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VARIATIONS OF THE OPEN CHANNEL MINIMUM RUNOFF OF THE PRIPYAT RIVER AT THE MOZYR GAUGING STATION: CURRENT STATUS AND FORECAST

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Abstract

The article presents the results of a study of the sample estimates stability of statistical parameters for various intervals of the time series of open channel minimum water discharges of the Pripyat River at the Mozyr gauging station for the period from 1877 to 2020. The intervals of the series that differ in the degree of anthropogenic impact on runoff and the type of atmospheric circulation are considered. A conclusion is made about the presence of statistically significant changes in the dynamics of the open channel minimum runoff of the Pripyat River at the Mozyr station, caused by both natural climatic and anthropogenic changes in the hydrological cycle.

1 Introduction

Rational use of water resources and planning of economic activity for the future is impossible without knowledge of the patterns of water content formation in the territory, manifested in fluctuations of river runoff, which are of a stochastic nature. The water regime of rivers can objectively characterize the moisture content of large territories, since the water runoff is formed on the catchment area and in an integrated form in the closing section. This is especially true for the open channel minimum runoff, i. e. the minimum summer-autumn runoff.

One of the main natural resources of the Belarusian Polesie is water resources, which are characterized by dynamics, and their complex and rational use is impossible without predictive quantitative assessments.

The purpose of this work was an objective assessment of fluctuations in the open channel minimum water runoff of the Pripyat River at the Mozyr gauging station to characterize the water regime of the Belarusian Polesie in modern conditions and in the near future.

2 Materials and methods

Belarusian Polesie is located in the south of Belarus and occupies an area of about 61 thousand km², which is about a third of the country's territory. The surface is water-glacial and lake-alluvial sandy lowland with ancient floodplain terraces. The climate is warm, unstable-humid, approaching forest-steppe in the southeast. The average January temperature is from –4.4 °C in the west to –7 °C in the east, July – from 18 °C to 19 °C. Precipitation is 520–645 mm per year [1]. Large-scale melioration in the middle of the last century and modern climate changes have made a significant contribution to the natural development of natural processes in the region.

In the study of temporary fluctuations in the water regime of rivers, the most complete information can be achieved by analysing long-term time series of hydrological characteristics that are formed from large catchments. For these purposes, a time series of open-channel minimum water discharges of the Pripyat River at the Mozyr gauging station were used (catchment area of 101,000 km^2). The main river, the Pripyat, with numerous tributaries and a dense network of drainage canals and ditches, with a large number of floodplain lakes, the catchment of which includes most of Polesie, is a typical trans boundary river of Europe, flows through the territory of two states, Belarus and Ukraine, and determines both the water regime of the region and its economy. The length of the studied time series is 144 years (from 1877 to 2020). The missing runoff values for 1877–1880, 1917, and 1941–1943 were calculated using the computer software package Hydrolog-2 [2, 3] using the river analogue of the Neman River at Grodno station, for which missing data on runoff were previously restored using the analogue river Neman at Smalininkai station[4]. One of the objectives of the study was to assess the stationary of time series of annual river runoff with varying degrees of anthropogenic load.

Long-term fluctuations of minimum open river channel water discharges (Q_{min}) are considered as a random process $Q_{min}(t)$ with discrete time $t \epsilon T$, taking integer values. In particular, the value $t = 1, 2,..., k$ can be attributed to the available series of observations for k years; the values $t = 0, k–1, k–2...$ relate to the previous period of time, and the value $t = k + 1, k + 2...$ – to the next. To describe the process $Q_{min}(t)$, a whole set of functions was used: mathematical expectation $m(t) = M\{Q(t)\}$, variance $D(t) = D\{Q(t)\}$, standard deviation $\sigma(t) = \sqrt{D(t)}$, probability distribution $F(x, t) = P\{Q(t) < x\}$; autocorrelation function $R(t,\tau) = corr\{Q(t), Q(t + \tau)\}$, etc. [5–7].

The assessment of the agreement between the adopted theoretical scheme and the empirical material was carried out using statistical hypotheses of the homogeneity of time series of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station according to the standard parametric Student's criteria (assessment of the t-statistic – the significance of norms) and Fisher's (assessment of the F-statistic – the ratio of variances).

3 Results and discussion

Figure 1 shows the long-term course of minimum open-channel water discharges of the Pripyat River at the Mozyr gauging station. The graph shows some cyclical oscillations: in the period from 1877 to 1893, there is a slight increase in water content, which is replaced by a decrease in water content until 1910, and then from 1939 to 1980 there is an increase in water discharges, then a decline until 1995 and then a decline until the end of the calculation period. At the same time, in 1913, 1933, 1980 and 1998, the highest minimum open-channel water discharges were observed for the entire observation period – 411, 421, 402 and 434 m^3/s, respectively. The lowest minimum summer-autumn water flow was observed in 2015 and amounted to 48 m^3/s.

