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Changes in the Hydrological Regime of the Volga River and Their Influence on Caspian Sea Level Fluctuations

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Abstract: In this study, spanning from 1938 to 2020, the hydrological changes in the Volga River and their repercussions on the Caspian Sea level were examined. Analysis reveals a correlation between high Volga River runoff and increased atmospheric precipitation in its basin. However, in recent years (2005–2020), a significant decline in the runoff coefficient at the Verkhneye Lebyazhie hydrological station, attributable to climate warming surpassing global temperature anomalies, has been observed. This warming's impact on river flow and sea level was quantified, resulting in a 133 cm decrease in sea level from 1977 to 2020. Notably, while, historically, Caspian Sea level changes mirrored Volga River runoff fluctuations until 2005, since 2006, the sea level has markedly dropped, decoupling from river runoff variations. Comparison with recent studies suggests that altered wind characteristics over the Caspian Sea, influencing surface evaporation, may have significantly contributed to this rapid sea level decline in recent years.

Keywords: Volga River; river runoff; atmospheric precipitation; Caspian Sea; climatic changes; anthropogenic factors

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1. Introduction

The Caspian Sea is the largest enclosed body of water in the world, with no direct connection to the world's oceans. Over its long history, the sea level has undergone many dramatic changes. Reviews of historical data on Caspian Sea level changes over the last millennium can be found in a number of publications [1–3].

Caspian Sea level fluctuations depend on many climatic, tectonic, and anthropogenic factors. These factors interact with each other in a complex way and change continuously in space and time. While in the Early Neogene, tectonic and, to a lesser extent, climatic factors had a predominant influence on sea level, at the present stage, climatic and anthropogenic factors come to the fore [4–6].

According to current understanding, the level of the Caspian Sea depends mainly on its water balance, which in turn is related to climatic factors and consists of the flow of the rivers feeding it, precipitation falling on its surface, and evaporation from its surface [6].

As is commonly known, in a number of natural and anthropogenic factors, the concentration of carbon dioxide and other greenhouse gases in the atmosphere is increasing, resulting in global warming.

Global warming has continued to break records in recent years. According to WMO data, the year 2020 was one of the warmest three years on record, with a global mean temperature anomaly of 1.2 ± 0.1 °C relative to temperatures over the period of 1850–1900. The last five years, as well as the last decade, were the warmest on record [7,8]. However, the rate of climate change is not uniform across the globe [9]. In the vast region of the

Siberian Arctic, temperature anomalies for 2020 were more than 3 °C, and in its central coastal parts, more than 5 °C above the global average [7]. In Kazakhstan, the Caspian region is characterized by the highest rate of increase in mean annual and seasonal air temperature [10]. In general, the temperature increase in the high latitudes of the Northern Hemisphere is more significant [9,11] than in the southern latitudes. This zone can also include the main part of the Volga River basin, where the temperature anomalies are about 2–3 times higher than the global temperature anomalies [12]. On the other hand, temperature anomalies vary for different months of the year [13].

Since air temperature is the most important characteristic of the climate, changes in its statistical structure lead to a restructuring of the heat and moisture transport processes in the atmosphere, which in turn affects the precipitation process [14].

One of the main elements of the Caspian Sea water balance is the mass of water brought by rivers [15,16]. About 130 rivers flow into the Caspian Sea, but the Volga, Kura, Ural, Terek, and Sulak rivers bring the main volume of runoff to the sea. According to some data, the Volga River accounts for more than 80% of the water brought into the Caspian Sea [17–20]. However, this share can be noticeably larger in different periods [21]. Therefore, Caspian Sea level fluctuations are largely determined by the variability of the Volga River flow [6]. Thus, studying the hydrological regime of the Volga River and its impact on the Caspian Sea level fluctuations is very relevant. From this point of view, this study investigated the changes occurring in the Volga River flow and the factors affecting them and analyzed the relationship between these changes and the Caspian Sea fluctuations.

The hydrological regime of the Volga River is also affected by anthropogenic factors (flow regulation by hydraulic structures built on the river since the 1950s, water use for economic purposes, etc.) [22–24].

It should also be kept in mind that the area along the banks of the Volga River is characterized by a high degree of industrial and agricultural development [25]. However, among the factors affecting the hydrological regime of the Volga River, the advantage of climatic factors is undoubted [23]. The average runoff volumes for the period of natural (1881–1957) and regulated (1961–2017) regimes according to the data of the Volgograd hydrological station are very close—256 km^3/year and 249 km^3/year, respectively [12].

The regulation had the most significant impact on the parameters of intra-annual runoff distribution and characteristics of the most important phase of the hydrological regime—spring flood [26,27].

A number of scientific works have been devoted to the study of this problem [6,20,23,26–34] which addresses various aspects of this problem. However, in these studies, the impact of climate warming on the Volga River runoff and, consequently, on the Caspian Sea level changes is not studied in detail.

This paper investigates the nature of the dependence of the Volga River flow on changes in climatic factors (precipitation and air temperature) in its basin during different periods of Caspian Sea level rise and fall. One of the main objectives of this study is to assess the impact of climate warming on changes in the hydrological regime of the Volga River, which in turn causes fluctuations in the level of the Caspian Sea. The work also considers other climatic factors, changes which may have led to changes in the Caspian Sea level.

2. Study Area

The Volga River is one of the largest rivers in the world and the largest river in Europe, the basin of which occupies one-third of the European part of Russia. The Volga is 3530 km long, and the basin covers an area of 1,360,000 km^2. Currently, the river basin harbors about 45% of industry and half of all agriculture in Russia. The river basin produces over 20% of all fish for the food industry [7].

The main source of the Volga River runoff is snowmelt and precipitation falling in its basin [3,22]. The Volga River flows into the largest inland body of water in the world—the Caspian Sea.

The Volga River is divided into three sections: the Upper Volga, the Middle Volga, and the Lower Volga. The Upper Volga originates at the source, which is located on the Valdai Upland and ends at the confluence of the Oka River into the Volga. The Middle Volga begins at the Oka River and ends at the confluence of another major tributary: the Kama River. The Lower Volga begins at the mouth of the Kama and ends at the mouth of the Volga itself (Figure 1).

