EREM 73/1

Journal of Environmental Research, Engineering and Management
Vol. 73 / No. 1 / 2017
pp. 33-47
DOI 10.5755/j01.erem.73.1.15799

Patterns and Forecast of Long-term Cyclical Fluctuations of the Water Runoff of Ukrainian Carpathians Rivers

Received 2017/06 | Accepted after revision 2017/07

http://dx.doi.org/10.5755/j01.erem.73.1.15799

Patterns and Forecast of Long-term Cyclical Fluctuations of the Water Runoff of Ukrainian Carpathians Rivers

Oleksandr Obodovskyi, Olga Lukianets
Taras Shevchenko National University of Kyiv
Glushkov prospekt, 2A, Kyiv, SMP680 Ukraine

Corresponding author: obodjvsksy58@qmail.com
Oleksandr Obodovskyi , Taras Shevchenko National University of Kyiv
Glushkov prospekt, 2A, Kyiv, SMP680 Ukraine

Knowledge of the cyclicity features in the fluctuations of river runoff, duration and nature of the low-water and high-water period interchange in one or other river basins, and especially their prediction, provides invaluable assistance in the planning and sound management of water resources, improving the operational efficiency of hydropower, reclamation and other water facilities. Currently, the interest in the study of long-term cyclical fluctuations in river runoff, as well as patterns of fluctuations of its underlying factor, has highly increased due to their use in long-term forecasts.

Time series of annual water runoff for basins of Tisza, Dniester and Prut rivers were estimated with the use of mathematical tools, methodological framework of which is based on a statistical means of summarizing, systemisation of the input data, evaluation methods of time random sets of runoff characteristics, methods of analysis of the time-series variability and manifestation of their structure.

Keywords: river, water runoff, random function, cyclicity, spatial synchrony, water content phase, correlogram, water content cycle, predictive estimation.

Physical and geographical features of the Ukrainian Carpathians river basins

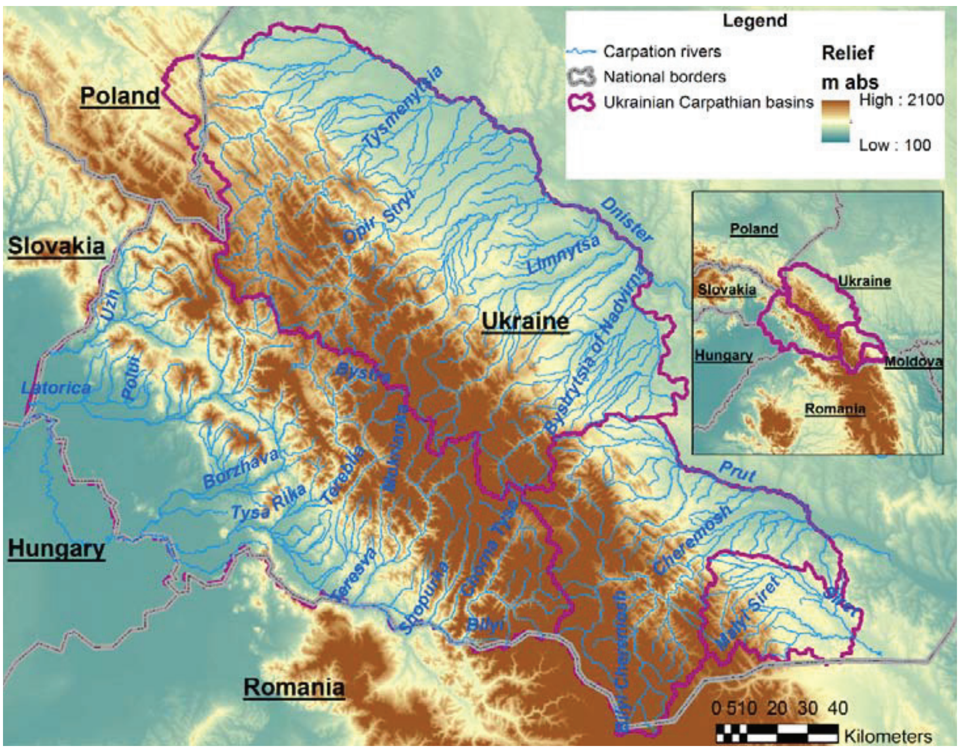
Ukrainian Carpathians are the territory of Ukraine (6% of the total area) located in the west and south-west and are the part of the great Carpathian mountain system (Carpathian arc) in Central Europe. In addition to Ukraine, they cover Poland, Slovakia, Czech Republic, Hungary and Romania. In Ukraine, the mountains spread from the southeast to the northwest at nearly 300 km in length and the width of 100–150 km (Sosyedko et al., 2010, Romaschenko et al., 2002).

The mountain relief makes a significant impact on the climate of the Ukrainian Carpathians – moderately continental with excessive and sufficient moisture, mild winters with thaws, unstable long spring, cool summer and warm autumn. There is a vertical climatic zoning that affects the interaction between the radiation and circulation processes. Here, the Atlantic and transformed continental air masses dominate. Anticyclonic circulation prevails over the cyclonic one. Cyclones, which come from the Mediterranean, are accompanied by significant rainfall and strong winds. In mountain areas of the Ukrainian Carpathians, the annual average precipitations are 1,100–1,800 mm, in the foothills – 800–1100 mm, and in the lowlands – 650–800 mm (Hrebin', 2010, Balabukh et al., 2015, Lukianets et al., 2015).

The river runoff distribution in the Ukrainian Carpathians in general repeats the distribution of precipitation. The average annual river runoff increases from 150 mm in the lower areas up to 350–600 mm in the foothills and reaches 800–950 mm in the mountains. Here, the most dense river network in Ukraine is formed – 1–1.2 km / km^2 (Romaschenko et al., 2002; Sosyedko et al., 2010). The main Carpathian watershed separates the basins of the rivers of different directions: the River Dniester and its main tributaries Stryy, Svicha, Tysmenytsya, Bystrytsya, Limnytsya as well as Danube tributaries Siret and Prut with Cheremosh to the north and north-east; and a tributary of the Danube, the River Tisza, with its main tributaries Teresva, Tereblia, Rika, Borzhava and Latoritsa falling from the mountain area to the south and south-west (Fig. 1).

Fig. 1

River basins of the Ukrainian Carpathians



It is necessary to stress the particular importance of analysing the temporal variability of Ukrainian Carpathians river runoff (Tisza, Dniester, Prut and Siret). First, they are the most abundant rivers of Ukraine, and second, the frequent floods, both in warm and cold periods of the year, qualify this territory as one of the most flood hazard regions of Europe by the intensity of their development and the simultaneous spread over the wide territory.

Background study temporal fluctuations of river runoff

The main features of the long-term fluctuations in the most of hydrological characteristics to a great extent (and sometimes crucially) are caused by the probabilistic nature of changes in the water runoff. Turbulent movement of air in the atmosphere is induced by the unstable meteorological characteristics in time and space. Large-scale atmospheric turbulence generates the probabilistic variability of hydrological characteristics and processes (Drozdov, O., & Grigor'eva, A., 1971). Another reason for the stochastic nature of river runoff fluctuations is that this process depends on many factors, the combination of which is random. An important element of the random nature of river runoff fluctuations is also associated with incomplete ideas of these factors and their impact on changing the river runoff over time. This is what determines the possibility and effectiveness of using the mathematical statistics tools and probability theory in order to describe the fluctuations of water runoff in rivers (Kajsl, 1972, Kartvelishvili, 1975, Vinogradov et al., 2008, Lukianets et al., 2015).

