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# Assessment of changes in the Viliya River runoff in the territory of Belarus

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**Abstract:** The research results of runoff changes in the River Viliya at 3 stations (Steshitsy Village, Vileyka Town and Mihalishki village) during the period 1946–2014 for the average annual, maximum, minimum summer-autumn and winter runoff are presented. It has been concluded that heterogeneity in the time series of the river runoff is caused by natural-climatic and anthropogenic factors. At Mihalishki Village the average annual runoff is about 59.7 $m^3 s^{-1}$, the maximum 1570 $m^3 s^{-1}$, minimum summer–autumn is 22.0 $m^3 s^{-1}$, the minimum winter runoff is 17.3 $m^3 s^{-1}$, and the environmental runoff is 21.1 $m^3 s^{-1}$. A forecast of runoff changes for the River Viliya, depending on forecasted climate change using the "Atlas of Global and Regional Climate Projections" was made on the basis of four scenarios RCP8.5, RCP6.0, RCP4.5, RCP2.6. The results of research indicate that significant changes in runoff will not occur as the forecasted climatic parameters did not change significantly. A forecasted decrease in spring runoff was investigated, thus reducing the minimum runoff is not essential. In the event of possible low water periods the Vileyka reservoir resources, involving the Olkhovskoye and the Snigyanskoye water reservoirs, can be used for compensation measures, which may be considered as the most reliable backup source of industrial water supply for the Belarusian Nuclear Power Plant.

**Key words**: runoff, water supply, minimum, the Viliya River, Belarusian Nuclear Power Plant

## Introduction

The main hydrological parameters of river runoff are not stable values. They change in both territory and in time under the influence and involvement of a variety of complex factors. The combination of these factors can be divided into natural and anthropogenic, which differ from the point of view of nature and the consequences of their impact on water resources. Natural factors determine the spatiotemporal variations of water resources, depending on the differences in their physical and geographical conditions. Permanent fluctuations take place relatively slowly, spread over a large area , are typically quasi-periodic in their nature and tend to a constant value. Periods of cooling and warming, as well as dry and wet periods alternate in time and the general state of water resources and their quality do not statistically change. The main feature of natural causes is that changes do not have a one-way trend. At the same time, the study of water resources and the impact of climate change and anthropogenic activities on runoff is an urgent worldwide task (Eum et al. 2016; Falter et al. 2015).

Anthropogenic factors are caused by different human activities. They affect the volume and quality of water resources in a relatively rapid and one-sided way, which is their main difference from natural causes. The types of economic activity that bring about changes in the quantitative and qualitative parameters of water resources are quite various. They depend on the physical and geographical conditions of the area, its water regime and character of use.

Currently, the anthropogenic impact on river basins has reached levels that can seriously affect river runoff and depend directly on the degree of reclamation and development of a territory. In Belarus human impact is manifested in changes in river runoff. The process of runoff fluctuations is affected by both human impact and natural factors. Therefore, one of the main tasks is to assess the degree of influence of these factors.

One of the most loaded rivers in Belarus is the River Viliya. As well as the impact of current climate fluctuations its waters are direct withdrawn to supply the Minsk-Vileyka Water System (MVWS),. Moreover, additional withdrawals of water from the river are planned to satisfy the needs of the Belarusian nuclear power plant (BelNPP). The problem is compounded by the fact that the River Viliya is a trans-boundary river between Belarus and Lithuania.

The purpose of this research is a multidirectional assessment of the river regime change in the runoff of the River Viliya in Belarus in current conditions and in the near future.

## Initial data and methods

The River Viliya (Lithuanian name River Neris) flows between the territory of Belarus and Lithuania, it is a right tributary of the River Neman ( River Nemunas). It has a length of 498 km, 264 km within Belarus. Its basin area covers 25100 km$^2$ and 11000 km$^2$ respectively, with an average annual water runoff of about 186 m$^3$ s$^{-1}$; the average slope of the water surface is 0.3‰. The river springs from a small swamp 1 km to the northeast of Velikoye Pole Village in the Dokshitsy region, it crosses the border with Lithuania 2 km northwest of Zherneli Village in the Ostrovets region and flows into the River Neman in Lithuania near the City of Kaunas. The main right tributaries in the territory of Belarus are the Rivers Servich, Naroch, and Strecha; left tributaries are the Rivers Dvinosa, Iliya, Usha, and Oshmyanka. High water begins in late March and lasts for about 50 days. The regime is characterized by intense spring floods (about 45% of the annual runoff) and low water standing in the summer low water period. After construction of the Vileyka reservoir the regime and discharge downstream of the dam are regulated within Belarus. the cities of Vileyka, Vilnius and Kaunas are located on the River Viliya. Almost all of the tributaries of the Viliya are channeled (Tareew and Tsyarentsew 2007).

The Vileyka reservoir was created in the first half of the 1970's and was opened in 1975–76. It is located in the Vileyka region at the confluence of the Rivers Servich, Ilia, and Kosutka 5 km east of Vileyka Town. It is the largest man-made water reservoir in Belarus. Its water surface area is 63.8 km$^2$; it is 27 km in length with a maximum width of 3 km and a maximum depth of 13 m. It has a coastline of 137 km, the volume of water is 238 hm$^3$ and its basin area is 4120 km$^2$. Water distribution is as follows: water flow through the dam in the River Viliya is about 75%, to the Minsk-Vileyka water system 20%, and for other purposes 5% (Tareew and Tsyarentsew 2007).

One of the purposes of the present research was to assess the stationary character of the time series of the Viliya River runoff with varying degrees of anthropogenic load. For these purposes we used different time series of runoff (annual, maximum, minimum summer-autumn and minimum winter) of the River Viliya at 3 stations: Steshitsy Village (basin area is $A$ = 1230 km$^2$, observation period from 1951 to 2014); Vileyka Town ($A$ = 4190 km$^2$, observation period from 1949 to 1974, from 1976 to 1979, and from 1981 to 2014); Mihalishki Village ($A$ = 10300 km$^2$, observation period from 1946 to 2014) kindly provided by the Brest Regional Center of Hydrometeorology and Environmental Monitoring. To facilitate the calculations a single calculation period from 1946 to 2014 with a duration of 69 years was selected. The missing and failing data were reconstructed using the computer software package "Hydrologist" (Volchek 1998) with the involvement of river-analogues, according to requirements (RUE "Stroytekhnorm" 2010). Paired linear regression equations were used to solve the problem of the missing data.

