ГЕОЭКОЛОГИЯ

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ANTHROPOGENIC IMPACT ON THE RIVERS OF THE BELARUSIAN POLESIE (USING THE LAN RIVER AS AN EXAMPLE)

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Abstract
The work is devoted to assessing changes in the water regime of the Lan River in modern conditions and the near future with the aim of developing a strategy for the rational use of the water potential of small rivers in the Belarusian Polesie region. There was a tendency towards an increase in annual runoff at the Loktyshi and Mokrovo gauging stations during the study period from 1948 to 2015, which was caused by anthropogenic factors in the form of amelioration measures; and in the upper reaches of the river at the Lognovichi gauging station there was a slight decrease in runoff caused by climatic influences. Testing the hypothesis about the homogeneity of the runoff series under consideration for periods with different averaging intervals has showed heterogeneity for some types of runoff. This was caused by intensive economic activity, which significantly disrupts the natural hydrological regime. A runoff forecast was made for the Lan River at the Mokrovo gauging station for the period up to 2035 based on archive of meteorological data using a multi-model ensemble of four CMIP5 scenarios. A slight decrease in runoff was predicted, caused by additional evaporation from the water surface of the reservoir due to increased air temperature, as well as a slight shift in the peak of the spring flood to March.

Keywords: runoff, anthropogenic factors, climate changes, forecast, Lan River, Belarusian Polesie.

АНТРОПОГЕННОЕ ВОЗДЕЙСТВИЕ НА РЕКИ БЕЛОРУССКОГО ПОЛЕСЬЯ (НА ПРИМЕРЕ РЕКИ ЛАНЬ)

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Реферат
Работа посвящена оценке изменений водного режима реки Лань в современных условиях и на ближайшую перспективу с целью разработки стратегии рационального использования водного потенциала малых рек Белорусского Полесья. За исследуемый период с 1948 по 2015 г. на гидропостах Локтыши и Мокрово наблюдалась тенденция к увеличению годового стока, что было обусловлено антропогенными факторами в виде проведения мелиоративных мероприятий, а в верховьях реки на гидропосте Логновичи наблюдалось некоторое уменьшение стока, вызванное климатическими воздействиями. Проверка гипотезы об однородности рассматриваемых рядов стока для периодов с различными интервалами осреднения показала неоднородность по некоторым типам стока. Это обусловлено интенсивной хозяйственной деятельностью, которая существенно нарушает естественный гидрологический режим. На основе архива метеорологических данных с использованием многомодельного ансамбля из четырех сценариев CMIP5 выполнен прогноз стока реки Лань в створе Мокрово на период до 2035 г. Прогнозируется незначительное уменьшение стока, вызванное дополнительным испарением с водной поверхности водохранилища из-за повышения температуры воздуха, а также небольшим смещением пика весеннего половодья на март.

Ключевые слова: сток, антропогенные факторы, изменения климата, прогноз, река Лань, Белорусское Полесье.

Introduction

The nature of fluctuations in water resources is determined by climatic factors, but starting from the second half of the 20th century, the role of the anthropogenic component in a number of cases becomes comparable to natural influences. Thus, it can be stated that the end of the 20th – beginning of the 21st century is characterized by pronounced climate variability and an increase in anthropogenic impact on water resources [1–4]. Natural causes determine the spatiotemporal fluctuations of water resources depending on differences in its physical and geographical conditions, as well as under the influence of the annual and secular course of climatic conditions affecting the formation of water resources. Intra-annual fluctuations occur constantly and consistently. The main feature of natural causes is that the changes that occur do not have a one-sided tendency [5–7].

Anthropogenic causes are the result of various types of human activities. They affect water resources and water quality relatively quickly and unilaterally, which is their main difference from natural causes [8, 9]. The types of economic activities that cause changes in the quantitative and qualitative characteristics of water resources are very diverse and depend on the physical and geographical conditions of the territory, the characteristics of its water regime and the nature of its use [10, 11].

The increased unevenness of precipitation and rising air temperatures in the territory of the Belarusian Polesie in recent decades have led to an increase in the frequency of drought events. In recent years, there have been numerous cases of shallowing, pollution and disappearance of small rivers under the influence of anthropogenic factors, which have recently been aggravated by modern climate change [12].

The listed climatic and anthropogenic factors have a huge impact on the formation of the river runoff of the Belarusian Polesie, therefore the main goal of this work was to assess changes in the flow regime of the Lan River in modern conditions and in the near future. Such an assessment will allow us to gain an understanding of the processes on the small rivers of the Belarusian Polesie and develop a scientifically based strategy for the conservation and rational use of the water potential of the small rivers in the region.

Materials and methods

The Belarusian Polesie is a unique natural site, with numerous small rivers and lakes, located in the south of Belarus and covers an area of about 61 thousand km², which is approximately a third of the country's territory. The length of the region's territory from west to east is about 500 km, from north to south – about 200 km. Small rivers of the Belarusian Polesie are very sensitive to changes in natural factors and anthropogenic impacts and are most vulnerable, unlike medium and large rivers.