Within the concept of probability, a change in any hydrological characteristics in different cross-sections along the length of the river is a random process that continuously changes over time. Often in hydrology, certain hydrological characteristics are studied over a certain period of time (e.g., average annual, average for the warm and cold seasons, average monthly water discharge, etc.). These characteristics can take only one value per year and processes of their long-term fluctuations are represented just by one implementation for the period of observation. For this reason, there are random processes for which obtaining statistical conclusions for single implementation is not only possible, but can even be realized with satisfactory precision at sufficient length of such implementation. Long-term fluctuations in each of these hydrological characteristics Q are treated as a random process $Q(t)$ with discrete time $t \in T$, which takes integer values (random sequence). In particular, the value $t = 1,2, \ldots, N$ can be attributed to the available number of observations for N years; values $t = N+1, N+2, \ldots$ refer to the following periods of time, and the value $t = 0, -1, -2, \ldots$ refers to the previous periods. In order to describe the process $Q(t)$, it is necessary to know the whole range of functions, the most important of which are: the function of mathematical expectation $m(t)=M\{Q(t)\}$; dispersion function $D(t)=D\{Q(t)\}$ or mean-square deviation $\sigma(t)=\sqrt{D(t)}$; probability distribution function $F(x,t)=P\{Q(t)<x\}$; autocorrelation function $R(t,\tau)=$ corr$\{Q(t), Q(t+\tau)\}$, etc.(Rozhdestvenskij et al., 1974, Khristophorov, 1994; Sikan, 2007).

Many scientists have been involved in the study of long-term runoff fluctuations, mainly its annual values. Much of the research has been devoted to finding the physical nature of river runoff cyclicity, the use of various methods of analysing its variability and mathematical models for describing the structure of time series (Alehin, 1963, Alehin, 1964, Drozdov et al., 1971, Druzhinin et al, 1966, Kalinin et al, 1967, Sosedko, 1974, Luk'yanets, et al., 1999, Luk'yanets et al., 2008, Lukianets et al., 2015). Positive results have been obtained by Yu A. Alehin, who for the first time used the apparatus of the random function theory to develop the extrapolation (dynamical and statistical) method of ultra-long-term forecasts of the average annual runoff of a number of rivers and other natural macro-processes (Alehin, 1963, Alehin, 1964). Availability of the in-series connection in a series of river runoff was firstly noted by P. A. Yukhymovych, who calculated for a series of river cross-sections the autocorrelation coefficients with time shifts τ =1, 2, 3 years. Later, they were represented in more full forms with shift of τ =30, in the form of empirical autocorrelation functions applied by I. P. Druzhynin to identify cyclical fluctuations in river runoff (Druzhinin et al, 1966).

Output data

The greatest success in the study of temporal runoff fluctuations can be achieved if one considers the long-time series of hydrological characteristics in large scale (Alehin, 1963, Alehin, 1964, Druzhinin et al., 1966, Kalinin et al., 1967, Sosedko, 1974, Lukyanets et al., 2015), i.e., the water runoff of large basins which are not significantly affected by random factors and local conditions. River runoff in a closing cross-section is an integral feature of humidifying the basin, which smooths randomness in the mode of precipitation in small areas.

For establishment of the patterns of long-term fluctuations of Ukrainian Carpathians river runoff and given the above circumstances, the average annual runoff values for major rivers were studied:

- *River Tisza* (near the hydrological stations Vylok with basin F = 9140 km^2, for the period of observations 1935–2012 and Vásárosnamény (Hungary) (F = 29057 km^2, 1883–2012));
- *River Prut* near city of Chernivtsy (F = 6890 km^2, 1895–2012);
- *River Dniester* near village of Zalischyky (F = 24600 km^2, 1882–2012).

Two hydrological cross-sections were taken from the River Tisza for restoration of the sequences of average annual water discharges at Vylok station for the period from 1883 to 1934 with water discharges at Vásárosnamény station. For these stations, there is a runoff synchronicity along the length of the river, as evidenced by the relationship between the average annual water discharges of two stations with the correlation ratio r = 0.84.

The studied average water runoff Q is considered as a random process Q *(t),* which is represented by sample $x_1 \ldots x_N$, i.e., set with N of its independent and homogeneous implementations. Independence means that the values $x_1 \ldots x_N$, randomly obtained in N experiments are independent in the aggregate. Uniformity means that all N experiments were conducted in the same conditions and value $x_1 \ldots x_N$ is subject to the same probability distribution function $F(x, t) = P\{Q(t)<x\}$ (condition of homogeneity of the series). The longer the sample, the more reliable estimate of $F(x, t)$ and its partial characteristics, such as the mathematical expectation and variance. The mean square errors of already made estimates tend to 0 at $N \to \infty$, and the estimates tend (in probability) to the actual values of Q characteristics. At the same time, all implementations must be set with continuous time t of implementation $x_i(t)$, for which the process $Q(t)$ is considered (Kajsl, 1972, Khristophorov, 1994, Sikan, 2007).

Estimate statistical homogeneity (stationary state)

Test of the statistical hypotheses of time series homogeneity is the most important issue in practical terms. It should be quite clear about how the accepted theoretical scheme is consistent with empirical data (Rozhdestvenskij et al., 1974, Khristophorov, 1994, Sikan, 2007, Lukianets et al., 2015). Quantitative assessment of intra-series uniformity of the average annual water discharges in the basins of major rivers of the Ukrainian Carpathians is performed by generalised standard parametric criteria: Student to test the significance of the mean values (statistics t) and Fisher to check the relation of variances (statistics F). As given in Table 1, the hypotheses of the parametric Student t and Fisher criteria about homogeneity of the average annual runoff series in the studied basins in terms of the importance of norms and relation of variance at a significance level of $2\alpha = 5\%$ are not rejected. Only for the River Prut by the city of Chernivtsy, the hypothesis of series homogeneity for a relation of variance with F statistics at significance level of $2\alpha = 5\%$ is rejected, i.e., the difference of the empirical data with the null hypothesis is statistically significant. As to the non-parametric criteria, one of the most stringent criteria – Wilcoxon-Mann-Whitney criterion – is used (statistics of the number of inversions U) (Table 2). Hypotheses about the homogeneity of the sequence of average annual water discharges for this criterion in all the studied basins for the Ukrainian Carpathians are not rejected.

To evaluate the homogeneity of the series of observations of the average annual water runoff, the total integral curves for hydrological stations of Tisza-Vylok; Dnister-Zalischyky; Prut-Chernivtsy (Figure 2) are built.

Relevant charts clearly demonstrate that sudden break points are absent. This indicates the homogeneity of the series of average annual water discharges, i.e., the absence of radical changes in the studied characteristics of water status on the main rivers of the Ukrainian Carpathians.

