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ANALYSIS OF WATER RESOURCES IN BELARUS IN VIEW OF CLIMATE CHANGES

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Abstract

The surface water resources of Belarus for the period 1956-2015 were specified. The redistribution of water resources in the basins of the main rivers and administrative regions was investigated. The refined map of the Belarusian river runoff has been built. Runoff forecasts for 11 rivers in the Neman River basin for two scenarios of A1B and B1 climate change were done. The results of forecasting indicate the increasing of runoff from 5.2% to 20.8%.

Key words: runoff, water resources, river, analysis, change, forecast

INTRODUCTION

The dynamics of water resources is inherent, and their integrated and rational use is impossible without the forecast of fluctuations and changes in time. The nature of fluctuations in water resources is determined by climatic factors, but since the second half of the 20th century, the role of the anthropogenic component in some cases becomes comparable with natural impacts. Thus, the end of 20th - beginning of 21st century is characterized by directed climatic variability and increase of anthropogenic load on the river runoff. This could affect the factors of runoff formation of small rivers in Belarus, their hydrological regime and environmental condition. At the same time, the study of water resources is an urgent worldwide task (Eum et al. 2016, Falter et al. 2015).

The territory of Belarus is in the zone of sufficient moisture. The uneven distribution of water resources in the country and during the year is the cause of many problems in the water sector. In these circumstances, the analysis of river runoff and its modeling in view of climate change is the most appropriate way of ensuring an adequate supply of water. The water reservoirs constitute the basis of fish breeding, irrigation, energy, recreation, etc. Previously, we performed the assessment of water resources of the Republic of Belarus in the beginning of 20th century (Volchak et al. 2013, Volchak et al. 2016).

In addition, water resources are changed by regulating the river runoff by artificial reservoirs. At the same time, it is necessary to comply with the condition that the total amount of artificial reservoirs in the basin of the small river should not exceed 70% of the annual runoff with 95% probability (Bulavko and Pluzhnikov 1982). Only with this approach to runoff regulation it is possible to preserve the properties of natural data of water resources.

The development of multivariate empirical-statistical models using multiple regression equations was further development of the concept of randomness as applied to the analysis and forecast of values for the temporal correlations of annual runoff in the multidimensional space vector predictor identified in the previous period using the equations of multiple linear regression, piecewise linear equations of linear regression, neural networks etc. At the same time, it is necessary to prove the possibility of extending the identified dependencies to the forecast period and the forecast of the predicate vector itself is required, which is no less difficult, especially for a significant period (Ismayilov and Fedorov 2001).

Taking into account the variability of runoff in time, as well as the increasing number of artificial reservoirs, there is a need for analysis of water resources in Belarus and modeling of runoff in view of climate change.

DATA SOURCES AND RESEARCH METHODS

The initial data for the studies were observations of different types of runoff at the existing hydrological stations in Belarus for the period from 1956 till 2015 years. If necessary, 1945 year was taken for the beginning of the calculation period – the time of postwar restoration of observations on the hydrological network.

The territory of Belarus has now 20,781 rivers, about 11 thousand lakes, 151 reservoirs, and 1,306 ponds. The total length of the rivers is 90,631 km. However, 19,291 rivers are small rivers, the length of which does not exceed 10 km (Table 1). The average density of the river network is 0.44 km/km^2. The maximum values are typical for the north of the country, where it reaches 0.60-0.80 km/km^2. The minimum values of 0.23-0.30 km/km^2 were observed in the south of Belarus. About 45% of Belarusian rivers are the rivers of the Baltic Sea basin, and 55% are the rivers of the Black Sea basin. Due to the properties of climatic conditions, from 146 km^3 annual precipitation 110 km^3 evaporates into the atmosphere and only 34 km^3 recycled into drainage areas, which is only 25%.

