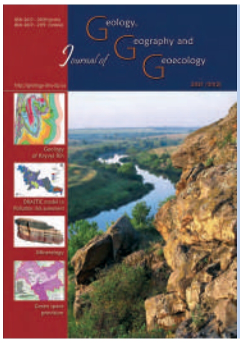

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Spring flood frequency analysis in the Southern Buh River Basin, Ukraine

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Abstract. The river floods are among the most dangerous natural disasters in the world. Each year, the spring floods cause the significant material damage in the different countries, including Ukraine. Knowledge of trends in such floods, as well as their probabilistic forecast, is of great scientific and practical importance. In last decades, the decreasing phase of cyclical fluctuations of the maximum runoff of spring floods has been observed on the plain rivers of Ukraine, including the Southern Bug River. In addition, there is an increase in air temperature. So, the actual task is the determine the modern probable maximum discharges estimates of spring floods in the Southern Buh River Basin as well as their comparison with the estimates that were computed earlier. It gives an opportunity to reveal possible changes of the statistical characteristics and values of the probable maximum discharges, to analyze and to discuss the reasons for these changes. For the investigation, we used the time series of the maximum discharges of spring floods for 21 gauging stations in the Southern Buh River Basin since the beginning of the observations and till 2015. The method of the regression on the variable that is based on the data of analogues rivers was used to bringing up the duration of the time series and restoration of the gaps. In the study, the hydro-genetic methods for estimation of the homogeneity and stationarity of hydrological series, namely the mass curve, the residual mass curve and the combined graphs. The distributions of Kritskyi & Menkel and Pearson type III for the frequency analysis were used. It has been shown in this study that the maximum discharges of spring floods of time series are quasi-homogeneous and quasi-stationary. It is explained the presence in the observation series of only increasing and decreasing phases of cyclical fluctuations, their considerable duration, as well as the significant variability of the maximal flow. The series of maximal runoff of spring floods are very asymmetric, which significantly complicates the selection of analytical distribution curves. The updated current parameters of the maximal spring flood runoff have not changed significantly. It can be assumed that such characteristics have already become stable over time, as the series of maximal runoff of spring floods already have phases of increasing and decreasing of long-term cyclic fluctuations.

Keywords: spring floods, stationarity, homogeneity, frequency analyses, cyclical fluctuations

Аналіз ймовірнісних характеристик весняних паводків у басейні річки Південний Буг, Україна

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Анотація. У світі весняні повені на річках – одне з найнебезпечніших стихійних явищ. Щорічно весняні повені завдають значних матеріальних збитків у різних країнах світу, у тому числі, і в Україні. Важливе наукове і практичне значення має знання тенденцій таких повеней, а також їхній імовірнісний прогноз. В останні десятиліття на рівнинних річках України, до яких відноситься і річка Південний Буг, спостерігається маловодна фаза циклічних коливань максимального стоку весняної повені. Окрім того, спостерігається підвищення температури повітря. Отже, актуальним завданням є визначення сучасних ймовірних характеристик максимальних витрат весняної повені в басейні річки Південний Буг, а також їхнє порівняння з оцінками, які було розраховано раніше. Це дозволить виявити можливі зміни статистичних характеристик максимальних витрат весняної повені, проаналізувати та обговорити причини цих змін. Для дослідження використано ряди спостережень максимальних витрат весняної повені для 21 гідрологічного поста в басейні річки Південний Буг з початку спостережень по 2015 р. Для отримання більш достовірних оцінок ряди спостережень було приведено до багаторічного періоду та по можливості відновлено пропуски методом парної регресії. Для оцінки однорідності і стаціонарності рядів спостережень використано гідролого-генетичні методи, а саме сумарну та інтегральну криву відхилень, суміщені хронологічні графіки. Для апроксимації емпіричних точок використано розподіл Крицького-Менкеля та розподіл III типу Пірсона. У дослідженні показано, що ряди максимальних витрат води весняної повені є квазіоднорідними та квазістаціонарними, оскільки мають тільки незавершені фази (підйому та спаду) довготривалих циклічних коливань. Ряди максимального стоку весняної повені є дуже асиметричними, що суттєво ускладнює побудову аналітичних кривих розподілу. Уточнені сучасні параметри максимального стоку весняної повені суттєво не змінились. Можна припустити, що такі характеристики вже стали стабільними з часом, оскільки ряди спостережень мають фази збільшення і зменшення довгострокових циклічних коливань.

Ключові слова: весняна повінь, стаціонарність, однорідність, ймовірність, циклічні коливання

Introduction

In the world, the extreme floods on the rivers cause considerable and prolonged flooding of the densely populated territories, which cause to damage a myriad of infrastructures such as buildings, roads, bridges, and barrages and sometimes also losses of human lives. The extreme floods are among the costliest natural hazards (Doe, 2006; Razmi et al., 2017; Blöschl et al., 2019). Since the natural disaster as extreme floods is the basis for planning and design of various hydraulic structures, hydrological forecasting, flood risk reflection characteristics such as trends of extreme floods and its changes, and its formation conditions, the probable maximal flood and its characteristics have a great practical importance. The determining of the probable maximal flood is the practical importance, especially for the planning, design, and operation of hydrotechnical structures (Apel et al., 2004; Blöschl et al., 2013; Okoli et al., 2019).

During the 20th century, many scientists developed the methodological approaches to the definition of flood estimates, which remain relevant today. Therefore, the statistical approaches, hydrometeorological methods, empirical formulas, different regionalization methods are usually used to flood estimates (Blöschl et al., 2013; Saghafian, 2014; Odry and Arnaud, 2017). At the same time, such research may have the related difficulties due to low precision of extreme flood discharge measurements and estimates, using comparatively short time series of observed flood data, limited data availability, as well as temporal variation in the data series due to variability in climate and to environmental changes, etc. Hence, the important task is obtaining reliable flood estimates. This can be achieved by using appropriate methodological approaches (McKerchar and Macky, 2001; Kjeldsen, 2015; Okoli et al., 2019).