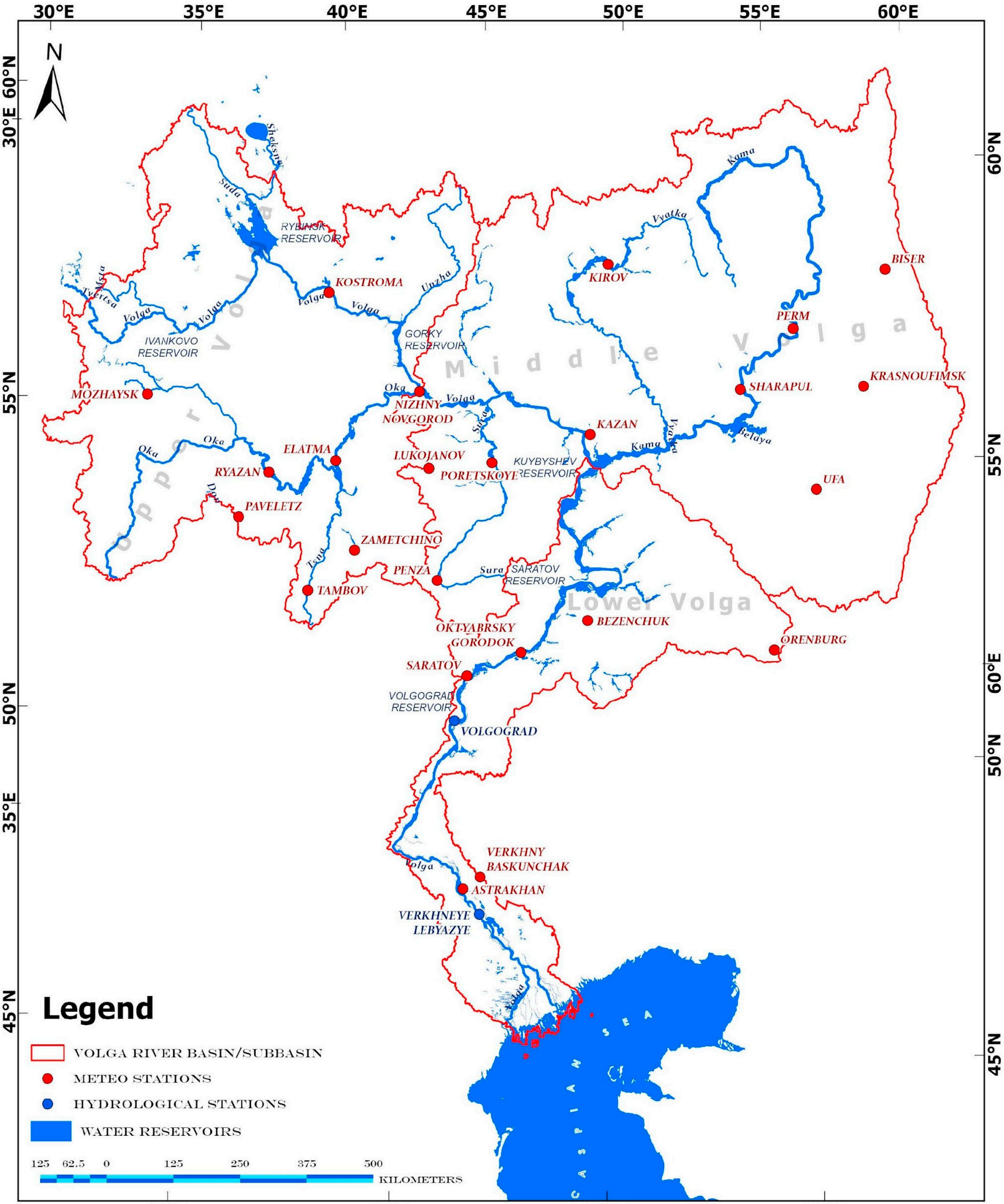


Figure 1. Location of hydrometeorological observation stations in the Volga River basin. Note: All observation stations indicated in the figure belong to the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet).

Four reservoirs were built in the upper reaches of the river: the Ivankovskoye, the Uglichskoye, the Rybinskoye, and the Gorkovskoye. All large reservoirs in the Upper Volga basin are used in an integrated way (hydropower, water transport, logging, water supply, fishery, and recreation) [35].

The climate of the Upper Volga basin is temperate continental with cold winters and moderately warm summers. Climate continentality increases from northwest to southeast. The average annual air temperature varies from 1.4 °C in the northeast to 3.7 °C in the southwest. The basin area belongs to the humid climate zone. The average long-term precipitation is 700–800 mm/year). Evaporation from the land surface within the territory under consideration, on average, consumes 70–80% of precipitation [35].

In its middle reaches, the Volga River receives four major tributaries: Oka, Sura, Vetluga, and Sviyaga. In this section, the Volga expands considerably, and the volume of water increases due to the tributaries. The Cheboksary Reservoir was built in the middle reaches of the Volga (Figure 1).

The lower reaches of the Volga are the widest and fullest, as most of the tributaries are concentrated in the Middle and the first kilometers of the Lower reaches. Four major tributaries flow into the Volga in this section: the Sok, the Samara, the Bolshoi Irgzhiz, and the Yeruslan (all tributaries are left tributaries) (Figure 1). In the Volgograd region, to the left of the main channel, there is a branch called Akhtuba, the channel of which is almost parallel to the Volga. Akhtuba accompanies the Volga to its very mouth. In its lower reaches, the Kuibyshevskoye, Volzhskoye, and Saratovskoye reservoirs were built (Figure 1).

The Volga Delta, the largest delta in Europe, starts from Astrakhan (Figure 1). The Volga riverbed is divided into five hundred arms and channels of various widths and depths.

The climate of the Middle and Lower Volga varies from quite humid in the northern part to arid continental desert climate in the southern part. In the north, the climate is characterized by moderately severe snowy winters and warm summers. The middle part of the basin experiences cold winters and hot summers. The south is characterized by relatively cold winters with little snow and hot, dry summers with frequent dry spells and droughts [3,34].

The Volga and its tributaries receive the bulk of their water from melting snow, which accounts for approximately 60%, while the remaining forty percent comes from rainwater. The largest amount of water in the Volga is observed in spring, during flooding, and in fall, during the period of heavy precipitation. In winter and summer, the water level in the river decreases significantly. The Volga freezes around November, only the upper and lower reaches, the Lower Volga freezes in December. It is released from ice fetters first in the lower reaches, approximately in early March, and in the upper reaches only in April [35].

According to the data of the Volgograd hydrological station for 1881–2016, the average annual runoff of the Volga River is 253 km^3/year. The maximum flow was observed in 1926 (389 km^3/year) and the minimum in 1975 (160 km^3/year) [12].

3. Used Data and Research Methodology

In this paper, based on long-term observations (1881–2018) of hydrometeorological observation points in the Volga River basin, data on air temperature, precipitation in the Volga River basin (https://climexp.knmi.nl, accessed on 2 May 2024) and its runoff (1938–2020), as well as data on the runoff of the most full-flowing rivers flowing into the Caspian Sea for the period 1959–2020 (http://www.caspcom.com, accessed on 2 May 2024) were collected and analyzed. Although precipitation observations at some stations located in the basin started in 1881, for most stations, they date back to later times. In addition, for various reasons, there were interruptions in observations at different times. For the period after 1938, it is possible to use data from a larger number of stations. For this reason, data from only 24 stations were used to determine the average precipitation for the basin (Figure 1). The amount of precipitation in the Volga River basin in each month, season, and year was determined by averaging the corresponding data from 24 stations. These data were then averaged for each period of the Caspian Sea level fall and rise.

In order to study the nature of the distribution of average annual precipitation in the Volga River basin, maps were created covering three different time periods (1938–1976, 1977–2005, and 2006–2020) in accordance with periods of Caspian Sea level variability using Inverse Distance Weighted (IDW) interpolation method on the ArcGIS Pro 3.1.3 platform. The basins of Upper Volga, Middle Volga, and Lower Volga were prepared by the application of the Hydrology Toolbox (including the Flow Direction, Watershed, and Basin tools). The river basin was mapped based on a DEM file with a resolution of 30 m (https://opentopography.org, accessed on 2 May 2024).

