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Analysis of long-term annual water runoff variability of the Desna River

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SUMMARY

The paper presents the results of the analysis of the long-term annual water runoff variability of the Desna River. To conduct the study were used average annual water discharge (Chernihiv stream gauge) for the period 1895-2020, that is the duration of the series was 126 values. The long-term changes in river water runoff are due to the multifactorial process of its formation and are a random process that is constantly changing over time. Verification the series for homogeneity by parametric criteria showed that they are homogeneous. Calculations of statistical for the entire initial time series and for segments of the studied sequence - for individual 30-year periods (consecutive and 15 years overlap) showed that the most stable are the norm and coefficient of variation. The difference integral curve of annual water discharge testified to the presence of water runoff cycles. The application of autocorrelation and spectral analysis allowed to identify the duration of cycles in the long-term variability of the average annual runoff of the Desna River. The autocorrelogram is traced multiple repetition of 25-year and 36-year cycles, the spectrogram - 11-14 and 19-24 years. Their joint analysis allowed us to identify a mutually confirmed cycle of 24-25 years.

Introduction. Analysis of long-term variability of annual river runoff is important in substantiating the strategy of water resources management in order to ensure sustainable economic development, economic planning for the future and environmental safety of territories and water bodies with possible climate change and significant anthropogenic load. The Desna Basin is significantly anthropization *(Samoilenko and Dibrova, 2019; Samoilenko et al., 2018)*. The object of study is the Desna River, the subject - the average annual water discharges according to observations of Chernihiv stage gauge. The presented study of long-term variability of annual runoff of the Desna River includes not only determination of its statistical distribution parameters for evaluation in practical use of calculated analytical runoff characteristics of a certain probability of exceeding, but also description of long-term fluctuations of river runoff based on identified stochastic patterns.

Method and Theory. The main features of long-term changes in most hydrological indicators of rivers are largely, and sometimes decisively, determined by the probabilistic nature of water runoff variability. This is due to the multifactorial process of river runoff formation due to the continuous influence of meteorological processes and various states of the underlying surface, the combination of which is random. Therefore, the change of any hydrological quantity in a certain section of the river within the framework of the probabilistic concept is a random process that is constantly changing over time. This determines the possibility and effectiveness of the application of mathematical statistics, probability theory, the theory of random variables and functions for the analysis of long-term variability of river runoff. It should be noted that the greatest success in studying the temporal variability of runoff can be achieved if we consider long time series of hydrological characteristics and water runoff from large basins, which are not significantly affected by random factors and local conditions. The studied hydrological gauge (Desna – Chernihiv) has one of the longest series of observations in Ukraine and its catchment area is 81400 km^2.

The first stage of the analysis is to test statistical hypotheses of homogeneity of time sequences according to standard parametric criteria: Student's t-test - to test the significance of average values and F-test (Fisher) - to test the ratio of variances *(Goroshkov, 1979; Rachmatullina and Grebin, 2014)*. Such verification is an important element in assessing the reliability of further statistical generalizations. The next step was the calculations of the main statistical parameters (norms, coefficients of variation and skewnesses) for the entire initial time series. To analyze their stability for the observation period sample estimates of statistical parameters for segments of the study sequence - for individual 30-year periods (consecutive and 15 years overlap) were considered. The choice of 30-year periods is based on the provisions of the WMO Technical Regulations *(WMO 2007; WMO 2015)* - the climatic norm of a certain hydrometeorological element is defined as the arithmetic mean over successive periods of 30 years, while the base level remains the period 1961-1990 and it will be persisted until there is a convincing scientific reason for its change.