Table 1

Results of the test for homogeneity of average annual water runoff of the major rivers of Ukrainian Carpathians by parametric criteria at significance level of $2\alpha = 5\%$

Homogeneity criteria	Statistics value		Results of hypothesis test
	empirical	theoretical	
1	2	3	4
River Tisza near the village of Vylok			
Student, statistics *t*	0.65	[-1.98,+1.98]	homogenous
Fisher, statistics *F*	1.25	[+1,+1.67]	homogenous
River Prut near city of Chernivtsy			
Student, statistics *t*	1.95	[-1.98,+1.98]	homogenous
Fisher, statistics *F*	2.33	[+1,+1.67]	heterogeneous
River Dniester near village of Zalischyky			
Student, statistics *t*	1.37	[-1.98,+1.98]	homogenous
Fisher, statistics *F*	1.33	[+1,+1.67]	homogenous

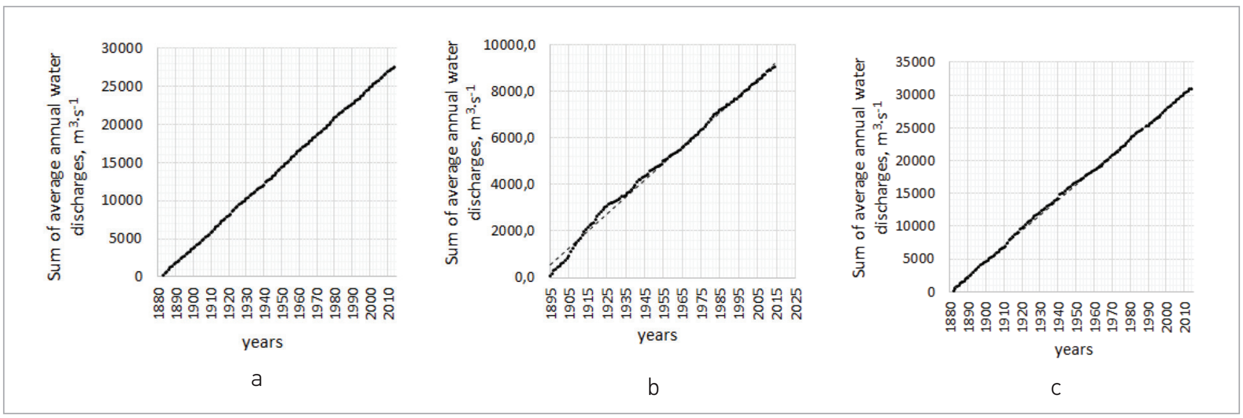
Table 2

Results of the test for temporal homogeneity of average annual water runoff of the major rivers of Ukrainian Carpathians by nonparametric criterion of Wilcoxon-Mann-Whitney at significance level of $2\alpha = 5\%$

Theoretical critical values of statistics *U*		Empirical quantity of inversions U_{EMP}	Results of hypothesis test
lower U_L	upper U_U		
1	2	3	4
River Tisza near the village of Vylok			
1692	2533	2129	homogenous
River Prut near city of Chernivtsy			
1376	2105	2050	homogenous
River Dniester near village of Zalischyky			
1719	2571	2434	homogenous

Fig. 2

Total integral curve of average water discharges: a) River Tisza – village Vylok; b) River Prut – city of Chernivtsy; c) River Dniester- village Zalischyky



Establishment of changes in water runoff in high-water and low-water periods

The apparatus of the random process theory is applied in the hydrological studies for description of the temporal sequences, which examines patterns of random phenomena in the dynamics of their development. Methods of the random process theory are increasingly used in hydrological practice. This is due to the fact that based on the description of the probabilistic structure of long-term changes of hydrological characteristics and identification of the patterns of their cyclical fluctuations, the extrapolation of time series with a view to forecasting is possible. The study of long-term fluctuations of hydrological characteristics includes certain necessary stages (Khristophorov, 1994, Sikan, 2007).

The cyclic fluctuations (cyclicity) mean the variability of time series values that have varying degrees of regularity, subject to the existence of mathematical expectations of the parameters of these fluctuations (Rozhdestvenskij et al., 1974, Khristophorov, 1994, Sikan, 2007).

Identification of the spatial synchronicity of the water content

In order to detect the spatial synchronicity of water content in the Ukrainian Carpathians rivers as an indicator of similarity of the studied series internal structure, the combined chronological charts of long-term fluctuations (Figure 3) are built and the correlation coefficients $r_{Q(t)}$ are identified between the time series of average annual water runoff of the rivers of adjacent basins (Table 3). As we can see, traced relations are statistically significant.

Fig. 3

Long-term fluctuations in average annual water runoff of Ukrainian Carpathians rivers

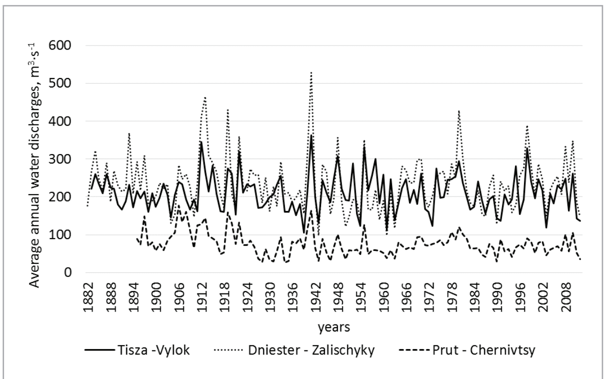


Table 3

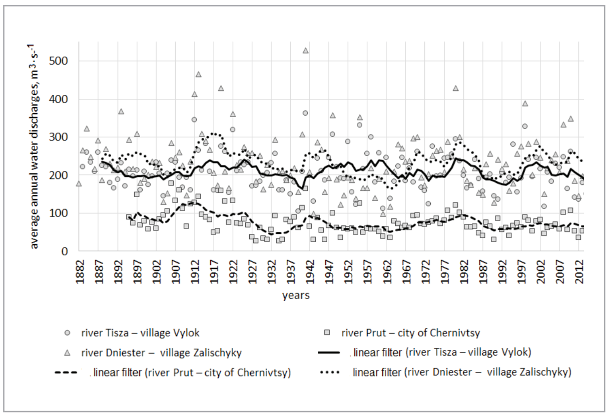
Correlation ratio of the time series and average annual water runoff of Ukrainian Carpathians rivers

River Tisza (Vylok) ↔ river Prut (Chernivtsy)	River Tisza (Vylok) ↔ river Dniester (Zalischyky)	River Prut (Chernivtsy) ↔ Dniester (Zalischyky)
1	2	3
Correlation coefficients $r_{Q(t)}$ with its standard error		
0.57±0.06	0.70±0.04	0.71±0.05

In addition, in order to identify the synchronous variability of water runoff and presence of random fluctuations in the initial time sequences, which are expressed in the form of waves, the smoothing of the original series is applied. Smoothing is a form of statistical filtering resulting in creation of the time series, in which the spectral components with high frequency of output sequence (or amplitude if waves) decreases. Figure 4 presents the chronological sequences of average annual water discharges of major rivers of the Ukrainian Carpathians (in the form of points – "white noise") and their smoothing. The temporal variability and synchronicity in the structure of the runoff series is clearly visible.

Fig. 4

The chronological sequences of average annual water discharges of major Ukrainian Carpathians rivers and their smoothing



It follows from the foregoing that breach of the stationary condition of the members of x_1... x_N may be manifested in the formation of higher and lower values. In particular, in long-term fluctuations of the river runoff, such break is shown in grouping of the years of high and low water content.