The value of the correlation coefficient ranged between $r = 0.65 \ldots 0.95$, which is significantly larger than the critical value $r_{cr} = 0.25$.

For the assessment of the impact of anthropogenic influences and natural factors on the runoff the original time series of runoff were analyzed for various averaging intervals: from 1946 to 2014 (the observation period, 69 years); from 1946 to 1976 (the period prior to the construction of the Vileyka water reservoir, 31 years); from 1977 to 2014 (the period of functioning of the Vileyka water reservoir, 38 years); from 1977 to 1987 (the period of functioning of the Vileyka water reservoir prior to the current warming of the climate, 11 years); from 1988 to 2014 (the period of operation of the Vileyka water reservoir taking into account the present warming of the climate, 27 years).

Figure 1 shows the schematic map of the Viliya River basin with basic river network, location gauging-stations, studied reservoirs and the BelNPP area.

For the statistical analysis of the runoff time series several methods were adopted:

- to identify the tendencies of the change in the runoff chronological oscillation charts were used, as well as differential integral curves and linear trends;

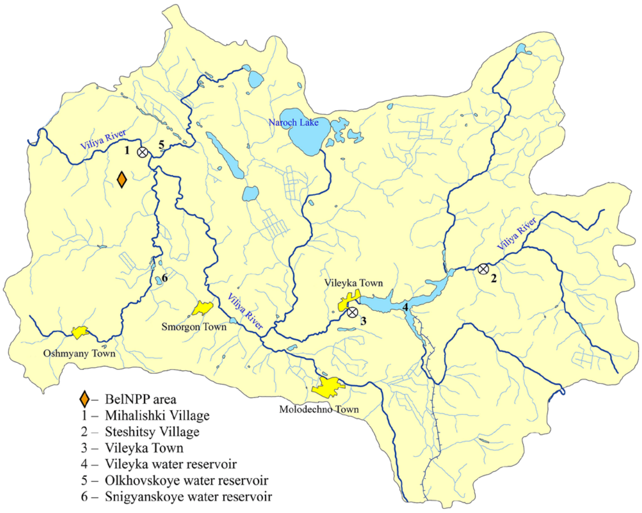

Fig. 1. Schematic map of the River Viliya basin

- for the assessment of the differences in the statistical parameters the *t*-test and *f*-test were used (Valuev et al. 1999).

When exploiting water resources it is vital to ensure the environmental sustainability of river basins. The main elements which characterize the possibility of effective use of river runoff are limiting discharges and the corresponding minimum water levels during the summer and autumn period and the period of winter low water. These discharges and water levels are some of the key parameters in the course of the year, both in terms of the functioning of aquatic ecosystems, and in terms of runoff and water drain.

In water management practice there is a widespread opinion that the environmental safety of the river is ensured by the preservation of its water runoff to the amount of 75% of the minimum monthly average runoff per year with 95% probability (MPRiOS 2003). In the European Union, from the 2000's, additional conditions for the ecological functioning of the river ecosystem have been applied with respect to requirements on the probability of the runoff conditions. These are related to the specific requirements of the high-speed runoff regime and the related channel processes, including sedimentation and sediment transport.

The assessment of environmental runoff should include not only the minimum values, but it also has to take into account intra-annual runoff distribution and variability of the data obtained in different years. To ensure the implementation of the transfer runoff the following transitions are obtained: $Q(50\%)_{env} \geq Q(75\%)_{month}$, $Q(75\%)_{env} \geq Q(95\%)_{month}$, $Q(95\%)_{env} \geq Q(99\%)_{month}$ (Fashchevskiy 1989). There are two similar options of the probabilities of transition:

1. 25% ⇒ 5%, 50% ⇒ 25%, and 99% ⇒ 95%;
2. 25% ⇒ 5%, 75% ⇒ 50%, and 99% ⇒ 95%.

The first option is closer to the method proposed by Markin (2005) with the addition of only one transition 25% ⇒ 5%. The second option was more intuitive, but is based on the above-mentioned approaches.

In the case of the minimum monthly runoff the Kritsky-Menkel density distribution function of the random variable most effectively describes the source data.

For the predictive assessment of the River Viliya runoff the method of hydrological and climatic calculations (HCC) based on a joint solution of the equations of water and heat power balance (Mezentsev 1995) was adapted. Taking into account the hydrological and climatic hypothesis by Mezentsev, a multi-factor model which included the standard equation of water balance of the land plot with an independent assessment of the main elements of the balance (precipitation, total evaporation and climatic runoff) on an annual basis was developed. The developed model was used for the assessment of possible changes in water resources of the rivers, depending on the various hypotheses of climatic variations and anthropogenic impacts on the basin parameters.

The equation of the water balance of the river basin area for a certain period of time has the following form:

$$Y_K(I) = H(I) - E(I) \pm \Delta W(I), \qquad [1]$$

where: $Y_K(I)$ – total climatic runoff (mm); $H(I)$ – total moisture resources (mm); E(I) – total evaporation (mm); $\Delta W(I)$ – change in moisture reserves of the layer of soil (mm); $I$ – averaging interval or time step of modeled river runoff (one month).

Total evaporation is calculated according to the formula:

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

where: $E_m(I)$ – maximum possible total evaporation (mm); $W_{HB}$ – lowest moisture content of the soil (mm); $V(I) = W(I) / W_{HB}$ – relative humidity of soil at the beginning of the calculation period; $KX(I)$ – the amount of measured precipitation (mm); $g(I)$ – groundwater component of the water balance (mm); $r(I)$ – parameter depending on the water-physical properties and mechanical composition of the soil; $n(I)$ – parameter, taking into account the physical and geographical conditions of runoff.

