff in the Basin of Tysa and Prut within Ukraine. In: Proceedings of the XXVIII Conference of the Danubian Countries on Hydrological Forecasting and Hydrological Bases of Water Management (Kyiv, November 6-8, 2019). Edited by V. Osadchiy, et al. Kyiv, Nika-Tsentr; DOI:10.15407/uhmi.conference.01.18, Corpus ID: 228979870.
6. Didovets, I., Lobanova, A., Bronstert, A., Snizhko, S, Fox Maule, C, and Krysanova, V. (2017). Assessment of Climate Change Impacts on Water Resources in Three Representative Ukrainian Catchments Using Eco-Hydrological Modelling. Water, 9, 204; doi:10.3390/w9030204.
7. Susidko, M.M., and Lukyanets, O.I. (2004). Zoning of the territory of Ukraine according to the degree of hydrological danger. UkrNDGMI, Issue 253, 196–204. (In Ukrainian) [Сусідко М.М., Лук'янець, О.І. (2004). Районування території України за ступенем гідрологічної небезпеки. УкрНДГМІ, Вип. 253, 196–204].
8. Sub-Basin Level Flood Action Plan for Tisza River Basin. (2009). Int. Commission for the Protection of the Danube River (ICPDR), Flood Protection Expert Group, 52 p. Available from https://www.icpdr.org/main/sites/default/files/FAP09_Tisza.pdf.
9. Lukianets, O., Moskalenko, S. (2019). Generalization and multi-annual variability of the maximum annual runoff river water in accordance with the hydrographic zoning of Ukraine. Hidrolohiia, hidrokhimiia i hidroekolohiia, № 2 (53), 6–20. (In Ukrainian) [Лук'янець, О.І., Москаленко, С.О. (2019). Узагальнення та багаторічна мінливість максимального річного стоку води річок відповідно до гідрографічного районування України. Гідрологія, гідрохімія і гідроекологія, Т. 2 (53), 6–20].
10. Gönczy, S., Fodor, G., Oláh, N., Nagy, T., Ésik, Z., and Szepesi, J. (2020). Geoheritage Values of the Northeastern Carpathians, Transcarpathia, Ukraine. Geoconservation Research, Vol. 3, Issue 2, 32–48; DOI: 10.30486/gcr.2020.1904340.1026.

11. Kirilyuk, M.I. (2001). Regime of formation of historical floods in the Ukrainian Carpathians. Environmental aspects of the formation of small rivers (problem analysis). Hydrology, hydrochemistry and hydroecology. [Resp. ed. V.K., Khilchevsky]. Kyiv, Nika-Center, Vol. 2, 146–156. (In Ukrainian) [Кирилюк, М.І. (2001). Режим формування історичних паводків в Українських Карпатах. Екологічні аспекти русло формування малих річок (аналіз проблеми). Гідрологія, гідрохімія і гідроекологія. [Відп. ред. В.К. Хільчевський]. Київ, Ніка-Центр, Т. 2, 146–156].

12. Konovalenko, O.S. (2016). Latorica. Encyclopedia of Modern Ukraine. Ed.: I.M. Dzyuba, A.I. Zhukovsky, M.G. Zheleznyak [and others]; National Academy of Sciences of Ukraine, Institute of Encyclopedic Research of the National Academy of Sciences of Ukraine. Available from https://esu.com.ua/article-53425. (In Ukrainian) [Коноваленко, О.С. (2016). Латориця. Енциклопедія Сучасної України. Редкол.: І.М. Дзюба, А.І. Жуковський, М.Г. Железняк [та ін.]; НАН України, НТШ, Інститут енциклопедичних досліджень НАН України].

13. Thematic maps of the Danube River Basin. Social and Economic Characteristics with particular attention to Hot Spots, Significant Impact Areas and Hydraulic Structures. (1999). Programme Coordination Unit UNDP/GEF Assistance. Zinke Environment Consulting for Central and Eastern Europe and Mihaela Popovici, Vienna, Austria; https://www.icpdr.org/sites/default/files/TA_THEMATIC_MAPS.pdf.

14. Flood issues and climate changes – Integrated Report for Tisza River Basin. (2018). Danube Transnational Programme JOINTISZA. Deliverable 5.1.2. https://www.interreg-danube.eu/uploads/media/approved_project_output/0001/36/49d50d0b2429884b0a1f2eafc8c158b70bc31679.pdf.