The climate of the Belarusian Polesie is determined by its geographical location in the temperate latitudes of the Northern Hemisphere. The amount and nature of the distribution of atmospheric precipitation over the territory of are determined by a number of factors, the main of which are the charac-

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teristics of atmospheric circulation and the terrain. On average, 600–650 mm of precipitation falls annually in Polesie. Deviations from long-term average values are often observed. In wet years, up to 800 mm of precipitation falls, in dry years it is about 500 mm. The study area is characterized by high air humidity throughout the year, which is due to the predominance of temperate sea air from the Atlantic Ocean, relatively low temperatures in the warm season, and vast areas occupied by wetland complexes and forests. Average annual air temperature within the territory of the Belarusian Polesie for the period 1988–2015 increased by 1.3 °C compared to the period 1945–1987 and amounted to 7.8 °C.

The Lan River is a typical river of Belarusian Polesie and the left tributary of the Pripyat River (Figure 1). The length of the Lan River is 147 km, the catchment area is 2190 km², the average annual water flow at the mouth is about 11.3 m³/s [13]. The floodplain is 0.6–1 km wide and is crossed by irrigation canals. The riverbed is canalized. The depth range in the river is 1.5–2.5 m. The width of the channel is 4–8 m, in the lower reaches 15–20 m. Small slopes of the channel and wide floodplains create favorable conditions for the accumulation of river water during high water and summer flash floods, which leads to swamping in the surrounding areas, a dense network of irrigation canals and ditches [14]. The Loktyshi reservoir of the riverbed type was created on the river in 1977 for water supply of the Loktyshi fish farm. The bottom of the reservoir is flat, mostly muddy. Water level fluctuations throughout the year are up to 2 m. The area of the reservoir is 15.9 km², length is 6 km, maximum depth is 4.9 m, maximum width is 4.2 km, water volume is 50.2 million m³, catchment area is 940 km² [13]. The highest flood level is observed in April, the average height above the low-water level before river regulation is 1.5 m, and the highest is 1.9 m (1947) near the village of Loktyshi.

Time series of runoff (annual, maximum, minimum summer-autumn and minimum winter) of the Lan River were used as initial data from 3 gauging stations: Lognovichi with a catchment area A = 480 km² and observation period from 1979 to 1988; Loktyshi (A = 909 km²; 1948–1977) and Mokrovo (A = 2550 km²; 1975–2015). For comparability of the results obtained, a single calculation period from 1948 to 2015 lasting 68 years was adopted. The restoration of gaps in data series was carried out using the "Hydrolog" computer software package [15] with the involvement of analogue rivers.