Table 1 presents selected estimates of the main statistical parameters of the considered time series of minimum open channel flow for the period from 1877 to 2020.

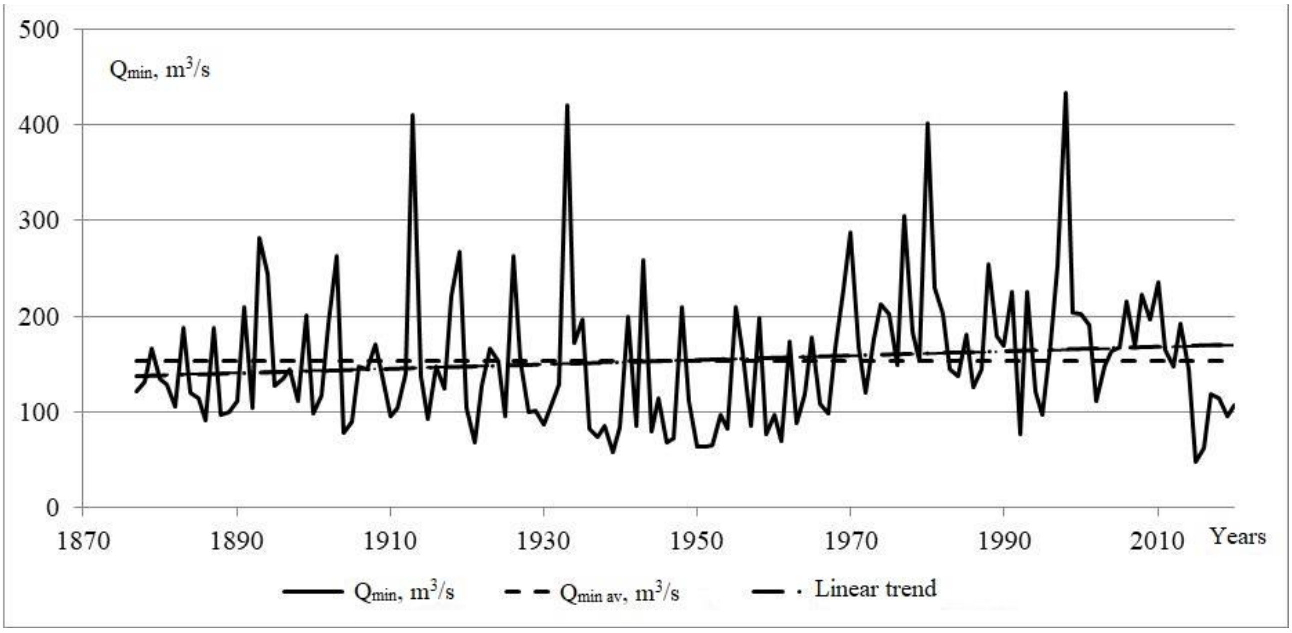


Figure 1 – Long-term course of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

Table 1 – Main statistical characteristics of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station for the period 1877–2020

Average runoff, $\bar{Q}_{min.s.}$, **m^3/s**	**Coefficients**		
	of variation C_v	**of asymmetry Cs**	**of autocorrelation $r(1)$**
154	0.47	1.48	0.20

The empirical curves of availability correspond to a three-parameter gamma distribution at $C_s = 3C_v$. Since the probability distribution function of the annual runoff at such parameter estimates differs slightly from the normal distribution function, the use of parametric criteria for testing statistical hypotheses can be considered acceptable. The histogram constructed for the minimum open channel water discharges shows that the distribution is close to normal (Figure 2).

Let us consider the stability of sample statistics (averages, variation coefficients) when changing the averaging periods in relation to the open channel minimum runoff of the Pripyat River at the Mozyr gauging station for 1877–2020 (n = 144 years). Testing for homogeneity of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station using parametric criteria at a significance level of $2\alpha = 5$ % yielded the following results: $t = 1.44 < t_{cr} = 1.98$ (the hypothesis on the significance of norms is not rejected) and $F = 1.02 < F_{cr} = 1.48$ (the hypothesis on the ratio of variances is not rejected), which indicates the homogeneity of the time series. To confirm the homogeneity hypotheses, a summary integral curve of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station was constructed [7]. As can be seen (Figure 3), there are no sharp turning points, which indicates the absence of fundamental changes in the studied characteristics of the water regime, although it has a slight bend in the years of active large-scale melioration.