In Ukraine, on the plain rivers the dangerous floods are observed during the spring period (Grebin, 2010; Gorbachova, 2015; Shakirzanova, 2015; Khrystyuk et al., 2017). In this paper, the spring flood estimates was carried out for the Southern Buh River Basin. The research for this river is actual because the river has significant importance for hydro-energy sector and agriculture. Thus, Southern Buh River Basin has 6929 ponds and 200 water reservoirs (Palamarchuk and Zakorchevna, 2006). In the different years, these reservoirs can accumulate from 20 to 70% of the local flow. Water river is widely used for irrigation, especially in drought years (Vyshnevskyi, 2000). The frequency approach is widely used for flood estimates in Ukraine. Typically, the statistic estimates are the updated every 5 years. This approach allows the use of modern data and, accordingly, to receive more reliable and accurate flood estimates.

The aim of this study is to determine the modern probable maximal discharges estimates of spring floods in the Southern Buh River Basin as well as their comparison with the estimates that were computed earlier. It gives an opportunity to reveal possible changes of the statistical characteristics and values of the probable maximal discharges, to analyze and to discuss the reasons for these changes.

The tasks of the research include:

– the use of the method of linear regression for the restoration of the data of observations in different years;

– the investigation of the homogeneity and stationarity of the observation series on based the graphical methods;

– the determination of 1% maximum discharges of spring flood of the rivers.

Materials and Methods

Southern Buh River is the second-longest river after the Dnipro River in Ukraine. It is the longest river that flowing exclusively through the territory of Ukraine – its length is 806 km. The basin river is on the Volyn-Podillia and Dnipro Uplands, as well as in the Black Sea lowland for the lower part of the basin. Its crosses three natural zones: forest, forest-steppe, and steppe. Catchment covers 10.6% of the territory of Ukraine. Southern Buh River Basin has the pear-shaped form: at the top part it is narrowed; in the middle and lower parts the basin is sharply asymmetrical (Fig. 1). Southern Buh River is plain river, because the average height of its catchment in the upper part is 300-320 m, in the lower part is 5-20 m, the average slope of water surface is 0.40% (Kaganer, 1969).

The atmosphere circulation is carrying out an important role for the formation of the basin climate. It is associated with the movement of an air masses from the Atlantic, Arctic, and Mediterranean. Moderate continental climate is typical for the river basin. Precipitation gradually decreases from the source to the mouth of the river. (Bauzha and Gorbachova, 2017). The summer rains (except for the strong) do not form a surface runoff at some catchments of steppe zone due to the intensive infiltration of rainwater into the soil and significant evaporation from river catchment. Furthermore, such rivers almost do not have an underground supply and in the summer-autumn period it dries up. In winter period, such rivers are usually frozen (Gorbachova and Khrystyuk, 2018). Southern Buh River basin is characterized by a clearly pronounced spring flood, during which it is forming from 35 to 60% of annual streamflow (Shakirzanova, 2015).

The Southern Buh Basin has extremely high anthropogenic loads. Hence, more than 8 000 artificial reservoirs were created in the basin, their total volume is close to 1.5 km³, which is almost equal to the runoff in the dry year of probability 95%. Its water is widely used for hydro-energy sector, industrial and municipal water supply, agriculture, irrigation, shipping, tourism, etc. (Bauzha and Gorbachova, 2017).

In this study we used the series of observations of 21 gauging stations of the Southern Buh River Basin (Fig. 1). The catchment areas are changing in the greater limits – from 92.5 to 46200 km^2. The period of observation on these rivers is from 14 (Southern Buh River – Selythse village) to 102 (Southern Buh River – Oleksandrivka village) years (since the beginning of the observations and till 2015) (Table 1).

To verify the reliability of observations data on the maximum discharges of the spring flood it was used the historical information. On several rivers, the observations were not conducted for some years. Some data series were with errors or have short duration of observed flood data.

The method of the regression on the variable that is based on the data of analogues rivers was used to bringing up the duration of the time series and restoration of the gaps. This method recommended for using as by «Guide to Hydrological Practices» WMO (2009), as and by the national guideline of Ukraine (BNR, 1983). It is carrying out provided that:

$$R \geq 0.7,\ l \geq 10,\ k/\sigma_k \geq 2 \quad (1)$$

where R is the correlation coefficient between discharge values of the corrected and analogue gauging stations; l is a number of joint observation years of corrected and analogue gauging stations; k is the regression coefficient; $\boldsymbol{\sigma}_k$ is the standard deviation of regression coefficient.

The determining probable characteristics of time series can be carried out only based on the homogeneous and stationary data. Nowadays, two methodi-