The most common way to identify tendencies of grouping of years with relatively large and small runoff values, which are caused by the intra-series correlation or presence of a cyclical trend, is a graphical analysis of the difference integral curve:

$$S_t = \sum_{i=1}^{n}(k_i - 1)\,/C_v \;; \qquad (1)$$

where

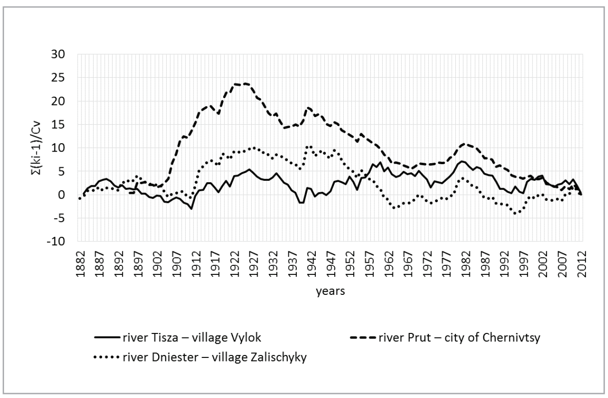
modular factor k_i – the ratio of $Q_i/\bar{Q}$, at the same time $\bar{Q}$ – the arithmetic mean of the whole series $Q_1, Q_2, \dots Q_i$; C_v – coefficient of variation of the series members; S_t – runoff accumulation curve.

For the analysis of long-term fluctuations, the difference integral curves of average annual water discharges of major Ukrainian Carpathians rivers are built (Figure 5).

A positive increasing amount of deviation S_t (a phase of high water content) on average means an increase of water runoff. A negative decreasing amount (phase of low water content) characterizes the average reduction of water runoff (Figure 5).

Fig. 5

Difference integral curves of average annual water discharges in River Tisza – village Vylok, River Prut – city of Chernivtsy, and River Dniester- village Zalischyky



Check of statistical reliability existence of water content phase and their duration

The statistical reliability of the existence of such groups (phases of high and low water content) and, therefore, a breach of stationary conditions can be checked by means of criteria of the series (Khristophorov, 1994). The series should be understood as any part of the sequence *n*, consisting of elements of the same kind. A series of elements n_1 includes members of the sequence, the value of which exceeds the sample mean (or median) number *a*, and a series of elements n_2 – the members with less value. The values form a series of higher values if: $x_{t-1} < a;\ x_t \geq a;\ \dots\ x_{t+k} \geq a;\ x_{t+k=1} < a$. A series of low values is detected similarly. After determining the total value of the quantity of series *u*, consisting of the quantity of high u_1 and low series u_2, the statistics of criterion is calculated:

$$t_u = \frac{u + 0{,}5 - m_u}{\sqrt{D_u}} \;; \qquad (2)$$

with parameters

$$m_u = \frac{2 \cdot n_1 \cdot n_2}{n} + 1 \quad \text{and} \quad D_u = \frac{2 \cdot n_1 \cdot n_2 \cdot (2 \cdot n_1 \cdot n_2 - n)}{n^2 \cdot (n-1)}.$$

Then, the significance level of criterion $\propto$ is assigned. The criterion of the series adopts the hypothesis if $|t_u| \leq t(\propto/2)$, where $t(\propto/2)$ is a normal distribution quantile, which corresponds to the probability of exceeding $\propto/2$. In particular, $t(\propto/2) = 2{,}58$ at the level of significance $\propto = 1\%$, $t(\propto/2) = 1{,}96$, at $\propto = 5\%$ and $t(\propto/2) = 1{,}64$ at $\propto = 10\%$.

Table 4 presents the calculation of design parameters for the major rivers of the Ukrainian Carpathians under the criterion of series and its statistics t_u

For water runoff values of the River Tisza – village Vylok and the River Dniester – village Zalischyky at significance level $\propto = 5\%$ the criteria statistics is $|t_u| \leq t(\propto/2)$. This means an abnormally low number of the series that indicates a statistically significant tendency to formation of the groups (series) of higher and lower values and the presence of a sufficiently high positive correlation between adjacent members of the sequence. For consistency of water discharges of the River Prut – city of

Table 4

Calculation of parameters under the criterion of series for determining the trends to the formation of a series of higher and lower runoff values for major rivers of the Ukrainian Carpathians at significance level of 2α=5%

River - hydrological station	Values of the parameters								
	n	n_1	n_2	u_1	u_2	u	m_u	$\sqrt{D_u}$	t_u
1	2	3	4	5	6	7	8	9	10
River Tisza – village Vylok	132	61	71	28	28	56	66.6	5.7	-1.79
River Prut – city of Chernivtsy	120	51	69	24	24	48	59.7	5.3	-2.10
River Dniester – village Zalischyky	133	57	76	27	28	55	66.1	5.6	-1.89

Chernivtsy, we obtained that $|t_u| \geq t(\propto/2)$ at the significance level of $\propto = 5\%$, i.e., with a 5% risk, one can argue that the number of the series was great, i.e., there is a statistically significant tendency of frequent changes in higher and lower values. However, the defined statistics for the River Prut – city of Chernivtsy is statistically reliable $|t_u|$ at a significance level of $\propto = 1\%$, when it does not exceed $t(\propto/2) = 2{,}58$.

The statistics of the longest length of series K is used as test statistics of the duration of higher or lower groups of year (Khristophorov, 1994). It is theoretically proved that for random independent sets the analytical value of the statistical duration of higher or lower groups of years K_α is expressed by the formula:

$$K_\alpha = [lg(-\frac{n}{ln(1-\alpha)})/lg2] - 1\ ; \qquad (3)$$

where

α – probability (in fractions of 1), along with which in sampling by volume in n members one can meet a series of elements of the higher or lower groupings with a length K or more.

When testing the hypothesis, the empirical value of statistics K is compared with the analytical K_α at a certain significance level α. According to the data on the average annual runoff and formation of the series with elements of higher or lower groups for the major rivers of the Ukrainian Carpathians, the hypothesis that the probability structure of the hydrological series meets the model of a random value by the criterion of the longest series K at significance level of 2α = 5% was tested. Analysis of the sequence of the groups demonstrated that the longest length of all the studied basins was related to the series consisting of elements of lower groups, and for the River Tisza – village Vylol and the River Dniester – village Zalischyky their length was 9 years (from 1983 to 1992 and from 1956 to 1964, respectively), i.e., the empirical values of statistics are K = 9 for the River Prut and for city of Chernivtsy, K = 8 (from 1956 to 1963). According to formula (3), the analytical values K_α are calculated: for the River Tisza – village Vylok K_α = 10.5; for the River Prut – city of Chernivtsy K_α = 10.2; and for the River Dniester – village Zalischyky K_α = 10.4. Since for all basins $K < K_\alpha$, it means that there are tendencies for groups in water runoff sequences and these trends are statistically significant. It is theoretically proved that the grouping of low-water years for the studied rivers of Ukrainian Carpathians can be 10 ± 2 years.

Structure of the cyclical fluctuations

In order to formalise the long-term fluctuations of annual water runoff of Ukrainian Carpathians rivers as cyclical fluctuations with groups of years of high and low values (high-water and low-water phases) and evaluate their quantitative parameters (duration, intensity), the autocorrelation analysis of time series of average annual water consumption for the River Tisza – village Vylok, the River Dniester – village Zalischyky, and the River Prut – city of Chernivtsy was appropriate and made. Application of this method is based on the acceptance of the hypothesis of stationary processes that cause fluctuations in the studied values.

The autocorrelation function $R(t, \tau) = \text{corr}\{Q(t), Q(t+\tau)\}$ characterizes the closeness of the relationship between the members of the temporal sequence of water consumption $Q(t)$. The function $R(t, \tau)$ is a sequence of linear correlation coefficients calculated with different distances between sections (or shift values) of the average annual water discharges on the time axis data (Rozhdestvenskij et al., 1974, Sosedko, 1974, Khristophorov, 1994, Sikan, 2007, Lukianets et al., 2008).