Table 1

Number of small rivers and their length

Intervals of length, km	Western Dvina		Neman		Bug	
	number	length	number	length	number	length
<10	4,895	10,682	5,230	11,764	955	2,920
10-25	183	2,724	272	4,053	60	990
26-50	42	1,482	46	1,503	8	277
51-100	16	1,159	23	1,677	6	390
Total	5,136	16,047	5,571	18,997	1,029	4,577
Intervals of length, km	Dnieper		Pripyat		Belarus	
	number	length	number	length	number	length
<10	3,758	11,534	4,453	11,924	19,291	48,824
10-25	340	5,310	257	4,095	1,112	17,142
26-50	76	2,570	62	2,156	234	7,988
51-100	35	2,477	15	863	95	6,566
Total	4,209	21,891	4,787	19,008	20,732	80,520

The runoff of Belarusian rivers decreases in the direction from north to south. This is due to decreasing of the spring flood runoff and increasing of evaporation in the warmer months. The north-east of the country has the most favorable conditions for humidification of river basins. For this area the typical runoff is 8 l/(s·km^2).

The main feature of the river runoff in Belarus is that it does not correspond to precipitation in time. Precipitation from summer is using for evaporation from the soil and water surface, for infiltration into the soil. And thus, precipitation with a period of warmth, which makes up 80% of their volume per annual value, is processed into the runoff only 20%. The spring flood is 50-60% when spring rainfall accounts for only about 20%. The type of rivers of Belarus is the East European. The freezing-over of rivers lasts from 80 to 140 days; the ice thickness is 30-60 cm.

For the forecast purposes Mezentsev's method of the hydrological-climatic calculations was adapted. The method is based on joint solution of the equations for water and thermal balances (Mezentsev 1995). During the research we devised a multifactor model that includes the standard equation of water balance. The developed model is used to assess the possible changes in runoff according to the various hypotheses of climate fluctuations and anthropogenic impacts on water resources.

The equation of water balance is following:

$$H(I) = E(I) + Y_K(I) \pm \Delta W(I), \tag{1}$$

where $H(I)$ – total humidity, mm; E(I) – total evaporation, mm; $Y_K(I)$ – total calculated runoff, mm; $\Delta W(I)$ – changes of humidity reserves of the active soil layer, mm; I – interval of averaging.

The total evaporation is given by:

$$E(I) = E_m(I)\left[1 + \left(\frac{\dfrac{E_m(I)}{W_{HB}} + V(I)^{1-r(I)}}{\dfrac{KX(I) + g(I)}{W_{HB}} + V(I)}\right)^{n(I)}\right]^{-\frac{1}{n(I)}}, \tag{2}$$

where $E_m(I)$ – maximum total evaporation, mm; W_{HB} – minimum humidity ratio of the soil, mm; $V(I) = W(I)/W_{HB}$ – relative index of the humidity of soils at the beginning of calculating; $KX(I)$ – sum of precipitation, mm; $g(I)$ – soil-water balance component, mm; $r(I)$ – parameter depending on water-physical properties and mechanical composition of soils; $n(I)$ – parameter depending on physical-geographical conditions of runoff.

Relative index of the soil humidity at the end of calculation period is determined from the following relations

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

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

The values $V_{av}(I)$ are compared with the relative index of the total humidity V_{TH}. If $V_{av}(I) \le V_{TH}$ then must be taken the calculated value of the relative average humidity, otherwise, when $V_{av}(I) \ge V_{TH}$ then taken $V_{av}(I) = V_{TH}$ and the value $(V_{av}(I) - V_{TH})\cdot W_{HB}$ refers to surface runoff.

The maximum total evaporation is according to the method described in (Volchak 1986).

The total humidity is defined as follows:

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

The solution of the equations system (1) – (4) is carried out iteratively. During calculating the initial value of the humidity is taken equal to the value of the minimum humidity ratio of the soil, i.e. $W(1) = W_{HB}$, where $V(1) = 1$. The convergence of the solution method is achieved for the fourth step of the calculation.

Adjustment of the calculated runoff is carried out using coefficients that take into account the influence of various factors on the formation of the measured runoff, i.e.

$$Y_P(I) = k(I) \cdot Y_K(I)\,, \tag{6}$$

where $Y_P(I)$ – total measured runoff, mm; $k(I)$ – coefficient taking into account the hydrographic parameters of the basin.