15. Obodovsky, O., Onyschuk, V., Rozlach, Z. et all. (2012). Latorica: hydrology, hydromorphology, channel processes. Kyiv National University, Kyiv, “Rivers of the Carpathians” Series. (In Ukrainian) [Ободовський, О.Г., Онищук, В.В., Розлач, З.В. та ін. (2012). Латориця: гідрологія, гідроморфологія, руслові процеси. Монографія. [За ред. О.Г. Ободовського], Київ, Видавничо-поліграфічний центр «Київський університет», Серія «Річки Карпат»].

16. Leta, V.V., Mykyta, M.M., Salyuk, M.R., Feketa, I.Yu., and Melnychuk, V.P. (2022). Water use in the Latoritsa river basin: condition and optimization. Hydrology, Hydrochemistry and Hydroecology, No. 1 (63), 30-39; DOI: https://doi.org/10.17721/2306-5680.2022.1.3. (In Ukrainian) [Лета, В.В., Микита, М.М., Салюк, М.Р., Фекета, І.Ю., Мельничук, В.П. (2022). Водокористування у басейні річки Латориця: стан та оптимізація. Гідрологія, гідрохімія та гідроекологія, № 1 (63), 30–39].

17. Kozak, O., and Didukh, Y. (2014). Assessment of mountain ecosystems changes under anthropogenic pressure in Latorica river basin (Transcarpathian region, Ukraine). Ekológia (Bratislava), Vol. 33, No. 4, 365–379; doi:10.2478/eko-2014-0033.

18. Central Geophysical Observatory named after Boris Sreznevsky. Available from http://cgo-sreznevskyi.kyiv.ua/index.php?lang=en&dv=main.

19. Stedinger, J.R., Vogel, R.M. and Foufoula-Georgia, E. (1993). Frequency Analysis of Extreme Events. Chapter 18. In Maidment, D.R., Ed., Handbook of Hydrology, McGraw Hill, New York, 18.1-18.66.

20. Cunnane, C. (1978). Unbiased plotting positions – A review. Journal of Hydrology, Vol. 37, Issues 3-4, 205–222; https://doi.org/10.1016/0022-1694(78)90017-3.

21. Apel, H., Merz, B., Thieken, and A.H. (2008). Quantification of uncertainties in flood risk assessments. International Journal of River Basin Management (JRBM), Vol. 6, No. 2, 149–162; DOI: 10.1080/15715124.2008.9635344.

22. Stefanyshyn, D.V. (2021). Probability assessment of the Kyiv reservoir overflow. Environmental safety and natural resources, 40 (4), 73–99; DOI: 10.32347/2411-4049.2021.4.73-99.

23. Anghel, C.G., Stanca, S.C., Ilinca, C. (2023). Extreme Events Analysis Using LH-Moments Method and Quantile Function Family. Hydrology, 10, 159; https://doi.org/10.3390/hydrology10080159.

24. Review of Applied-Statistical Methods for Flood-Frequency Analysis in Europe. (2012). Editors: Castellarin, A., Kohnová, S., Gaál, L., Fleig, A., Salinas, J.L., Toumazis, A., Kjeldsen, T.R., and Macdonald, N. NERC/Centre for Ecology & Hydrology, 122 p. Available from https://nora.nerc.ac.uk/id/eprint/19286/.
25. Ren, M., He, X., Kan, G., Wang, F., Zhang, H., Li, H., Cao, D., Wang, H., Sun, D., Jiang, X., Wang, G., and Zhang, Z. (2017). A Comparison of Flood Control Standards for Reservoir Engineering for Different Countries. Water, 9, 152; doi.org/10.3390/w9030152.
26. Makkonen, L. (2006). Plotting Positions in Extreme Value Analysis. Journal of Applied Meteorology and Climatology, Vol. 45, 334–340; https://doi.org/10.1175/JAM2349.1.
27. Ahmad Shukri Yahaya, Norlida Md. Nor, Nor Rohashikin Mat Jali, Nor Azam Ramli, Fauziah Ahmad, and Ahmad Zia Ul-Saufie (2012). Determination of the Probability Plotting Position for Type I Extreme Value Distribution. Journal of Applied Sciences, 12, 1501–1506; DOI: 10.3923/jas.2012.1501.1506.
28. Ologhadien, I. (2021). Study of Unbiased Plotting Position Formulae for the Generalized Extreme Value (GEV) Distribution. European J. of Eng. and Technology Research, Vol. 6, Issue 4, 94–99; DOI: http://dx.doi.org/10.24018/ejers.2021.6.4.2468.
29. Van der Spuy, D., and du Plessis, J.A. (2022). Flood frequency analysis – Part 2: Development of a modified plotting position. Water SA 48(2), 120–33; https://doi.org/10.17159/wsa/2022.v48.i2.3848.2.
30. Stefanyshyn, D.V. (2023). Testing a numerically-analytical method for prediction design maxima discharges of floods using plotting position formulas: the river Uzh case, the "Uzhhorod" gauging station data, Environmental safety and natural resources, 46:2, 138–162; doi.org/10.32347/2411-4049.2023.2.138-162.
31. Stefanyshyn, D.V. (2023). A Design Water Discharge Maxima Forecasting Method Based on Observation Data Using Plotting Position Formulas, in: Proceedings of the International scientific and practical conference "Modeling, Control and Information Technologies", 6, 199–202; doi.org/10.31713/MCIT.2023.061.
32. Hossein Hassani, H., and Silva, E.S. (2015). Forecasting with Big Data: A Review. Ann. Data. Sci., 2(1), 5–19; DOI 10.1007/s40745-015-0029-9.