For better spatial comparison of the results, the ordinates of the autocorrelation functions are calculated as normalised values (Sosedko, 1974, Sikan, 2007). As a normalising factor, in this case, we took a variance D_Q of sequence *Q(t)*. Then, the correlation $k_Q(\tau)$ and the autocorrelation function $R_Q(\tau)$ of a stationary random process were estimated by the formulas:

$$k_Q(\tau) = \frac{1}{n-\tau-1}\sum_{i=1}^{n-\tau}(Q_i - \bar{Q}) \cdot (Q_{i+\tau} - \bar{Q}). \quad (4)$$

$$R_Q(\tau) = \frac{k_Q(\tau)}{D_Q}; \quad (5)$$

where

n – length of implementation (number of series members); τ – distance between the sections; $\bar{Q}$ – arithmetic mean (assessment of mathematical expectation).

It should be noted that in case of an increase in τ, the common period in which the pair correlation coefficient is estimated decreases. Therefore, sampling ordinate errors of the autocorrelation function (Sikan, 2007) inevitably increase. In practice of the hydrological calculations, the following restrictions are assigned for shift τ:

$$\tau \approx \frac{1}{3 \div 4} \cdot n. \quad (6)$$

Therefore, the scope of shift values is taken from τ = 2 to τ = 30, given the length of implementation *n* for studied sequences of average annual water discharges (the number of series members is 130 years for the River Tisza – village Vylok, 118 years for the River Prut – city of Chernivtsy, and 131 years for the River Dniester – village Zalischyky).

To assess the statistical significance of the defined ordinates of the autocorrelation function, the confidence limits $CL_{R(t)}$ 95% of exceedance probability were defined (Table 5) as follows (Sosedko, 1974, Lukyanets et al., 2015):

$$95\%\ CL_{R(\tau)} = \frac{-1 \pm 1{,}64(n-\tau-2)^{0{,}5}}{n-\tau-1}. \quad (7)$$

Table 5

Confidence limits ($CL_{R(t)}$) 95% of probability of exceedance of the autocorrelation functions of average annual water runoff for the major rivers of the Ukrainian Carpathians

River - hydrological station	$CL_{R(\tau)}$	
	Lower limit	Upper limit
1	2	3
River Tisza – village Vylok	0.14	0.16
River Prut – city of Chernivtsy	0.14	0.16
River Dniester – village Zalischyky	0.14	0.15

When analysing the correlograms $R_Q(\tau)$ for the River Tisza – village Vylok, the River Dniester – village Zalischyky, and the River Prut – city of Chernivtsy (Figure 6), one can mark features in their structure. The consistent course of functions $R_Q(\tau)$ is traced, which, depending on the shift value, takes positive or negative values. As part of the accepted implementation area (from τ = 2 to τ = 30 years), the functions reach maximums at certain points and between them it is reduced to negative values.

Fig. 6

Correlogram of time sequences of average annual water consumption for the River Tisza – village Vylok, the River Dniester – village Zalischyky, the River Prut – city of Chernivtsy

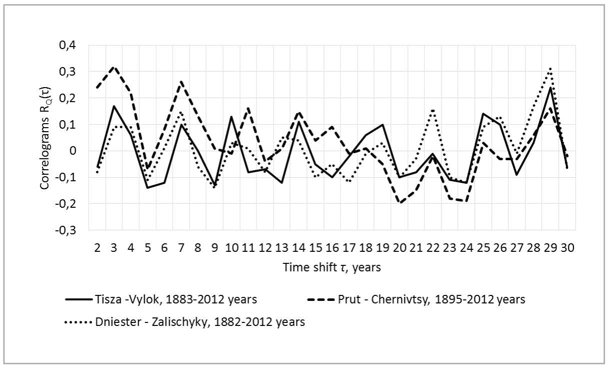


Table 6 shows the evaluation of cyclicity in the form of cycle duration – number of years – that exceed confidence limits of 95% probability of exceedance or close to them. It is believed that these estimates represent through frequency of average annual water discharges the natural fluctuations in water content of studied river basins. The presence of distinct cyclicity of the autocorrelation functions indicates that the structure of time

Table 6

Duration of the average annual water runoff cycles for major rivers of the Ukrainian Carpathians by autocorrelation analysis at 5% significance level

River - hydrological station	Cycle duration (number of years)
1	2
River Tisza – village Vylok	3, 29
River Prut – city of Chernivtsy	3, 7, 11, 29
River Dniester – village Zalischyky	7, 29

series has stochastic dependency between their elements and real continuous cyclical fluctuations, which are not accidental in terms of their origin.

When reviewing the estimates of cycles, it is revealed that some river basins are grouped by repeatability of water content levels. Thus, in the basins of Tisza, Prut and Dniester, the cycles with a duration of 3, 7 and 29 years dominate. The first of them relates to the rain floods in the Carpathian Mountains, which form the internal peaks in the basic cycle (or phases of water content). Basic cyclicity of 29 years is a repeatability in this cycle of years groups with high and low water content (high-water and low-water phases).

Prediction estimates of the Ukrainian Carpathians river runoff fluctuations

For the prediction estimates of water runoff fluctuations, the water content phases were allocated in the runoff series of the River Tisza – village Vylok, the River Dniester – village Zalischyky, and the River Prut – city of Chernivtsy, given the basic cycle frequency (29 ± 2 years), the defined duration of low-water phases (10 ± 2 years) and that there is a spatial synchronicity of water runoff in the stated basins. For reliable assessment of runoff fluctuations, the periods of phases were taken similar for all basins by terms of time limits and chronology. Table 7 presents the periods of high-water and low-water phases, average water discharges for periods of the water content phases and prediction estimates for the major rivers of the Ukrainian Carpathians for the period until 2050 with indication of the

Table 7

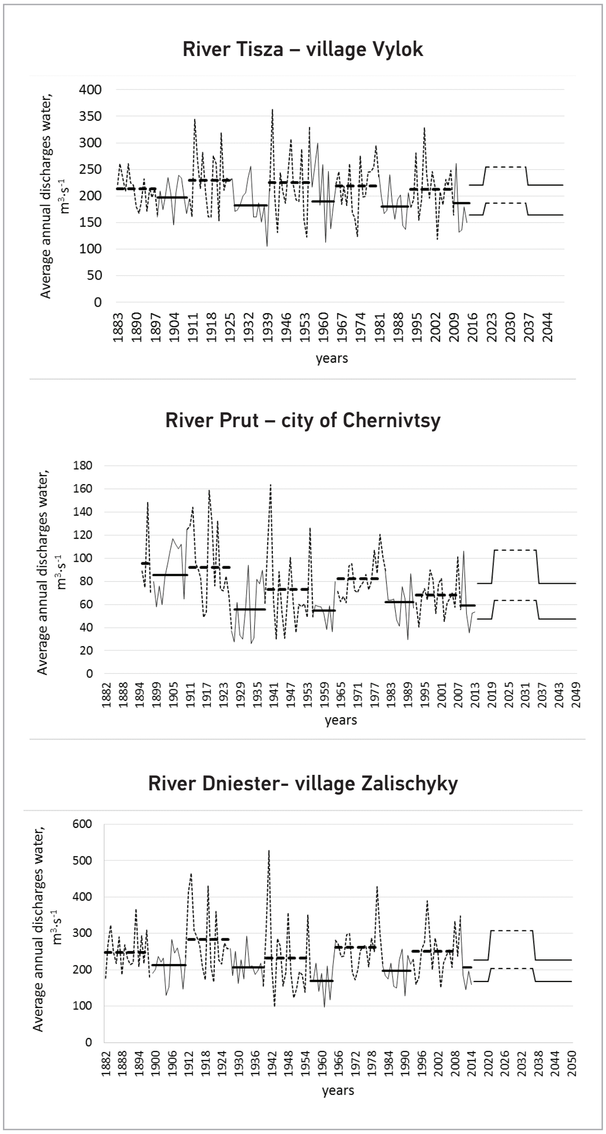
Average water consumption for period of water content phases and prediction estimates of the runoff of major rivers of the Ukrainian Carpathians for the period until 2050