As is known, the flow of the Volga River is influenced by precipitation falling into its basin, evaporation from the surface of the earth and the river, as well as reservoirs built in its floodplain, temperature, and humidity, as well as anthropogenic factors. In turn, the Volga River is one of the main factors influencing the Caspian Sea level, along with evaporation from its surface and precipitation falling on its surface.

Various methods of mathematical statistics, including trend (linear and polynomial) and correlation analyses, were used to compare time series of data to identify their development trend and the possible relationship between them.

To better analyze the influence of various factors on the Volga River flow and sea level, difference integral curves were constructed. The difference integrals are presented in the form:

$$\varphi(n) = \sum_{i=1}^{n} (k_i - 1)/C_v \tag{1}$$

where n is the serial number of the time series element; $\varphi(n)$ is the difference integral for the n_{th} element of the time series; k_i is the modular coefficient, which is determined by the ratio of the current value x_i of the time series to its mean value $\underline{x}$; C_v is the coefficient of variation, which is determined by the ratio of the standard deviation σ of the time series to its mean value $\underline{x}$; $\varphi(n)$ is the dimensionless quantity [12,16].

The difference integral curve is convenient to use when studying the influence of elements of the water balance of closed reservoirs, including the Caspian Sea, on their water level. Because the current level of a reservoir depends not so much on the current value of the water balance elements but on the sum of accumulated positive and negative deviations from the average.

As a rule of thumb, in the 20th century, the periods of the Caspian Sea level decline are considered to be 1930–1977, the period after 1995, and the rise of 1978–1995 (Figure 2) [3,7,16]. However, in this paper, for most of the calculations, as in [26], we used the date 2005 instead of 1995 since the sea level did not change significantly in the period 1995–2005, and a real noticeable drop in sea level began in 2005. On the other hand, as can be seen from Figure 3, the maximum of the difference integral curve of the annual runoff of the Volga River was found not in 1995 but in 2005, i.e., the trend of runoff decrease began only after 2005.

The statistical significance of trends is established by the following inequality.

$$\frac{R}{\sigma_R} \geq s \tag{2}$$

where R is the pairwise correlation coefficient between elements of the time series and the corresponding values on the regression curve; s is the critical value of Student's criteria for the required level of significance; σ_R is the random mean square error, which is determined by

$$\sigma_R = \left(1 - R^2\right)/\sqrt{(n-1)}, \tag{3}$$

where n is the number of elements in the time series [36].

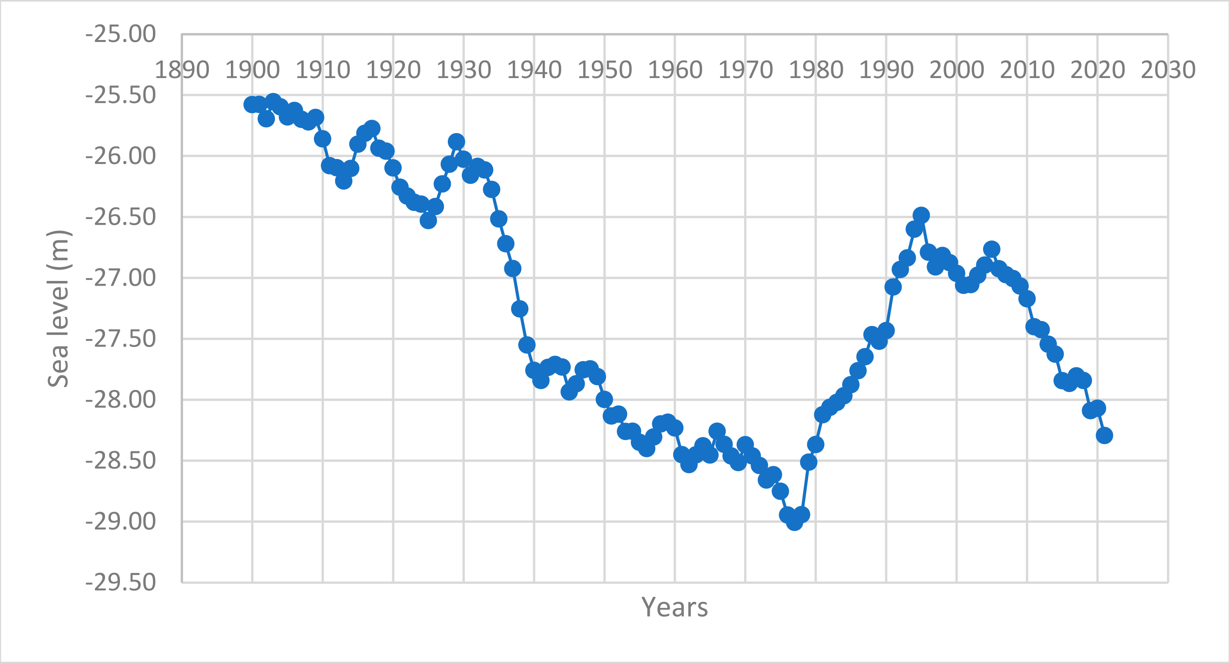


Figure 2. Changes in the annual average water level of the Caspian Sea during the period of 1900–2021 observations, according to the data of Mahachcala hydrological station (Russia).

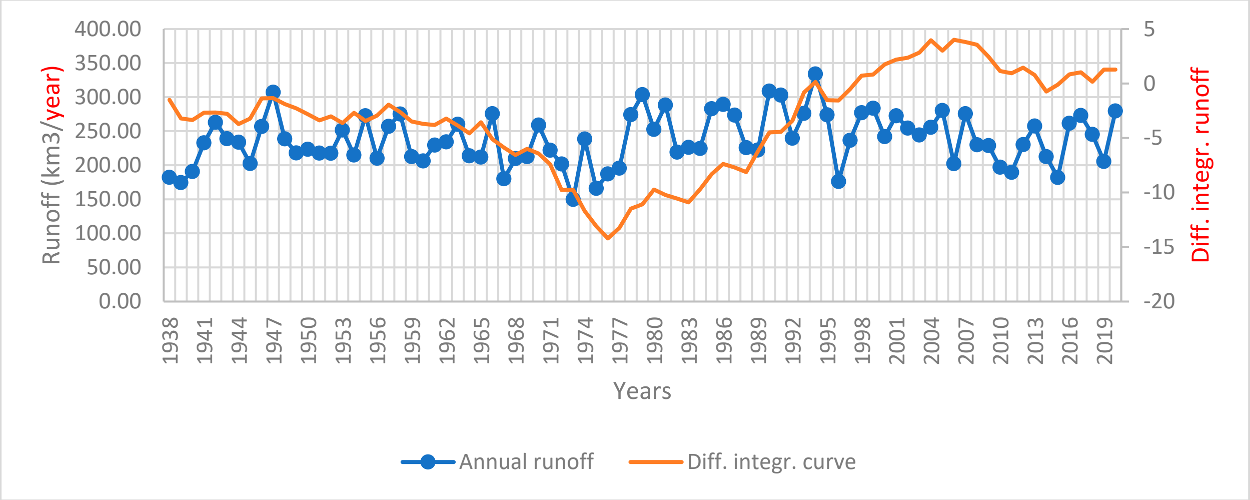


Figure 3. Long-term variability of annual runoff of the Volga River at Verkhneye Lebyazhye gaging station in 1938–2020 and its difference integral curve.

