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The intra-annual streamflow distribution of Ukrainian rivers in different phases of long-term cyclical fluctuations

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In this article, the analysis of homogeneity and stationarity of the mean monthly discharges of the rivers of Ukraine was carried out by means of hydro-genetic methods with the use of observation series on 305 water gauging stations from the very beginning of the observation till 2010 inclusive. An integral curve was used for the estimates of homogeneity of the observation series. Difference-integral curves were used for estimation of stationarity of the observation series and for the study of their long-term cyclical fluctuations. It turned out that most series of the mean monthly discharges were homogeneous. The observation series that have a full cycle of long-term cyclical fluctuations (dry and wet phases) are stationary, whereas other observation series are quasi-stationary. The intra-annual streamflow redistribution occurs depending on dry and wet phases of long-term cyclical fluctuations. It is shown that the terms, the duration of periods and seasons of intra-annual streamflow distribution should define cyclical fluctuations because the mean monthly discharges change in dry and wet phases. Therefore, it is necessary to carry out development of the schemes of the components of intra-annual streamflow distribution for the rivers of Ukraine because such schemes were defined on the short observation series in 50–80s of the 20th century without considering a long-term cyclical fluctuation streamflow.

Key words: intra-annual streamflow distribution, cyclical fluctuations, homogeneity, stationarity, hydro-genetic methods

INTRODUCTION

The intra-annual streamflow distribution has a great practical importance. The information about intra-annual streamflow distribution is used for various water management goals: design of reservoirs, exploitation of hydroelectric stations, the size of irrigation areas, development of measures for flood protection, etc.

Climatic factors and surface basin factors have defined the intra-annual streamflow distributions. The climatic factors have formed a common type of intra-annual streamflow distribution of the physical-geographical zone.

The surface basin factors (the area and form of the basin, hydrogeological conditions, presence of lakes, marshes, forests, etc.) have defined the characteristics of intra-annual streamflow distribution. Anthropogenic factors have changed the intra-annual streamflow distribution. This vastly complicates calculations [1].

The common characteristics of the intra-annual streamflow distribution of Ukrainian rivers were studied at the period of intensive hydraulic construction in the 50–80s of the 20th century. The periods and duration of hydrological seasons of Ukrainian rivers were defined; main calculation methods of intra-annual streamflow distribution were designed, and the regionalization of Ukraine's territory on types of intra-annual streamflow distribution was carried out [2–4]. Since the moment of development of scientific positions on the regularity of intra-annual streamflow distribution of Ukrainian rivers, for most water gauging stations the observation series increased by two and more times. In modern papers by Ukrainian researchers, tendencies of the intra-annual streamflow distribution were studied, and their changes under influence of the climatic change were shown in [5–7]. In many papers that were written in different countries, e. g. in papers [8–11], the analysis of a long-term cyclical fluctuation streamflow was performed. However, it should be noted that such analysis is most often used for studies of the mean annual flow and less so for studies of intra-annual fluctuations.

The objective of this paper is the research of the intra-annual streamflow distribution of Ukrainian rivers on the basis of the analysis of data from the beginning of the observation till 2010 using hydro-genetic methods of estimation of homogeneity and stationarity as well as the analysis of the long-term cyclical fluctuation streamflow.

DATA AND METHODOLOGY

The conditions of forming of the intra-annual streamflow distribution of Ukrainian rivers are various; it is conditioned by physical-geographical characteristics of the Ukrainian territory. The Ukrainian rivers are located in the forest, forest-steppe, steppe zones, and in the conditions of the high-altitude zones (the East Carpathians and Crimea mountains). In the paper [12], it was described that catchments of different physical-geographical zones have a different correlation of the main elements of water balance (flow, precipitation, evaporation) that are the main zonal climatic factors of forming of the intra-annual streamflow distribution. The azonal factors of river basins also vary: the geomorphological structure of the basin, the soil type, the presence of karst, marshes, vegetable cover, the height of the basin above the sea level, the declivity exposition, the economic activity, etc. In general, the snow-melt flood and the summer–autumn low water are characteristic of distribution of the intra-annual plain rivers of Ukraine. The intra-annual distribution of Ukrainian Carpathian Mountain Rivers (the Danube River Basin and right-bank tributaries of the Dniester River) has snow–rain floods (a cold period of a year) and rainfall floods (a warm period of a year). The intra-annual streamflow distribution of the Crimea rivers has two distinct periods: flood (winter–spring) and low water (summer–autumn). The flood season accounts for almost 80% of the entire streamflow of the Crimea Mountain Rivers.