The relative humidity of the soil at the end of the calculation period is calculated from the following correlations:

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

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

The total moisture resources are indicated in the following way:

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

The solution of the system of [2]–[5] equations is arrived at by using the iteration method, as long as the relative humidity of the soil at the beginning of the calculation period is not equal to the value of the relative humidity at the end of the last period.

The simulation of water balance is carried out in the form of a computer program in two stages. The first stage involves the setting of a model using the known components of the water and heat balance of the analyzed basin. The purpose during the setting of the model is to achieve the greatest compliance of the measured and calculated runoff. The first stage ends with the output of modeling parameters and errors.

The second stage involves a direct calculation of the water balance of the analyzed river basin using the parameters obtained in the first stage. The calculation of the elements of the water balance is made by taking into account the specific parameters of the considered basin (Volchak and Parfomuk 2007).

The solution of the water balance equation for the basin area is related to the determination of the average value of the elements which are under observation at individual points of the basin. Therefore, one of the main components of the modeling of the water regime is a correct assessment of the environmental parameters and averaging in terms of the basin. This requires the use of interpolation and averaging of the used values. The averaging methods and quantitative parameters of the main elements of water balance for the conditions of Belarus were developed earlier (Valuev et al. 1991; Valuev et al. 1994).

The predicted changes in the River Viliya runoff at Mihalishki Village were realized as follows. The model was set using the average long-term data on the river runoff, precipitation, air temperature and humidity deficits; the derived parameters were stored in the developed computer program and the predicted values for the corresponding perspective were entered for the weather stations.

## Results and discussion

### Changes of runoff parameters in the River Viliya

A reduction in the annual runoff of the River Viliya at Mihalishki Village and Vileyka Town was observed (Fig. 2). It is caused by the withdrawal of runoff in the MVWS. For the maximum runoff across the whole river there is a significant reduction which results from natural factors (throughout the territory of Belarus there is a decrease in the maximum runoff of spring flood (Loginov and Volchek 2006a, 2006b). The general trend of the change of the minimum runoff in the territory of Belarus is a widespread increase in winter runoff caused by the current warming of the climate in the cold season, which causes frequent thaws and increases runoff. The summer runoff did not change except for the Polesye region, where there was an increase in runoff caused by large-scale land amelioration and the drawdown of groundwater stocks (Volchek and Volchek 2012). The fluctuations in the minimum runoff at Vileyka Town and Mihalishki Village, in both the summer-autumn and winter period are defined by the mode of operation of the water reservoir and are predictable.

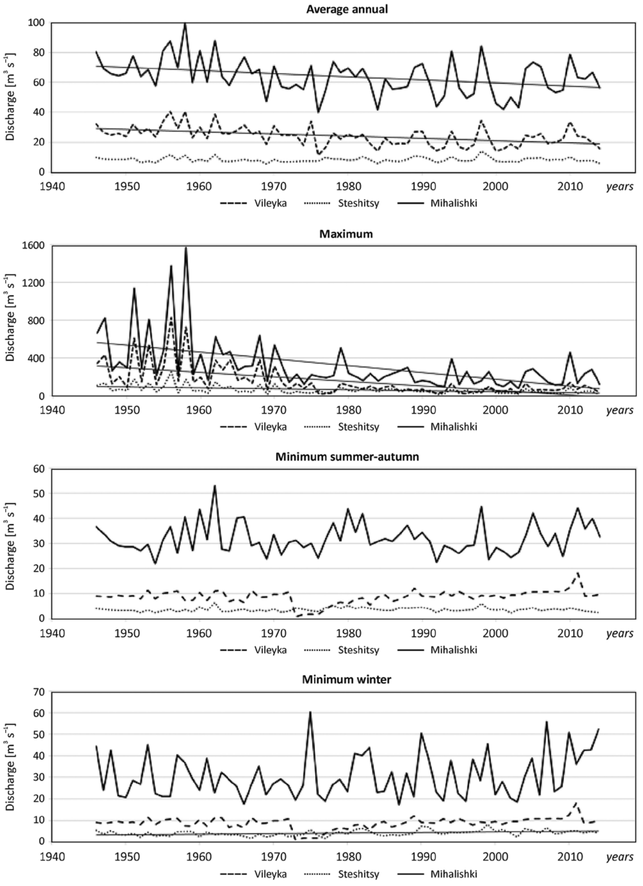

Fig. 2. Chronological course of the River Viliya runoff in different seasons; statistically significant at the level 0.05 linear trends (straight lines)

The rate of runoff change in the River Viliya was assessed using linear gradients (α) numerically equal to the product of the regression coefficient of linear trends (a) over 10 years. The gradient represents the change in runoff rate by m$^3$ s$^{-1}$ for 10 years. The values of the gradients and their significance using the correlation coefficients are given in Table 1.

For the period 1946–2014 the statistically significant negative linear gradients are valid for average annual runoff at Vileyka Town and Mihalishki Village: –1.53 and –2.10 m$^3$ s$^{-1}$ in the period of 10 years respectively. This is caused by the withdrawal of water for the MVWS. The gradients of maximum runoff are negative and statistically significant at all stations, and amount to –10.2, –47.9, –71.9 m$^3$ s$^{-1}$ for 10 years respectively.

Table 1. Statistical parameters of linear trends of runoff changes in the River Viliya