4. Obtained Results

As is known, the annual runoff of the Volga River is directly related to the amount of precipitation falling into its basin. Therefore, to begin with, the nature of a possible connection between them was investigated. For this purpose, we used runoff data from the hydrological station Verkhneye Lebyazhie, which is located at the nearest distance from the Volga delta (Figure 1), and precipitation data from 24 meteorological stations located in different parts of the river basin. Figure 4a–c show the distribution of annual precipitation over the Volga River basin for various periods of rising and falling levels of the Caspian Sea.

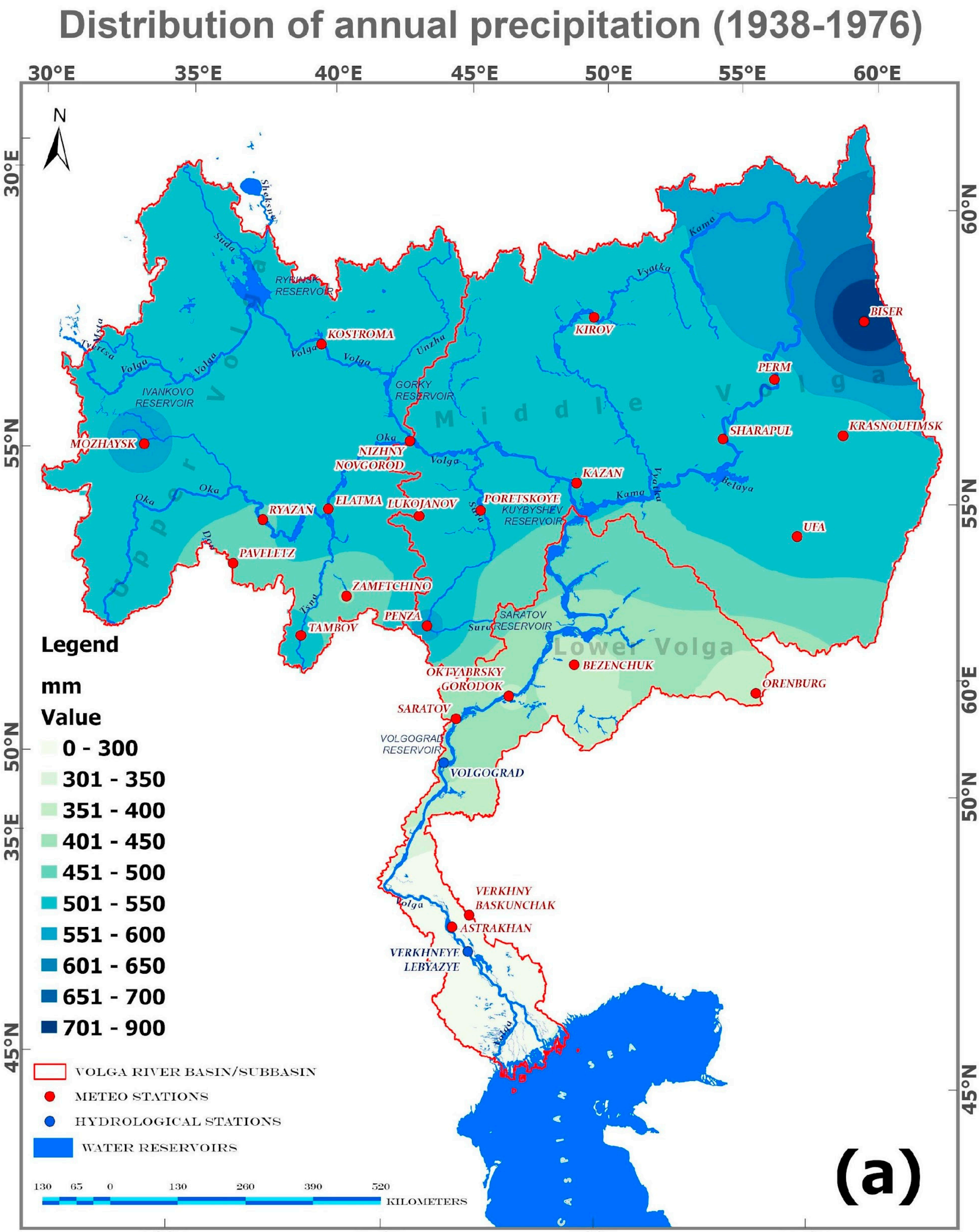
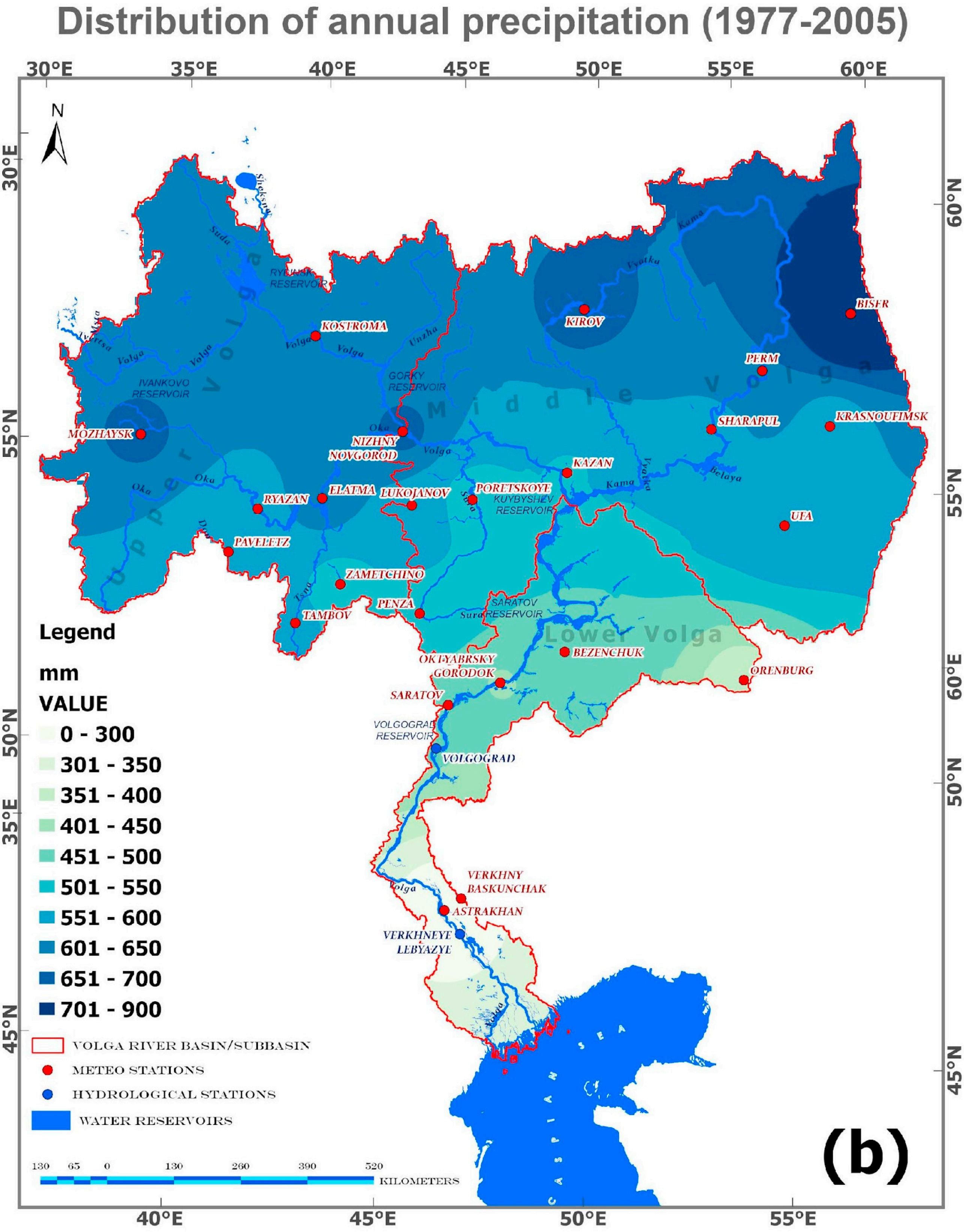