In the paper, for the study of the intra-annual streamflow distribution of Ukrainian rivers, the mean month discharges on 305 water gauging stations from the very beginning of the observation till 2010 inclusive were used. The intra-annual streamflow distribution on the Ukrainian territory was characterized by the observation data presented in Fig. 1. The duration of observations is characterized by the data in Table 1. The largest quantity of water gauging stations has the duration of observations about 50–70 years.

The distribution of water gauging stations in basins is uneven (Table 2). Therefore, observations on the small basins are almost absent throughout the entire territory. The Crimea River and Danube River Basins (Ukrainian part) are the exceptions. Medium rivers have the largest quantity of water gauging stations. There are only two water gauging stations at the Prychornomorye Rivers. One water gauging station has a short observation series. The streamflow of another river has a regulated flow. Therefore, the Prychornomorye Rivers are not studied.

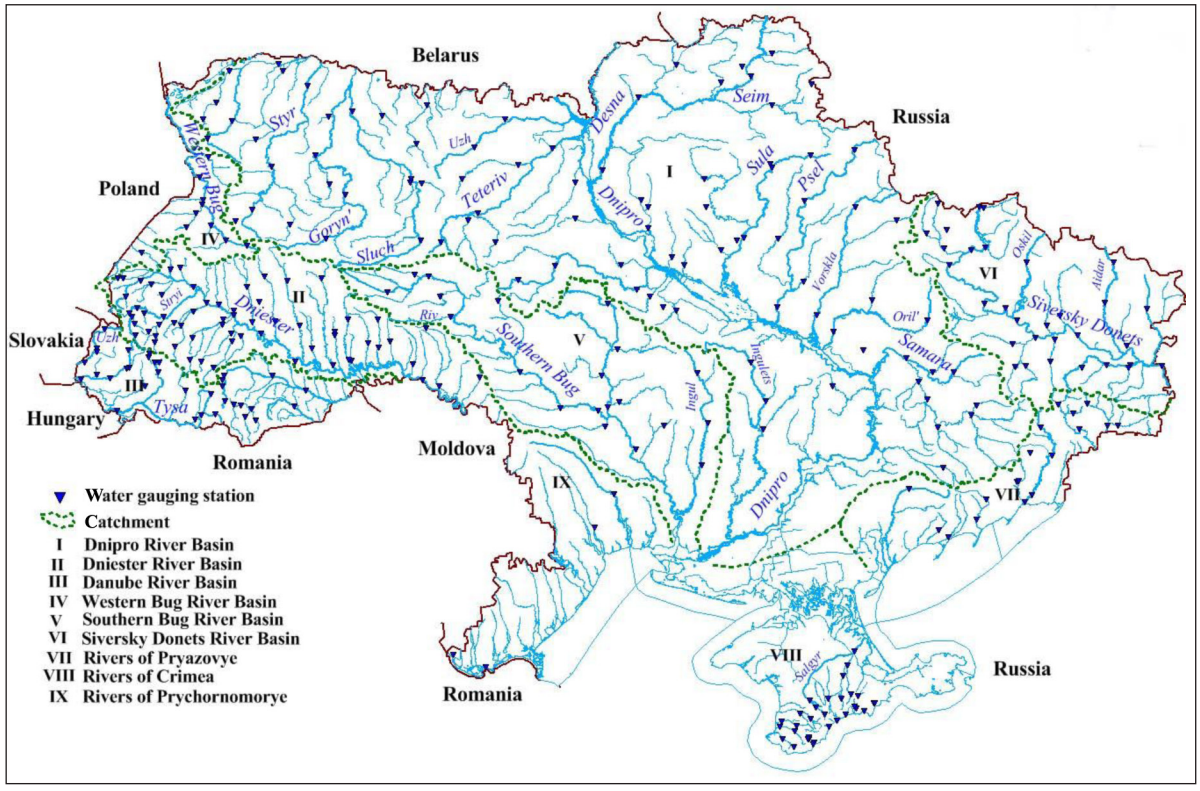

Fig. 1. Water gauging stations and the main catchments of rivers on the territory of Ukraine

The determination of the terms, duration of periods and seasons of the intra-annual streamflow distribution has been carried out for the water economic year that begins from the first month of the high water season. The beginning of the high water season is the first month, which has the mean monthly discharge more than the mean annual discharge for the year. The water economic year is divided into two periods: limiting and non-limiting. In

Table 1. **Duration of observations on the water gauging stations at Ukrainian rivers**

Years	Quantity of water gauging stations								
	Dnipro River Basin	Dniester River Basin	Danube River Basin	Western Bug River Basin	Southern Bug River Basin	Siversky Donets River Basin	Rivers of Pryazovye	Rivers of Crimea	Rivers of Prychornomorye
20–30	3	6	1	–	–	–	1	–	1
31–40	4	5	1	1	–	1	–	2	–
41–50	9	5	4	2	1	11	1	9	–
51–60	35	24	17	5	3	11	7	4	1
61–70	22	18	11	2	6	5	7	11	–
71–80	15	2	–	–	7	1	2	4	–
81–90	5	1	–	–	2	1	–	1	–
91–100	–	2	2	–	1	1	–		–
>100	1	–	–	–	–	–	–		–
Total	94	63	36	10	20	31	18	31	2

Table 2. **Quantity of water gauging stations on rivers depending on the catchment area**

Catchment area, km²	Quantity of water gauging stations								