| Type of runoff | Average annual | | | Maximum | | | Min. summer–autumn | | | minimum winter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki |
| Averaging period 1946–2014 | | | | | | | | | | | | |
| $\alpha \cdot 10$, m$^3$ s$^{-1}$ | –0.02 | –1.53 | –2.10 | –10.20 | –47.90 | –71.90 | 0.03 | 0.31 | 0.12 | 0.24 | 0.31 | 0.95 |
| *r* | –0.02 | **–0.48** | **–0.35** | **–0.46** | **–0.58** | **–0.51** | 0.07 | 0.23 | 0.04 | **0.37** | 0.23 | 0.18 |
| Averaging period 1946–1976 | | | | | | | | | | | | |
| $\alpha \cdot 10$, m$^3$ s$^{-1}$ | –0.63 | –2.11 | –5.62 | –23.70 | –83.50 | –151.0 | –0.02 | –1.59 | –0.64 | –0.24 | –1.56 | –0.63 |
| *r* | **–0.38** | –0.31 | **–0.41** | **–0.38** | **–0.38** | **–0.38** | –0.02 | **–0.49** | –0.09 | –0.21 | **–0.49** | –0.06 |
| Averaging period 1977–2014 | | | | | | | | | | | | |
| $\alpha \cdot 10$, m$^3$ s$^{-1}$ | –0.20 | 0.16 | –0.33 | –7.06 | –0.24 | –12.80 | –0.34 | 1.40 | –0.13 | 0.24 | 1.39 | 2.94 |
| *r* | –0.13 | 0.04 | –0.03 | **–0.34** | –0.01 | –0.15 | **–0.47** | **0.66** | –0.02 | 0.20 | **0.66** | 0.30 |
| Averaging period 1977–1987 | | | | | | | | | | | | |
| $\alpha \cdot 10$, m$^3$ s$^{-1}$ | –2.36 | –3.86 | –12.7 | 17.10 | 16.60 | –52.30 | –1.22 | 3.38 | –4.39 | –0.11 | 3.38 | 0.17 |
| *r* | **–0.64** | –0.33 | **–0.47** | 0.29 | 0.16 | –0.18 | **–0.61** | **0.67** | –0.30 | –0.03 | **0.67** | 0.01 |
| Averaging period 1988–2014 | | | | | | | | | | | | |
| $\alpha \cdot 10$, m$^3$ s$^{-1}$ | –0.61 | 0.66 | 0.83 | –4.51 | 11.90 | 12.50 | –0.31 | 0.82 | 2.27 | –0.11 | 0.80 | 4.75 |
| *r* | –0.27 | 0.09 | 0.06 | –0.16 | 0.28 | 0.10 | –0.32 | 0.33 | 0.29 | –0.07 | 0.32 | 0.32 |

Note: The marked values are statistically significant at the level $p < 0.05$.

This is caused by the effects of anthropogenic factors – the filling of the reservoir, and natural – the current climate warming. For minimum runoff a statistically significant positive gradient was observed in winter at Steshitsy Village and amounted to 0.24 m$^3$ s$^{-1}$ for 10 years, which is typical of the whole territory of Belarus (Volchek and Gryadunova 2010).

For the period 1946–1976 a widespread decrease in runoff was noted. The mean annual runoff at Steshitsy and Mihalishki Villages showed a statistically significant decrease, the gradient was –0.63 and –5.62 m$^3$ s$^{-1}$ in the period of 10 years respectively. The maximum runoff at all stations also decreased: –23.7, –83.5, –151 m$^3$ s$^{-1}$ in the period of 10 years. The minimum runoff in the summer-autumn and winter periods significantly decreased and at Vileyka Town was –1.59 and –1.56 m$^3$ s$^{-1}$ in the period of 10 years respectively.

For the period 1977 to 2014 the predominant tendency was a reduction of runoff. The maximum and minimum summer-autumn runoff at Steshitsy Village significantly decreased by –7.06 and –0.34 m$^3$ s$^{-1}$ in the 10 year period respectively. A statistically significant increase in the minimum runoff gradient at Vileyka Town resulted from features of water reservoir management.

For the period 1977 to 1987 a prevalence of low runoff gradient was observed, with the repetition of the previous period.

During the current climate warming period statistically significant gradients were not observed. This is due to the influence of the water reservoir regime.

## Analysis of the runoff series homogeneity

The empirical curves of probability for all averaging periods correspond to three-parameter gamma-distribution, and the correlation of the asymmetry coefficient ($C_s$) to the coefficient of variation ($C_v$), as a rule, does not exceed $C_s = 1 \dots 2C_v$. As the function of the probability distribution for such assessment parameters is slightly different from the normal distribution function, the use of parametric criteria for the verification of statistical hypotheses can be applied (Table 2).

The stability of the sample statistics (average, coefficients of variation) for the averaging period 1946–1976 and 1977–2014 (the assessment of the MVWS influence), 1977–1987 and 1988–2014 (before and during the contemporary warming) for all types of runoff at the River Viliya stations using Student and Fisher statistical criteria was analyzed (Table 3).

The next step of the research was to analyze the changes in the runoff of the River Viliya caused by activity of the MVWS, i.e. to compare the changes which occurred in the runoff in the periods 1946–1976 and 1977–2014. The common analysis of Table 2 and 3 showed that the average annual runoff in the River Viliya at Vileyka Town and Mihalishki Village decreased by 6.3 and 7.2 m$^3$ s$^{-1}$ respectively, and the variances are statistically significant. This is due to the intake of water in the MVWS. The maximum runoff significantly decreased and amounted to 31.9, 187.5, 261 m$^3$ s$^{-1}$ respectively, and the nature of the fluctuations also changed; the amplitude of oscillation significantly decreased. This was caused by the filling of

Table 2. Statistical parameters of the River Viliya runoff in different averaging periods