Modeling the water balance of the river is realized in a computer program and is performed in two stages. The first step is to configure the model for known components of water and thermal balances of the studied river. The first stage ends with plotting the calculated and measured runoff figures and outputting the modeling error. The example of modeling average annual runoff and its intra-annual distribution is shown in Figure 1.

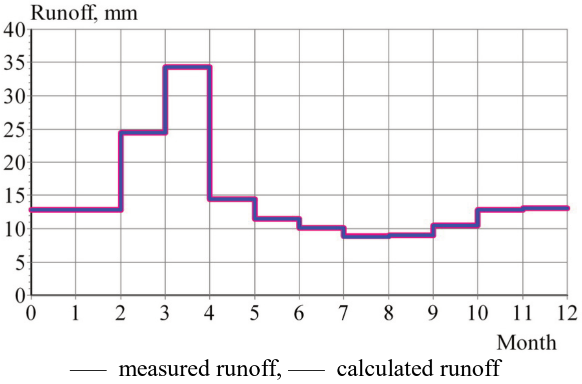

Fig. 1. Measured and calculated runoff for the Neman River at the Stolbtsy Station

The measured and calculated runoffs are very close; therefore the model is correct. The obtained model parameters were used for the numerical experiment.

The second stage is a direct modeling the water balance of the river using the parameters obtained during model calibration. The calculation of the water balance is tailored to the specific characteristics of the studied river. The simulation results indicate high accuracy of the calculation of the water balance for both practical applications and theoretical studies that tested for a lot of rivers in Belarus with basin area of about 1,000 km^2 (Volchak and Parfomuk 2007).

Thus, the developed computer program with available data on precipitation, air temperature, air humidity deficits and modern values of the water runoff, as well as hydrographic parameters of the basin provides forecast values of the water balance of rivers.

The technique of simulation has been tested on almost all climatic parameters that gave the opportunity to attract additional large amount of hydrometeorological information that are included in the balance equations.

When setting up models by the proposed method have problems with the definition of parameters for the winter months. The fact that the model did not accurately included the thaw for the recent years. Therefore, we conducted an adjustment model taking into account the thaw. The obtained difference between measured and calculated runoff treated runoff formed during thaws, which were recorded in the settings of the model. When forecasting runoff this component was added directly to the runoff and its value was subtracted from precipitation. The values of runoff during thaws were adjusted for the predicted temperature of the corresponding month. In the first approximation the value of runoff can be taken from the ratio of monthly air temperatures and runoff during the period of thaw.

Forecasting changes of river runoff was carried out by the following scheme. The model was adjusted for average long-term data on river runoff, atmosphere precipitation, air temperature and deficits of air humidity, obtained parameters remained in computer. Then entered forecast value for those weather stations that were used in the setting model. The last stage was reading the settings of the model and carrying out the runoff forecast.

DISCUSSION AND RESULTS

One of the last fundamental works on the assessment of surface waters in Belarus was published in 1996 (Pluzhnikov et al. 1996). Over the past twenty years, the country's water resources have been subject to transformation due to the impact of natural and anthropogenic factors on the runoff. The refined surface water resources of Belarus for the period from 1956 to 2015 and data on the runoff transformation in the 60-year interval under study in relation to the observation period up to 1996 in the basins of the main rivers of Belarus are given in Table 2.

The total water resources of Belarus have not changed. At the same time, there was a redistribution of natural water resources in the basins of the main rivers. Along with the increase in the Pripyat River runoff and a slight increase in the water runoff of the Western Dvina River, the decrease in surface water resources of the other rivers in recent years was noted. The increase of surface water resources of Brest and Gomel regions is noted, and Grodno region is characterized by a decrease in water resources due to a decrease in the water runoff of the Neman and Vilia Rivers.

In order to clarify the water resources of Belarus a map of the average annual runoff of the rivers of Belarus was created (Fig. 2). The data for the map includes runoff from 1956 to 2015 according to current hydrological stations. The number of used stations is sufficient to correctly display information about the annual runoff on the territory of Belarus.

The most significant decrease in runoff is investigated for the Neman River basin, so further we performed the runoff forecasting in view of climate change. The Neman River is one of the main rivers in Belarus. It is a typical transboundary river in Europe, flows through the territory of the two countries (Belarus and Lithuania) and can serve as a testing ground to assess various changes.