	Dnipro River Basin	Dniester River Basin	Danube River Basin	Western Bug River Basin	Southern Bug River Basin	Siversky Donets River Basin	Rivers of Pryazovye	Rivers of Crimea	Rivers of Prychornomorye
10–100	1	2	6	1	1	–	–	16	–
100–1 000	38	45	20	3	15	9	11	10	–
1 000–10 000	41	14	8	6	–	13	7	2	2
>10 000	14	2	2	–	4	9	–	–	–
Total	94	63	36	10	20	31	18	28	2

turn, the limiting period is subdivided into two seasons: limiting and non-limiting. The limiting season constitutes the months that have the least discharges per year for a multi-annual period [13].

Analysis of homogeneity and stationarity of the mean monthly discharges is carried out by means of hydro-genetic methods on the basis of methodical approaches that were developed in papers [14–16]. Homogeneity of the observation series is the absence of unidirectional changes of hydrological characteristics (refers to one genetic series – floods, rain floods, etc.) over time on the backdrop of its variability because of the long-term cyclical fluctuations. Stationarity of the observation series is the constancy of the average value of hydrological characteristics over time if the observation series has at least one full closed cycle (dry and wet phases) of the long-term fluctuations. These two determinations are the identical conceptions, particularly as the observation series have the representative period (dry and wet phases) for determination of the stable average value. If an observation series does not have a representative period, then the observation series is quasi-stationary if such observation series is homogeneous. The validity of determinations of the stable average value of hydrological characteristics was presented in the paper by V. G. Andriyanov [17]. Temporary variability of the mean monthly discharges was analysed using the observation series that have a long-duration observation period.

The integral curve determines homogeneity of the observation series in time. The integral curve is used to detect the influence of anthropogenic factors (hydraulic structures, canals) and climate change (presence of trends in the data series). If the integral curve does not have "jumping", "emissions" or unidirectional deviation, then the process of forming of runoff is homogeneous in the study area and conversely. The integral curve is defined by the formula [17]:

$$W = \sum_{t=1}^{T} w(t), \tag{1}$$

where W is the total streamflow for the time period T; $w(t)$ is the streamflow of *t-th* year.