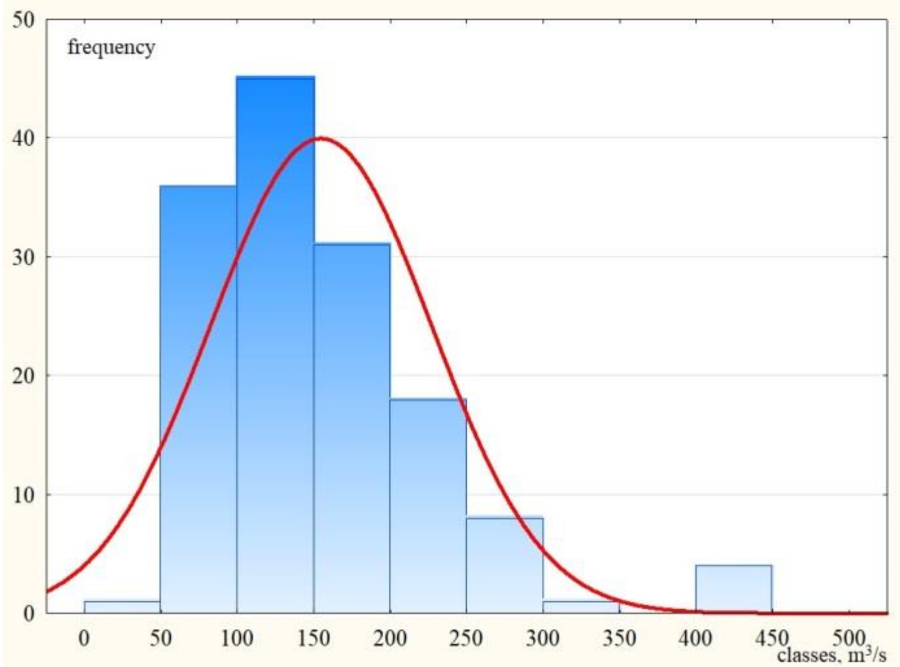


Figure 2 – Histogram of the distribution of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

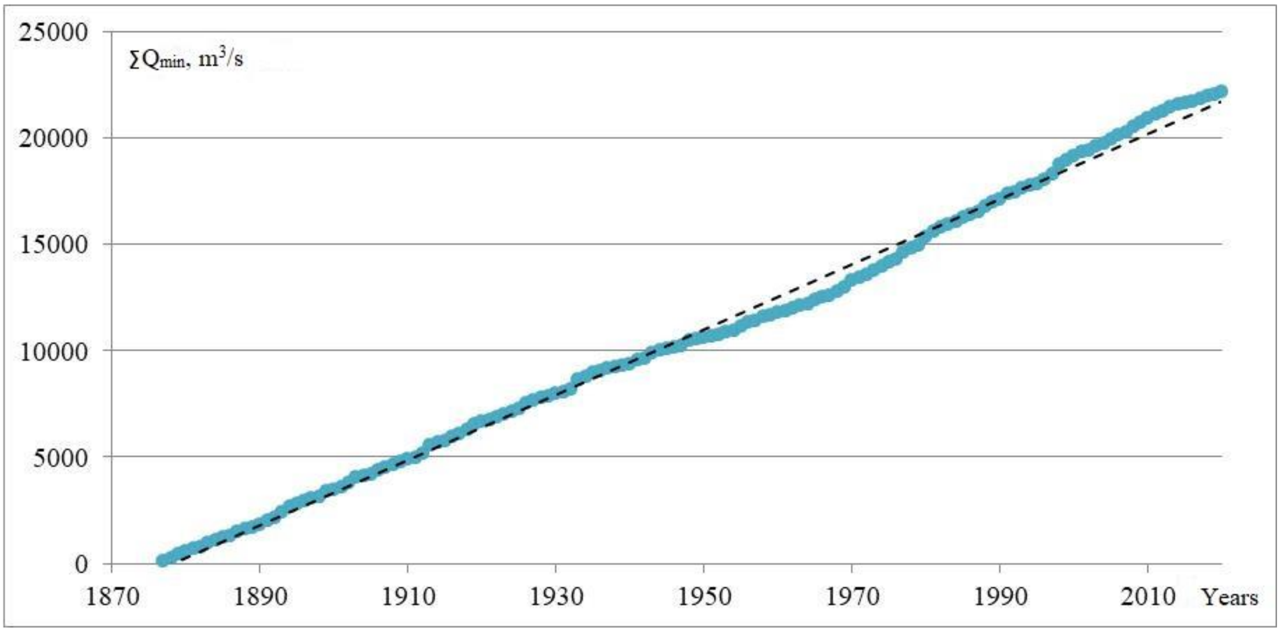


Figure 3 – Total integral curve of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

To study the impact of large-scale melioration and modern global warming, a comparative analysis of three intervals was performed: 1877–1964 – the period of minimal anthropogenic impacts; 1965–1986 – the period of active melioration impacts; 1987–2020 – the period of modern global warming. Table 2 shows the main statistical parameters of these intervals of the studied time series, and table 3 shows the matrix of Student's and Fisher's statistical criteria and their critical values.