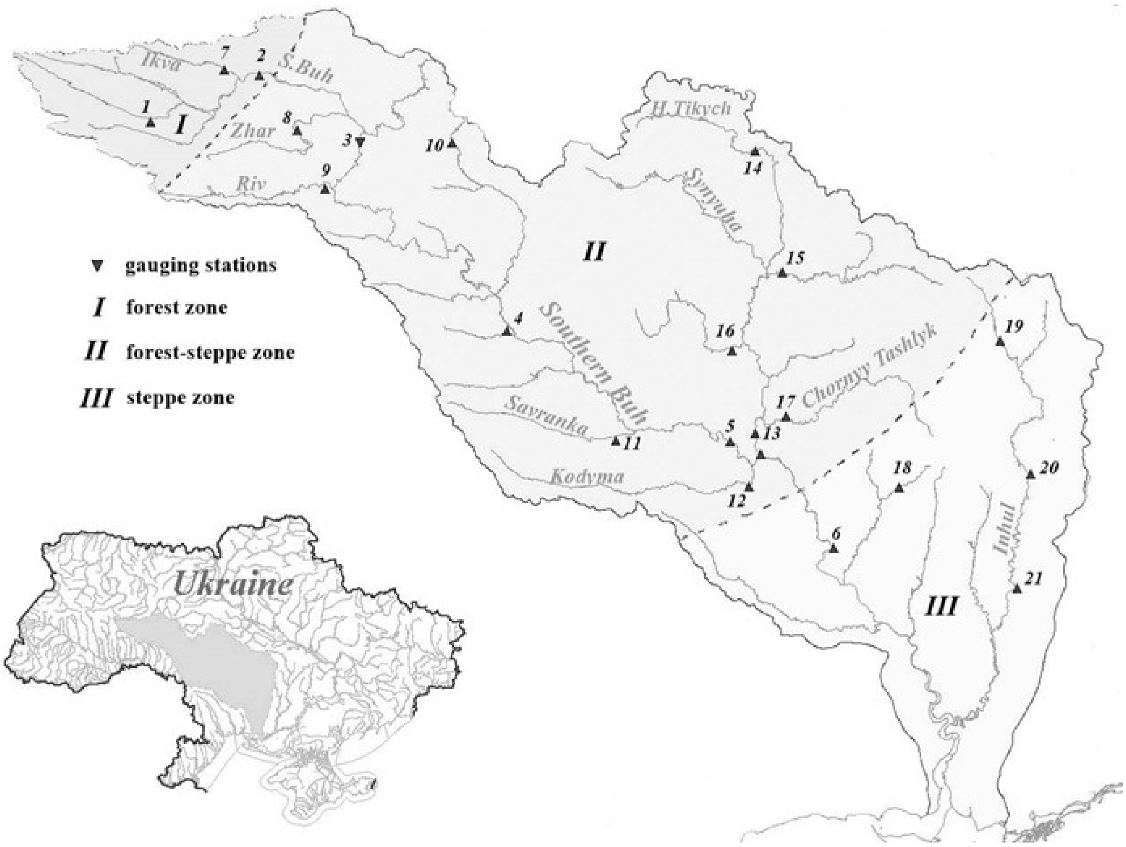

Fig. 1. Scheme of the Southern Buh River Basin and location of the 21 water gauging stations (numbering of stations is based on Table 1)

Table 1. Basin characteristics of gauging stations of the Southern Buh River

No	River	Location of the gauging station	Catchment area (km^2)	Study period and its duration, years
1	Southern Buh	Pyrohivtsi village	827	1964-2015 / 52
2	Southern Buh	Lelitka village	4000	1926-43, 1945-46, 1964-2015 / 72
3	Southern Buh	Selyshche village	9100	2002-2015 / 14
4	Southern Buh	Trostyanchyk village	17400	1930-41, 1946-94, 1996-2015 / 81
5	Southern Buh	Pidhir'ya village	24600	1926-43, 1958-2015 / 76
6	Southern Buh	Oleksandrivka village	46200	1914-2015 / 102
7	Ikva	Stara Synyava village	439	1946-93, 1996-2015 / 68
8	Zhar	Lityn village	692	1931-88, 1990-94, 1996-2015 / 82
9	Riv	Demydivka village	1130	1916-18, 1922-41,1945-88, 1990-94, 1996-2015 / 91
10	Sob	Zoziv village	92.5	1945-88, 1990-94, 1996-2006, 2008, 2010-13, 2015 / 66
11	Savranka	Osychky village	1740	1936-39, 1945-2015 / 75
12	Kodyma	Katerynka village	2390	1931, 1933-41, 1945-88, 1990-2015 / 80
13	Synyuha	Synyuhyn Brid village	16700	1925-31, 1933-89, 1991-2015 / 89
14	Hnylyy Tikych	Lysyanka village	1450	1945-2015 / 71
15	Velyka Vys	Yampil village	2820	1925-1941, 1943, 1945-91, 1993-2015 / 87
16	Yatran'	Pokotylove village	2140	1955-2010 / 61
17	Chornyy Tashlyk	Tarasivka village	2230	1933-43, 1945-88, 1990-2015 / 81
18	Mertvovid	Kryva Pustosh village	252	1949-88, 1991-94, 1996-2015 / 64
19	Inhul	Kropyvnytskyi city	840	1945-81, 1983-88, 1992-2006, 2008-12, 2014-15 / 65
20	Inhul	Sednivka village	4770	1954-2015 / 62
21	Inhul	Novogorozhene village	6670	1931-1941, 1945-2015 / 82

cal approaches detecting changes in the hydrological series of observations that are widely used worldwide: deterministic and statistical (Kundzewicz and Robson, 2004; WMO-No. 168, 2009; Gorbachova, 2014). In the paper, Kundzewicz and Robson (2004) it is showed that the hydrological series are characterized by some features (they are non-normal, seasonal, and serially correlated). Therefore, the statistical criteria to analyze changes of hydrological series of observations should be used only after their transformation, particularly resampling methods should be made. The graphical method and historical data are used to confirm the results of the statistical criteria.

In this paper, the deterministic approach based on graphical methods for estimation of the homogeneity and stationarity of hydrological series are used. These methods include correlation graphs, frequency of values, histograms, mass curves, double mass curves, residual mass curves, chronological charts, and etc. (Chow et al., 1988). During the 20th century the methodical approaches of using graphical methods were developed. Thus, Rippl (1883) invented and proposed to use the mass curve and residual mass curve for the design of the reservoirs and Merriam (1937) is the author of the double mass curve that he used for a research of hydrometeorological series change. In the papers, Gorbachova (2014, 2016) showed that with the complex use of certain graphical (hydro-genetic) methods can successfully carry out the assessment of homogeneity and stationarity of hydrological series. The mass and residual mass curves, and combined graphs of hydrological characteristics were proposed for the complex analysis of observation data. This methodological approach has already been used to investigation the homogeneity and stationarity of streamflow of Ukrainian rivers (Gorbachova et al., 2013; Gorbachova, 2015; Zabolotnia et al., 2019).

The mass curve is used to detect the influence of anthropogenic factors (hydraulic structures, canals) and of climate change (the presence of trends in the data series). The generation of runoff in the study area is homogeneous, and vice versa when the mass curve is not detected "hopping", "outliers" or unidirectional deviation. The mass curve is defined with the following formula:

$$Q = \sum_{t=1}^{T} Q(t) \tag{2}$$

where Q is the total discharge of river for time period T; $Q(t)$ is the discharge of t^{th} year.

The residual mass curve was used for the assessment of the observation series stationarity. The analysis allows the definition of the stationarity of data series, the sustainability of the mean value of the hydrological characteristic over a long period of time. The mean value of the time series is stable in the presence of at least one dry and wet phase of a long-term cyclical fluctuations of time series. The residual mass curve is defined by Andreyanov's formula (1959):

$$f(t) = \frac{\sum_{t=1}^{T}(k(t)-1)}{C_v} \quad (3)$$

where C_v is the variation coefficient of time series; $k(t) = Q(t)/Q_0$ is the modular coefficient; $Q(t)$ and Q_0 is the discharge of t^{th} year and mean discharge for the period T.

Combined graphs of hydrological characteristics allow the definition of the synchrony/asynchrony of long-term fluctuations in different rivers within the one hydrological homogeneous area. In turn, the synchronous fluctuations are indicated on the homogeneous climatic conditions of runoff formation.