Cyclical fluctuations of mean monthly discharges, consequently, their stationarity is investigated by the difference-integral curve that is defined according to [18]

$$\frac{\sum_{t=1}^{T} (k(t) - 1)}{C_v} = f(t), \tag{2}$$

where C_v is variation coefficients of streamflow; $k(t) = Q(t)/Q_0$ is modulus coefficients; $Q(t)$ and Q_0 are the discharge of *t-th* year and the average discharge for the time period T.

If observation series have a relatively short observation interval, the combined graphs will be used for validation of the results.

RESULTS AND DISCUSSION

The significant anthropogenic activity (hydraulic structures, water intake for industry, agriculture, population, cutting down forest, etc.) has impact on the streamflow of many rivers of Ukraine. It is clear that, in the first place, such impact is reflected in the seasonal streamflow. In this regard, it

would be necessary to restore the anthropogenic streamflow to the natural streamflow. However, in practice, it cannot be carried out because of poor quality of water management information [19].

Analysis of integral curves created for all studying observation series has shown that most of observation series are homogeneous because no significant points of fracture in the curves direction were found on the graphs (e. g. Fig. 2a). Some slight variations in the curves direction are associated with long-term cyclical fluctuations (Fig. 2b) and are manifested through presence of only dry and wet phase fluctuations in the observation series. However, such variations do not break the common curve direction; therefore, the observation series are homogeneous.