Table 2 – Main statistical parameters of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station for different intervals

Period	**Statistical parameters**				
	***N*, years**	**$Q_{min.\ s.\ av.}$, m^3/s**	***Cv***	***Cs***	***r*(1)**
1877–1964	88	139	0.50	1.84	0.06
1965–1987	23	187	0.37	1.57	0.14
1988–2020	52	171	0.42	1.31	0.37

The analysis of the average values of the open channel minimum water discharges for the three periods under consideration shows that the null hypothesis can be accepted only between the periods 1965–1987 and 1988–2020. For the periods 1877–1964 and 1965–1987, as well as 1877–1964 and 1888–2020, the null hypothesis of equality of means should be rejected. This is due to the massive melioration of Polesie, when centuries-old groundwater reserves were discharged, as evidenced by the highest river water discharges (Table 2). At the same time, there is no reason to reject the null hypothesis for variances. Thus, the nature of fluctuations in the open channel minimum water discharges of the Pripyat River at the Mozyr station is stable. No differences in autocorrelation coefficients were found using criterion statistics at the 5 % significance level [8].

Table 3 – Statistical criteria (numerator) for different intervals of the time series of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station and their critical values (denominator)

Period	**1965–1987**		**1988–2020**	
	***t*-test for means**	***F*-criterion for dispersions**	***t*-test for means**	***F*-criterion for dispersions**
1877–1964	**2.97/2.03**	1.02/1.67	**2.18/2.00**	1.10
1965–1987	–	–	0.87/2.01	1.07/1.97

Note: Highlighted values are statistically significant.

When studying the patterns of long-term fluctuations in river runoff, a joint analysis of the runoff dynamics and generalized characteristics of atmospheric circulation is of undoubted interest. The latter is usually represented by the classification of Vangengeim – Girs, based on three forms of circulation W (western), E (eastern) and C (meridional) [9]. This issue for meteorological series is considered in detail in the monograph by V. Loginov [10], where their complete analysis is given. Therefore, in this paper we will briefly dwell on the relationship between the open channel minimum runoff of the Pripyat River at the Mozyr gauging station and the type of atmospheric circulation. As can be seen from table 4, the range of changes in the characteristics of the minimum open channel runoff is quite significant and its extreme values are significantly greater (less) than similar values for the n-year periods of the original series.

The hypothesis about the homogeneity of the considered parameters of the open channel minimum runoff for periods with different circulation types was tested using the Student's and Fisher's tests. As the analysis showed, for some segments the differences in the parameters are significant and can be considered statistically significant. According to the mathematical expectation, the following periods are statistically distinguishable: 1881–1890 (atmospheric circulation type C) from 1891–1928 (W), 1965–1988 (E) and 1989–2010 (W); 1891–1928 (W) from 1949–1964 (E+C), 1989–2010 (W) and 2011–2020 (E); 1940–1948 (C) and 1965–1988 (E); 1949–1964 (E+C) and 1989–2010 (W); 1965–1988 (E) and 1949–1964 (E+C) and 2011–2020 (E); 1989–2010 (W) and 2011–2020 (E). The period 1965–1988 (E) and 1989–2010 (W) are the periods with the highest water levels, so they differ from most other periods, including 1891–1928 (W) with a similar circulation type. If we arrange the periods of atmospheric circulation types in descending order of water content, the minimum water discharges of the open channel of the river Pripyat, the following picture is obtained: W – E – W – E – C – C – E – E+C. The considered segments are less heterogeneous in terms of dispersion. Here, the greatest variability is observed in the period 1929–1939 (E), which is statistically distinguishable from the periods: 1891–1928 (W), 1949–1964 (E+C), and 2011–2020 (E). For the remaining periods, statistically significant differences in the nature of runoff fluctuations were not established. Thus, the analyzed series of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station is heterogeneous in terms of mathematical expectation and dispersion. At the same time, it can be assumed that for individual time periods with predominance of one or another type of atmospheric circulation, the stationary conditions are met. The transition from one state to another occurs in natural conditions under the influence of external climatic factors, which significantly change the relationship between precipitation and evaporation within the territory of the Pripyat basin. Long-term fluctuations in the flow of the Pripyat River are caused by climatic factors, the reason for which lies in the processes of large-scale moisture exchange in the ocean-atmosphere-land system [9].