On average for the period from 1956 to 2015, runoff of the Neman River in spring accounts for 41% of the annual runoff. During the summer-autumn season 37% of the total annual runoff is observed and 22% is observed during the winter season. The November runoff is higher than in October, except for years with exceptionally high runoff. The greatest water flow in the winter season occurs in January.

Table 2

Natural resources of river waters of Belarus for the basins of the main rivers in 1956-2015 (numerator – underlined) and changes in runoff in relation to the period up to 1996 (denominator – not underlinded)

River basin	River runoff, km^3/year									
	local					general				
	probability, %					probability, %				
	5	25	50	75	95	5	25	50	75	95
Western Dvina	10.6 0.1	7.8 0.1	6.9 0.1	5.5 0.0	4.4 0.1	22.3 0.4	16.4 0.2	14.1 0.2	11.6 0.3	9.0 0.4
Neman	8.0 -0.5	6.7 -0.4	6.2 -0.4	5.4 -0.5	4.9 -0.3	8.1 -0.5	6.8 -0.4	6.3 -0.4	5.5 -0.5	5.0 -0.3
Vilia	2.9 -0.3	2.4 -0.3	2.1 -0.2	1.8 -0.2	1.4 -0.4	2.9 -0.3	2.4 -0.3	2.1 -0.2	1.8 -0.2	1.4 -0.4
Bug	2.8 -0.2	1.6 -0.2	1.3 -0.1	0.9 -0.2	0.7 -0.1	2.8 -0.2	1.6 -0.2	1.3 -0.1	0.9 -0.2	0.7 -0.1
Pripyat	11.2 1.3	7.6 1.1	6.6 1.0	5.0 0.6	3.5 0.4	23.9 1.7	16.8 1.5	14.4 1.4	11.0 0.9	8.3 1.3
Dnieper	16.3 -0.1	11.8 0.1	11.0 -0.3	9.5 0.1	7.8 0.2	28.2 0.0	20.3 0.1	18.7 -0.2	15.6 -0.1	13.1 0.3
including:										
Berezina	6.3 0.1	5.0 0.1	4.5 0.0	4.0 0.1	3.4 0.1	6.3 0.1	5.0 0.1	4.5 0.0	4.0 0.1	3.4 0.1
Sozh	4.9 -0.1	3.4 -0.1	3.0 0.0	2.4 -0.1	1.8 -0.2	10.6 0.0	7.6 0.1	6.6 0.2	5.4 0.2	4.4 0.1
Total area	**51.8** **0.3**	**37.9** **0.4**	**34.1** **0.1**	**28.1** **-0.2**	**22.7** **-0.1**	**88.2** **1.1**	**64.3** **0.9**	**56.9** **0.7**	**46.4** **0.2**	**37.5** **1.2**

Comparative analysis of the water regime of the Neman River for the period of observations from 1956 to 2015 has shown that there were systematic changes. These include a significant decrease of the peak flow during the spring flood and a moderate increase of the flow in summer-autumn and especially in winter seasons. These changes are connected to appropriate climatic variations observed in the same period. An increase of minimum runoff is observed in the summer-autumn period and caused by climatic factors and human impact in the form of wide-scale melioration projects. Though the scale of these projects in the Neman River Basin is much less than implemented in Polesye, nevertheless it cannot be ignored. In the last years, the number of freshet periods for very high-flow years has increased up to 4, for the high-flow years this number increased from 2 to 3 per year to 3 to 4 per year. Similarly runoff variations were observed on other rivers of the Baltic Sea Basin in the Republic of Belarus.