| Type of runoff | Average annual | | | Maximum | | | Min. summer-autumn | | | minimum winter | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki | Steshitsy | Vileyka | Mihalishki |
| Averaging period 1946–2014 | | | | | | | | | | | | |
| $Q$, m$^3$ s$^{-1}$ | 8.27 | 24.0 | 63.7 | 61.6 | 152.0 | 319.0 | 3.73 | 8.81 | 32.1 | 4.16 | 8.80 | 30.7 |
| $C_v$ | 0.19 | 0.27 | 0.19 | 0.72 | 1.09 | 0.88 | 0.22 | 0.30 | 0.19 | 0.31 | 0.30 | 0.34 |
| $C_s$ | 1.11 | 0.47 | 0.35 | 1.90 | 2.32 | 2.67 | 0.95 | –0.52 | 0.95 | 0.67 | –0.52 | 0.88 |
| $Q_{p=5\%}$, m$^3$ s$^{-1}$ | 11.40 | 32.8 | 72.10 | 147.0 | 507.0 | 872.0 | 5.17 | 12.2 | 38.2 | 6.48 | 12.2 | 48.3 |
| $Q_{p=95\%}$, m$^3$ s$^{-1}$ | 6.32 | 16.9 | 53.40 | 18.5 | 16.3 | 72.2 | 2.76 | 6.43 | 27.3 | 2.42 | 6.43 | 18.5 |
| Averaging period 1946–1976 | | | | | | | | | | | | |
| $Q$, m$^3$ s$^{-1}$ | 8.09 | 27.5 | 67.6 | 79.2 | 255.0 | 463.0 | 3.51 | 8.25 | 31.6 | 3.59 | 8.25 | 29.3 |
| $C_v$ | 0.19 | 0.23 | 0.18 | 0.72 | 0.79 | 0.77 | 0.22 | 0.36 | 0.20 | 0.29 | 0.36 | 0.33 |
| $C_s$ | 1.05 | 0.08 | 0.38 | 1.27 | 1.37 | 1.77 | 1.86 | –1.40 | 1.43 | 0.36 | –1.40 | 1.44 |
| $Q_{p=5\%}$, m$^3$ s$^{-1}$ | 9.78 | 37.5 | 80.5 | 207.0 | 689.0 | 1234.0 | 4.89 | 13.1 | 43.6 | 5.10 | 13.1 | 46.6 |
| $Q_{p=95\%}$, m$^3$ s$^{-1}$ | 6.82 | 19.4 | 57.7 | 19.9 | 66.0 | 131.0 | 2.59 | 5.45 | 23.5 | 2.46 | 5.45 | 19.5 |
| Averaging period 1977–2014 | | | | | | | | | | | | |
| $Q$, m$^3$ s$^{-1}$ | 8.43 | 21.2 | 60.5 | 47.3 | 67.5 | 202.0 | 3.91 | 9.27 | 32.5 | 4.62 | 9.26 | 31.7 |
| $C_v$ | 0.19 | 0.24 | 0.18 | 0.49 | 0.51 | 0.48 | 0.20 | 0.25 | 0.18 | 0.29 | 0.25 | 0.35 |
| $C_s$ | 1.16 | 0.71 | 0.16 | 0.33 | 0.59 | 1.43 | 0.46 | 1.08 | 0.51 | 0.56 | 1.09 | 0.55 |
| $Q_{p=5\%}$, m$^3$ s$^{-1}$ | 10.2 | 29.1 | 71.4 | 93.2 | 134.0 | 402.0 | 5.42 | 13.0 | 38.4 | 6.55 | 13.0 | 49.9 |
| $Q_{p=95\%}$, m$^3$ s$^{-1}$ | 7.11 | 15.5 | 51.3 | 16.4 | 25.6 | 94.9 | 2.85 | 6.90 | 27.4 | 3.22 | 6.89 | 18.8 |
| Averaging period 1977–1987 | | | | | | | | | | | | |
| $Q$, m$^3$ s$^{-1}$ | 8.26 | 21.1 | 61.2 | 60.1 | 78.3 | 237.0 | 4.34 | 7.02 | 34.4 | 4.00 | 7.02 | 29.0 |
| $C_v$ | 0.15 | 0.18 | 0.15 | 0.33 | 0.45 | 0.40 | 0.15 | 0.24 | 0.14 | 0.33 | 0.24 | 0.32 |
| $C_s$ | –0.21 | –0.39 | –0.77 | 0.02 | –0.24 | 2.59 | 0.33 | –0.29 | 1.15 | 0.26 | –0.29 | 0.49 |
| Averaging period 1988–2014 | | | | | | | | | | | | |
| $Q$, m$^3$ s$^{-1}$ | 8.50 | 21.2 | 60.2 | 42.1 | 63.2 | 188.0 | 3.74 | 10.2 | 31.8 | 4.87 | 10.2 | 32.8 |
| $C_v$ | 0.21 | 0.26 | 0.20 | 0.54 | 0.53 | 0.51 | 0.21 | 0.19 | 0.19 | 0.26 | 0.19 | 0.36 |
| $C_s$ | 1.24 | 0.83 | 0.34 | 0.65 | 0.99 | 1.31 | 0.81 | 2.92 | 0.60 | 0.91 | 2.90 | 0.47 |

Note: $Q$ – mean runoff, $C_v$ – coefficient of variation ,$C_s$ – asymmetry coefficient, $Q_{p=5\%}$ – runoff of 5% probability, $Q_{p=95\%}$ – runoff of 95% probability.

Table 3. Statistical criteria (t – Student, F – Fisher) for different averaging intervals and types of the River Viliya runoff

| Station | Steshitsy | | Vileyka | | Mihalishki | |
|---|---|---|---|---|---|---|
| Criterion | *t* | *F* | *t* | *F* | *t* | *F* |
| Type of runoff | average annual | | | | | |
| 1946–1976, 1977–2014 | 0.90 | 1.19 | **4.56** | 1.50 | **2.50** | 1.29 |
| 1977–1987, 1988–2014 | 0.47 | 2.06 | 0.04 | 2.06 | 0.28 | 1.25 |
| | maximum | | | | | |
| 1946–1976, 1977–2014 | **2.93** | **6.00** | **5.13** | **34.4** | **3.93** | **13.7** |
| 1977–1987, 1988–2014 | 1.21 | 1.33 | 1.21 | 1.12 | 1.45 | 0.53 |
| | minimum summer–autumn | | | | | |
| 1946–1976, 1977–2014 | **2.13** | 1.55 | 1.57 | 1.55 | 0.62 | 1.27 |
| 1977–1987, 1988–2014 | **2.43** | 1.43 | **5.04** | 1.38 | 1.61 | 1.61 |
| | minimum winter | | | | | |
| 1946–1976, 1977–2014 | **3.67** | 1.79 | 1.55 | 1.55 | 0.96 | 1.34 |
| 1977–1987, 1988–2014 | 1.85 | 1.10 | **5.02** | 1.39 | 1.06 | 1.61 |

Note: the marked values are statistically significant at the level 0.05.

the reservoir during this period and the frequent winter thaws. The statistically significant increase in the minimum summer-autumn runoff at Steshitsy village, which amounted to 0.4 m$^3$ s$^{-1}$, was caused by meliorative interventions (Loginov and Volchek 2006b). The increase of the minimal winter runoff was 1.03, 1.01 and 2.4 m$^3$ s$^{-1}$ respectively. The increase was recorded at Steshitsy Village and was statistically significant due to winter thaws. The assessment of the changes in the water runoff in terms of current climate warming is of particular interest. For this purpose two periods (1977–1987 and 1988–2014) were compared. The analysis showed statistically significant changes in the minimum summer-autumn runoff at Steshitsy Village and Vileyka Town. In the first case there was a runoff decrease of 0.6 m$^3$ s$^{-1}$, and in the second – an increase by 3 m$^3$ s$^{-1}$.