Table 4 – Main statistical parameters of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station for different periods

Period	***n*, years**	**Type of atmospheric circulation**	**Statistical parameters**					
			***Q*, m³/s**	**σ, m³/s**	***Cv***	***r*(1)**	**α10, years**	***r***
1881–1890	10	C	124	35.2	0.28	–0.36	–21.4	–0.28
1891–1928	38	W	157	66.3	0.42	–0.02	–5.26	–0.08
1929–1939	11	E	137	103	0.75	0.20	–57.2	–0.18
1940–1948	9	C	130	72.4	0.56	–0.47	–10.5	–0.04
1949–1964	16	E+C	110	48.6	0.44	–0.05	22.7	0.22
1965–1988	24	E	189	69.5	0.37	0.11	12.1	0.12
1989–2010	22	W	190	71.38	0.38	0.18	13.6	0.12
2011–2020	10	E	120	44.6	0.37	0.48	–80.9	–0.55

The concept of cyclicity of long-term fluctuations in the open channel minimum runoff was used in parallel with the concept of randomness. Cyclic fluctuations (cyclicity) are understood as the variability of the values of time series, which has a different degree of regularity, provided that there are mathematical expectations of the parameters of these fluctuations. When analysing observation series, identifying the cyclicity of long-term fluctuations comes down to determining groups of years with increased and decreased runoff values. The most common way to identify trends in grouping years with relatively large and small flow values, which are due to correlations within the series or the presence of a cyclic trend, is a graphical analysis of the difference integral curve (Figure 4).

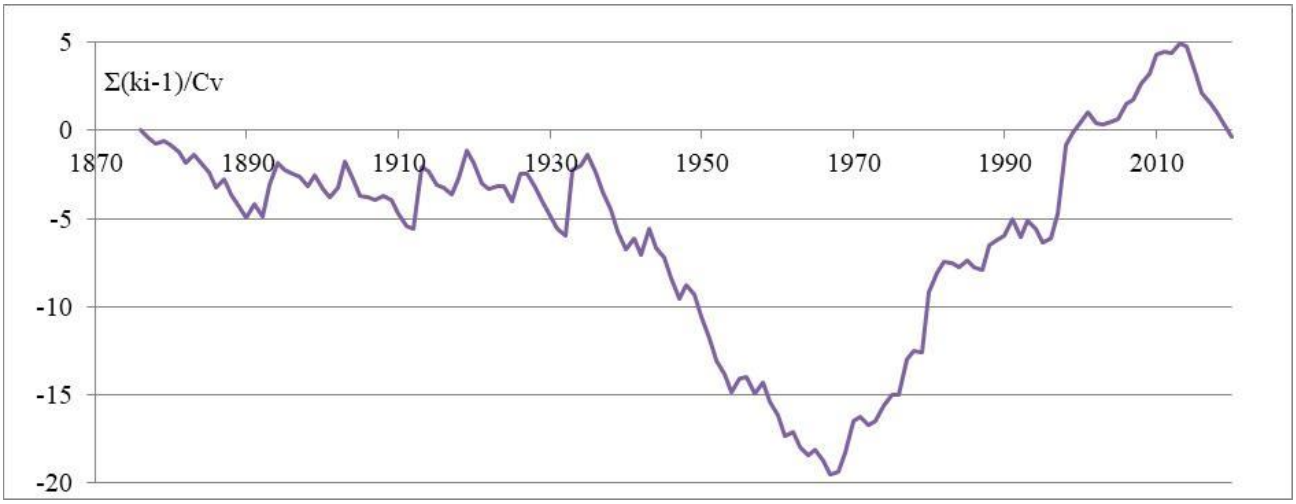


Figure 4 – Normalized difference integral curve of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

The difficulty in using cycles to forecast runoff is their aperiodicity, since the phase, amplitude and duration of the cycle change without visible patterns. In addition, there is no consensus on the nature of these cycles: there is no objective method for identifying and analysing river water cycles. It is believed that cycles are caused either by the influence of external (cosmophysical factors), or by self-oscillatory processes in the Earth's atmosphere-hydrosphere system, or by the natural properties of any random sequence.

Based on samples of different lengths, statistical parameters of runoff were estimated and the degree of their change from sample to sample was studied. Samples were constructed as sections of the studied series, differing in the starting point and length. In particular, segments of the series were considered that differed in the degree of anthropogenic impact on runoff and the type of atmospheric circulation. In addition, statistical parameters were determined for segments of the original series, obtained as a result of the procedure of moving 20-year, 30-year, 35-year and 50-year averaging. The homogeneity of sample statistical parameters was tested using Student's and Fisher's test criteria [11].