The study uses graphical analysis of the difference integral curve, which is a common way to identify long-term variability of river water runoff characteristics such as trends in the grouping of years with relatively high and low values. Autocorrelation and spectral analyzes were used to formalize the long-term variability of annual water runoff in the form of cyclic fluctuations. The autocorrelation function characterizes the closeness of the relationship between the values of the time sequence and is a sequence of linear correlation coefficients calculated with different values of offsets along the time axis. Spectral analysis is based on the dynamic modification of the principal components' method, the transformation of a one-dimensional time series into a multidimensional series, and the subsequent application of the principal components' method to the obtained multidimensional time series. A spectral function is used to study the periodic properties of random processes. The main statistical characteristic of spectral analysis is its spectral density *(Pekárová et al., 2019)*.

Results. The study used observations of the average annual water runoff for the period 1895-2020. Thus, the long-term sequence of annual runoff of the Desna River near Chernihiv city was 126 years (values) (Figure 1). Verification for temporal homogeneity of the average annual water runoff and its variability

was performed according to parametric criteria (Student's t-test and F-test) at a significance level of 2α = 5%. As a result, the hypothesis of homogeneity of the sequence of annual water discharges of the Desna River near Chernihiv city is not refuted in terms of the significance of norms and the ratio of variances.

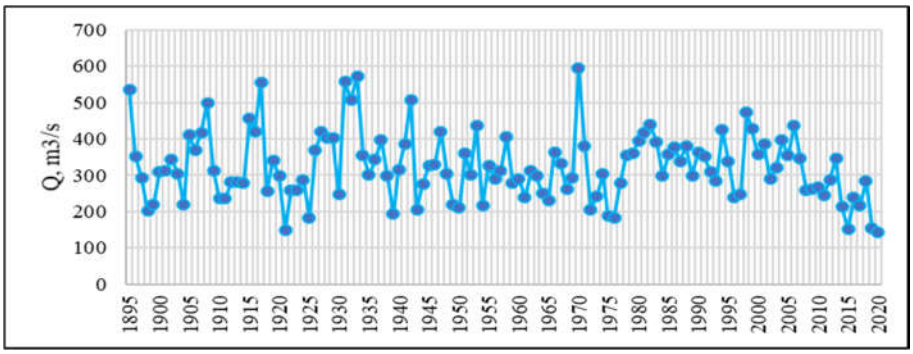

Figure 1 *Long-term sequence of average annual water discharges (Desna – Chernihiv).*

The results of calculations of the main statistical parameters for the entire initial series of annual water discharges and their sample estimates for the sequences of the studied sequence - for individual consecutive 30-year periods and for 30-year periods with 15 years overlap are presented in Table 1. To estimate long-term variability of basic parameters of average annual runoff used the average absolute deviation of a random variable, which is the arithmetic mean of the deviations of the variable from its modulo norm.

Table 1 *Statistical parameters of the distribution of the average annual runoff for 30-year periods and their average absolute deviation from the values for the long-term period (Desna – Chernihiv)*

Stream gauge	Statistical parameters	Periods								Average absolute deviation (average)	
		1895-2020	1901-1930	1916-1945	1931-1960	1946-1975	1961-1990	1976-2005	1991-2020	d, m^3/s	d, %
Desna - Chernihiv	$\bar{Q}$	**323**	327	346	341	306	324	348	302	11,3	3,5
	C_v	**0,29**	0,28	0,32	0,29	0,27	0,26	0,18	0,28	0,01	4,2
	C_s	**0,57**	0,42	0,43	0,73	1,35	0,77	-0,45	0,03	0,3	46,0

$\bar{Q}$ - norm, m^3/s; C_v - coefficient of variation; C_s – skewness.

The norm of annual runoff of the Desna River, determined for the studied 30-year periods, varies in the range of 0.4–7% compared to the norm of a long-term period, and on average by 3.5% (Figure 2). The lowest deviation (0.4%) from the value of long-term period is observed for the period of climatic norm (1961-1990).

The coefficients of variation for 30-year segments in comparison with its long-term value vary in the range of 0.3–11%, which indicates that a series of average annual water discharges is characterized by low variability. Based on the calculations, the skewness coefficient has the highest variability. The deviation over 30-year periods relative to its average value for the entire observation period is 26–95%.