## Current statistical estimates of the River Viliya runoff at Mihalishki Village

For river basins with intensive economic activity the calculation of hydrological parameters is made using two schemes (RUE “Stroytekhnorm” 2010):

- bringing the hydrological time series to natural homogeneous stationary conditions;
- hydrological time series are brought to domestic water runoff for the observation period and are based on the assumption that the current complex of economic activities has already begun at the beginning of observation.

The second scheme was used in the current research. The violation of the homogeneity of the time series of the River Viliya runoff at Mihalishki Village takes place for the average annual and maximum runoff (Table 3). The recovery of the runoff for the whole period of observations was carried out using regression methods in the period 1946 to 1976, and as the analog river, the River Viliya at Steshitsy Village was used. The recovered series were tested for homogeneity using statistical methods. The identification of the main hydrological parameters was performed using data for the period 1946–2014 without the introduction of the amendments on economic activity (Table 4). In this case, the Pearson distribution of type III for the average annual runoff was used, and for maximum runoff – a three-parameter Kritsky-Menkel gamma distribution (RUE “Stroytekhnorm” 2010). The minimum runoff does not require the recovery, as water releases from the reservoir during water shortage periods were regulated in terms of the natural runoff.

Thus, the values of the runoff of the River Viliya at Mihalishki Village can be used as the basis for the acceptance of certain management decisions.

## Environmental runoff

The River Viliya and its tributaries have great environmental importance for ensuring favorable conditions for anadromous, catadromous and other species of fish, as well as for the conservation of the biological and landscape diversity of the surrounding areas. The Lithuanian part of the River Viliya (the River Neris) is an area of “Natura 2000”, which was created for the protection of salmon, otters, river lamprey, bitterling and other fish species.

The specialists of the Central Research Institute for the Complex Use of Water Resources (CRICUWR) applied mathematical modeling of the water regime taking into account the runoff conditions in terms of the high-speed mode and the application of the calculated depth analysis of the River Viliya runoff at Mihalishki Village and obtained a value of environmental runoff of about 20.8 m$^3$ s$^{-1}$ and a corresponding water level of approximately 118.5 m of the Baltic System of Heights at the average speed of water runoff 0.4 m$^3$ s$^{-1.}$

The environmental and free runoff (difference between natural and environmental runoff) of the Viliya at Mihalishki Village were determined using well-known methodology (Volchek et al. 2017; Fashchevskiy 1996). As the procedure of bringing the series to the homogeneous conditions of the runoff used the second scheme, which takes into account the impact of existing consumers on the basin area, the environmental and free runoff were determined taking these consumers into consideration (Table 5).

Table 4. Statistical parameters of the River Viliya runoff at Mihalishki Village for the period 1946–2014

| Parameters | Type of runoff | | | |
|---|---|---|---|---|
| | Average annual | Maximum | Min. summer-autumn | Minimum winter |
| $Q$, m$^3$ s$^{-1}$ | 59.7 | 262 | 32.1 | 30.7 |
| $Q_{p=1\%}$, m$^3$ s$^{-1}$ | 89.1 | 973 | 41.9 | 59.8 |
| $Q_{p=5\%}$, m$^3$ s$^{-1}$ | 78.9 | 621 | 38.2 | 48.3 |
| $Q_{p=50\%}$, m$^3$ s$^{-1}$ | 58.7 | 222 | 31.9 | 29.5 |
| $Q_{p=95\%}$, m$^3$ s$^{-1}$ | 44.2 | 84.5 | 27.3 | 18.5 |
| $Q_{p=99\%}$, m$^3$ s$^{-1}$ | 35.5 | 58.0 | 25.7 | 15.4 |
| $C_v$ | 0.18 | 0.71 | 0.19 | 0.34 |
| $C_s/C_v$ | 2.89 | 2.81 | 4.95 | 2.58 |

Table 5. Annual runoff distribution of the River Viliya at Mihalishki Village

| Months | Water content of the year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Medium | | | Low water | | | Very low water | | |
| Type of runoff | natural | environmental | free | natural | environmental | free | natural | environmental | free |
| March | 90.9 | 67.9 | 22.9 | 86.5 | 67.9 | 18.5 | 84.9 | 67.9 | 16.9 |
| April | 128 | 90.9 | 37.3 | 152 | 90.9 | 60.9 | 114 | 90.9 | 22.7 |
| May | 67.5 | 48.0 | 19.5 | 54.3 | 48.0 | 6.3 | 59.9 | 48.0 | 12.0 |
| June | 56.1 | 28.9 | 27.2 | 38.0 | 28.9 | 9.1 | 36.1 | 28.9 | 7.21 |
| July | 44.4 | 24.3 | 20.1 | 49.5 | 24.3 | 25.2 | 30.3 | 24.3 | 6.06 |
| August | 35.9 | 21.1 | 14.9 | 30.6 | 21.1 | 9.6 | 26.3 | 21.1 | 5.25 |
| September | 36.2 | 21.1 | 15.1 | 33.3 | 21.1 | 12.3 | 26.3 | 21.1 | 5.25 |
| October | 43.6 | 23.3 | 20.3 | 39.5 | 23.3 | 16.2 | 29.1 | 23.3 | 5.81 |
| November | 54.9 | 25.5 | 29.4 | 48.6 | 25.5 | 23.1 | 31.9 | 25.5 | 6.36 |
| December | 46.3 | 28.8 | 17.6 | 52.8 | 28.8 | 24.0 | 36.0 | 28.8 | 7.18 |
| January | 40.9 | 23.4 | 17.5 | 41.8 | 23.4 | 18.5 | 29.2 | 23.4 | 5.83 |
| February | 59.5 | 21.6 | 37.9 | 33.5 | 21.6 | 11.9 | 26.9 | 21.6 | 5.38 |
| Year | 58.7 | 35.4 | 23.3 | 55.0 | 35.4 | 19.6 | 44.2 | 35.4 | 8.82 |

