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SPATIAL AND TEMPORAL VARIABILITY OF THE SURFACE RIVER RUNOFF IN BELARUS

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Abstract

An assessment of changes in the surface river runoff of Belarus in modern conditions is given. Significant negative trends were found for the series of the percentage of surface runoff in the total volume of annual runoff for the period 1948–2017. The greatest decrease in surface runoff is observed in the south of Belarus. The degree of synchronicity of fluctuations of the long-term surface runoff of large rivers of Belarus is estimated. A modern map of the average annual modules of the surface river runoff distribution in Belarus has been obtained.

Keywords: surface runoff, underground runoff, hydrograph dissection, long-term variability, surface runoff modulus.

ПРОСТРАНСТВЕННО-ВРЕМЕННАЯ ИЗМЕНЧИВОСТЬ ПОВЕРХНОСТНОГО СТОКА РЕК БЕЛАРУСИ

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Реферат

В работе дана оценка изменений поверхностного стока рек Беларуси в современных условиях. Для рядов доли поверхностного стока в общем объеме годового стока обнаружены значимые отрицательные тренды за период 1948–2017 гг. Наибольшее уменьшение поверхностного стока наблюдается на юге Беларуси. Выполнена оценка степени синхронности колебаний многолетнего поверхностного стока крупных рек Беларуси. Получена современная карта распределения среднемноголетних модулей поверхностного стока рек Беларуси.

Ключевые слова: поверхностный сток, подземный сток, расчленение гидрографа, многолетняя изменчивость, модуль поверхностного стока.

Introduction

Assessment of modern resources of the surface river runoff in connection with the ongoing global climatic changes is one of the urgent and complex tasks of hydrology. Today, scientific research on the dynamics of surface runoff in Belarus has not been carried out enough. However, the solution of this problem is important both from the scientific and practical point of view. Surface waters being one of the components of water resources are of great economic importance.

River runoff is combined of the surface and underground runoff. Surface runoff in the warm season is rarely observed in most of the territory of Belarus, which is a consequence of changes in the infiltration properties of the soil. During this period th surface runoff can be noted only after heavy rains. The problem in assessing surface runoff is as follows:

– this resource varies both in territory and in time;
– surface runoff, unlike underground, is characterized by extreme unevenness throughout the year.

The purpose of this work is to study the modern features of the spatial and temporal variability of the surface runoff resources of the rivers in Belarus through the analysis of long-term series of hydrological observations.

The realization of this goal consists in the consistent fulfillment of the following tasks:

– selection of a representative calculation period of hydrological observations to identify spatial-temporal patterns of surface runoff formation;
– reduction of river runoff data to a single multi-year period;
– substantiation of the methodology for assessing the surface runoff of the rivers in Belarus;
– quantitative assessment of the surface river runoff in Belarus;
– selection of the method of spatial interpolation of the studied characteristics of the river runoff;
– construction the map of the modules of the surface runoff of the rivers in Belarus;
– assessment of changes in the spatial-temporal transformation of the surface runoff of the rivers in Belarus.

Materials and methods

The observational data from the State Institution "Republican Center for Hydrometeorology, Control of Radioactive Contamination and Environmental Monitoring" of the Ministry of Natural Resources and Environmental Protection of the Republic of Belarus for the current hydrological stations for the period of instrumental observations published in the materials of state cadasters was used.

An important factor in the assessment of surface runoff is the choice of a representative period from the general data. The use of series of observations of the average annual, maximum and minimum river runoff rates for hydrological studies requires the selection of a calculation period for which the following conditions must be met:

– the average values of the series of observations correspond to the norm;
– the completed period of fluctuations in water content is traced;
– the length of the series is sufficient to assess the required empirical availability of water.

According to [1], the amount of observations of river runoff is considered representative for determining the average long–term value if the average square error of the calculated value of the hydrological characteristic does not exceed 10% for annual runoff and 20% for maximum and minimum runoff.