The Kritskyi & Menkel, Pearson type III and Gumbel distributions for the frequency analysis were used (Kritskyi & Menkel, 1940; WMO, 2009; BNR, 1983; Chow et al., 1988). The empirical probability distribution is defined by the formula (BNR, 1983):

$$P_m = (m|n+1)100\ \%, \quad (4)$$

where $\boldsymbol{m}$ is ordinal number of hydrological series members that arranged in the decreasing order; $\boldsymbol{n}$ is the total number of hydrological series members.

Statistical parameters of the analytical probability distribution, namely the mean discharge of the data series, the variation, and skewness coefficients are defined by the method of moment and method of maximal likelihood according to methodical approaches that were showed in the WMO (2009).

The fitting criterion χ^2 to check the results of analytical curve approximation of empirical points was used (Chow et al., 1988).

Results and their analysis

In accordance with formula (2), in the Southern Bug River basin for the 21 gauging stations the graphs of the mass curve of maximal discharges of spring floods were created. Examples of such curves for some rivers are shown in the Fig. 2.

The analysis of these graphs shows that the observations series are inhomogeneous, because a point of inflection is on them, after which the tendency of maximal discharges changes. At the same time, this type curves indicates the absence of unidirectional stable trends of maximal discharges of spring floods of the Southern Bug River basin. Such tendencies are typical also for other plain rivers of Ukraine (Shakirzanova, 2015; Gorbachova et al., 2016; Zabolotnia et al., 2019). Such observations series have the mass curve of convex type. The residual mass curves were created to identify the reasons for such a tendency of maximal discharges of spring flood of the rivers (Fig. 3). Their analysis showed that for the period 1970-1980 for all rivers was the transition from the increasing to decreasing phases of the long-term cyclical fluctuation. The decreasing phase continues to this day and its completion cannot be predicted. The different phases of cyclic fluctuations are observed in the

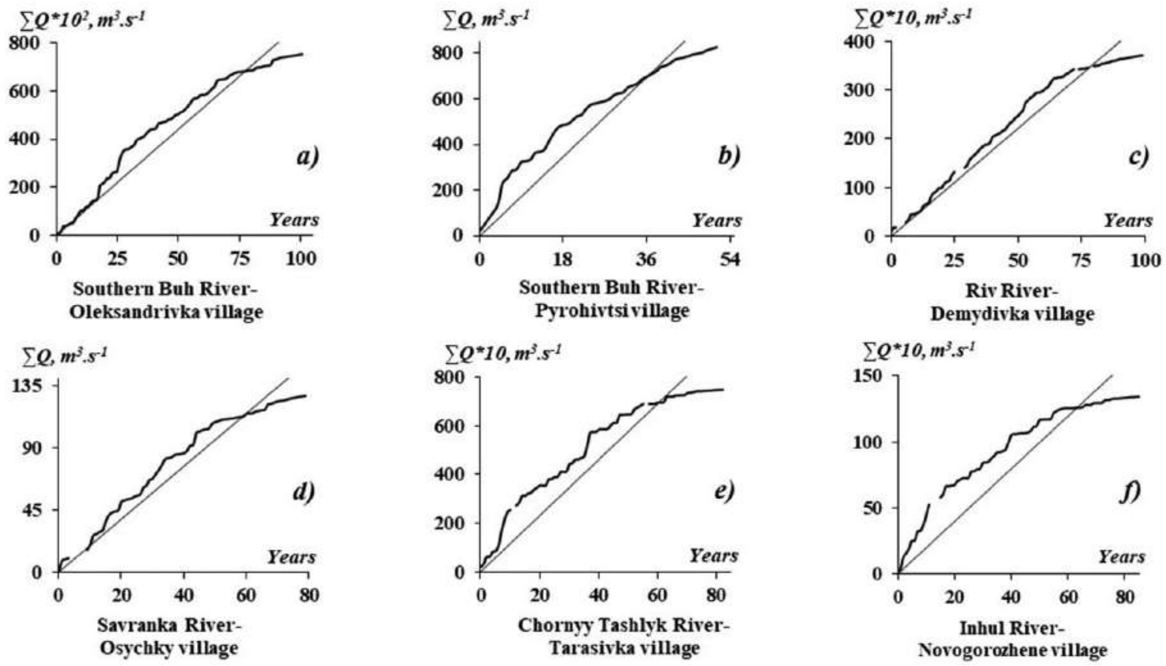

Fig. 2. Some mass curves of the maximal discharges of spring floods of the Southern Buh River Basin

various directional changes of streamflow (Pekarova et al., 2003; Gorbachova, 2015). Also, these phases have a significant difference in the mean values (Gorbachova, 2015). Furthermore, the maximum flow of rivers has considerable variability (its values are several times higher than the values of average annual and minimum flow). The feature of the maximum flow of spring flood of plain rivers is the long duration of cyclical fluctuations phases. For example, at the Southern Buh River hydrological station on Oleksandrivka village the data series of maximal spring flood (the observations have been carried out since 1914), have not yet completed a decreasing phase that began in 1970 (Fig. 3). This series of observations also do not have the complete increasing phase of fluctuations since observations began at a time when the increasing phase was already in progress. Consequently, at the Southern Buh River hydrological station on Oleksandrivka village the maximal flow of spring floods with the duration of observation at 102 years (1914-2015), does not have a full cycle of long-term fluctuations.

plain rivers. For mountain rivers, the mass curves have the sinuous type. In the study (Shakirzanova, 2015) it is shown that in the Southern Buh River Basin the climatic factors of spring floods have long-term cyclical fluctuations. The cyclical fluctuations of climatic factors of the formation of spring floods of rivers are also shown in the papers (Khrystyuk, 2013; Khrystyuk et al., 2017). The classification of hydrographs by similar shapes in them was carried out and it was shown that the presence of similar in shape hydrographs in the time series of classes indicates that from time to time the similar formation conditions of water flow at the catchment area repeats due to cyclicity of climatic and, as a consequence, of hydrological processes. In the study (Khrystiuk et al., 2020) the cyclicity of spring floods based on the classification of hydrographs by the facet method in the Southern Buh River Basin is showed.