As can be seen from figure 5 and 6, the extreme values of the mathematical expectation of different averaging periods have a significant range. This is due to the low-water period of the 30–70s of the last century, which introduces significant differences into the time series of the open channel minimum water discharges of the Pripyat River at the Mozyr station. Such differences in the parameter estimates indicate the use of the hypothesis of non-stationarity of the considered time series, which is confirmed by testing the hypothesis of homogeneity of the considered statistical parameters for different smoothing periods, which, with a confidence probability of 5 %, discrepancies in these parameters can be recognized as statistically significant in all cases under consideration. Comparison of long-term sliding changes in averages and variances shows weak synchronicity in their changes.

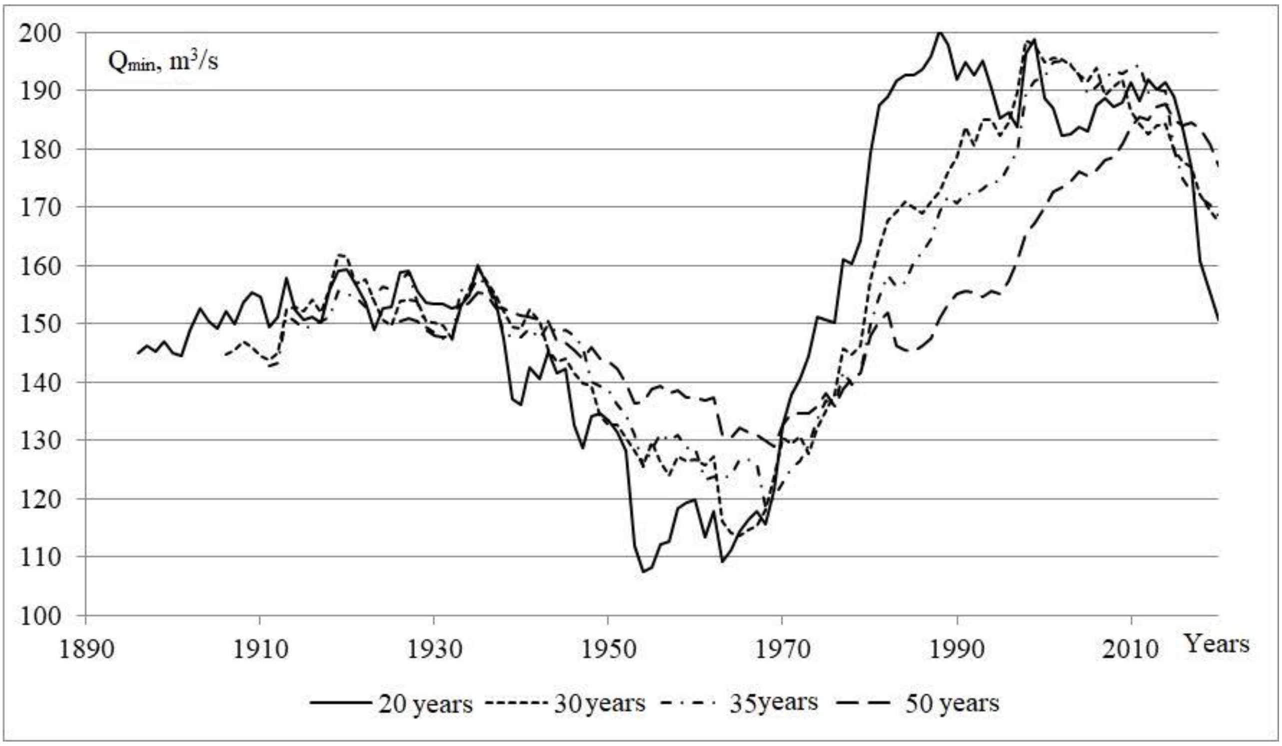


Figure 5 – Dynamics of moving averages for different periods of averaging the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

The greatest dispersion is observed at the beginning of the 20th century to its middle, while the average values of runoff at this time were not extreme. At the same time, the high-water period of the last quarter of the 20th century coincided with increased runoff variability. High runoff variability in the 30–70s of the 20th century falls on both the years of high and low water content.

Due to the fact that both criteria give comparable results, the use of the cyclicity principle (quasi-periodicity) in the analysis and forecast of long-term fluctuations in the minimum summer-autumn runoff is acceptable.

When the trend is not clearly expressed, it is necessary to consider together the sample autocorrelation (ACF) and partial autocorrelation (PACF) functions of the given process, with the help of which the nature of the change in the open channel minimum runoff of the rivers is determined. In this case, the following criteria for assessing the degree of non-stationarity of the process and choosing a model are used, given in [9, 12].

In our case, the ACF and PACF have a significant value at $\tau = 1$ and $\tau = 10$, while all other values of their ordinates are statistically insignificant and are characterized by alternating positive and negative values (Figure 7).