In this study, a method based on the use of "dynamic" estimates of hydrological parameters was used to assess the representative period [2]. Based on the results of the application of this method, as well as the study of the cyclicity of the long-term series of the runoff of the rivers of Belarus, the 70-year period of 1948-2017 was chosen as the calculation period for assessing the long-term variability of the surface runoff, and the period of 1953-2017 was chosen for constructing the map of the modules of the surface runoff [3].

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When working with spatial data, first of all it is necessary to understand how effective the monitoring network is [4]. In [5] the optimal number of hydrological observation stations for the values of the runoff of the rivers of Belarus was investigated. The study shows that the number of runoff monitoring stations is sufficient to solve various water management and hydrological problems. At the same time, the number of hydrological observation stations for annual runoff is minimal. Based on this, the construction of the map in this work was carried out using data on 120 hydrological stations evenly located on the territory of Belarus. The reduction of series with a short duration of observation periods to a multi-year period for calculating the values of surface runoff and constructing a map was carried out using the computer software complex "Hydrologist-2" [6].

Since measurements of surface runoff are not carried out by an instrumental method, the hydrograph dismemberment method is used to determine it. The use of this method makes it possible to isolate the underground component from the runoff hydrograph. The most difficult task is the dismemberment of runoff for periods of high water and large floods. In the literature, there are various approaches to the assessment of underground runoff in these phases of the water regime. The methods of dissection of the hydrograph are reflected in the works of B. V. Polyakov, B. I. Kudelin, K. V. Voskresensky, M. I. Lvovich, O. V. Popov [7-10].

In practice, when there is a lack of information about the relationship of river and groundwater, it is often assumed for lowland rivers that the amount of underground supply at the time of peak flood is equal to zero. Since the rivers of Belarus are characterized by a mixed type of nutrition, in this work, as the basis for the model for determining surface runoff, the method of dissection of hydrograph B.P. Polyakov is used, according to which, as the spring flood rises, underground nutrition sharply decreases and stops altogether when the flood peak passes. Then, when the flood subsides, the underground runoff gradually increases, which is due to the return of water by the floodplain of the river [11]. Annual values of surface runoff are calculated as the difference between annual and underground runoff:

$$Q_{suf_i} = \begin{cases} Q_i - \bar{Q}_{min}\ , \ i < t_n \\ Q_i - \left(Q_{t_n} + \frac{(i-t_n)(Q_{t_{max}}-Q_{t_n})}{t_{max}-t_e}\right), \ t_n \le i < t_{max} \\ Q_i - \left(Q_{t_{max}} + \frac{(i-t_{max})(Q_{t_e}-Q_{t_{max}})}{t_e-t_{max}}\right), \ t_{max} \le i < t_e \\ Q_i - \bar{Q}_{min}\ , \ i > t_e \end{cases} \quad (1)$$

where $i = \overline{1,n}$ – the number of the day in the year;

n – the number of days in the year;

t_n – the number of the day in the year corresponding to the beginning of the flood;

t_{max} – the number of the day in the year corresponding to the peak of the flood;

t_e – the number of the day in the year corresponding to the end of the flood;

Q_i,, m³/s – river runoff water consumption on the i-th day of the year,

$Q_{t_{max}}$, m³/s – water consumption on the day corresponding to the peak of the flood,

$\bar{Q}_{min}$, m³/s – arithmetic mean values of the average monthly minimum winter and summer-autumn water consumption.

The values of t_{max}, t_n and t_e can be obtained by the method described in detail in [12]. Figure 1 shows a graph of the dismemberment of the average long-term hydrograph of the Pripyat River at the Mozyr city constructed for the representative period according to the average daily river runoff.