The annual distribution of environmental runoff was calculated according to the percentage distribution of natural runoff in a very dry year of the River at Mihalishki Village. The results closely correlate to those of other authors using other methods; therefore the value of environmental runoff, consistent with the actual value and the free runoff in the very low water months, is 5.25 m$^3$ s$^{-1.}$

Table 6. The assessment of particularly low water periods of the River Viliya runoff at Mihalishki Village

| Year | Low water period [days] | Date | Average daily runoff [m$^3$ s$^{-1}$] |
|---|---|---|---|
| 1950 | 7 | 4.01 | 23.40 |
| | | 5.01 | 22.50 |
| | | 6.01 | 22.90 |
| | | 7.01 | 23.50 |
| | | 8.01 | 23.40 |
| | | 9.01 | 23.10 |
| | | 10.01 | 23.10 |
| | 4 | 14.01 | 22.30 |
| | | 15.01 | 20.70 |
| | | 16.01 | 21.80 |
| | | 17.01 | 22.80 |
| 1954 | 1 | 27.11 | 22.10 |
| 1955 | 1 | 1.12 | 21.40 |
| 1961 | 1 | 31.12 | 23.10 |
| 1976 | 2 | 27.12 | 23.00 |
| | | 28.12 | 22.80 |
| 1988 | 1 | 2.12 | 23.20 |
| 1992 | 14 | 15–28.08 | 23.10 |
| | 3 | 1.09 | 22.50 |
| | | 2.09 | 22.50 |
| | | 3.09 | 23.10 |
| 2002 | 2 | 3.12 | 21.70 |
| | | 4.12 | 22.50 |

The calculated environmental runoff is a relative value and it depends on the adopted model of calculation. Therefore, the actual data of considerable probabilities observed on the river can provide some indications for the assessment of environmental runoff.

The analysis of minimum water runoff of the River Viliya at Mihalishki Village for the whole period of observations gave the following results: the smallest runoff in the open channel period amounted to 22.0 m$^3$ s$^{-1}$ and was noted on two occasions from 02.07 to 03.07.1954; the lowest runoff of the winter period was 17.3 m$^3$ s$^{-1}$ and was observed on 26.12.1986. Table 6 shows the results of the analysis of very low water periods of the River Viliya runoff at Mihalishki Village.

## Forecast assessment of the runoff changes of the River Viliya on the territory of Belarus

The time series of observations of air temperature and precipitation for the period from 1961 to 2010 according to the data provided by meteorological stations evenly spaced along the river basin were used for assessing the runoff changes.

The trends in the meteorological parametersof the River Viliya basin were presented in (Korneev et al. 2015). As a summary, the results of assessments of the trends in meteorological parameters, according to the information of the meteorological station at Vileyka Town are presented in Table 7.

Table 7. The results of calculations of the meteorological parameters of trends in the River Viliya basin for the period 1986 to 2010 in comparison to the period 1961 to 1986

| The interval averaging | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | XII–II | III–V | VI–VIII | IX–XI | Year |
| Changes in temperature [°C] | | | | | | | | | | | | | | | | |
| 2.8 | 2.3 | 1.5 | 1.1 | 0.1 | 0.4 | 1.4 | 0.7 | 0.0 | 0.0 | 0.0 | 0.5 | 1.9 | 0.9 | 0.8 | 0.0 | 0.9 |
| Changes in rainfall [%] | | | | | | | | | | | | | | | | |
| 16 | 22 | 5 | –19 | 9 | 14 | 0 | 1 | –1 | 4 | –18 | –12 | 6 | –2 | 5 | –5 | 1 |

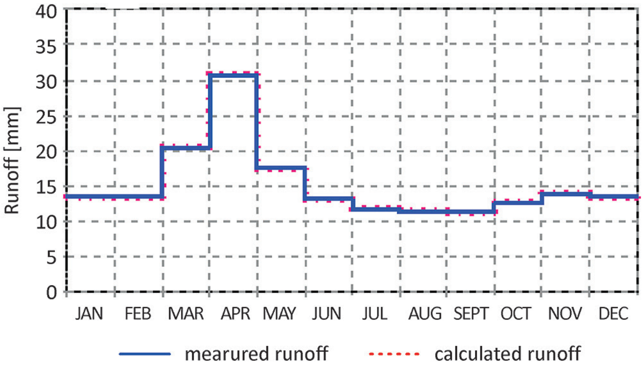

Fig. 3. The measured and calculated runoff of the River Viliya at Mihalishki Village (the results of the model set up)

A detailed analysis of changes in runoff in the River Neman basin including the River Viliya at Mihalishki Village was made before (Korneev et al. 2015; Volchak and Parfomuk 2014).

Figure 3 presents graphical materials of the runoff forecasting model settings. The time step of modeled river runoff was one month in accordance with formula [1] and the period of model calibration was 1946–2014. The model parameters were then used to forecast the runoff with projected values of air temperature and relative precipitation.

A forecast of air temperature and relative precipitation was made for the short term (2016–2035) with the help of the "Atlas of Global and Regional Climate Projections" (IPCC 2013a–d). A map of changes in average and global values of the above parameters in different seasons of the year was obtained. It was based on the use of a multi-model ensemble of the four scenarios RCP8.5, RCP6.0, RCP4.5, RCP2.6 (Volchek et al. 2017).

Seasonal values which are taken from the Atlas show changes in relevant parameters relative to the period of observations 1949–2015. Changes of air temperature specified for the four calendar seasons, and of precipitation – for two (April–September and October–March). Based on the monthly average percentage distribution within each season for the period 1949–2015 the division values were made according to. Thus, seasonal distribution of changes in air temperature and precipitation for the period 2016–2035 was obtained. Figure 4 shows the observed and predicted values of the River Viliya runoff.