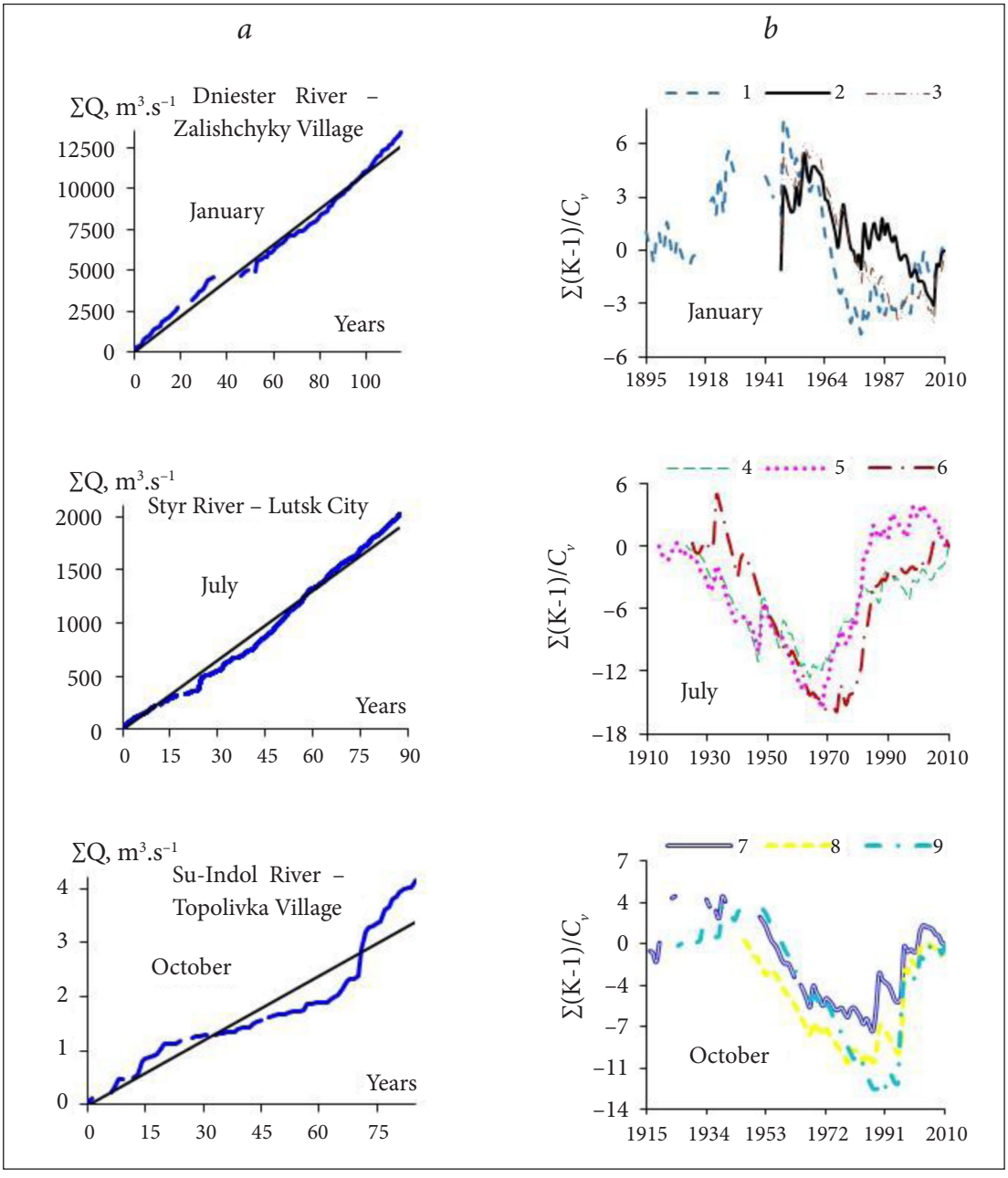

Fig. 2. Integral (*a*) and difference integral (*b*) curves of the mean month discharges of some rivers of Ukraine (1 – Dniester River – Zalishchyky Village; 2 – Uzh River – Uzhhorod City; 3 – Tysa River – Rakhiv Town; 4 – Styr River – Lutsk City; 5 – Seim River – Mutin Village; 6 – Southern Bug River – Oleksandrivka Village; 7 – Belbek River – Fructove Village; 8 – Uchan-Su River – Yalta City; 9 – Su-Indol River – Topolivka Village)

Rivers of Mountainous Crimea are the exceptions because such rivers have a significant anthropogenic influence (reservoirs, ponds, water intake, etc.), snow–rain flood regime, presence of the karst phenomenon on the catchments. For such rivers, the integral curves have more expressed deviations in the direction; although it can be seen that these deviations are also dependent on cyclical fluctuations and rain floods. Rain floods are characterized by a sharp increase in water levels and discharges in the Mountain Rivers of the Crimea.

The observation series that have a full cycle of long-term cyclical fluctuations (dry and wet phases) are stationary. So, for some rivers of Ukraine, average values of the mean monthly discharges (Fig. 3) do not change significantly over time if the observation series have a representative period (dry and wet phases of long-term cyclical fluctuations) (Table 3). The average values have significant changes for dry or wet phases of cyclical fluctuations as well as for arbitrary periods (without a full closed cycle of fluctuations). For some rivers of Ukraine, the mean monthly discharges do not have a representative period for the determination of the stable average value. Such observation series are quasi-stationary.