Due to the high labor intensity and unavailability of observation data on the average daily runoff in some cases, without loss of accuracy of the results (based on the constructed long-term hydrographs on the average monthly runoff), it is permissible to use the average monthly runoff values to dissect the hydrograph of the river runoff in Belarus and the allocation of underground runoff:

$$Q_{ugr_k} = \begin{cases} Q_{ugr\ l.w._k}\ , \ k \le 2 \\ \frac{1}{2} Q_{ugr\ l.w._2}\ , \ k = 3 \\ 0, \quad k = 4 \\ \frac{1}{2} Q_{ugr\ l.w._6}\ , \ k = 5 \\ Q_{ugr\ l.w._k}\ , \ k \ge 6 \end{cases} \quad (2)$$

where k – number of the settlement calendar month,

$$Q_{ugr\ l.w._k} = \begin{cases} Q_k,\ Q_k < \bar{Q}_{1,2,7-12} \\ \bar{Q}_{1,2,7-12},\ Q_k \ge \bar{Q}_{1,2,7-12} \end{cases},$$

$\bar{Q}_{1,2,7-12}$ – average monthly runoff for the months corresponding to the lower indices.

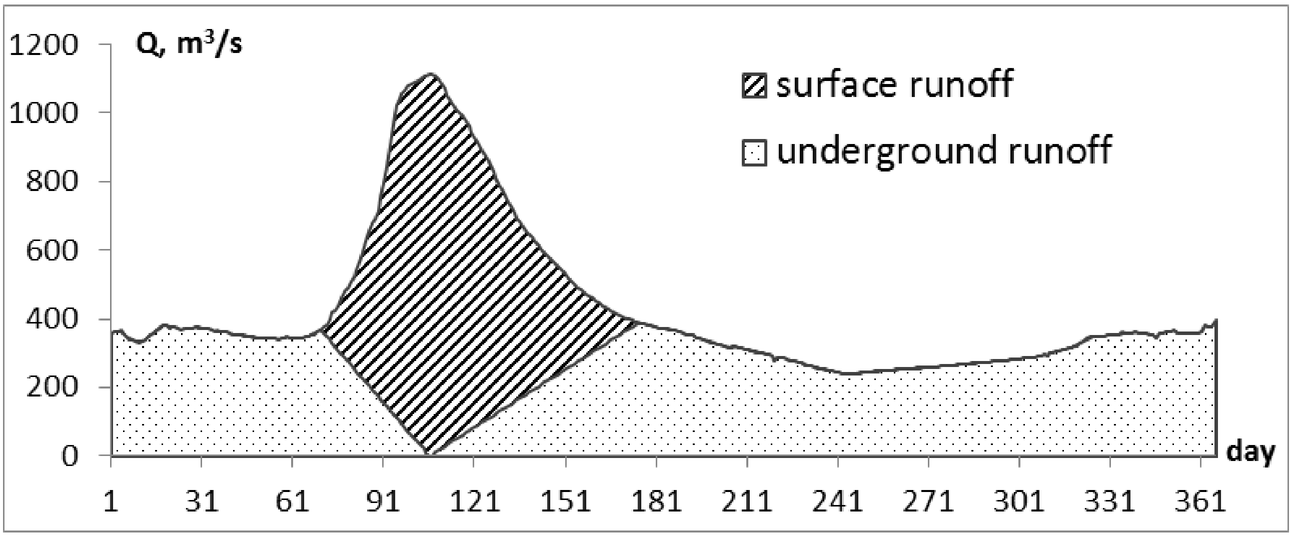
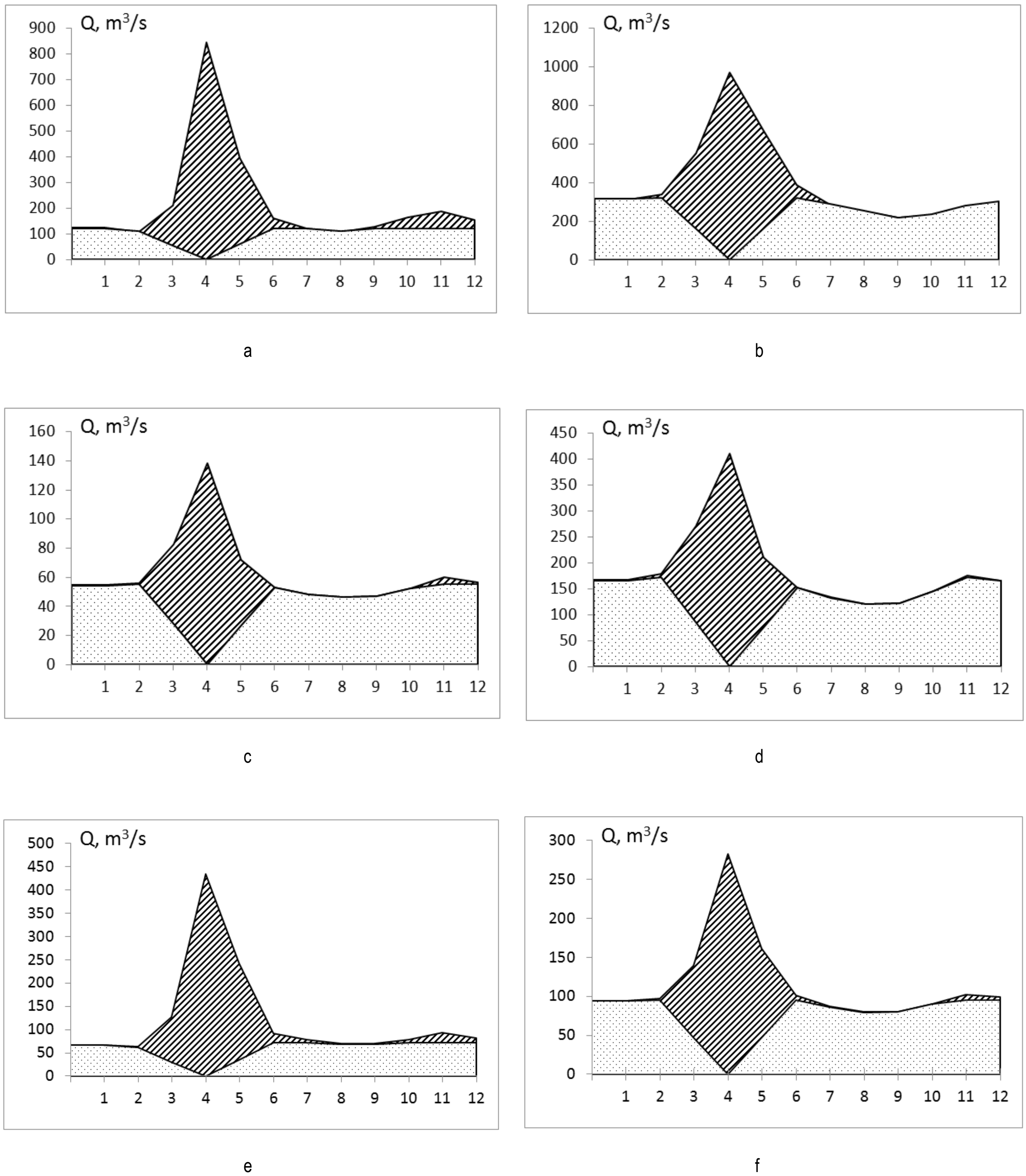


Figure 1 – The average long-term hydrograph of the Pripyat River at the Mozyr city built for the period 1948-2017 according to the average daily river runoff

Results and discussion

Long-term variability of surface runoff.