Figure 4. *Cont.*



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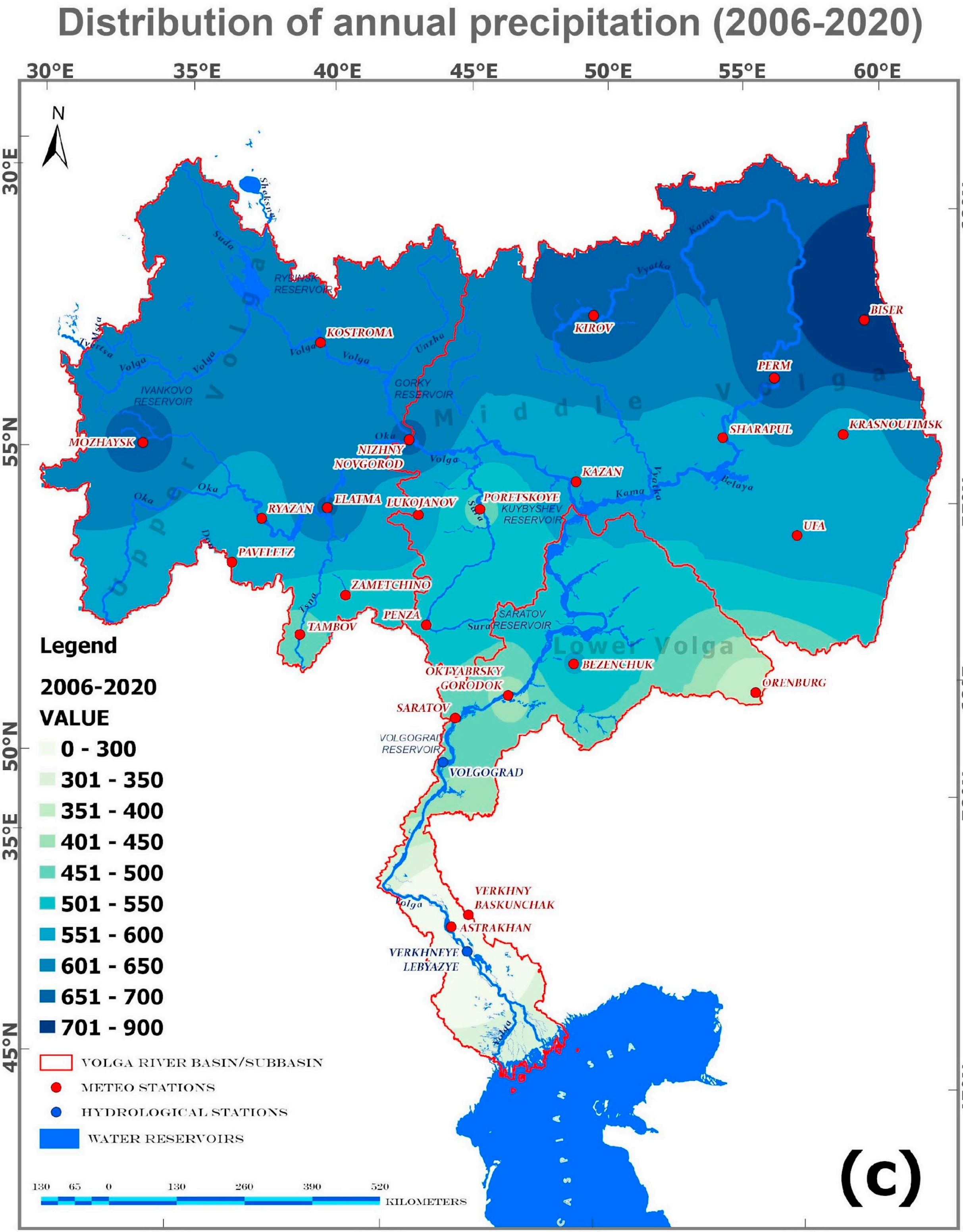

Figure 4. Distribution of annual precipitation over the Volga River basin for various periods: (**a**) 1938–1976; (**b**) 1977–2005; (**c**) 2006–2020.

As can be seen from Figure 5, in general, periods of high flow values of the Volga River correspond to periods of high precipitation in the basin, while periods of low flow correspond to periods of lower precipitation. It should be noted that for each period, precipitation volumes in the river basin were calculated by multiplying the average annual precipitation in mm by the basin area.

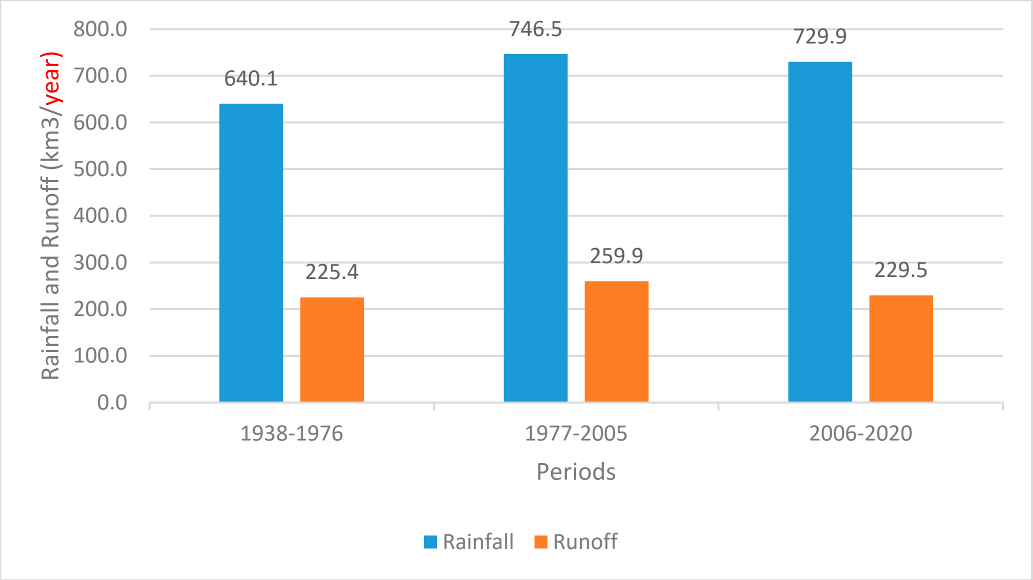

Figure 5. Comparison of precipitation volumes in the Volga River basin and its runoff at the Verkhnoe Lebyazhie hydrological post for different time periods.