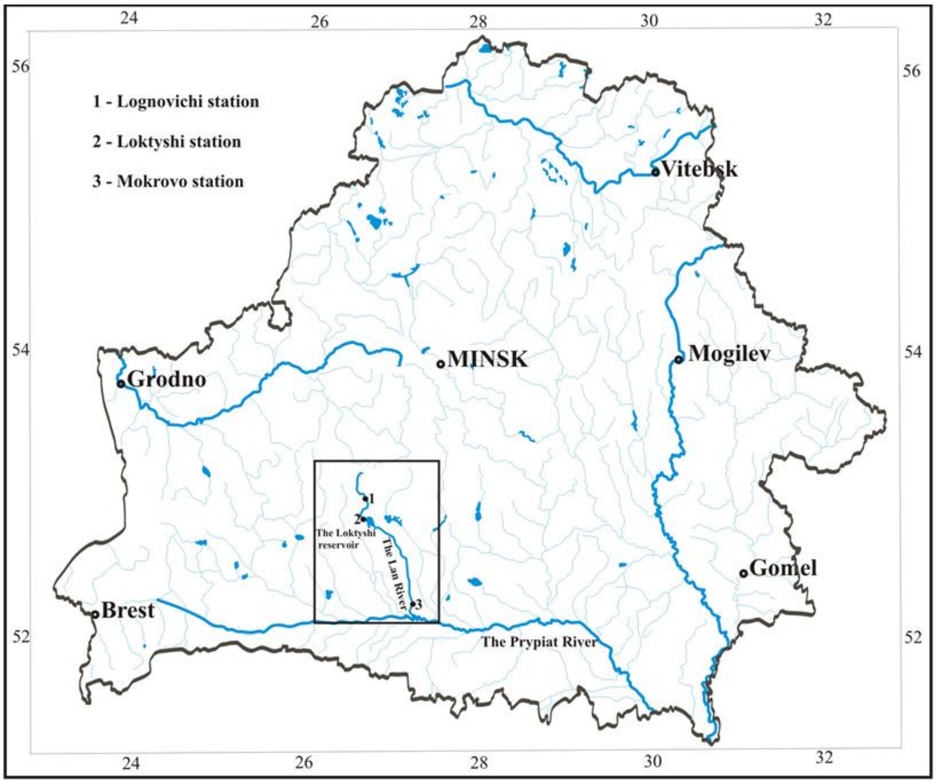

Figure 1 – The map of the study area

The "Hydrolog" computer program was developed in 2009 on the basis of regulatory documents and methods used in hydrology, and software is constantly being improved to take into account modern requirements in the field of hydrological calculations. The program implements many functions, one of which is the extension of time series in the absence of observational data. For this purpose, up to 9 analogue rivers from the region under study are used in automatic or manual mode. The runoff correlation coefficient between the time series of the river under study and the analogue river is used as an indicator. The program displays an assessment of the calculation period and statistical information about analogue rivers, and implements a graphical representation of the hydrographs and the difference integral curve of the studied catchment. Next, to extend the time series of the river under study, one-, two-, or three-factor models are formed depending on the required values of the correlation coefficients and the ratio of the regression coefficients to their standard deviation. For extension models, it is possible to view the given statistical parameters of the original series (norm, dispersion, coefficients of variation, asymmetries and autocorrelation). Direct extension of the hydrological series under study is carried out using several regression equations in descending order of pair or multiple correlation coefficients. When extending, the main statistical parameters of the original and extended series are compared with the corresponding graphical representation. The "Hydrolog" software has been used in many organizations in Belarus and, during experimental testing, has shown very good results, including for solving the problem of extending hydrological series [15, 21].

The method of hydrological-climatic calculations was adapted for forecast in runoff changes of the Lan River. The method is based on the joint solution of the equations of water and heat-energy balances [16]. An algorithm and a computer model that includes a standard equation for the water balance of a land area with an independent assessment of the main elements of the balance (precipitation, evapotranspiration and climatic runoff) on an annual basis have been developed. The adapted model was used to assess possible changes in river water resources depending on certain hypotheses of climate fluctuations and anthropogenic impacts on the characteristics of the catchment area.

The equation of the water balance of the river basin for a certain period of time is as follows:

$$Y_C(I) = H(I) - E(I) \pm \Delta W(I) , \qquad (1)$$

where $Y_C(I)$ – the total climatic runoff [mm]; $H(I)$ – the total humidification resources [mm]; $Z(I)$ – the total evaporation [mm]; $\Delta W(I)$ – changes in moisture reserves of the active soil layer; I – averaging interval.

Total evaporation is calculated as follows:

$$Z(I)=Z_m(I)\left[1+\left(\frac{\frac{Z_m(I)}{W_{HB}}+V(I)^{1-r(I)}}{\frac{X(I)+g(I)}{W_{HB}}+V(I)}\right)^{n(I)}\right]^{-\frac{1}{n(I)}},\qquad(2)$$

where $Z_m(I)$ – the maximum evaporation [mm]; W_{HB} – the smallest moisture content of the soil [mm]; $V(I)=\frac{W(I)}{W_{HB}}$ – the relative humidity of soil at the beginning of the calculated period; $X(I)$ – the amount of precipitation [mm]; $g(I)$ – the groundwater component of the water balance [mm]; $r(I)$ – the parameter that depends on the water-physical properties and mechanical composition of soil; $n(I)$ – the parameter that takes into account physical and geographical conditions of runoff.

Relative soil moisture at the end of the calculation period is determined from the ratios

$$V(I+1)=V(I)\cdot\left(\frac{V_{cp}(I)}{V(I)}\right)^{r(I)};\qquad(3)$$

$$V_{cp}(I)=\left(\frac{\frac{KX(I)+g(I)}{W_{HB}}+V(I)}{\frac{E_m(I)}{W_{HB}}+V(I)^{1-r(I)}}\right)^{\frac{1}{r(I)}}.\qquad(4)$$

The obtained values $V_{cp}(I)$ are compared with the relative value of the total moisture capacity V_{PB}. If $V_{cp}(I)\le V_{PB}$, then the calculated value of the relative average humidity is taken, otherwise, $V_{cp}(I)=V_{PB}$ is taken into account for the calculation, the difference ($V_{cp}(I)-V_{PB}$)$\cdot W_{HB}$ refers to surface runoff.

The amount of atmospheric precipitation in the months of the cold period, minus the amount of total evaporation, is transferred to the flood period, i.e. for the month of March.

The total moisture resources are determined as follows:

$$H(I)=KX(I)+W_{HB}(V(I)-V(I+1)).\qquad(5)$$

The solution of the system of equations (1)–(5) is carried out using the iteration method until the value of the relative humidity of the soil at the beginning of the calculation interval is equal to the value of the relative humidity at the end of the last interval. When calculating, the initial value of humidity is taken equal to the value of the lowest moisture capacity, i. e. $W(1)=W_{HB}$, where $V(1)=1$.

Climate runoff is adjusted using coefficients that take into account the influence of various factors on the formation of riverbed runoff, i. e.

$$Y_R(I)=k(I)\cdot Y_C(I),\qquad(6)$$

where $Y_R(I)$ – total riverbed runoff [mm]; $k(I)$ – coefficient taking into account the hydrographic parameters of the catchment.