The absence of a full cycle of long-term fluctuations in the observation series of the maximal flow of spring floods of rivers makes such data an unrep-

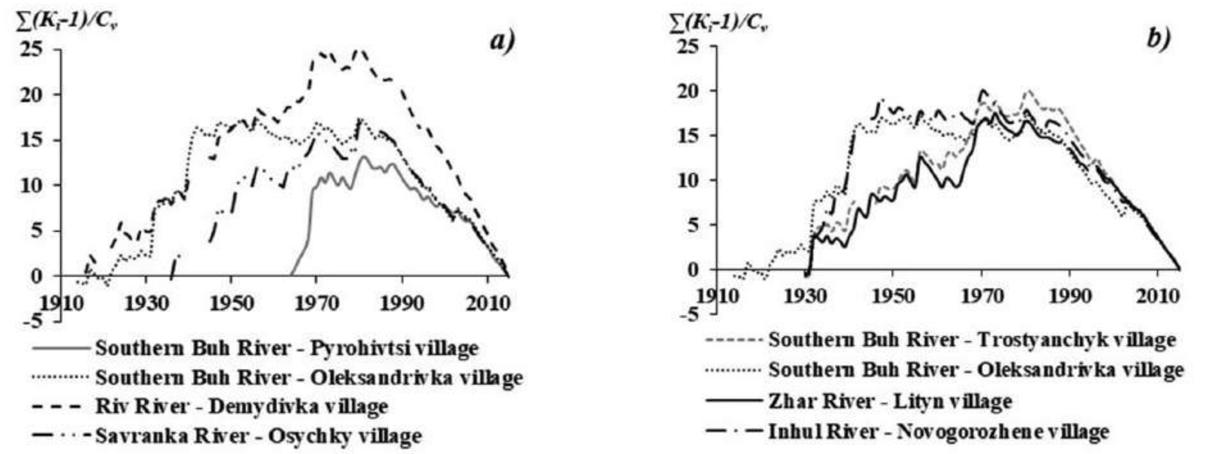

Fig. 3. Some the residual mass curves of the maximum flow of spring floods in the Southern Buh River Basin

Therefore, the presence in the observation series of maximal flow of spring floods of plain rivers in only increasing and decreasing phases of cyclical fluctuations, their considerable duration, as well as the significant variability of maximal flow are forming the convex type of mass curves. Also, a mass curve type has a temporary character and occurs when a combined analysis of different phases of long-term cyclical fluctuations, namely only increasing and decreasing phases. The observation series can be classified as quasi-homogeneous. The conclusions are indirectly confirmed by the analysis of the maximal flow of spring floods of mountain rivers. Such studies (Gorbachova and Barandich, 2016; Zabolotnia et al., 2019) is shown that the phases of cyclic fluctuations of mountain rivers have a much shorter duration than

resentative for the correct determination of stable mean value (Andreyanov, 1959). The many scientists identify such series as non-stationary. Especially when only statistical criteria are used to analyze the homogeneity and stationarity of the data series (Kundzewicz and Robson, 2004; Gorbachova and Bauzha, 2013). An example of the mean value change of observation series depending on the presence or absence of a representative period was shown in paper (Gorbachova, 2015). At the present, in the Southern Buh River Basin the observation series of maximum flow of spring floods can be attributed to temporarily quasi-stationary. Therefore, it is essential to update the statistical characteristics every 5 years.

The basin of the Southern Buh River, the conditions for the formation of the maximal flow of spring floods are homogeneous, because at all hydrological stations the fluctuations of the maximal flow of spring floods are synchronous and syn-phase (Fig. 3). It also shows that the anthropogenic impact does not have a significant effect on the maximal flow of spring floods because rivers with natural flow have the same tendency as the rivers with the hydraulic structures. It also facilitates the selection of rivers of analogues. For short series of observations, it is necessary (if possible) to carry out them the increase duration. This will allow such series to have the information about extreme floods that were observed in the increasing phase of long-term cyclical fluctuations in the Southern Buh River Basin. For example, these are the same data series as for Southern Buh River – Pyrohivtsi village (Fig. 3a) and for Southern Buh River – Selyshche village (Table 1).

In accordance with the requirements to calculations (1), the increased duration and restoration of the gaps in the time series by the method of regression on the variable based on the data of analogue rivers were carried out. An analysis of the results shown that in the time series remained some gaps, but their percentage was significantly decreased (Table 2). In the Southern Buh River Basin there are difficulties with the choice of analogue rivers because observations do not cover small rivers and some tributaries (Gorbachova and Khrystyuk, 2018).

Hence, at the Southern Buh River water gauging station on the Oleksandrivka village, the time series has the longest duration without gaps (102 years). This station is the closing water gauging station on the Southern Buh River, consequently, its catchment area is the largest in basin (Fig. 1, Table 1). However, it cannot be an analogue for the time series that were obtained from catchments with small areas. All other time series have gaps in observations due to military actions, reconstruction, etc. The restored time series allows obtaining the more reliable calculated statistical characteristics of the maximal discharges of spring floods in the Southern Buh river basin, which are shown in the Table 2. However, we have some difficulties with the selection of the analytical curves when approximating the empirical points of spring floods in the Southern Buh river basin. We found that the distributions Kritskyi & Menkel and Pearson type III can be used for plotting analytical curves (Fig. 4 and Table 3).

The Gumbel distribution is generalized extreme value distribution. However, in the Southern Buh River Basin the Gumbel distribution cannot be used to generate analytical curves, because the lower part of such curves is in the range of negative values. The Pearson type III distribution also could not be used for some series of observations for a similar reason. Therefore, basically the analytical curves of Kritskyi & Menkel distribution to determine the values of maximal discharges of spring floods with 1% probability were used. Although, these curves also do not correspond very well the empirical points according to the analysis by fitting criterion χ^2 (Table 3). This situation can be explained by the fact that the observation series of spring floods are very asymmetric, because it has only a few extreme discharges. For short series (for example, it has only one extreme discharge), it is generally impossible to select the analytical curve without restoring the historical discharges. These are such series of observations as for water gauging stations of the Southern Buh – Pyrohivtsi village and the Sob – Zoziv village.