Period (years)	Phase water content	Number of years in phase	Period average water content discharges, $m^3 \cdot s^{-1}$		
	↑ - high-water, ↓ - low-water		River Tisza – village Vylok, $F = 9140$ km²	River Prut – city of Chernivtsy, $F = 6890$ km²	River Dniester – village Zalischyky, $F = 24600$ km²
1	2	3	4	5	6
1883–1898	↑	15	214		248
1899–1911	↓	13	197		212
1912–1927	↑	16	230	93	283
1928–1939	↓	12	182	56	206
1940–1955	↑	16	225	73	233
1956–1964	↓	9	190	54	169
1965–1981	↑	17	219	83	262
1982–1992	↓	11	180	62	195
1993–2009	↑	16	215	69	250
The predicted values with standard deviations in phase water content ($m^3 \cdot s^{-1}$) (in water discharges in phases)					
2010–2020÷21	↓	11÷12	187±7 (±42)	57±4 (±23)	195±16 (±43)
2021–2037÷38	↑	16÷17	220±6 (±51)	80±9 (±33)	256±17 (±77)
2038–2048÷49	↓	11÷12	187±7 (±42)	57±4 (±23)	195±16 (±43)

standard deviations in the water content phase and variation in water consumption inside the phases. Figure 7 presents a graphical representation of the obtained results.

Fig. 7

Fluctuations in water content and their prediction estimates for major basins of the Ukrainian Carpathians

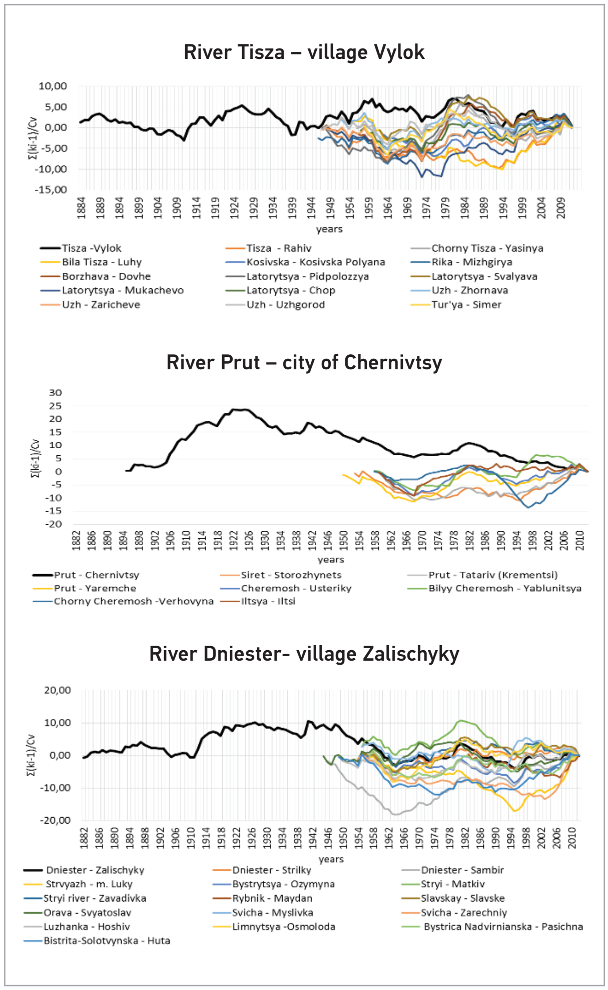


In order to understand the variability of river runoff within the major basins of the River Tisza – village Vylok, the River Dniester – village Zalischyky, and the River Prut – city of Chernivtsy, the combined difference integral curves of average annual water discharges of major rivers of Ukrainian Carpathians and rivers in their basins (Figure 8) were built.

Analysis of Figure 8 demonstrated that internal cyclical fluctuations of river water content in the basins of major river systems had an identical structure. Using the limits for high-water and low-water phases of major rivers (River Tisza – village Vylok, River Dniester – village Zalischyky, River Prut – city of Chernivtsy), the average water discharges in the water content phase were defined for rivers of each large basin wherein the water runoff was observed. As the calculations demonstrated there was a clear cyclical variability for all the rivers, which was similar to major river systems and is well

Fig. 8

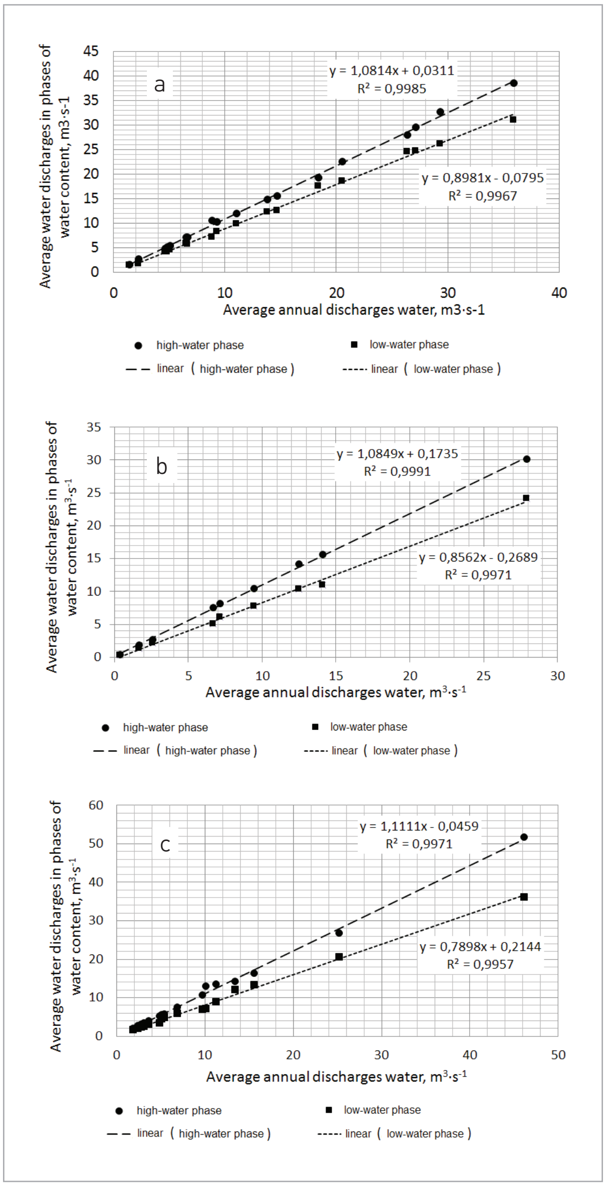
Combined difference integral curves of average annual water discharges of major rivers of the Ukrainian Carpathians and rivers in their basins



evident in Figure 9, which demonstrates the ratio of average long-term water discharges of rivers separately for Tisza, Prut and Siret, Dniester and their values in the periods of high-water and low-water phases.