Modeling of the river water balance is implemented in the form of a computer program and is carried out in two stages. At the first stage, the model is calibrated taking into account the known components of the water-heat balance of the river under study. The goal of model tuning is to achieve the best possible conformity between measured and calculated runoff. The model parameters are varied for all possible values until a match is found between the two runoff types. The first stage ends with the construction of runoff graphs and the output of the modeling error (Figure 2). Good conformity between measured and calculated runoff indicates the validity of the model. The obtained model parameters then used to conduct a numerical experiment [20].

The second stage is a direct calculation of the water balance of the river under study, using the parameters obtained during model calibration. The calculation of the elements of the water balance of the river is carried out taking into account the specific features of the watershed under consideration and described in [17].

The simulation modeling technique have been tested on almost all the main climatic characteristics, which made it possible to attract an additional large amount of hydrometeorological information about possible variants of values and changes included in the balance equations of random variables.

The modeling results indicate a high accuracy of water balance calculations for both practical application and theoretical research, which has been tested on a large number of rivers in Belarus with a catchment area of about 1000 km², where hydrometric observations are carried out [17]. Thus, the created computer program in the presence of data on precipitation, air temperature, air humidity deficits for the calculation period and modern values of river runoff, as well as hydrographic characteristics of the watershed, allows one to obtain predictive estimates of the water balance of small rivers of the Belarusian Polesie for the estimated future [20].

To obtain forecast estimates of meteorological values, time series of observations were used for the period from 1986 (the beginning of the increase in average annual air temperatures) to 2015 with monthly increments. For this period, linear trends were constructed for monthly and annual values of atmospheric precipitation, air temperature and air humidity deficits, and the resulting parameters were used to obtain average monthly and annual values for the period until 2035. The procedure for assessing climatic parameters for the estimated future is presented in more detail in the work [18].

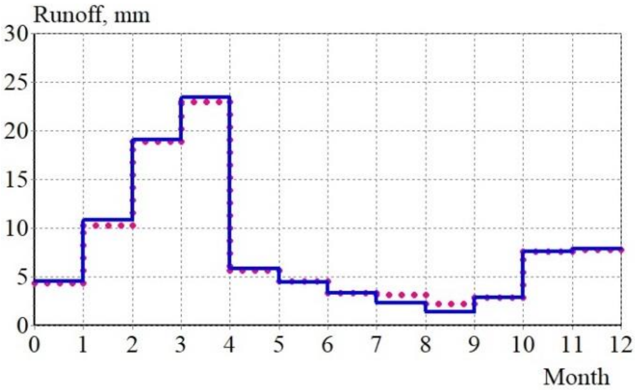

Figure 2 – Measured (------) and calculated (- - -) runoff during model calibration

Results and discussion

At the first stage of research, a procedure was carried out to bring hydrological series to a single calculation period from 1948 to 2015. Table 1 shows the main hydrological parameters of annual runoff, as well as the annual runoff of the different probabilities, determined using a three-parameter gamma probability distribution for two periods: directly from measured data and from representative period (68 years) for 3 gauging stations of the Lan River.

Figure 3 shows the long-term course of annual runoff for 3 gauging stations of the Lan River.

There was a tendency towards an increase in annual runoff along the Loktyshi and Mokrovo gauging stations by about 0.2 m³/s for 10 years. That was largely due to amelioration of the second half of the last century [19]. At the same time, there was a decrease in runoff (0.09 m³/s for 10 years) in the upper reaches of the river (the Lognovichi gauging station), that mostly were caused by climatic influences. For the maximum runoff throughout the river, there was a significant decrease in the maximum runoff due to natural factors (everywhere in Belarus there was a decrease in the maximum spring flood runoff [20]) and the accumulation of part of the spring flood runoff by the Loktyshi reservoir. The general trend of changes in the minimum runoff on the territory of Belarus was a widespread increase in winter runoff caused by modern climatic warming in the cold period, as a result of frequent thaws and an increase in runoff; summer runoff has not changed with the exception of the Belarusian Polesie, where there has been a slight increase in runoff caused by large-scale amelioration [18]. Fluctuations in the minimum runoff at the Loktyshi and Mokrovo gauging stations, both in summer-autumn and in winter, are determined by the operating regime of the reservoir and are predictable.