Discussion

The last frequency analysis of observation data for the maximal discharges of spring floods of the Southern Buh River Basin was carried out in the paper of Gorbachova and Khrystyuk, 2018. In this paper, the calculation was carried out for the data to 2010 and were shown that values of maximal discharges of spring floods with 1% probability have the tendency to decrease in relation to the calculations which was completed according to the data to 1980. A comparative analysis of the results of this study with the results introduced in the paper of Gorbachova et al. (2018) showed that the values of maximal discharges of spring floods with 1% probability as well as its statistical characteristics not significantly changed (Table 3, columns 6, 7, 8, and 10). Consequently, such a parameter as the mean values of maximal discharges of spring floods already became stable over time. It is ensured by the presence in the time series of the increase and decrease phases of long-term cyclical fluctuations (Fig. 3). Thus, the analysis of cyclic fluctuations of the maximal flow is especially important when the frequency analyses are carried out.

Conclusions

The research presents the results of the spring floods estimates of the Southern Buh River Basin. The analysis of the homogeneity and stationarity of the maximal discharges of spring floods showed that time series are quasi-homogeneous and quasi-stationary. It is explained by the features of the maximal flow of spring floods of plain rivers, namely presence in the observation series only increasing and decreasing phases of cyclical fluctuations, their considerable duration, as well as the significant variability of maximal flow.

Table 2. The maximal discharges of spring floods of 1% probability in the Southern Buh River Basin

№	River	Location of the gauging station	Calculated period, years	Percentage of restored/missed data	Statistical parameters			Parameter definition method	$Q_{1\%}$, m^3 s^{-1}
					Q_{mean}, m^3 s^{-1}	C_v	C_s/C_v		
1	Southern Buh	Pyrohivtsi village	(1916-2015)	36/12	24.3/25.5	0.80/0.76	2.31/2.30	MLE	93.4/92.7
2	Southern Buh	Lelitka village	(1917-2015)	14/13	140/122	1.15/0.85	3.11/2.37	MLE	783/687
3	Southern Buh	Selyshche village	(1914-2015)	85/1	272	1.12	2.51	MOM	1479
4	Southern Buh	Trostyanchyk village	(1916-2015)	11/8	418/422	1.02/0.94	2.49/2.25	MLE	2036/1877
5	Southern Buh	Pidhir’ya village	(1915-2015)	17/8	470/442	0.97/0.81	2.42/2.42	MOM	2265/2266
6	Southern Buh	Oleksandrivka village	(1914-2015)	0/0	737/767	1.18/1,17	2.92/3.33	MOM	4400/4340
7	Ikva	Stara Synyava village	(1916-2015)	18/14	21.6/22.1	1.12/1.00	2.31/2.29	MOM	115/105
8	Zhar	Lityn village	(1916-2015)	6/11	23.8/24.5	1.05/1.02	2.64/2.63	MLE	120/121
9	Riv	Demydivka village	(1916-2015)	1/7	40.9/42.0	0.88/0.85	2.05/1.98	MLE	167/165
10	Sob	Zoziv village	(1928-2015)	8/17	6.97/6.18	1.39/1.50	2.50/3.00	MLE	46.4/44.7
11	Savranka	Osychky village	(1915-2015)	17/9	29.3/29.0	1.76/1.50	2.83/3.20	MOM	248/246
12	Kodyma	Katerynka village	(1917-2015)	8/11	34.0/29.1	1.74/1.50	2.50/3.68	MLE	285/290
13	Synyuha	Synyuhyn Brid village	(1915-2015)	7/5	413/420	1.35/1.37	2.22/2.82	MOM	2678/2768
14	Hnylyy Tikych	Lysyanka village	(1917-2015)	17/11	83.8/85.6	1,52/1.37	2.18/2.17	MLE	610/559
15	Velyka Vys	Yampil village	(1917-2015)	5/7	75.4/68.0	1.60/1.58	2.36/2.40	MLE	577/522
16	Yatran’	Pokotylove village	(1917-2015)	25/13	124/129	1.53/1.46	2.19/2.32	MLE	913/906
17	Chornyy Tashlyk	Tarasivka village	(1917-2015)	9/9	105/110	1.39/1.32	2.16/2.07	MLE	696/687
18	Mertvovid	Kryva Pustosh village	(1917-2015)	20/15	21.6/22.1	1.51/1.50	2.10/2.08	MLE	156/158
19	Inhul	Kropyvnytskyi city	(1917-2015)	17/17	52.3/51.5	1.37/1.39	2.15/2.12	MLE	341/341
20	Inhul	Sednivka village	(1917-2015)	24/13	208/220	1.36/1.28	2.20/2.08	MLE	1342/1327
21	Inhul	Novogorozhene village	(1917-2015)	8/9	188/195	1.37/1.31	2.18/2.08	MLE	1228/1214

Note: MLE – Maximum likelihood estimation method, MOM – Method of moments; in columns 6, 7, 8, and 10, the numerator shows the values that were calculated for the data to 2015, the denominator shows the values that were calculated for the data to 2010 (Gorbachova et al., 2018)

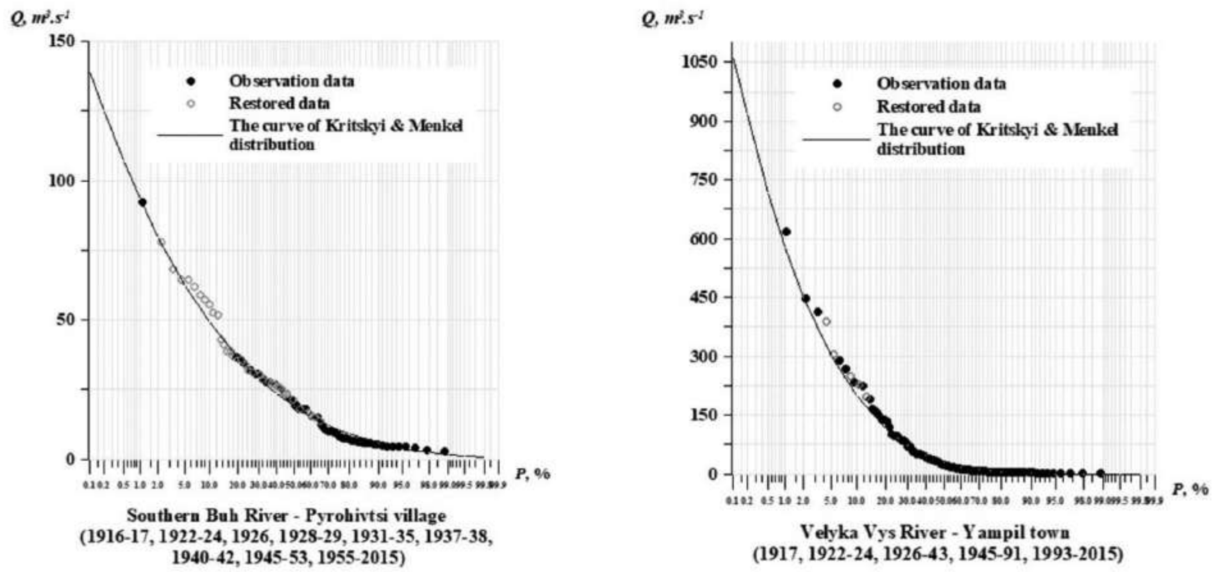

Fig. 4. Probability curves of the maximal discharges of spring floods in the Southern Buh River Basin