Figure 6 shows the dynamics of the annual runoff of the Volga River for the period of 1938–2020, according to data from the hydrological station Verkhneye Lebyazhie, which is located at the smallest distance from the river delta and annual precipitation averaged over the river basin.

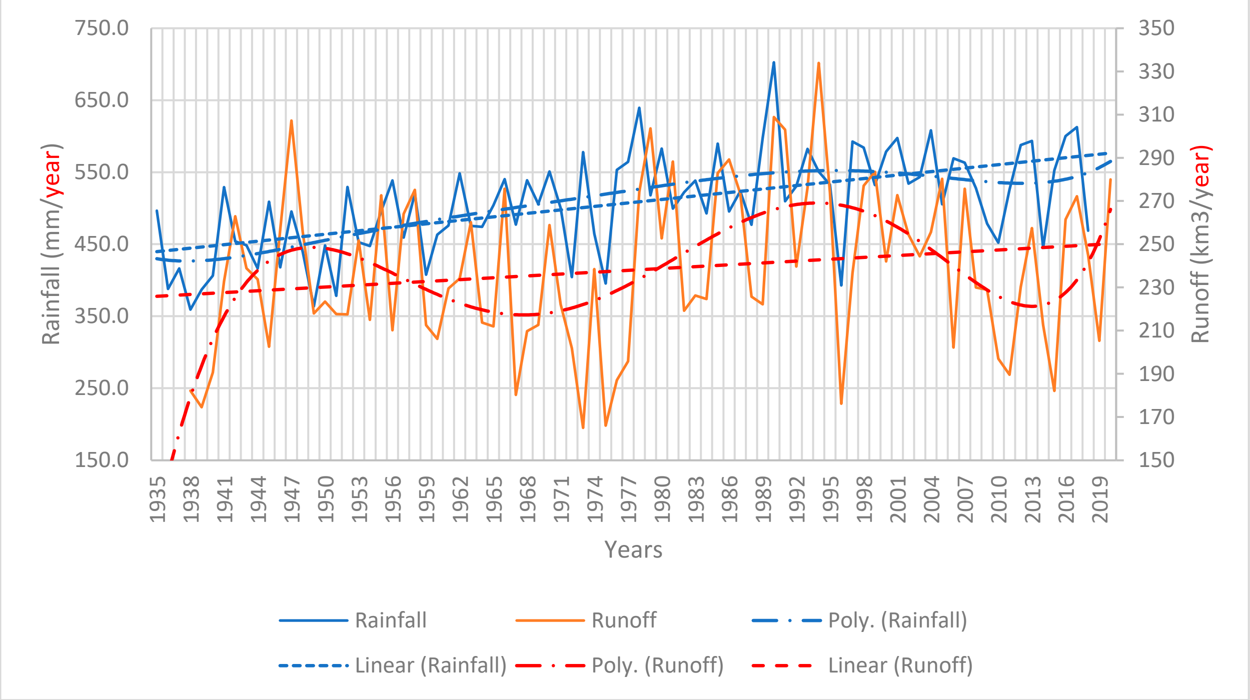

Figure 6. Dynamics of annual runoff according to data of the hydrological station Verkhneye-Lebyazhie, located in the southern part of the Volga River, and the amount of annual precipitation averaged over the river basin.

As can be seen from Figure 6, the annual precipitation averaged over the basin area has a statistically significant upward trend during the period under consideration. Annual runoff also has a slight upward trend, but it is not statistically significant. Because at the considered significance level (0.05), condition (2) is not satisfied (Table 1).

Table 1. Characteristics of linear and polynomial trends of time series of annual runoff of the Volga River and amount of annual precipitation averaged over the territory of its basin (according to Figure 6).

	Linear Regression			**Polynomial Regression**		
	Equation	$\mathbf{R^2}$	$\mathbf{R/\sigma_R}$	**Equation**	$\mathbf{R^2}$	$\mathbf{R/\sigma_R}$
Runoff	y = 0.2856x + 225.6	0.0345	1.73	$y = 2 \times 10^{-8}x^6 - 3 \times 10^{-6}x^5 - 0.0001x^4 + 0.0304x^3 - 1.4869x^2 + 26.074x + 96.836$	0.2519	6.05
Rainfall	y = 1.6096 + 438.15	0.3215	7.56	$y = 3 \times 10^{-8}x^6 - 7 \times 10^{-6}x^5 + 0.0006x^4 - 0.0292x^3 + 0.6513x^2 - 3.77x + 432.99$	0.3785	8.96

Note: At a significance level of 0.05 and a length of the time series of data—82, the critical value of Student's test is about 2.

A linear trend shows the general trend of change in a random variable over a certain period. From this point of view, it can be said that for the period 1938–2020, the general increase in precipitation did not lead to an adequate increase in the flow of the Volga River. To understand the reason for this contradiction, polynomial regression curves of the 6th degree were constructed since linear trends cannot show internal fluctuations in individual time intervals (Figure 6).

As can be seen from Figure 6, the polynomial curve for annual precipitation up to about 2000 has an ascending line; up to 2012, there is a slight decrease and then a slight increase.

If we do not take into account the sharp decrease in precipitation in 1996, the ascending line would have continued until 2005. The polynomial curve of the Volga River flow has a clear oscillation, showing periods of increase and decrease. As can be seen from Table 1, the polynomial curve characterizes temporal changes in the river flow better than the linear trend.

To verify the possible relationship between precipitation averaged over the territory of the river basin and the Volga River runoff, correlation coefficients were calculated for 1938–2020 as a whole and for separate periods of the Caspian Sea level fall and rise (Table 2).

Table 2. Correlation coefficients between annual precipitation averaged over the Volga River basin and river runoff at the Verkhneye Lebyazhye hydrological site.

Periods	**Correl. Coef.**	**Correl. Coef. with Shift 1 Year**
1938–2020	0.35	0.46
1938–1976	0.13	0.18
1977–2005	0.15	0.38
2006–2020	0.51	0.73

Both pairwise correlation and correlation when the river flow is shifted one year ahead were considered. The presence of flow shift versus precipitation is also evident in Figure 6. As can be seen from Table 2, the correlation with the shift gives relatively high values of the coefficients, which can be explained by the fact that for most of the basin, autumn and winter precipitation falls in the form of snow [6,12], which participate in the formation of runoff somewhat later, as a result of their melting. However, this does not mean that the maximum correlation between Volga River runoff and precipitation is achieved with a time shift of 1 year.