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Table 1 – Statistical parameters and annual runoff of the Lan River for 2 periods

Parameter		Gauging station		
		Lognovichi (A=480 km²)	Loktyshi (A=909 km²)	Mokrovo (A=2550 km²)
Number of years		10 / 68	29 / 68	40 / 68
Period		1979–1988/1948–2015	1948-1977/1948-2015	1975-2015/1948-2015
Average runoff, m³/s		1.90±0.17 / 2.04±0.07	3.68±0.19 / 4.09±0.13	8.84±0.53 / 8.59±0.46
Autocorrelation coefficient		0.37 / 0.16	-0.17 / 0.19	0.28 / 0.12
Flow rate, m³/s		1.94 / 2.04	3.71 / 4.12	8.84 / 8.59
Coefficient of variation (Cv)		0.22 / 0.27	0.29 / 028	0.29 / 0.36
Ratio (Cs/Cv)		3.5 / 3.0	5.5 / 4.0	2.5 / 2.0
Runoff of the different probabilities, m³/s	1 %	3.06 / 3.41	6.35 / 6.79	13.9 / 15.8
	5 %	2.64 / 2.91	5.26 / 5.76	12.1 / 13.3
	25 %	2.17 / 2.32	4.15 / 4.65	9.96 / 10.2
	50 %	1.89 / 1.98	3.58 / 4.00	8.68 / 8.32
	75 %	1.66 / 1.70	3.22 / 3.48	7.51 / 6.69
	95 %	1.38 / 1.35	2.64 / 2.88	6.09 / 4.76
	99 %	1.21 / 1.16	2.37 / 2.53	5.22 / 3.67

Note – The numerator (or the left value) shows data determined from observation period; the denominator (or the right value) shows data determined from representative period.

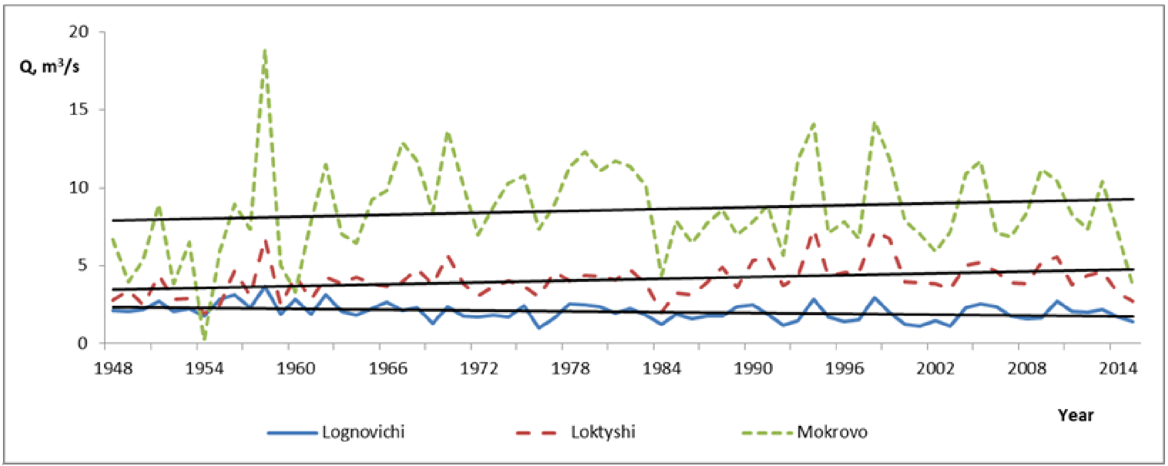

Figure 3 – The long-term courses of annual runoff of the Lan River and trends showed by straight lines for each gauging station

To assess the influence of anthropogenic impacts and natural factors on runoff, the original time series of runoff were analyzed for various averaging intervals: from 1948 to 2015 (the entire observation period, 68 years); from 1948 to 1977 (period before the commissioning of the Loktyshi reservoir, 30 years); from 1978 to 2015 (period of operation of the Loktyshi reservoir and the Loktyshi fish farm, 38 years). Table 2 presents sample estimates of the main statistical parameters of the considered runoff time series for various averaging periods.

Empirical supply curves for all averaging periods correspond to a three-parameter gamma distribution, and the ratio of the asymmetry coefficient (*Cs*) to the coefficient of variation (*Cv*), as a rule, does not exceed *Cs = 3Cv*. Since the runoff probability distribution function for such parameter estimates differs slightly from the normal distribution function, the use of parametric criteria for testing statistical hypotheses can be considered acceptable. Histograms constructed for the water flow rates under consideration indicate that the distribution is close to normal. Then the stability of sample statistics (averages and coefficients of variation) for the averaging periods 1948–1977 and 1978–2015 (assessment of the influence of the reservoir) in relation was analyzed. Table 3 shows the matrix of the Student and Fisher statistical tests for the considered types of the Lan River runoff.

Joint analysis of the Tables 2 and 3 allowed considering runoff changes of the Lan River caused by the construction of the Loktyshi reservoir by comparing the changes that occurred with runoff for the periods 1948–1977 and 1978–2015. Over the periods under review, the runoff at the Lognovichi gauging station decreased by 0.23 m³/s, at the Loktyshi gauging station it increased by 0.74 m³/s, and at the Mokrovo gauging station there occurred no statistically significant changes. The analysis of variances has shown changes in the structure of fluctuations in the average annual runoff of the river as the F-criteria values did not exceed critical values. The maximum runoff decreased significantly by 10.0, 30.6, and 32.7 m³/s respectively, while the nature of the oscillations also changed, and the amplitude of the oscillations significantly decreased. That was mostly caused by the filling of the reservoir during this period and frequent winter thaws [19]. The minimum summer-autumn river runoff increased only at the Loktyshi station (0.81 m³/s), which is statistically significant and caused by the influence of the reservoir; at the other stations some statistically insignificant increase in runoff was observed.