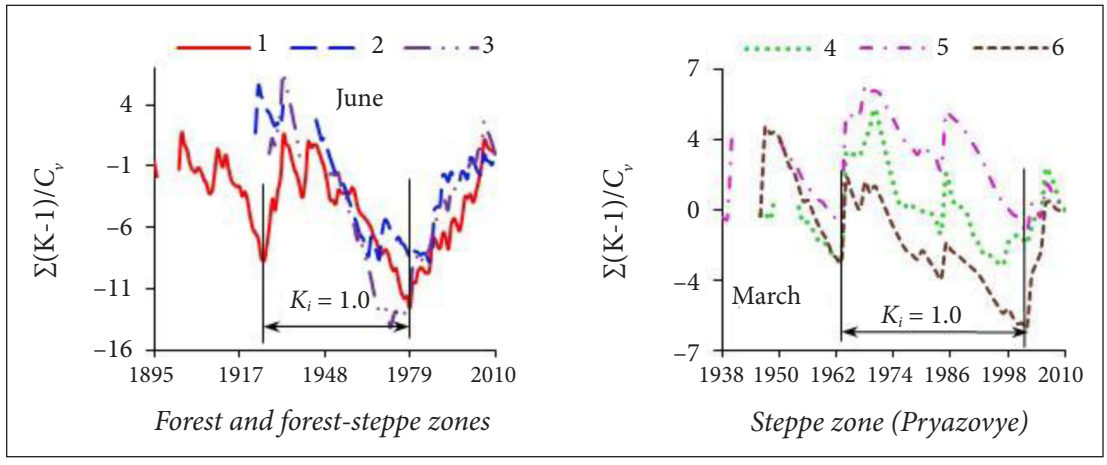

Fig. 3. The difference integral curves of the mean month discharges of some rivers of Ukraine (1 – Desna River – Chernihiv City; 2 – Sluch River – Sarny Town; 3 – Psel River – Zapsillya Village; 4 – Mokra Volnovakha River – Nikolaivka Village; 5 – Obytichna River – Prymorsk Town; 6 – Kalchyk River – Mariupol Town)

Table 3. **The mean monthly discharges of some rivers for different periods for forest and steppe zones of Ukraine**

Period	Average value, m³/s	% from normal	Note
Desna River – Chernihiv City (June, forest zone)			
1926–1979	290	–	normal
1886–1979	280	3.4	with full cycle
1886–1998	293	1.0	with full cycle
1886–2010	300	3.4	with full cycle
1886–1925	264	9.0	dry phase
1926–1938	372	28	wet phase
1941–1979	268	7.6	dry phase
1980–2010	356	23	wet phase
Mokra Volnovakha River – Nikolaivka Village (March, steppe zone)			
1964–2002	1.00	–	normal
1946–49, 1954–2002	0.95	5.0	with full cycle
1946–49, 1954–2010	0.97	3.0	with full cycle
1946–49, 1954–70	1.21	21	without full cycle
1965–2002	0.78	22	wet phase