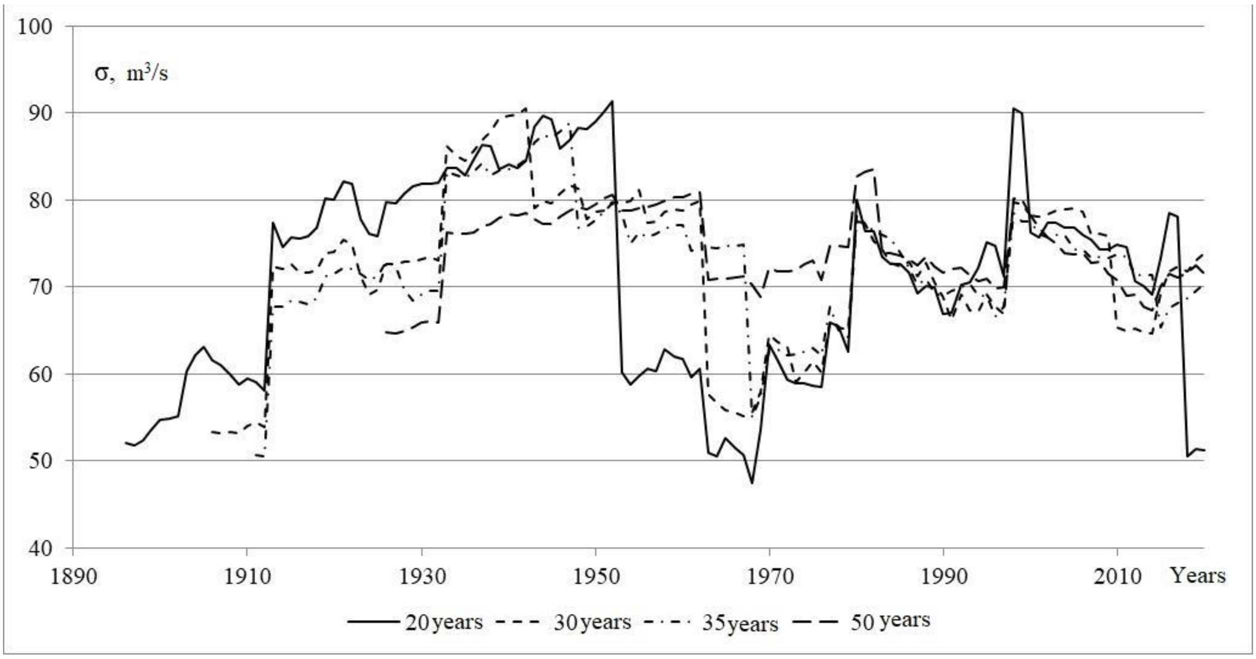
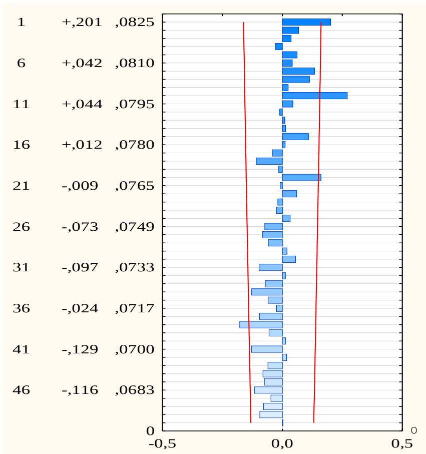
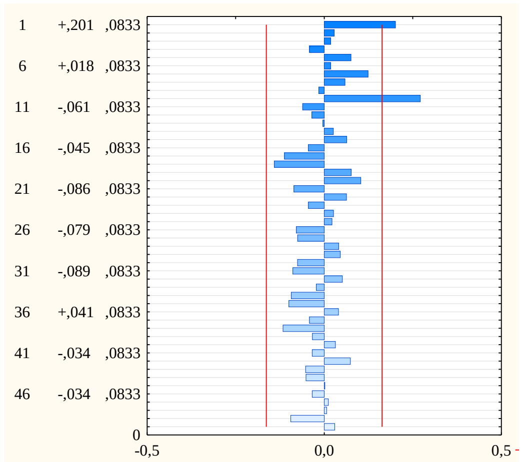


Figure 6 – Dynamics of moving dispersions for different periods of averaging the open channel minimum runoff of the Pripyat River at the Mozyr gauging station

a)



b)



Therefore, the considered process of minimum open channel runoff can be identified by the AR(1) model, of the following type:

$$Q_{\min.s.}(t) = Q_{av.\min.s} + r(1)\cdot[Q_{\min.s.}(t-1) - Q_{av.\min.s}] + \xi(t), \quad (1)$$

where $Q_{\min.s.}(t)$ and $Q_{\min.s.}(t-1)$, m^3/s – open channel minimum runoff rates in the t and preceding (t-1) years; $\xi(t)$ – Gaussian "white noise" with zero mean and $\sigma_\xi = \sigma_Q \cdot \sqrt{1-r(1)^2}$.