The nature of fluctuations in the minimum summer-autumn runoff judging by the F-criteria has not undergone significant changes, except at the Logvinovichi gauging station. The minimum winter runoff increased everywhere, respectively by 0.47, 0.61 and 1.26 m³/s; and in all cases statistically significant. That was as a result of winter thaws above the reservoir and below an anthropogenic factor was added in the form of water releases from the reservoir. In addition, the nature of fluctuations in the minimum winter runoff has also changed, except at the Loktyshi gauging station. Thus, testing the hypothesis about the homogeneity of the considered parameters of annual, maximum, minimum summer-autumn and minimum winter runoff for periods with different averaging intervals was based on the use of the Student and Fisher criteria; and as the analysis showed the differences in the parameters are significant for some segments and can be recognized statistically reliable.

Runoff changes of the Lan River for 3 gauging stations under consideration were assessed using linear gradients numerically equal to the product of the regression coefficient of linear trends (α) by 10 years. The gradient characterizes the change in water flow in m³/s by 10 years. The values of runoff gradients and their significance using correlation coefficients are given in Table 4.

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Table 2 – Statistical parameters of the Lan River runoff for different averaging periods

Runoff type	Annual			Maximum			Minimum summer-autumn			Minimum winter		
Gauging station	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo
1948–2015												
Q_{av}, m^3/s	2.04	4.12	8.59	2.90	60.8	45.7	0.534	1.52	2.50	0.741	1.47	3.96
C_v	0.27	028	0.36	0.67	0.83	0.95	0.22	0.38	0.64	0.693	0.457	0.597
C_s	0.60	0.80	0.40	0.67	0.83	0.95	0.22	0.39	0.65	3.25	1.07	0.981
$Q_{p=1\%}$, m^3/s	3.41	6.79	15.8	139	225	231						
$Q_{p=5\%}$, m^3/s	2.91	5.76	13.3	90.9	159	137						
$Q_{p=25\%}$, m^3/s	2.32	4.65	10.2	45.5	85.4	56.1						
$Q_{p=50\%}$, m^3/s	1.98	4.00	8.32	33.2	48.6	35.3	0.513	1.50	2.20	0.628	1.36	3.45
$Q_{p=75\%}$, m^3/s	1.70	3.48	6.69				0.446	1.13	1.37	0.432	1.03	2.32
$Q_{p=95\%}$, m^3/s	1.35	2.88	4.76				0.373	0.658	0.612	0.268	0.693	1.29
$Q_{p=99\%}$, m^3/s	1.16	2.53	3.67				0.334	0.403	0.305	0.197	0.529	0.838
1948–1977												
Q_{av}, m^3/s	2.22	3.71	8.36	45.3	81.3	67.0	0.523	1.05	2.74	0.518	1.17	3.21
C_v	0.27	0.29	0.46	0.76	0.71	0.94	0.29	0.43	0.66	0.37	0.63	0.78
C_s	1.06	1.58	1.38	3.42	1.76	3.29	1.71	1.06	1.66	1.10	3.76	4.31
$Q_{p=5\%}$, m^3/s	3.15	5.26	14.8	103	191	178						
$Q_{p=10\%}$, m^3/s	2.88	4.79	12.8	81.2	155	135						
$Q_{p=90\%}$, m^3/s	1.64	2.81	4.66				0.340	0.554	0.998	0.277	0.558	1.31
$Q_{p=95\%}$, m^3/s	1.52	2.64	4.02				0.310	0.467	0.760	0.237	0.488	1.10
1978–2015												
Q_{av}, m^3/s	1.99	4.45	8.88	35.3	49.7	34.3	0.553	1.86	2.39	0.984	1.78	4.47
C_v	0.27	0.26	0.30	0.57	0.95	0.72	0.16	0.21	0.68	0.74	0.34	0.46
C_s	0.68	1.29	0.75	2.28	2.85	4.00	0.96	0.43	1.69	4.05	1.34	0.91
$Q_{p=5\%}$, m^3/s	2.83	6.16	12.2	68.7	134	76.9						
$Q_{p=10\%}$, m^3/s	2.61	5.67	11.3	57.3	102	60.4						
$Q_{p=90\%}$, m^3/s	1.43	3.37	6.61				0.427	1.39	0.858	0.396	1.17	2.33
$Q_{p=95\%}$, m^3/s	1.31	3.19	6.11				0.404	1.28	0.651	0.331	1.06	1.94

Table 3 – Statistical criteria for various averaging intervals and types of the Lan River runoff