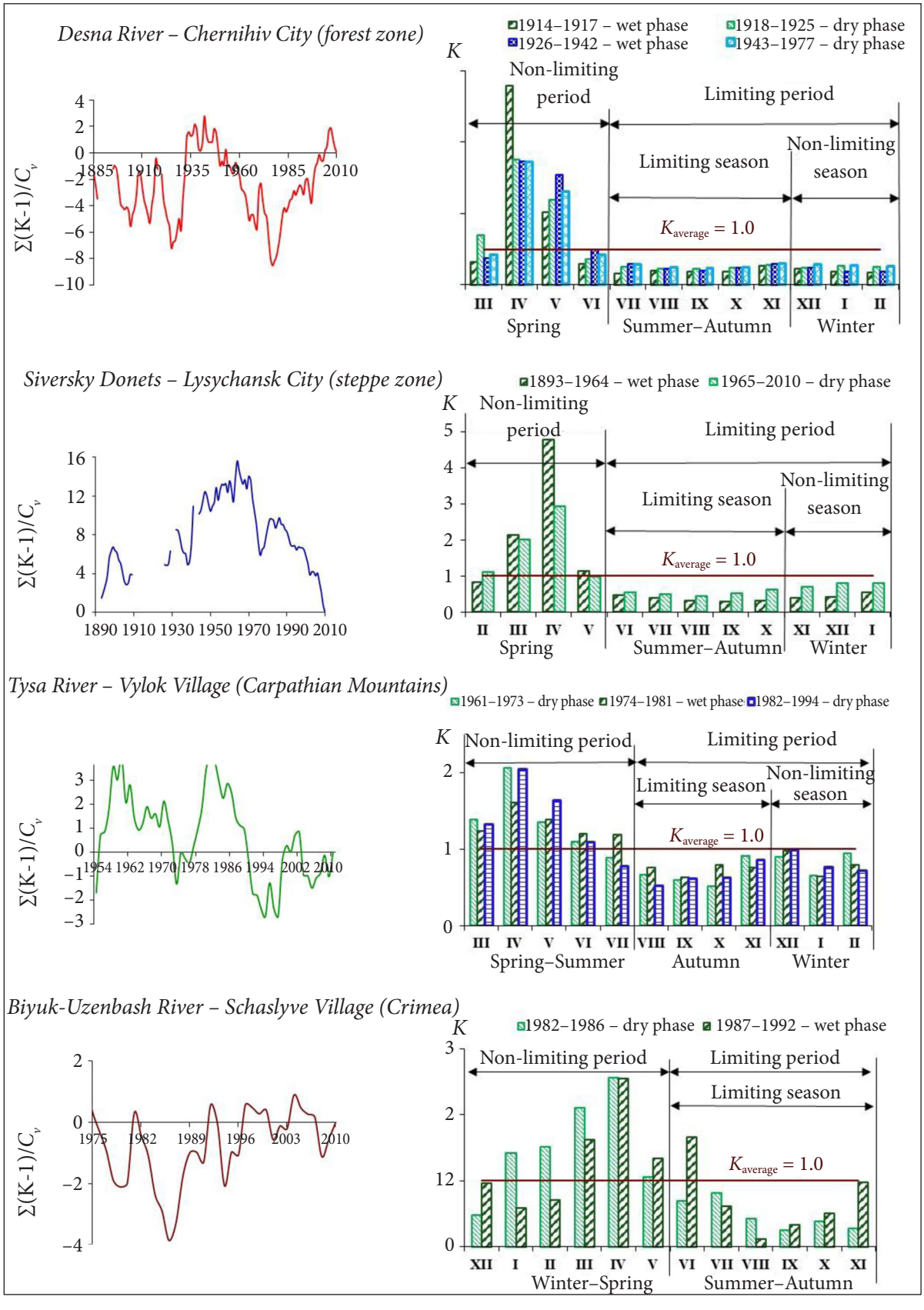

Fig. 4. The difference integral curves of the mean annual streamflow (*a*) and periods of duration of the water economic year (*b*) in different phases of cyclical fluctuations of discharges in some rivers of Ukraine

It turned out that for every physical-geographic zone of Ukraine, the mean monthly discharges are characterized by synchronous fluctuations (Figs. 2, 3). It is allowed to carry out the analysis of cyclical fluctuations on some representative series with the longest observation periods that are located in a separate physical-geographical zone.

In the study, it was found that the intra-annual streamflow redistribution occurs depending on the phase of long-term cyclical fluctuations of the mean annual streamflow. For plain rivers (e. g. Desna, Siversky Donets), the dry phase in relation to the wet phase is characterized by lower discharges during spring flood and by higher discharges during summer–autumn low water. For mountain rivers (e. g. Tysa, Biyuk-Uzenbash), the wet phase in relation to the dry phase is characterized by lower discharges during snowmelt floods and by higher discharges during rain floods (Fig. 4).

Most of the rivers of Ukraine have a short observation series for the study of long-term cyclical fluctuation streamflow (Table 1). So, the observation series with long-term cyclical fluctuations of streamflow were not found for the mountain rivers. In this case, short-term cycle fluctuations were used for the study. At the same time, it can be seen that the cycles significantly differ from each other by the total duration, duration of the phases, discharge values, etc. (Fig. 3). Therefore, for obtaining stable regulations, it is necessary to analyse some different long-term cycles. Unfortunately, for many rivers in Ukraine, such analysis cannot be carried out. On many rivers, the observations have begun in the 40–50s of the 20th century. Many water gauging stations had undergone reconstruction, optimization, etc. Military actions were carried out on the territory of Ukraine at various times in the 20th century. This led to the fact that even long series of observations have gaps. It is clear that such low-quality data are not very suitable for the research. In addition, the azonal factors (declivities exposition, geological structure, etc.) have significant impact on the formation of streamflow mountain rivers that can break common regulations of streamflow formation in individual catchments.