On the basis of model (2) the average long-term hydrographs are constructed for the average monthly runoff rates of river runoff, divided into underground and surface components. Figure 2 shows the obtained hydrographs for 6 hydrological stations of the largest rivers in Belarus.



a – the Western Dvina River at the Vitebsk city;
b – the Pripyat River at the Mozyr city;
c – the Vilia River at the Mikhalishki town;
d – the Neman River at the Grodno city;
e – the Dnieper River at the Orsha city,
f – the Berezina River at the Bobruisk city

Figure 2 – Average long–term hydrographs of river runoff

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Figure 2 shows that for all the considered sections the largest river runoff values are observed in April. The decline of the spring flood is especially prolonged for the Pripyat and Dnieper basins, gradually turning into summer floods. On the rest of the rivers under consideration, the rise and fall of the spring flood are proceeding at a faster pace. Since the main feature of modern changes in the water regime of the rivers of Belarus is the redistribution of runoff within the year, which occurs with a relative constancy of average annual water consumption, it is advisable to consider the percentage of surface runoff (d_{suf}, %) in the total annual runoff and the long-term variability of this indicator (Figure 3).

a – the Western Dvina River at the Vitebsk city;
b – the Pripyat River at the Mozyr city;
c – the Vilia River at the Mikhalishki town;
d – the Neman River at the Grodno city;
e – the Dnieper River at the Orsha city,
f – the Berezina River at the Bobruisk city

Figure 3 – Change in surface runoff in the total river runoff for the period 1948-2017

The analysis of linear trends in the series of the surface runoff percentage shows that in general there is a decrease in the values of the considered characteristics of the runoff. Linear negative trends are statistically significant at the 5% level.

For all the studied rivers, a synchronous course in long-term changes in the percentage of surface runoff in the total annual runoff is clearly traced, which is confirmed by positive significant correlation coefficients between these values (Table 1).

Table 1 – Correlation matrix of the surface runoff in the total annual runoff of the pairwise compared rivers of Belarus

	the Berezina River	the Dnieper River	the Pripyat River	the Neman River	the Vilia River
the Western Dvina River	0.61	0.72	0.48	0.54	0.54
the Berezina River		0.73	0.74	0.78	0.81
the Dnieper River			0.65	0.70	0.72
the Pripyat River				0.78	0.67
the Neman River					0.84

To assess the long-term variability of surface runoff, the periods differing in climatic conditions, but long enough to identify various trends, were analyzed: 1948, 1987, 1988, 2017 (taking into account the fact that 1988 corresponds to the beginning of an intensive increase in average annual air temperatures in Belarus).

Table 2 – The change (in %) of the average long-term values of indicators for the period 1988–2017 in relation to the period 1948–1987

	maximum runoff	minimum summer-autumn runoff	minimum winter runoff	percentage of surface runoff
the Western Dvina River	-21	4	46	-4
the Pripyat River	-33	12	23	-9
the Vilia River	-56	0	12	-11
the Neman River	-39	-5	21	-8
the Dnieper River	-30	28	47	-7
the Berezina River	-51	8	23	-10

It can be seen from Table 2 that the percentage of surface runoff for the period 1988-2017 for all the considered rivers has been decreased by 4–11%. The main reason for the decrease in the surface runoff of the rivers in Belarus in the last 30-year period is climate change. This is explained by the fact that due to the increase in winter temperatures, accompanied by winter thaws, increased infiltration of melt water into the soil in winter and spring, the underground component of runoff has significantly increased. A significant decrease in flood runoff in all catchments of Belarus is compensated by increased runoff (in most cases underground) in winter.

The assessment of the effect of changes in the maximum and minimum runoff on the dynamics of surface river runoff was carried out in two stages. At the first stage, paired regression relationships were revealed between changes in the two periods under consideration of surface runoff (ΔQ_{suf}, %) and maximum runoff (ΔQ_{max}, %), surface runoff and minimum summer-autumn runoff ($\Delta Q_{min\,s.a.}$, %), surface runoff and minimum winter runoff ($\Delta Q_{min\,w.}$, %). The results obtained at the first stage allow us to conclude that the effect of changes in the maximum and minimum winter runoff rates of river runoff on surface runoff is most significant (*r*=0.92 and *r*=0.86, respectively). It is worth noting that the decrease in the surface runoff of the rivers of Belarus was decisively influenced by a decrease in the maximum runoff. Based on this, at the second stage, in order to identify the cumulative relationship between the dynamics of surface runoff, the maximum water runoff of spring flood and the minimum winter runoff of river runoff, the following relationship was considered: $\Delta Q_{suf} = f(\Delta Q_{max},\ \Delta Q_{min\,w.})$. The analytical expression of this relationship for the territory of Belarus is given below:

$$\Delta Q_{suf} = 0.12\Delta Q_{max} + 0.06\Delta Q_{min\,w.} - 5.05. \quad (3)$$

This relationship has a high correlation coefficient *r*=0.94. Using the model (3) it is possible to obtain predictive estimates of changes in surface runoff depending on various options for changing the maximum and minimum runoff (Table 3).

Table 3 – Forecast estimates of changes (in %) in the percentage of surface runoff depending on changes in the maximum water consumption of the spring flood and minimum winter river runoff

ΔQ_{max}, % \ $\Delta Q_{min\,w.}$, %	-10	0	10	20	30	40	50
10	-4.4	-3.85	-3.3	-2.75	-2.2	-1.65	-1.1
0	-5.6	-5.05	-4.5	-3.95	-3.4	-2.85	-2.3
-10	-6.8	-6.25	-5.7	-5.15	-4.6	-4.05	-3.5
-20	-8	-7.45	-6.9	-6.35	-5.8	-5.25	-4.7
-30	-9.2	-8.65	-8.1	-7.55	-7	-6.45	-5.9
-40	-10.4	-9.85	-9.3	-8.75	-8.2	-7.65	-7.1
-50	-11.6	-11.05	-10.5	-9.95	-9.4	-8.85	-8.3

Despite the presence of a general trend towards a decrease in surface runoff for the period 1988–2017 in relation to the period 1948–1987, when considering the variability of surface runoff over ten-year periods, an increase in surface runoff is observed for most of the studied strata over the last two decades of the study period (1998–2007, 2008–2017). This circumstance indicates the need for further study of the dynamics of surface runoff, the proportion of spring flooding, the maximum costs of spring flooding, the magnitude of rain floods in order to ensure the safety of the population and sustainable economic development.

Spatial structure of surface runoff.

Due to the fact that the surface runoff, which represents the water resources of the land, is an integral value, and measurements are carried out discretely, to represent its spatial structure, a runoff module is used, which is numerically equal to the runoff rate per unit area, which makes it possible to obtain comparable water characteristics for different river catchments. This makes it possible to represent surface runoff in the form of maps based on the principle of climatic runoff and obtain hydrological characteristics at those points where there are no observations.

The surface runoff map used today for the territory of Belarus (built in 2000 [13]) has lost its relevance to one degree or another for a number of reasons. Firstly, they do not meet the requirements of regulatory documents, in particular the TCP, according to which the determination of calculated hydrological characteristics should be based on data from long-term hydro meteorological observations with a single calculation period, while regular observations of recent years are mandatory [1]. This will allow taking into account the processes of global climate warming and anthropogenic impacts that have intensified in recent decades, which undoubtedly left its mark on the formation of the runoff of rivers in Belarus. Secondly, the development of spatial interpolation methods and computer technologies make it possible to objectively construct maps of the surface modules of the runoff of rivers in Belarus. In this regard, the issue of constructing a modern map of the surface runoff module of the rivers of Belarus becomes very relevant.

The construction of a map of the surface runoff of the rivers of Belarus was carried out using the ArcGIS software. The ArcGIS software package allows you to visualize large amounts of statistical information that has a geographical reference, create and edit maps of different scales [14]. The family of geoinformation software products of ArcGIS offers a wide range of tools for spatial modeling, which is carried out using a special geostatistical analysis module (Geostatistical Analyst).