Gauging station	Lognovichi		Loktyshi		Mokrovo	
Runoff type	t	F	t	F	t	F
Annual	**2.19**	1.29	**2.68**	1.22	1.20	**1.94**
Maximum	**2.07**	**2.55**	**2.47**	1.63	**2.85**	**5.69**
Minimum summer-autumn	1.25	**2.62**	**7.77**	1.24	1.42	1.23
Minimum winter	**3.93**	**11.7**	**4.50**	1.14	**1.94**	**2.44**

Note – Bold values are statistically significant

Table 4 – Statistical parameters of linear trends in the Lan River runoff changes for different averaging periods

Runoff type	Annual			Maximum			Minimum summer-autumn			Minimum winter		
Gauging station	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo	Lognovichi	Loktyshi	Mokrovo
1948–2015												
$\alpha \cdot 10$, m^3/s	**-0.09**	**0.19**	0.18	**-2.76**	**-8.13**	**-7.76**	0.003	**0.218**	-0.117	**0.113**	**0.182**	**0.513**
r	**-0.34**	**0.34**	0.12	**-0.23**	**-0.34**	**-0.39**	0.00	**0.76**	-0.15	**0.44**	**0.53**	**0.40**
1948–1977												
$\alpha \cdot 10$, m^3/s	**-0.27**	0.34	**1.62**	0.11	-8.59	-2.61	-0.006	**0.413**	0.388	0.026	**0.395**	0.749
r	**-0.42**	0.30	**0.42**	0.00	-0.15	-0.04	-0.00	**0.84**	0.21	0.13	**0.57**	0.26
1978–2015												
$\alpha \cdot 10$, m^3/s	-0.05	0.06	-0.50	**-6.10**	-6.80	**-7.96**	**-0.028**	0.065	**-0.501**	0.123	0.015	0.416
r	-0.11	0.06	-0.22	**-0.37**	-0.19	**-0.41**	**-0.36**	0.18	**-0.37**	0.22	0.03	0.23

Note – Bold values are statistically significant

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For the entire period under consideration (1948–2015), a statistically significant linear gradients occurred for average annual runoff at the Lognovichi gauging station – negative (-0.09 m³/s by 10 years), and at the Loktyshi gauging station – positive (0.19 m³/s by 10 years). At all gauging stations the gradients of maximum runoff are negative and statistically significant and amount to -2.76, -8.13, and -7.76 m³/s by 10 years, respectively. It caused by the effect of anthropogenic factor (the filling of the reservoir) and natural factor (modern climate warming). For the minimum runoff a statistically significant positive gradient was observed in the summer-autumn period at the Loktyshi gauging station and amounted to 0.218 m³/s by 10 years; in the winter a runoff increase was observed at all gauging stations and amounted to 0.113, 0.182; 0.0513 m³/s by 10 years, respectively, and it is typical for the entire territory of Belarus [18]. For the period 1948–1977 a decrease in runoff was observed at the Lognovichi gauging station and at the Mokrovo gauging station; there was some increase in the average annual runoff (-0.27 and 1.62 m³/s by 10 years, respectively). No significant changes have been established in the maximum runoff at all gauging stations, although there was some tendency towards a decrease in runoff. The minimum runoff, both summer-autumn and winter, increased statistically significantly only at the Loktyshi gauging station and amounted to 0.413 and 0.395 m³/s by 10 years, respectively. Between 1978 and 2015 (the operating time of the reservoir) the prevailing trend was a decrease in runoff. The maximum and minimum summer-autumn runoff at the Lognovichi and Mokrovo gauging stations decreased statistically significantly -6.10; -7.96; -0.028; -0.501 m³/s by 10 years, respectively. Thus, statistical heterogeneity was established, i. e. in the Lan River basin there was intensive economic activity that significantly disrupts the natural hydrological regime.

Trends in climate fluctuations at the global and regional levels are confirmed by: an increase in global air temperature at the earth's surface, a decrease in the area of sea ice in the Arctic basin and snow cover on land, and an increase in the average sea level. According to research by leading climatologists, the change in global temperature in the 20th – early 21st centuries is characterized by general warming, which on average on Earth amounted to 0.75 °C. During this time, the intra-annual structure of atmospheric precipitation has changed significantly. Monthly precipitation values in April-May and, especially, in August decreased by approximately 20 %. Trends in long-term fluctuations in air temperature extremeness indices are consistent with the fact of global warming, when annual minimums and maximums increase, and the range between them decreases (the minimums increase faster than the maximums), and the number of days with frost decreases. Table 5 presents modeling of changes in meteorological characteristics in the territory of Belarusian Polesie until 2035, which was carried out on the basis of an archive of meteorological data using the CMIP5 multi-model ensemble of four scenarios (RCP8.5, RCP6.0, RCP4.5, RCP2.6) [21, 22].