The forecast of runoff changes of the River Viliya for the period 2016–2035 was made using the forecasted climate values. Obtained values of the runoff characterize the long-term average and monthly values. As a result of the research it was concluded that significant changes in runoff will not occur as forecasted climatic parameters did not change significantly. The forecasted decrease in spring runoff was investigated, thus reducing the minimum runoff is not essential.

## The perspectives of new water consumers in the basin area

The obtained hydrological parameters of water runoff of the River Viliya at Mihalishki Village take into account the structure of the existing water consumers and the need to make informed project decisions. One of the major consumers in the Viliya basin in the near future will be the industrial water supply for the Belaru-

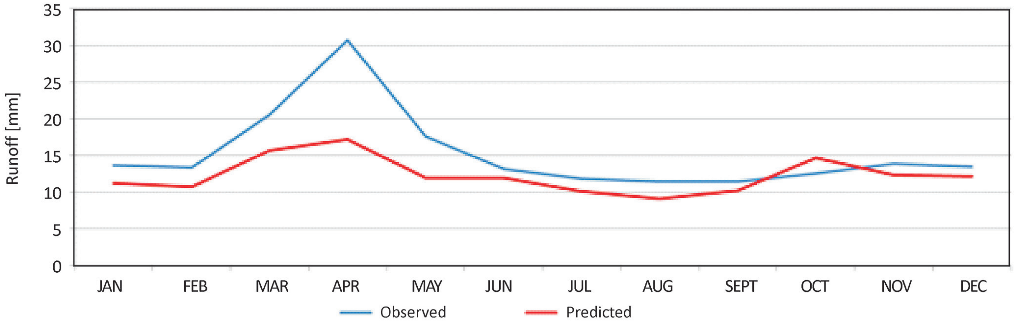

Fig. 4. Observed and predicted hydrographs of the River Viliya runoff at Mikhalishki Village

sian Nuclear Power Plant. The territory of the BelNPP is located in the North-Western part of Belarus within the Ostrovets region near the City of Grodno. The River Viliya is considered to be the main source of technical water supply for the BelNPP. To ensure a reliable and uninterrupted water supply a constant replenishment of fresh water for two power reactors of about 2.54 m$^{3}$ s$^{-1}$ is needed, and for four reactors – about 5.08 m$^{3}$ s$^{-1}$.

The hydrological research and environmental assessment of the impact of the BelNPP made by CRICUWR specialists in 2008–2009 has shown that the resources of the River Viliya as a source of industrial water supply of BelNPP are sufficient.

The minimum average river runoff of 95% probability at Mihalishki Village is 26.3 m$^{3}$ s$^{-1}$. Therefore, the minimum allowed water runoff in the River Viliya after the water intake for the industrial water supply for the BelNPP in any hydrological conditions should be not be less than 21.1 m$^{3}$ s$^{-1}$.

In the event of possible low water periods the Vileyka reservoir resources can be used for compensation measures, which may be considered as the most reliable backup source of industrial water supply for the BelNPP.

The analysis of the planned water intake from the Vileyka reservoir for the purposes of pumping by the MVWS for other water consumers makes it possible for CRICUWR experts to conclude the feasibility and the possibility of using the Vileyka water reservoir as the primary backup source of industrial water supply of the BelNPP. A significant factor which has to be considered during the organization of the water releases from the Vileyka water reservoir is the relative distance of the reservoir (more than 100 km) from the placement of the surface water intake point of the BelNPP, which causes a 3–4 day time water travel lag. Therefore, in the event of water shortages in terms of the implementation of environmental restrictions the water releases may be carried out from the Olkhovskoye water reservoir and (or) the Snigyanskoye water reservoir which are closer to the BelNPP.

Thus, the additional consumptive use of the NPP and planned future growth of irrevocable withdrawals for the needs of water supply will not exceed 10% of the runoff of 95% probability and will not have a significant impact on the hydrological regime of the River Viliya.

## Conclusion

On the basis of a comprehensive analysis of hydrometric information for the River Viliya at Steshitsy Village, Vileyka Town and Mihalishki Village with respect to the annual average, maximum, minimum summer–autumn and winter runoff from 1946 to 2014 it was possible to ascertain the heterogeneity in the time series of average annual water runoff at Vileyka Town and Mihalishki Village. The heterogeneity of the maximum water runoff at all the stations and the heterogeneity of the minimum summer–autumn and winter runoff at Vileyka Town and Steshitsy Village were investigated. At Mihalishki Village the average annual runoff is about 59.7 m$^{3}$ s$^{-1}$, maximum is 1570 m$^{3}$ s$^{-1}$, minimum summer–autumn is 22.0 m$^{3}$ s$^{-1}$, and the minimum winter runoff is 17.3 m$^{3}$ s$^{-1.}$

The results of runoff prediction indicate that significant changes in runoff will not occur as forecasted climatic parameters did not change significantly. The forecasted decrease in spring runoff was investigated, thus reducing the minimum runoff is not essential.

The functioning of the Minsk-Vileyka Water System has the greatest influence on the water regime of the River Viliya . Over 110 hm3 of water is annually withdrawn in the basin of the Dnieper River, which is about 91% of water withdrawn in the river basin. The volume of water withdrawal of the River Viliya at Mihalishki Village is less than 10% of the annual runoff in terms of 95% probability; therefore it should not have a significant impact on the river flow regime.

Minimum average monthly runoff in terms of 95% probability of the River Viliya at Mihalishki Village is approximately 26.3 m$^{3}$ s$^{-1}$. The additional consumption by the Belarusian Nuclear Power Plant and the planned future growth of irrevocable withdrawals for the needs of water in the river basin would not exceed 10% of the runoff in terms of 95% probability.

In the case of the possible water shortage periods the Vileyka water reservoir resources involving the Olkhovskoye and the Snigyanskoye water reservoirs may be used. These reservoirs may be considered to be the most reliable backup source of industrial water supply for the BelNPP.

Thus, additional consumption of water by the BelNPP and planned future growth of irrevocable withdrawals for the needs of water intake from the river basin would not have a considerable impact on the hydrological regime of the River Viliya.

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