The choice of a suitable interpolation method when constructing the map at the first stage was carried out experimentally. For this purpose, in this study, various deterministic and geostatistical methods were used to obtain the spatial distribution of modules of surface river runoff: the Inverse Distance Weighing method (IDW), Global Polynomial Interpolation (GPI), the Radial Basis Function method (RBF) and Ordinary Kriging (OK).

The results of interpolation by the IDW method showed that the isolines have a broken character in places, there are a large number of local closed areas on the surface and the law of geographical zonality is incorrectly expressed. Interpolation by the GPI method was carried out using polynomials of 2-6 degrees. With this method of interpolation, smoothed isolines were obtained that meet the requirements for compliance with the principle of geographical zonality when constructing runoff maps, however, the values of the runoff modulus went beyond the extreme reference points, in some cases even went into negative values, which is unacceptable when constructing runoff modulus distribution maps.

Three of the five basic functions used in RBF interpolation are: fully regularized spline (CRS), multi-square function (MQ), thin-film spline (TPS). When interpolated by BRF (TPS), the values of the runoff modulus went beyond the extreme reference points, and the use of the BRF(CRS) method led to the presence of a large number of closed local areas in the north-west of Belarus. The isolines obtained by BRF (MQ) and OK have a smooth shape, without a set of local regions, so further research was carried out using these two interpolation methods.

To evaluate and compare the characteristics of the two selected interpolation methods, the paper uses cross-validation by calculating several statistical measurements (root-mean-square error, average absolute error as a percentage, systematic error and coefficient of determination [15]. As a result of the analysis of cross-validation and the results of calculations of indicators for assessing the accuracy of the RBF (MQ) and OK interpolation methods, RBF(MQ) was chosen as an interpolation method for constructing a map of the modules of the surface runoff of the rivers of Belarus. The map constructed using the chosen interpolation method is shown in Figure 4.

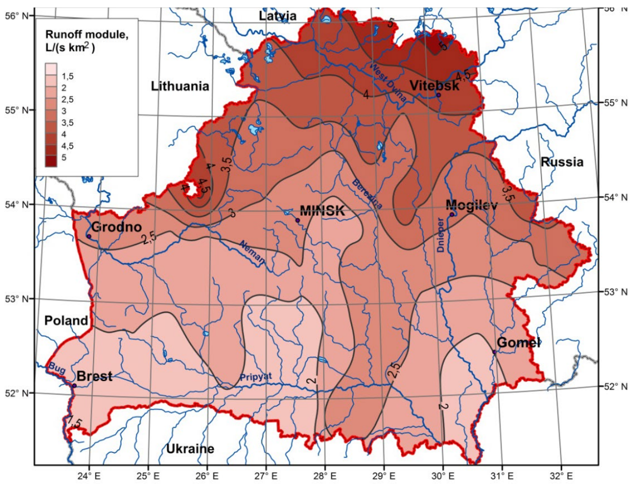

Figure 4 – Map of the surface runoff modules of rivers in Belarus for the period 1953–2017

The analysis of the constructed map allows us to conclude that the regularities of the formation of the surface runoff of the rivers of Belarus are subject to latitudinal zonality, which is determined by climatic factors. Some deviations of runoff isolines from latitudinal directions are caused by the hydrological structure of river basins. The minimum values of runoff in the south of Belarus are caused by reduced precipitation in this area compared to the northern part of the country and increased temperature in this region.

Conclusion

A characteristic trend of the long-term variability of the surface river runoff in Belarus has been a significant (by tens of percent) decrease in the amount of surface runoff. The greatest decrease in runoff is observed in the basins of the Pripyat and Berezina rivers. As a result of the performed studies a modern map of the average annual modules distribution of the surface river runoff in Belarus has been obtained. The updated data on the runoff distribution can be transformed into modern global hydrological maps. The use of mapping results can determine the planning of economic activities, the development of engineering applications that ensure the conservation and rational use of water resources, as well as their sustainable management.

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