The restoring of the gaps in the time series is especially important step in the investigation because it allowed obtaining information about extreme floods that were observed in the increasing phase of long-term cyclical fluctuations of the Southern Buh River Basin. It contributes to obtaining more reliable and stable over time of the statistical characteristics of time series.

In the Southern Buh river basin, we have some difficulties with the selection of the analytical curves when approximating the empirical points of spring floods. Such empirical distributions are very asymmetric due to the presence of only a few extreme discharges. The calculation characteristics of the

Table 3. Check of spring flood series for compliance distribution laws in the Southern Buh River Basin

№	River - gauging station	$\chi^2(\alpha, \nu)$	χ^2	Compliance	Distribution low
1	Southern Buh – Pyrohivtsi village	12.6	7.91	compliant	Krytsky & Menkel
2	Southern Buh – Lelitka village	12.6	18.9	not compliant	Krytsky & Menkel
3	Southern Buh – Selyshche village	12.6	11.2	compliant	Pearson type III
4	Southern Buh – Trostyanchyk village	12.6	21.0	not compliant	Krytsky & Menkel
5	Southern Buh – Pidhir’ya village	12.6	9,04	compliant	Pearson type III
6	Southern Buh – Oleksandrivka village	12.6	48.5	not compliant	Krytsky & Menkel
7	Ikva – Stara Synyava village	12.6	6.56	compliant	Pearson type III
8	Zhar – Lityn village	12.6	9.31	compliant	Krytsky & Menkel
9	Riv – Demydivka village	12.6	11.2	compliant	Krytsky & Menkel
10	Sob – Zoziv village	12.6	29.6	not compliant	Krytsky & Menkel
11	Savranka – Osychky village	12.6	37.1	not compliant	Krytsky & Menkel
12	Kodyma – Katerynka village	12.6	40.4	not compliant	Krytsky & Menkel
13	Synyuha – Synyuhyn Brid village	12.6	10.5	compliant	Pearson type III
14	Hnylyy Tikych – Lysyanka village	12.6	44.7	not compliant	Krytsky & Menkel
15	Velyka Vys – Yampil village	12.6	24.5	not compliant	Krytsky & Menkel
16	Yatran – Pokotylove village	12.6	47.5	not compliant	Krytsky & Menkel
17	Chornyy Tashlyk – Tarasivka village	12.6	27.8	not compliant	Krytsky & Menkel
18	Mertvovid – Kryva Pustosh village	12.6	37.2	not compliant	Krytsky & Menkel
19	Inhul – Kropyvnytskyi city	12.6	12.1	compliant	Krytsky & Menkel
20	Inhul – Sednivka village	12.6	30.3	not compliant	Krytsky & Menkel
21	Inhul – Novogorozhene village	12.6	34.6	not compliant	Krytsky & Menkel

maximal discharges of spring floods already became stable over time. It is ensured by the presence in the time series of the increase and decrease phases of long-term cyclical fluctuations.

The research results can be used by scientific and project organizations for getting more reliable estimations of time series and to plan and design of different hydraulic structures, as well as for regional planning and management of water resources of the Southern Buh River Basin.

References

Apel, H., Thieken, A.H., Merz, B. and Blöschl, G., 2004. Flood risk assessment and associated uncertainty. Natural Hazards and Earth System Science, 4(2), 295-308. https://SRef-ID: 1684-9981/nhess/2004-4-295

Andreyanov, V.G., 1959. Ciklicheskie kolebanija godovogo stoka i ih uchet pri gidrologicheskih raschetah [Cyclical fluctuations of annual runoff and their account at hydrological calculations]. Proceedings of Russian State Hydrological Institute, 68, 3-49. (in Russian).

Bauzha, T. and Gorbachova, L., 2017. The features of the cyclical fluctuations, homogeneity, and stationarity of the average annual flow of the Southern Buh river basin. Annals of Valahia University of Targoviste. Geographical Series, 17(1), 5-17. https://doi.org/10.1515/avutgs-2017-0001

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P, Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, Sh., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K. and Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature, 573(7772), 1-4. https://doi.org/10.1038/s41586-019-1495-6

Blöschl, G., Sivapalan, M., Savenije, H., Wagener, T. and Viglione, A. (Eds.), 2013. Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales. Cambridge University Press, Cambridge, UK.

BNR, 1985. Stroitel'nye normy i pravila. Opredelenie raschetnyh gidrologicheskih harakteristik SniP 2.01.14-83. [The building norm and rules. The determination of the calculation hydrologic characteristics 2.01.14-83]. State committee USSR on the construction. Moscow, Stroyizdat. (in Russian).

Chow, V.T., Maidment, D.R. and Mays, L.M., 1988. Applied hydrology. McGraw-Hill International Editions.

Doe, R., 2006. Extreme Floods: A History in a Changing Climate. Sutton Publishing, Phoenix Mill, Thrupp, Stroud, Gloucestershire, UK.

Gorbachova, L., 2014. Metodychni pidhody ocinky odnoridnosti i stacionarnosti gidrologichnyh rjadiv cpocterezhen'. [Methodical approaches the assessment of the homogeneity and stationarity of hydrological observation series]. Hydrology, Hydrochemistry and Hydroecology, 5(32), 22-31. (In Ukrainian).

Gorbachova, L., 2015. The intra-annual streamflow distribution of Ukrainian rivers in different phases of long-term cyclical fluctuations. Energetika, 61(2), 71-80. https://doi.org/10.6001/energetika.v61i2.3134

Gorbachova, L., 2016. Misce ta rol' gidrologo-genetichnogo analizu sered suchasnyh metodiv doslidzhenja vodnogo stoku richok [Place and role of hydrogenetic analysis among modern research methods runoff]. Proceedings of Ukrainian Hydrometeorological Institute, 268, 73-81. (In Ukrainian).