Fig. 9

Ratio of average water discharges of the rivers in basins of Tisza (a), Prut and Siret (b), right bank of Dniester (c) during the period of high-water and low-water phases and their average long-term values



As follows from Figure 9, for the rivers of basin Tisza, the estimate of the average runoff in high-water $\bar{Q}_{h-w}$ and low-water $\bar{Q}_{l-w}$ phases at average long-term water discharges $\bar{Q}$ can be made by regression equation:

$$\bar{Q}_{h-w} = 1.0814 \cdot \bar{Q} + 0.0311\,. \quad (8)$$

$$\bar{Q}_{l-w} = 0.8981 \cdot \bar{Q} - 0.0795\,. \quad (9)$$

For the Rivers Prut and Siret similarly:

$$\bar{Q}_{h-w} = 1.0849 \cdot \bar{Q} + 0.1735\,. \quad (10)$$

$$\bar{Q}_{l-w} = 0.8562 \cdot \bar{Q} - 0.2689\,. \quad (11)$$

And the right bank of the River Dniester:

$$\bar{Q}_{h-w} = 1.1111 \cdot \bar{Q} - 0.0459\,. \quad (12)$$

$$\bar{Q}_{l-w} = 0.7898 \cdot \bar{Q} + 0.2144\,. \quad (13)$$

Probable errors in determining the average water consumption in high-water and low-water periods are generalised in Table 8. They are presented as a percentage and determined by the ratio of values of average water discharges in corresponding water-content phase.

The proposed regression equations (8)–(13) were tested according to the data of previous years at hydrological stations for the rivers of basins of Tisza, Siret and Prut, and

Table 8

Probable deviation of calculated values of average water runoff in high-water and low-water phases

River basins	Probable deviation of calculated values of average water runoff, %	
	high-water phase	low-water phase
1	2	3
River Tisza	±3	±4
River Prut	±11	±7
River Dniester	±7	±8

Dniester with the definition of the probability of non-exceedance of the permissible deviation p in high-water and low-water phases, which is defined by the formula:

$$p = n/N \cdot 100 \; ; \quad (14)$$

where

n – number of prediction estimates within the limits of probable deviations; N – total number of made estimates.

Availability of predictive estimates under their verification by the actual average data for rivers of Ukrainian Carpathians was 94% for high-water periods and 75% for low-water periods.

High availability of the proposed equations and significance of built relationships (approximation of all reaches R^2 = 0.99) enabled us to generalise probable average water discharges, which can be expected in the high-water and low-water phases of the cycle, depending of their average long-term values (Table 9).

Table 9

Generalised ratio of average water discharges of the rivers of basins Tisza, Siret and Prut and the right bank of Dniester in periods of high-water and low-water phases and their average long-term values

longstanding average water discharges, $m^3 \cdot s^{-1}$	for rivers of basin of Tisza			for rivers of basins Prut and Siret			for rivers of the basin of the right bank of Dniester		
	water content		difference in the phases of water content, $m^3 \cdot s^{-1}$	water content		difference in the phases of water content, $m^3 \cdot s^{-1}$	water content		difference in the phases of water content, $m^3 \cdot s^{-1}$
	high-water phase, $m^3 \cdot s^{-1}$	low-water phase, $m^3 \cdot s^{-1}$		high-water phase, $m^3 \cdot s^{-1}$	low-water phase, $m^3 \cdot s^{-1}$		high-water phase, $m^3 \cdot s^{-1}$	low-water phase, $m^3 \cdot s^{-1}$	
1	2	3	4	5	6	7	8	9	10
0.5	0.57	0.37	*0.20*	0.72	0.16	*0.56*	0.51	0.49	*0.02*
1.0	1.11	0.82	*0.29*	1.26	0.59	*0.67*	1.07	1.00	*0.06*
2.0	2.19	1.72	*0.48*	2.34	1.44	*0.90*	2.18	1.79	*0.38*
3.0	3.28	2.61	*0.66*	3.43	2.30	*1.13*	3.29	2.58	*0.70*
4.0	4.36	3.51	*0.84*	4.51	3.16	*1.36*	4.40	3.37	*1.02*
5.0	5.44	4.41	*1.03*	5.60	4.01	*1.59*	5.51	4.16	*1.35*
6.0	6.52	5.31	*1.21*	6.68	4.87	*1.81*	6.62	4.95	*1.67*
7.0	7.60	6.21	*1.39*	7.77	5.72	*2.04*	7.73	5.74	*1.99*
8.0	8.68	7.11	*1.58*	8.85	6.58	*2.27*	8.84	6.53	*2.31*
9.0	9.76	8.00	*1.76*	9.94	7.44	*2.50*	9.95	7.32	*2.63*
10.0	10.85	8.90	*1.94*	11.02	8.29	*2.73*	11.07	8.11	*2.95*
12.0	13.01	10.70	*2.31*	13.19	10.01	*3.19*	13.29	9.69	*3.60*
14.0	15.17	12.49	*2.68*	15.36	11.72	*3.64*	15.51	11.27	*4.24*
16.0	17.33	14.29	*3.04*	17.53	13.43	*4.10*	17.73	12.85	*4.88*
18.0	19.50	16.09	*3.41*	19.70	15.14	*4.56*	19.95	14.43	*5.52*
20.0	21.66	17.88	*3.78*	21.87	16.86	*5.02*	22.18	16.01	*6.17*
22.0	23.82	19.68	*4.14*	24.04	18.57	*5.47*	24.40	17.59	*6.81*
24.0	25.98	21.47	*4.51*	26.21	20.28	*5.93*	26.62	19.17	*7.45*
26.0	28.15	23.27	*4.88*	28.38	21.99	*6.39*	28.84	20.75	*8.09*
28.0	30.31	25.07	*5.24*	30,55	23.70	*6.85*	31.06	22.33	*8.74*
30.0	32.47	26.86	*5.61*	32.72	25.42	*7.30*	33.29	23.91	*9.38*
32.0	34.64	28.66	*5.98*	34.89	27.13	*7.76*	35.51	25.49	*10.02*
34.0	36.80	30.46	*6.34*	37.06	28.84	*8.22*	37.73	27.07	*10.66*
36.0	38.96	32.25	*6.71*	39.23	30.55	*8.68*	39.95	28.65	*11.31*
38.0	41.12	34.05	*7.08*	41.40	32.27	*9.13*	42.18	30.23	*11.95*
40.0	43.29	35.84	*7.44*	43.57	33.98	*9.59*	44.40	31.81	*12.59*
42.0	45.45	37.64	*7.81*	45.74	35.69	*10.05*	46.62	33.39	*13.23*
44.0	47.61	39.44	*8.18*	47.91	37.40	*10.51*	48.84	34.97	*13.88*
46.0	49.78	41.23	*8.54*	50.08	39.12	*10.96*	51.06	36.55	*14.52*
48.0	51.94	43.03	*8.91*	52.25	40.83	*11.42*	53.29	38.12	*15.16*
50.0	54.10	44.83	*9.28*	54.42	42.54	*11.88*	55.51	39.70	*15.80*

The obtained results (see Table 9) can be used for predictive estimates of the possible values of average runoff in high-water and low-water phases of the water content of any river of the Ukrainian Carpathians. For example, the river in Tisza basin has average long-term water discharges of 11.0 $m^3 \cdot s^{-1}$. Then, the average water discharges in the high-water phase (e.g., 2021–2037 ÷ 38 years) is expected to be 11.93 $m^3 \cdot s^{-1}$ (interpolation between the values of 10.85 and 13.01 $m^3 \cdot s^{-1}$ (according to Table 9), corresponding to the values of average long-term water discharges of 10.0 and 12.0 $m^3 \cdot s^{-1}$). Taking into account the probable error, which is 3% for the high-water phase from the expected value (Table 8), the prediction estimation is 11.93 ± 0.36 $m^3 \cdot s^{-1}$, i.e., in the range of 11.6 to 12.3 $m^3 \cdot s^{-1}$.