Table 5 – Forecast estimates of changes in meteorological parameters in the territory of Belarusian Polesie until 2035

Time interval												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air temperature (°C)												
2.4	2.2	1.9	1.6	1.4	1.6	2.0	1.9	1.7	1.6	1.7	2.0	1.8
Precipitation (%)												
9.0	5.0	2.0	-6.0	-7.0	-8.0	-12.0	-10.0	-6.0	-4.0	3.0	4.0	-2.5
Deficiency of air humidity (%)												
0.1	0.1	0.2	0.3	0.5	-0.3	-0.4	-0.3	-0.1	0.0	0.0	0.0	0.0

Using the considered methodology, we made forecast estimates for the Lan River at the Mokrovo gauging station for the future until 2035. Due to the significant anthropogenic impact on the Lan River runoff, model adjustment was carried out along the river analogue of the Tsna river at the Detlovichi gauging station. The rivers are located in close proximity to each other and have very similar geomorphological characteristics and climatic conditions. Figure 4 presents current and forecast values of river runoff for ensemble of four climate scenarios (RCP8.5, RCP6.0, RCP4.5, RCP2.6).

Table 6 shows the results of modeling forecast estimates of changes in the average long-term runoff of the Lan River for 2035 year.

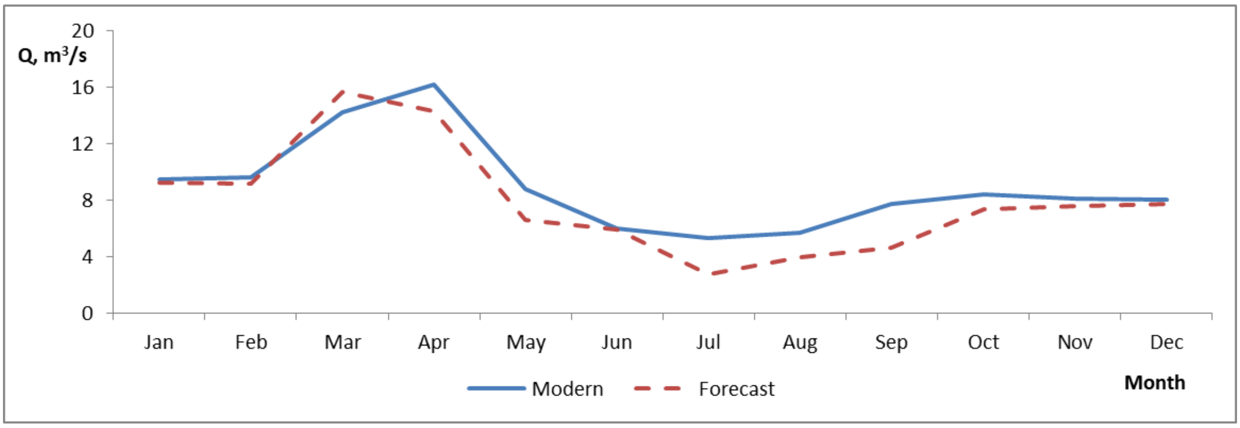

Figure 4 – Modern and forecast hydrographs of the Lan River runoff at the Mokrovo gauging station

Table 6 – Forecast estimates of changes in average long-term runoff of the Lan River for 2035

Time interval												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Modern runoff rates, m³/s												
9.46	9.60	14.2	16.2	8.78	5.99	5.32	5.69	7.74	8.38	8.10	8.01	8.89
Forecast runoff rates, %												
97.3	95.4	109.9	88.3	74.8	98.8	51.7	68.9	59.6	87.1	93.5	96.1	90.0
Forecast runoff rates, m³/s												
9.20	9.15	15.6	14.3	6.57	5.92	2.75	3.92	4.61	7.30	7.57	7.70	8.00

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As can be seen from Table 6, significant changes in runoff will not occur, since the forecast climate parameters have not changed significantly. A slight decrease in runoff is predicted, caused by additional evaporation from the water surface of the reservoir, due to an increase in air temperatures, and there will be a slight shift in the peak of the spring flood to the month of March [21].

Conclusion

A comprehensive analysis of hydrometric information on the of the Lan River runoff at the Lognovichi, Loktyshi and Mokrovo gauging stations for the period from 1948 to 2015 was carried out. A decrease in the average annual runoff at the Lognovichi station was established, at the same time there was runoff increase at the Loktyshi station. In terms of maximum runoff, a decrease was observed at all considered gauging stations. An increase in the minimum summer-autumn runoff was observed at the Loktyshi gauging station; a minimal winter runoff increase was observed in all areas.

Based on the runoff time series analysis, a hydrological-climatic hypothesis, and the CMIP5 multi-model ensemble of four scenarios (RCP8.5, RCP6.0, RCP4.5, RCP2.6) the modeling of changes in the Lan River runoff until 2035 was carried out. The obtained results contain a slight decrease in runoff and shift in the maximum spring runoff to earlier dates.

It is established that the Loktyshi Reservoir has the great influence on the volume and regime of the Lan River runoff, which requires strict adherence to scientifically based regimes for managing the water regime of the reservoir.

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