The beginning of the non limiting period changes in dry and wet phases of long-term cyclical fluctuations of streamflow. For example, for the wet phase of the water gauging station Siversky Donets River – Lysychansk City, the first month of the non-limited period is April, and for the dry phase it is March. Hence, the errors may occur if the determination of the terms, duration of periods and seasons of the intra-annual streamflow distribution is carried out without taking into account long-term cyclical fluctuations. The components of the intra-annual streamflow distribution can reliably define whether the observation series have one representative period – dry and wet phases of long-term cyclical fluctuations.

CONCLUSIONS

Analysis of homogeneity and stationarity of the mean monthly streamflow of Ukrainian rivers by means of hydro-genetic methods has shown that most of the observation series are homogeneous and stationary. Some rivers that have significant anthropogenic influence (hydraulic structures, water intake for industry, agriculture, population, cutting down forest, etc.) are exceptions. The observation series that have a full cycle of long-term cyclical fluctuations (dry and wet phases) are stationary, while other observation series are quasi-stationary.

The mean monthly discharges are characterized by the synchronous fluctuations in all physic-geographic zones of Ukraine.

As a result of long-term cyclical fluctuations of a streamflow, the intra-annual streamflow redistribution occurs in the Ukrainian rivers. For plain rivers, the dry phase in relation to the wet phase is characterized by lower discharges during spring flood and by higher discharges during summer–autumn low water. The mountain rivers have the following tendency: the wet phase in relation to the dry phase is characterized by lower discharges during snow-melt floods and by higher discharges during rain floods.

The terms, the duration of periods and seasons of the intra-annual streamflow distribution should define the long-term cyclical fluctuations because the mean monthly discharges change in dry and wet phases. It is necessary to carry out the development of new schemes of the components of intra-annual streamflow distribution for the rivers of Ukraine because the actually

existing schemes were determined on a short observation time series with the presence of fragments of dry or wet phase cyclical fluctuations.

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Liudmila Gorbačiova

UKRAINOS UPIŲ NUOTĖKIO METINIS PASISKIRSTYMAS SKIRTINGOSE ILGALAIKIŲ CIKLINIŲ SVYRAVIMŲ FAZĖSE

Santrauka

Straipsnyje pateikta Ukrainos upių mėnesio debitų vienalytiškumo ir stacionarumo analizė. Naudoti hidrogenetiniai metodai, duomenys imti iš 305 stočių nuo stebėjimo pradžios iki 2010 m. imtinai. Tyrime panaudotas integralinių kreivių metodas vertinant stebėjimų eilių vienalytiškumą. Skirtuminės-integralinės kreivės buvo panaudotos stebėjimo eilių stacionarumui įvertinti ir jų ilgalaikių ciklinių svyravimų tyrimui. Nustatyta, kad mėnesio vandens debitų eilės daugiausia yra vienalytiškos. Stebėjimų eilės, kurios turi pilną upių nuotėkio svyravimų ciklą (sausą ir vandeningą fazes), yra stacionarios, kitos – pusiau stacionarios. Priklausomai nuo vandeningų ir sausų fazių ilgalaikiuose cikliniuose upių nuotėkio svyravimuose, vyksta nuotėkio metinis perskirstymas. Nustatant upių nuotėkio metinio pasiskirstymo terminus, periodų trukmes ir sezoniškumą būtina atsižvelgti į ciklinius svyravimus, šiame tyrime imtas sausų ir vandeningų fazių daugiametis mėnesio vandens debito vidurkis. Vertinant Ukrainos upių nuotėkį būtina atlikti schemų, sudarančių ekonominius vandens metus, patikslinimą, nes jos buvo nustatytos pagal trumpas eiles neatsižvelgiant į ilgalaikius ciklinius upių nuotėkio svyravimus.

Raktažodžiai: metinis upių nuotėkio pasiskirstymas, cikliniai svyravimai, vienalytiškumas, stacionarumas, hidrogenetiniai metodai