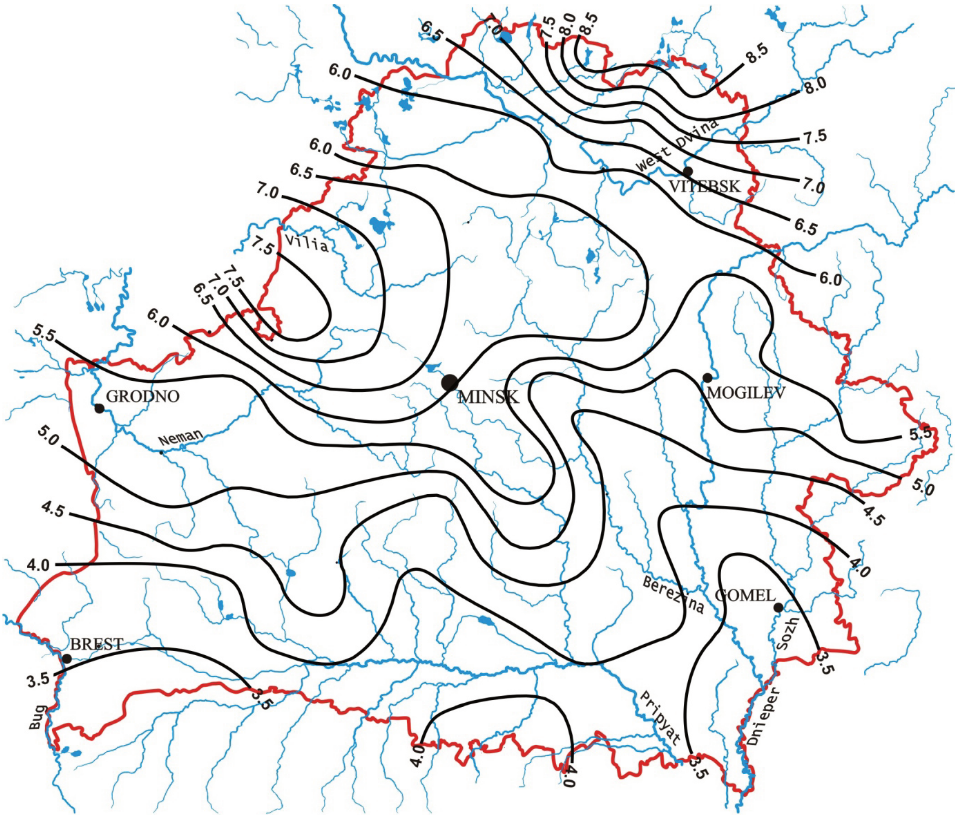

Fig. 2. The map of the average annual runoff of rivers in Belarus for the period 1956-2015, l/(s·km^2)

Runoff forecasts for 11 rivers in the Neman River basin for two scenarios of A1B and B1 climate change were done in two options. The first option is forecasting without considering the thaw and the second option with regard to thaw. The results consist of the model configuration as well as modern and forecast calculated values of the river runoff. Based on the analysis of the obtained forecasts the changes in river runoff for the Neman River basin preference should be given to the second option.

Tables 3 and 4 show the forecasted values of runoff changes for the two scenarios of climate change in percent to the modern level.

The results for the A1B scenario indicate the increasing of runoff from 8.6% for the Vilija River to 20.8% for the Schara River. Scenario B1 has shown a minor change in runoff from 5.2% for the Naroch River up to 17.0% for the Oshmyanka River.

Table 3

Forecast changes in runoff for the A1B scenario in 2035, % to 2015

River	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Neman	Stolbtsy	117.1	119.2	111.8	112.5	130.6	197.4	61.4	67.6	130.0	89.4	102.3	114.5	114.3
Neman	Mosty	118.8	124.8	126.2	111.8	153.6	178.3	98.2	99.1	102.5	66.2	110.9	116.5	119.0
Neman	Grodno	123.3	124.6	102.9	129.0	173.0	134.4	95.3	100.6	105.9	84.6	109.3	123.6	120.3
Isloch	Borovikovshina	123.5	123.1	113.5	114.5	145.1	207.6	82.0	90.6	102.3	90.8	103.9	118.9	118.1
Gavya	Lubiniata	123.5	120.5	101.1	121.1	186.9	173.3	96.3	81.1	102.4	83.8	118.4	123.9	119.8
Schara	Slonim	115.9	116.5	115.1	115.9	160.0	178.3	85.8	77.2	143.7	93.9	106.7	114.8	120.8
Svisloch	Sukhaya Dolina	118.8	127.1	94.3	121.6	177.3	115.7	79.4	97.0	104.3	81.9	108.5	121.9	113.0
Vilija	Steshytsy	119.9	116.9	116.5	109.2	137.5	143.2	82.0	72.3	71.7	94.2	98.7	114.7	108.6
Vilija	Mikhalishki	119.1	111.9	99.0	112.9	176.0	109.8	109.2	67.0	69.8	100.0	105.0	114.9	110.3
Naroch	Naroch	118.5	113.0	107.8	108.4	140.4	146.2	151.7	95.2	72.8	95.7	98.8	114.6	113.8
Oshmyanka	Bolshiye Yatsiny	121.3	119.5	116.4	118.6	133.9	228.3	78.8	88.1	102.2	91.0	103.4	117.7	118.9