Gorbachova, L. and Bauzha, T., 2013. Complex analysis of stationarity and homogeneity of flash flood maximum discharges in the Rika River basin. Energetika, 59(3), 167-174. https://doi.org/10.6001/energetika.v59i3.2708

Gorbachova, L.O. and Barandich, S.L., 2016. Prostorovo-chasova minlyvist' maksymal'nogo stoku vody vesnjanogo vodopol'ja i pavodkiv zmishanogo prohodzhdennja richok Ukrainy. [Spatio-temporal fluctuations of maximum flow of spring floods and snow-rain floods of Ukrainian rivers]. Proceedings of Ukrainian Hydrometeorological Institute, 269, 107-114. (In Ukrainian).

Gorbachova, L. and Khrystyuk, B., 2018. Calculation approaches of the probable maximum discharge of spring flood at ungauged sites in the Southern Buh River Basin, Ukraine. Annals of Valahia University of Targoviste. Geographical Series, 18(2), 107-120. https://doi.org/10.2478/avutgs-2018-0012

Grebin, V.V., 2010. Suchasnyj vodnyj rezhym richok Ukrainy (landshaftno-gidrologichnyj analiz). [The Modern Water Regime of Rivers in Ukraine (Landscape-Hydrologic Analysis)]. Kyiv, Nika-Centr. (In Ukrainian).

Kaganer, M.S. (Eds.), 1969. Resursy poverhnostnyh vod SSSR. Ukraina i Moldavija. Srednee i nizhnee podneprov'e. [The surface water resources of USSR. Ukraine and Moldova. The Middle and Lower Dnieper]. Leningrad: Gidrometeoizdat, 6(1), 884. (in Russian).

Khrystyuk, B.F., 2013. Metodyka klassyfikacii gidrografiv richok za kriterijamy analogichnosti. [The technique of the classification of river hydrographs by criteria of analogy]. Hydrology, Hydrochemistry and Hydroecology, 3(30), 15-20. (In Ukrainian).

Khrystyuk, B., Gorbachova, L. and Koshkina, O., 2017. The impact of climatic conditions of the spring flood formation on hydrograph shape of the Desna River. Meteorology Hydrology and Water Management. Research and Operational Applications, 5(1), 63-70. https://doi.org/10.26491/mhwm/67914

Khrystiuk, B., Gorbachova, L., Prykhodkina, V., 2020. Faceted classification of the hydrograph shapes of the spring floods of the Southern Buh river. Geografický Časopis, 72(1), 71-80. https://doi.org/10.31577/geogrcas.2020.72.1.04

Kritskiy, S.N. and Menkel, M.F., 1940. Obobshhennyj podhod k raschetam upravlenija stoka na osnove matematicheskoj statistikiю [A generalized approach to streamflow control computations on the basis of mathematical statistics]. Gidrotekhn. Stroit., 2, 19-24. (In Russian).

Kjeldsen, T. R., 2015. How reliable are design flood estimates in the UK? Journal of Flood Risk Management, 8(3), 237-246. https://doi.org/10.1111/jfr3.12090

Kundzewicz, Z.W. and Robson, A.J., 2004. Change detection in hydrological records – a review of the methodology. Hydrological Sciences Journal, 49(1), 7-19. https://doi.org/10.1623/hysj.49.1.7.53993

McKerchar, A.I. and Macky, G.H., 2001. Comparison of a regional method for estimating design floods with two rainfall-based methods. Journal of Hydrology (New Zealand), 40(2), 129-138. https://www.jstor.org/stable/43922046

Odry, J. & Arnaud, P., 2017. Comparison of Flood Frequency Analysis Methods for Ungauged Catchments in France. Geosciences, 7(88). https://doi.org/10.3390/geosciences7030088

Okoli, K., Breinl, K., Mazzoleni, M. and Di Baldassarre G., 2019. Design Flood Estimation: Exploring the Potentials and Limitations of Two Alternative Approaches. Water, 11(4), 729. https://doi.org/10.3390/w11040729

Palamarchuk, M.M. & Zakorchevna, N.B. (Edit.), 2006. Vodnyj fond Ukrainy: dovidkovyj posibnyk. [Water Fund of Ukraine. Reference guide]. Kyiv, Nika-Center. (In Ukrainian).

Pekarova, P., Miklánek, P. and Pekár, J., 2003. Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th-20th centuries. Journal of Hydrology, 274, 62-79. https://doi.org/10.1016/S0022-1694(02)00397-9

Razmi, A., Golian, S. and Zahmatkesh, Z., 2017. Non-Stationary Frequency Analysis of Extreme Water Level: Application of Annual Maximum Series and Peak-over Threshold Approaches. Water Resour. Manag, 31, 2065-2083. https://doi.org/10.1007/s11269-017-1619-4

Saghafian, B., Golian, S. and Ghasemi, A., 2014. Flood frequency analysis based on simulated peak discharges. Nature Hazards, 71, 403-417. https://doi.org/10.1007/s11069-013-0925-2

Shakirzanova, Zh. R., 2015. Dovgostrokove prognozuvannja harakteristik maksimal'nogo stoku vesnjanogo vodopillja rivninnih richok ta estuariïv teritoriï Ukraïny: monografija. [Long-term forecasting of characteristics maximum runoff spring flood plain rivers and estuaries in Ukraine: monograph]. Odesa, FOP Bondarenko M.O. (In Ukrainian).

Vyshnevskyi, V., 2000. Richky i vodoimy Ukrainy. Stan i vykorystannia: monografija. [Rivers and reservoirs of Ukraine. Condition and use: monograph]. Kyiv, Vipol. (In Ukrainian).

WMO (World Meteorological Organization), 2009. Guide to Hydrological Practices, Vol. II, Management of Water Resources and Application of Hydrological Practices, sixth edition, WMO-No. 168, World Meteorological Organization, Geneva, Switzerland.

Zabolotnia, T., Gorbachova, L. and Khrystyuk, B., 2019. Estimation of the long-term cyclical fluctuations of snow-rain floods in the Danube basin within Ukraine. Meteorology Hydrology and Water Management. Research and Operational Applications, 7(2), 3-11. https://doi.org/10.26491/mhwm/99752