Further calculations with a time resolution of 1 month showed that the greatest correlation between annual precipitation and runoff is observed when the second is shifted

4–6 months ahead. At the same time, the maximum shift (6 months) was observed in the period 1938–1976 and the minimum (4 months) in 2006–2020, which can be explained by climate warming.

The relatively low value of the correlation coefficient for the period 1938–1976 can be explained by the disruption of the hydrological regime of the river due to the process of filling newly constructed large reservoirs with water [3,5,24,27,28,35,37,38].

The data in Table 2 and Figure 7 show the degree of synchronization of changes in river flow and precipitation in the river basin. However, it is important to determine the degree to which the amount of precipitation in the basin can be converted into river runoff (runoff coefficient). As mentioned above, for this purpose, the volumes of relevant precipitation that fell in the river basin were calculated by multiplying the basin-averaged precipitation by the basin area (1,360,000 km^2). The results of these calculations are shown in Figure 5 and Table 3.

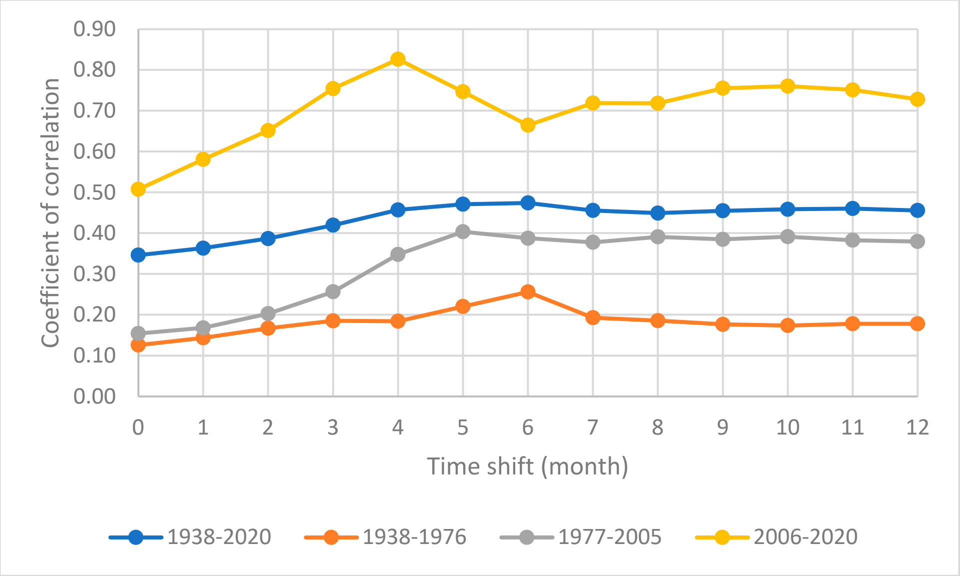

Figure 7. Correlation coefficients between annual precipitation averaged over the river basin. Volga and river flow in the hydrological area of Verkhneye Lebyazhye for different values of the time shift.

Table 3. Comparison of precipitation volumes in the Volga River basin and its runoff for different periods.

Periods	Temperature anomalies (°C)	Rainfall		Runoff (km^3/Year)	Runoff Coefficient	Runoff (Restored) (km^3/Year)	Annual Loss of Runoff (km^3/Year)
		mm/Year	km^3/Year				
1938–1976	−0.47	470.1	640.1	225.4	0.352	225.4	0
1977–2005	0.45	548.9	746.5	259.9	0.348	262.8	2.9
2006–2020	1.41	536.7	729.9	229.5	0.314	256.9	27.4

Since here precipitation and river flow are given in volume units, it is possible to estimate the runoff coefficient for different time periods. As shown in Table 3, this coefficient was 0.352 for the period 1938–1976 but decreased in subsequent periods. A particularly noticeable decrease is observed for the period 2006–2020.

Table 3 shows that for the period 1938–1976, the low value of Volga River runoff was related to low precipitation in its basin, although the runoff coefficient was the highest. For the period 1977–2005, the highest runoff values were also mostly associated with relatively high precipitation, as the runoff coefficient changed slightly. For the period 2006–2020, although precipitation decreased slightly (Figure 4a–c and Table 3) relative to the period

1977–2005, the river flow decreased quite dramatically. As can be seen from the table, this is caused by a significant decrease in the runoff coefficient.

To explain the reason for the observed variability of the runoff coefficient, we plotted the joint plots of the time course of this ratio with air temperature anomalies in the Volga River basin. The temperature anomalies are defined as

$$\Delta T = T_i - T_n,$$

where T_i is the average temperature of the i-th period, and T_n is the temperature norma. As in Mamedov et al., 2009 [14], the average annual temperatures of the period 1961–1990, recommended by WMO, are taken as the temperature norm.

Temperature anomalies are calculated from observations of 3 meteorological stations, Elatma, Kazan, and Perm (Figure 1), for the periods 1938–1976, 1977–2005, and 2006–2020. According to our calculations, for the Elatma station, this norm is 4.6 °C, for the Kazan station 3.7 °C and for Perm −1.5 °C. Table 3 shows the temperature anomaly values averaged over three stations for each period. A negative value of the temperature anomaly in Table 3 shows that, on average, the period 1938–1976 was colder than in 1961–1990, and a positive value is the opposite.

Statistically significant at the 0.05 level, the 6th-degree polynomial regression curves clearly show the approximate rise and fall periods of these parameters (Figure 8 and Table 4).

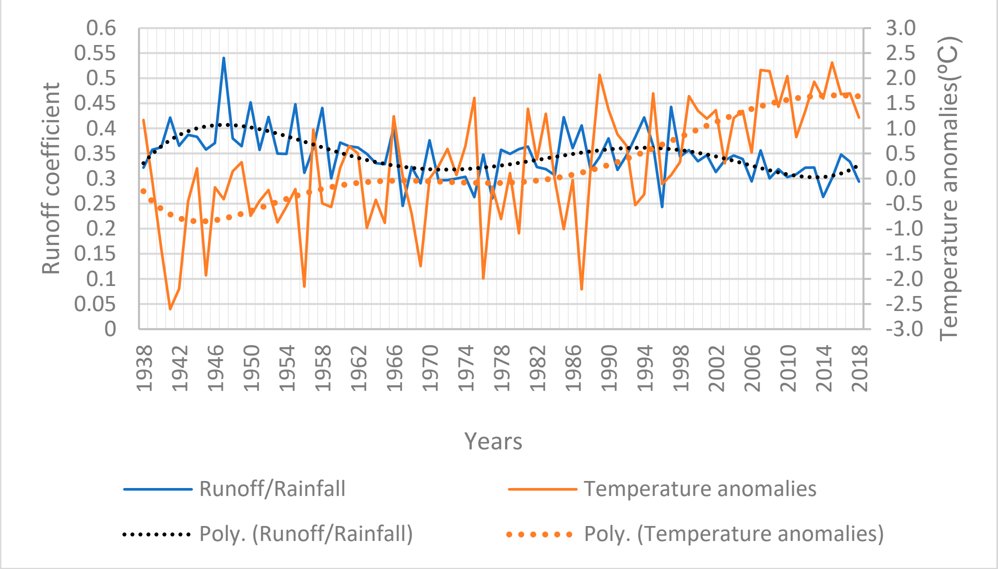

Figure 8. Time courses of runoff coefficient and air temperature anomalies of the Volga River basin for the period 1938–2020.