Table 4

Forecast changes in runoff for the B1 scenario in 2035, % to 2015

River	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Neman	Stolbtsy	106.2	111.5	112.2	90.7	110.4	187.8	25.5	64.5	133.3	109.5	110.2	114.5	105.7
Neman	Mosty	105.3	113.1	112.1	100.0	142.9	172.9	65.9	82.5	144.7	94.0	105.8	116.5	112.8
Neman	Grodno	102.3	114.9	101.9	111.4	138.0	134.4	77.5	78.2	157.8	104.4	103.1	121.1	112.8
Isloch	Borovikovshina	113.6	116.3	116.7	90.8	126.8	195.9	106.0	92.9	120.0	103.5	108.4	125.2	115.3
Gavya	Lubiniata	100.0	110.0	111.7	91.4	151.9	153.3	128.1	38.7	136.0	109.4	115.7	122.8	113.8
Schara	Slonim	101.8	107.8	108.6	97.1	134.4	172.6	61.2	76.3	153.3	113.5	115.0	113.0	112.3
Svisloch	Sukhaya Dolina	93.2	113.9	100.0	102.2	142.2	114.7	58.8	84.6	161.1	105.4	102.3	118.2	107.4
Vilija	Steshytsy	102.0	105.4	111.2	87.5	107.6	147.7	110.1	107.3	104.0	110.8	98.7	118.6	107.1
Vilija	Mikhalishki	98.5	100.0	102.9	90.6	137.7	128.8	139.5	90.4	106.1	118.1	104.3	117.9	109.2
Naroch	Naroch	101.3	103.9	119.8	84.4	107.9	151.7	85.1	84.2	100.9	111.6	98.8	119.5	105.2
Oshmyanka	Bolshiye Yatsiny	114.0	112.8	107.1	92.9	124.7	208.3	110.9	103.0	122.6	102.6	108.0	124.6	117.0

CONCLUSION

The quantitative assessment of water resources of the Republic of Belarus is given. The redistribution of surface water resources in the basins of the main rivers and administrative regions has been established, while the total natural resources of the country's river waters have not changed. These changes in the river runoff in modern conditions are based mainly on the increasing of the intensity of the atmosphere circulation, which is clearly demonstrated in (Loginov and Volchak 2006).

We developed a mathematical model to forecast runoff for the Neman River basin. Modeling of runoff changes for the two scenarios of climate change A1B and B1 taking into account the thaw was carried out. The results for the A1B and B1 scenarios indicate the increasing of runoff from 5.2% for the Naroch River to 20.8% for the Schara River. Development of compensation measures to reduce impacts from increased runoff of the Neman River is the subject of further research.

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ANALIZA ZASOBÓW WODNYCH NA BIAŁORUSI W ZWIĄZKU ZE ZMIANAMI KLIMATYCZNYMI

Streszczenie

Określono zasoby wód powierzchniowych Białorusi na okres 1956-2015. Przeanalizowano redystrybucję zasobów wodnych w dorzeczach głównych rzek i regionów administracyjnych. Zro-biona została mapa spływu rzek Białorusi. Wygenerowano prognozy spływu 11 rzek w dorzeczu Niemna dla dwóch scenariuszy zmian klimatu A1B i B1. Wyniki prognoz wskazują na zwiększenie odpływu z 5,2% do 20,8%.