Similarly, in the studied river with average long-term water discharges of 11.0 $m^3 \cdot s^{-1}$ in the low-water phase (2038–2048 ÷ 49 years), it is expected to be 9.8 ± 0.39 $m^3 \cdot s^{-1}$, i.e., in the range of 9.4 to 10.2 $m^3 \cdot s^{-1}$.

Conclusions

Thus, it could be stated that numbers of the runoff characteristics of the studied basins are similar in terms of the structure and the common pattern of stochastic relationships and cyclical fluctuations are inherent in them.

High reliability of the cycles with periods of 29 ± 2 years demonstrates a stable frequency of high-water (17 ± 2 years) and low-water periods (10 ± 2 years). That is to say, the features found in the structure of time series of the water runoff characteristics can be qualified as cyclical. That is what made it possible to provide prediction estimates of water content of the major rivers of the Ukrainian Carpathians and rivers in their basins. Until 2020–2021, the low-water phase will continue, and then the high-water phase with the duration of 16–17 years can be expected, and from 2037–2038, the low-water level will again continue until 2048–2049.

References

Alehin, Ju. M. (Ed.) (1963) Statistical forecasts in geophysics (86 p.) Leningrad, Russia.

Alehin, Ju. M. (Ed.) (1968) Multiple linear extrapolation macroprocesses (dynamical and statistical prediction method). Proceedings of LGMI, Issue 28 (pp. 46-59). Leningrad, Russia.

Balabukh, V., & Lukianets, O. (2015) Climate change and its consequences in Rakhiv district of Transcarpathian region. Scientific collection: HYDROLOGY, HYDROCHEMISTRY AND HYDROECOLOGY, vol. 2(37) (pp. 132-148). Kyiv, Ukraine.

Vinogradov, Ju., Vinogradova, T. (2008) Modern problems of hydrology *(*320 p.). Moskow: Akademija, Russia.

Hrebin', V. (Ed.) (2010) The modern water regime of rivers Ukraine (landscape and hydrologic analysis) (316 p.) Kyiv: Nika, Ukraine.

Drozdov, O., & Grigor'eva, A. (1971) Long-term cyclical fluctuations in precipitation in the USSR (158 p.). Leningrad: Gidrometeoizdat, Russia.

Druzhinin, I. et al (1966) River runoff and geophysical processes (295 p.). Moskow: Nauka, Russia.

Kajsl, Ch. (1972) Time series analysis of hydrological data (138 p.). Leningrad: Gidrometeoizdat, Russia.

Kalinin, G., Davydova, A. (1967) The study of cyclical fluctuations of river flow of the northern hemisphere (pp. 35-44). Moskow: MGU, Russia.

Kartvelishvili, N. (1975) Stochastic hydrology (162 p.). Leningrad: Gidrometeoizdat, Russia.

Luk'yanets, O. & Sosyedko, M. (1998). Die Abflussbewertung auf nächste Jahre in den Karpaten unter Berücksichtigung der mehrjaehrigen Abflusschwankungen. Sammelband der XIX. Konferenz der Donaulaender (pp. 393-401). Osijek, Kroatien.

Luk'yanets, O. & Sosyedko, M. (1999) Long-term water level fluctuations in the Carpathians. Book of abstracts: *International Conference «Natural phenomena in the Carpathians»* (pp.195-199). Rachiv, Ukraine.

Luk'yanets, O., Sosyedko, M., & Balabukh, V. (2008). Forecast's assessment of water content in Ukraine in the first half of XXIth century. Book of abstracts: *XXVI Conference of Danubian countries on the hydrological forecasting and hydrological bases of water management*, 2-4 June. (pp. 111-112). Bled, Slovenia.

Lukyanets, O., Kaminska, T. (2015) Regularities and spatial synchrony of perennial cyclical fluctuations in the water runoff of the Ukrainian Carpathians rivers. Scientific Bulletin of Chernivtsi University: Collection of scientific papers: Vol. 744-745: Geography (pp. 18-24). Chernivtsi, Ukraine.

Lukianets, Olga & Obodovskyi, Iurii (2015) Spatial, Temporal and Forecast Evaluation of Rivers' Streamflow of the Drainage Basin of the Upper Tisa under the Conditions of Climate Change. Scientific Journal: ENVIRONMENTAL Research, Engineering and Management, No. 71(1) (pp. 36-46). Kaunas: KTU, Lithuania.

Rozhdestvenskij, A. & Chebotarev, A. (1974) Statistical methods in hydrology (pp. 356-415). Leningrad: Gidrometeoizdat, Russia.

Romaschenko, M., Savchuk, D. (2002) Water element. Carpathian floods. Statistics, reasons, regulation (pp.150-200). Kyiv: Ahrarna nauka, Ukraine.

Sikan, A. (2007) Statistical treatment of hydrometeorological information (pp.160-180). St.Petersburg, Russia.

Sosedko, M. (1974) The study of cyclical fluctuations of rainfall runoff in the basin Dniester. Scientific papers of UHMI, № 127 (pp. 16-37). Kyiv, Ukraine.

Sosyedko, M. & Luk'yanets, O. (2010). The Carpathians – flood danger region of Ukraine. Basin runoff forecasting system in Zakarpattya: Methodical and technological basis of its components (pp. 38-63). Kyiv, Ukraine.

Khristophorov A. (1993) Reliability calculations river flow (166 p.). Moskow, Russia.

Khristophorov A. (1994) Theory of stochastic processes in hydrology (143 p.). Moskow, Russia.

Ukrainos Karpatų upių vandens nuotėkio ilgalaikių ciklinių svyravimų modeliai ir prognozė

Gauta:
2016 m. liepa

Priimta spaudai:
2017 m. liepa

Oleksandr Obodovskyi, Olga Lukianets

Taras Shevchenko Nacionalinis Kijevo universitetas, Kijevas, Ukraina

Žinios apie cikliškumo savybes upių nuotėkio svyravimuose, žemo vandens lygio ir aukšto vandens lygio keitimosi pobūdis ir trukmė, ypač jų prognozavimas suteikia neįkainojamą pagalbą planuojant ir tinkamai valdant vandens išteklius, didinant hidroenergijos, melioracijos ir kitų vandens įrenginių eksploatacinį efektyvumą. Šiuo metu domėjimasis ilgalaikių ciklinių upių nuotėkio svyravimais, o taip pat pagrindinio svyravimo faktoriaus modeliavimu labai padidėjo dėl duomenų naudojimo ilgalaikėse prognozėse. Metiniai vandens nuotėkiai buvo apskaičiuoti Tisos, Dniestro ir Pruto upių baseinams. Skaičiavimams naudojamos matematinės priemonės, pagrįstos statistiniais metodais, statistiniais vidurkiais, įvesties duomenų sisteminimo priemonėmis, laiko atsitiktinių rinkinių vertinimo metodais nuotėkio savybėms tirti, laiko eilučių kintamumo analizės metodai.

Raktiniai žodžiai: upė, vandens nuotėkis, atsitiktinė funkcija, cikliškumas, erdvinė sinchronija, vandens telkinio fazė, korelograma, vandens ciklas, prognozinis įvertinimas.