The difference integral curves give a representation of water runoff fluctuations *(Bolbot and Grebin, 2019)*. A positive increasing sum of deviations means an average increase in the values of the characteristics of river water runoff and a negative decreasing sum characterizes the average decrease in water runoff. The positive increasing together with the negative decreasing sum form the full water cycle of the studied runoff characteristic. The constructed difference integral curve of annual water discharges of the Desna River near Chernihiv city indicates the presence of two water cycles (Figure 3).

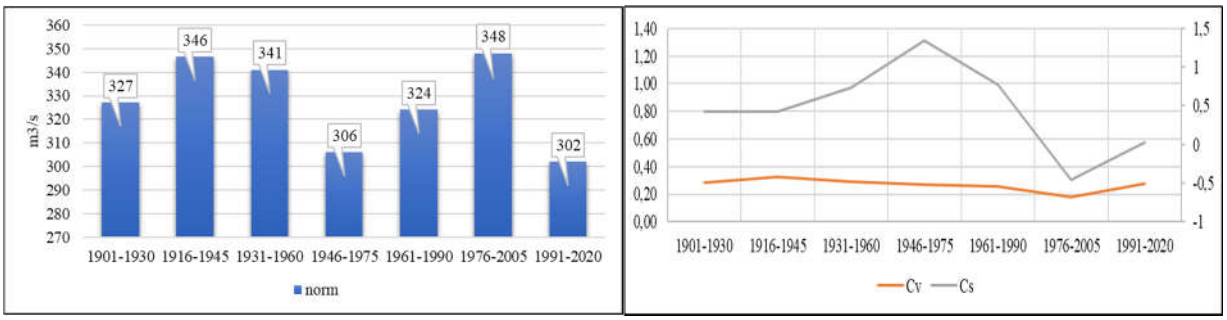

Figure 2 *Long-term change of the main statistical parameters of the distribution of the average annual water runoff - norms, coefficients of variation and skewnesses, over 30-year periods with 15 years overlap (Desna – Chernihiv).*

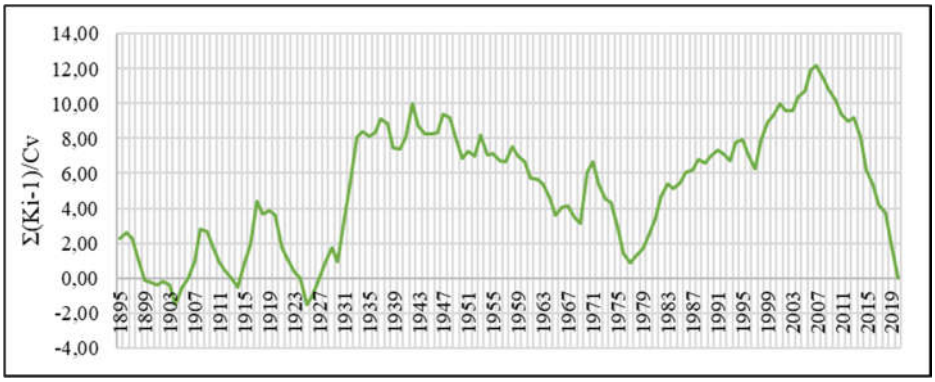

Figure 3 *Difference integral curve of average annual water discharges (Desna – Chernihiv).*

Difference integral curves are useful for studying directed changes in runoff, but they are only an auxiliary method in the calculations. Autocorrelation (Figure 4) and spectral analysis (Figure 5) were used to identify the duration of cycles in the long-term variability of the average annual runoff of the Desna River.