In accordance with equation (1) for the time series of minimum water discharges of the open channel minimum runoff of the Pripyat River at the Mozyr gauging station at $r(1) = 0.20$ and $Q_{av.min.s.} = 154$ m^3/s (table 1), as well as σ_ξ = 72.4 m^3/s and σ_Q = 70.9 m^3/s.

$$Q_{\min.s.}(t) = 0.20\cdot Q_{\min.s.}(t-1) + 123 + \xi(t).$$

The correlation coefficient between the open channel minimum runoff rates of the current year and the previous year is r = 0.20> $r^T(141, 5\%) = 0.16$.

Of practical interest is the identification of patterns in the dynamics of the main hydrological parameters: smooth increase or decrease (monotonic trend), periodic changes (cyclic trend), constancy over some periods of time and sharp changes when moving from one segment to another (step trend). All these situations can be described by a polynomial approximation of the trend of the type [9]:

$$Q_{av}(t) = a_0 + \sum_{i=1}^{k} a_i \cdot \phi_i(t), \quad (2)$$

where $\varphi_i(t) \ldots \varphi_k(t)$ – given time functions; $a_0 \ldots a_k$ – regression coefficients.

Time functions can be either linear, power, exponential or logarithmic for a monotonic trend, or trigonometric for a cyclical trend and piecewise constant for a step trend. In all these cases, the parameters $a_0 \ldots a_k$ are estimated from the available series of observations $X_1 \ldots X_n$.

The first term in the right-hand side of (2) can be interpreted as the runoff caused by the atmospheric precipitation of the previous year, accumulated by the river basin and discharged into the riverbed in the current year. In this case, the random component $\xi(t)$ in (2) should obviously include that part of the runoff of the current year that is formed due to precipitation in the first half of this year. As a result, the following equations can be written [9]:

$$Q(t) = a \cdot Q(t-1) + b \cdot W_{pr}(t) + \xi(t_1), \quad (3)$$

$$Q(t) = c \cdot W_{pr}(t-1) + d \cdot W_{pr}(t) + \xi(t_2), \quad (4)$$

where $W_{pr}(t)$ and $W_{pr}(t-1)$ – precipitation of the first half of the current year and the entire volume of precipitation of the previous year.

With time series of annual values of precipitation and river runoff, the coefficients *a*, *b*, *c*, *d* from (4) and (5) can be determined using the multiple regression apparatus. With regard to the Pripyat basin at the Mozyr station for the open channel minimum water runoff rates, the following equations were obtained:

$$Q(t) = 0.059 \cdot Q(t-1) + 0.493 \cdot W_{pr}(t) + 71.02 + \xi(t_1), \quad (5)$$

$$Q(t) = 0.205 \cdot W_{pr}(t) + 0.120 \cdot W_{pr}(t-1) - 9.173 + \xi(t_2). \quad (6)$$

The multiple correlation coefficient for equation (5) is $R = 0.48 > R^T_{(73, 5\%)} = 0.231$, and for equation (6) is $R = 0.58 > R^T_{(73, 5\%)} = 0.231$.

We have attempted to describe the fluctuations in the minimum open channel water flow rates of the Pripyat River at the Mozyr station using a complex Markov model with a shift of up to 50 years. Regression-correlation analysis has shown that $Q(t-1)$; $Q(t-7)$ and $Q(t-10)$ and special type of model can be used to construct the model:

$$Q(t) = 0.267 \cdot Q(t-1) + 0.220 \cdot Q(t-7) + 0.220 \cdot Q(t-10) + 43.5 + \xi(t). \quad (7)$$

The multiple correlation coefficient for equation (7) is $R = 0.43 > R^T_{(94, 5\%)} = 0.203$.

4 Conclusion

The conducted assessment of the degree of homogeneity of the main statistical parameters of the open channel minimum runoff of the of the Pripyat River at the

Mozyr gauging station for almost 150 years can be considered conditionally homogeneous, statistically significant changes in the open channel minimum flow occur only in certain intervals due to natural climatic changes in the hydrological cycle. When analyzing the patterns of long-term fluctuations in the open channel minimum runoff of the rivers, the use of methods of the theory of random processes should be combined with an analysis of the genesis of the process under consideration and the natural and economic factors that determine it, primarily climatic ones.

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