The article was received 27.05.2024 and was accepted after revision 11.09.2024

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ПРОГНОЗУВАННЯ РОЗРАХУНКОВИХ МАКСИМАЛЬНИХ ВИТРАТ ВОДИ ПАВОДКІВ НА РІЧЦІ ЛАТОРИЦЯ ЗА ДАНИМИ ГІДРОЛОГІЧНОГО ПОСТА «МУКАЧЕВО» З ВИКОРИСТАННЯМ ФОРМУЛ ЕМПІРИЧНОЇ ЙМОВІРНОСТІ

Анотація. У статті наведено результати прогнозування розрахункових максимальних витрат води паводків на річці Латориця в межах м. Мукачево з використанням формул емпіричної ймовірності за даними гідрологічних спостережень на гідрологічному посту «Мукачево». При вирішенні поставленої задачі застосовано новий непараметричний метод прогнозування за даними спостережень. Метод ґрунтується на екстраполяції розбіжності між статистичними оцінками річних ймовірностей перевищення пікових витрат води, отриманими за допомогою різних формул емпіричної ймовірності. Завдання досліджень розглядається в межах гіпотези стаціонарності максимального стоку річки з використанням ряду даних щодо максимальних витрат річки Латориця, спостережених на гідропосту «Мукачево» з 1947 по 1999 рік.

Всього було використано тринадцять формул емпіричної ймовірності. Вибір формул був довільним. Усі застосовані в дослідженні формули розглядалися як допустимі альтернативи оцінювання емпіричних ймовірностей перевищення спостережених витрат, а отримані за їх допомогою результати – як експертні оцінки, які відображають схильність носіїв рішення при розробці стратегій управління повенями до більш обережних, але більш вартісних, або до менш вартісних, але більш ризикованих варіантів рішень.

Для зменшення епістемічної невизначеності оцінок емпіричних ймовірностей перевищення екстремальних витрат, отриманих за різними емпіричними формулами, використовувалося правило Фішберна. Згідно з цим правилом рівень значущості оцінок емпіричних ймовірностей перевищення екстремальних витрат води, отриманих за різними формулами емпіричної ймовірності, встановлювався їх ранжуванням в порядку зменшення важливості їх значення при прийнятті рішення. Залежно від вибраного варіанту поведінки носія рішення щодо значущості емпіричних оцінок, отриманих за різними формулами емпіричної ймовірності, було обчислено наступні, «зважені» за рангом, оцінки розрахункових пікових витрат (щорічними ймовірностями перевищення 1%, 0,5% та 0,2%): (1) зважені оцінки для верхньої межі (sup-оцінки), що можуть відповідати схильності носія рішення до більш обережних варіантів рішень; (2) зважені оцінки для нижньої межі (inf-оцінки), що можуть відповідати схильності носія рішення до менш вартісних, але більш ризикованих варіантів рішень в стратегіях управління повенями. В якості можливих теоретичних альтернатив, які можуть використовуватися для прогнозування розрахункових значень максимальних витрат води, розглядалися п'ять параметричних розподілів ймовірностей: 1) трьохпараметричний гамма-розподіл Крицького-Менкеля; 2) розподіл Пірсона III типу; 3) екстремальний розподіл I типу (розподіл I типу Гумбеля); 4) логарифмічний розподіл Пірсона III типу; 5) двохпараметричний логарифмічно-нормальний розподіл. Статистичні параметри сукупності для вибраних параметричних розподілів ймовірності оцінювалися за вибірковою статистикою методом моментів.

Ключові слова: Щорічна ймовірність перевищення, розрахункова максимальна витрата води, епістемічна невизначеність, екстраполяція, повінь, прогнозування, дані спостережень, параметричні розподіли ймовірності, формули емпіричної ймовірності, «зважені» оцінки.

Стаття надійшла до редакції 27.05.2024 і прийнята до друку після рецензування 11.09.2024

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