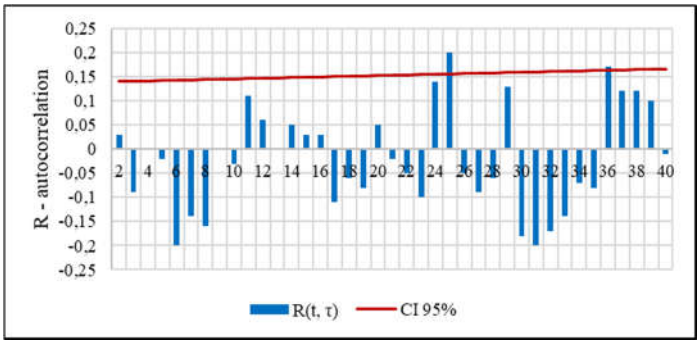

Figure 4 *Autocorrelation function of the average annual water runoff (Desna – Chernihiv) with a offset from 2 to 40 years.*

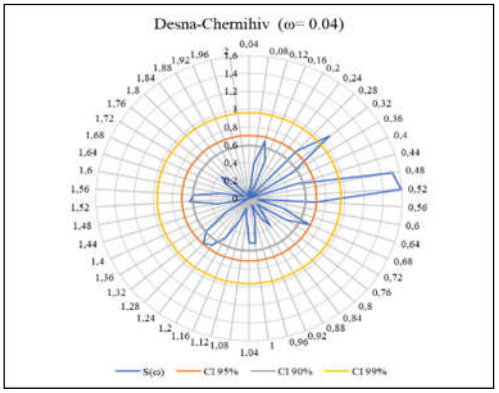

Figure 5 *Spectral density function (with frequency ω = 0.04) of the average annual water runoff (Desna – Chernihiv).*

Given the specifics of water runoff series, the value of the time offset τ_m for the construction of the autocorrelation function gives the following restriction: $\tau_m = [1/(3\div4)] \cdot n$, where n is the length of the series. Therefore, the range of offset values, taking into account the length of realization of the average annual water discharges of the Desna River (126 years), is accepted from 2 to 40 years. Analyzing the autocorrelogram, it is possible to note features in its structure. Positive ordinates of the autocorrelation

function, which exceed the confidence limits, determine the duration of the predominant river water cycle with a 95% probability. As can be seen from Figure 4, multiple recurrences are observed in the form of 25-year and 36-year cycles.

The method of spectral analysis allows to decompose the variance of the studied function into its components at different circular frequencies $\omega = 2\pi/T$ *(Khristoforov, 1994)*. The value of the spectrogram calculated at one or another frequency is considered reliable if it exceeds the accepted $Cl_{S(\omega)}$, which indicates the existence of the cyclic frequency detected in this range *(Luk'yanets' and Kamins'ka, 2015)*. Analyzing the functions of the spectral density (with a frequency of $\omega = 0.04$) of the time sequences of the annual water discharges for the Desna River near Chernihiv city, established that the spectral densities of 0.46-0.56 and 0.26-0.34 predominate. So, this corresponds to cyclicity of 11-14 and 19-24 years (Figure 5).

Conclusions. Thus, in the course of the study it was established that the average annual water discharges of the Desna River near Chernihiv city for the period 1895-2020 is homogeneous, both in terms of equality of norms and the ratio of variances. The analysis of statistical parameters - norms, coefficients of variation and skewnesses for the whole initial series of annual water discharges and for separate consecutive 30-year periods and for 30-year periods with 15 years overlap showed that the most stable distribution parameters are norm and coefficients of variation. Thus, these parameters are characterized by slight variability over time. The norm of annual runoff of the Desna River for the studied 30-year periods changes by an average of 3.5% compared to the norm for long-term period and the coefficient of variation - by 4.2%. The difference integral curve of annual water discharges testified to the presence of water cycles. The application of autocorrelation and spectral analysis allowed to identify the duration of cycles in the long-term variability of the average annual runoff of the Desna River. The joint analysis of the autocorrelogram and the spectrogram allowed to allocate the mutually confirmed cycle of 24-25 years.

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