Table 4. Characteristics of polynomial trends of time series of runoff coefficient of the Volga River and temperature fluctuations over the territory of its basin (according to Figure 7).

	Polynomial Regression		
	Equation	**R^2**	**R/σ_R**
Runoff/rainfall	$y = 8 \times 10^{-10}x^6 - 2 \times 10^{-7}x^5 + 3 \times 10^{-5}x^4 - 0.0013x^3 + 0.031x^2 - 0.2841x + 0.0029$	$R^2 = 0.4425$	**10.7**
Temperature anomalies	$y = 3 \times 10^{-11}x^6 - 3 \times 10^{-9}x^5 - 2 \times 10^{-7}x^4 + 4 \times 10^{-5}x^3 - 0.0017x^2 + 0.0229x + 0.3094$	$R^2 = 0.3415$	**7.98**

As can be seen from Figure 8, the areas with the highest values of the runoff coefficient correspond to the lowest values of temperature anomalies. Thus, from 1938 to 1965, when negative air temperature anomalies prevailed, the highest values of the runoff coefficient were observed. In this period, the gradual increase in anomalies was accompanied by a decrease in the runoff coefficient.

For 1966–1982, both negative and positive temperature anomalies were noted, but their noticeable trend was not observed. The runoff coefficient had a slight upward trend during this period.

Since 1995, positive temperature anomalies were mainly observed, and their rapid growth was noted. At the same time, there was a relatively sharp decrease in the river flow. As can be seen from Figure 8, for the period 1976–2020, the rate of temperature increase is about 0.5 °C/10 years, which is close to that obtained by other authors [12,39]. This is significantly higher than for the global temperature (0.18 °C/10 years) [40].

5. Discussions

All this shows that the value and sign of air temperature anomalies significantly affect the runoff coefficient. As can be seen from Figure 6, the coefficient increases with negative anomalies and decreases with positive anomalies. Thus, in recent years, a significant decrease in runoff of the Volga River with a slight decrease in precipitation in its basin can be explained by the sharp positive temperature anomalies, which are noticeably larger than for global temperature [12].

As is known, with increasing air temperature, the intensity of evaporation from the surface of water bodies and land increases. This is especially true for reservoirs constructed on the Volga River, which have significant mirror areas [22,32,38]. Increasing temperatures also exacerbate anthropogenic impacts in the Volga River basin as irretrievable water consumption for municipal and agricultural needs increases.

Considering actual data on the Volga River runoff and precipitation in its basin during different periods of its increase and decrease, an approximate estimate of the annual average loss of river runoff as a result of increased air temperature in the river basin has been made.

For this purpose, the expected values of river runoff for the periods 1977–2005 and 2006–2020, if the runoff coefficient was as in the period 1938–1976 (0.352), were calculated from the actual values of precipitation. Using these data, the average annual runoff losses of the Volga River as a result of climate warming were estimated for each period (Table 3). Total river flow losses can be calculated with the following formula:

$$L = L_1 + L_2 = mp_1 + np_2, \tag{4}$$

where L is the total river flow losses for the period 1977–2020, L_1 is the river flow losses for the period 1977–2005, L_2 is the river flow losses for the period 2006–2020, m is the number of years in the first period, n is the number of years in the second period, p_1 is the average annual flow losses in the first period, and p_2 is the average annual flow losses in the second period.

As can be seen from Table 3, the average annual loss of runoff is defined as the difference with the deduction of the corresponding stock value from its predicted value. The reconstructed or predicted runoff is calculated by multiplying the average annual precipitation by the 1938–1976 runoff coefficient.

Using the data in Table 3, we can estimate the total flow losses of the Volga River for the period 1977–2020 using Formula (4):

$$L = 28 \times 2.9 + 15 \times 27.4 = 81.2 + 411 = 492.2 \text{ km}^3. \tag{5}$$

Thus, due to climate warming, the loss of flow of the Volga River for the period 1977–2020 amounted to 492.2 km^3. Dividing this volume of water by the area of the Caspian Sea (371,000 km^2), we can obtain 132.7 cm (or 1.33 m), which shows the layer of water that the sea has lost due to the effect of climate warming on the Volga River flow.

According to the data of the hydrological station found by Makhachkala in 2020, the level of the Caspian Sea was −28.07 m relative to the level of the world ocean (Baltic system). However, in the absence of climate warming, the sea level would be −26.74 m, i.e., closer to the level of 1995–2005.

It should be noted that over the period 1930–1976, the sharp decrease in the Volga River flow and, consequently, in the level of the Caspian Sea were associated with a sharp decrease in precipitation in its basin, as well as the filling of newly constructed reservoirs and partially anthropogenic water withdrawal [5,6,12,33].

Over the period of 1977–2005, the increase in the Volga River runoff and, consequently, the Caspian Sea level was mainly due to an increase in precipitation in the river basin, but without anthropogenic irretrievable water withdrawal and climate warming, the increase in runoff and sea level would have been much greater. The current reduction in the Volga River flow, with a slight decrease in precipitation and unchanged anthropogenic water withdrawal, is most likely due to climate warming.

It should be noted that by the end of the 1980s, anthropogenic irretrievable water withdrawal from the Volga River amounted to about 26 km^3/year, and the difference between actual and "natural" sea levels reached almost 1.5 m [41].

In the following years, the volumes of anthropogenic losses of river flow on average did not change significantly, and in some time intervals decreased due to the reduction in irrigated land area and irrigation rates. In [20] calculations of the Caspian Sea level performed using a water-balance model. In the absence of water consumption in the basin of rivers flowing into the Caspian Sea, its level could reach high values (minus 24 m) instead of the actual level of minus 27.17 m by the year 2010.

It should be noted that the water volume of 492.2 km^3 obtained by us in expression (5) shows that part of the total flow loss of the Volga River is associated with climate warming in its basin. Therefore, under natural conditions, the level of the Caspian Sea could even be higher than minus 24 m by 1.33 m.

It can be said that almost all climate scenarios predict a further increase in global and regional temperatures, including the study area [8].

If we consider that the results obtained in this study mainly confirm the predictions of modern Caspian Sea level models [42], we can expect that in the future, the runoff coefficient and, consequently, the efficiency of precipitation conversion into runoff will tend to decrease. This means that under the current level of precipitation in the Volga River basin and climate warming, its flow will decrease. Under current conditions, an annual precipitation of 585.4 mm would be required to ensure the formation of an annual river flow of 250 km^3. For comparison, for the period 1938–1976, the corresponding value would be 522 mm, and for the period 1977–2005—528.2 mm.

The study of the relationship between the Volga River flow and the Caspian Sea level is of great importance. Figure 9 shows joint plots of the time course of the annual runoff of the Volga River according to the observations of Verkhneye Lebyazhye point and sea level for the period 1938–2020 according to the data of Makhachkala point, as well as the total runoff of all rivers flowing into the sea (1959–2020).

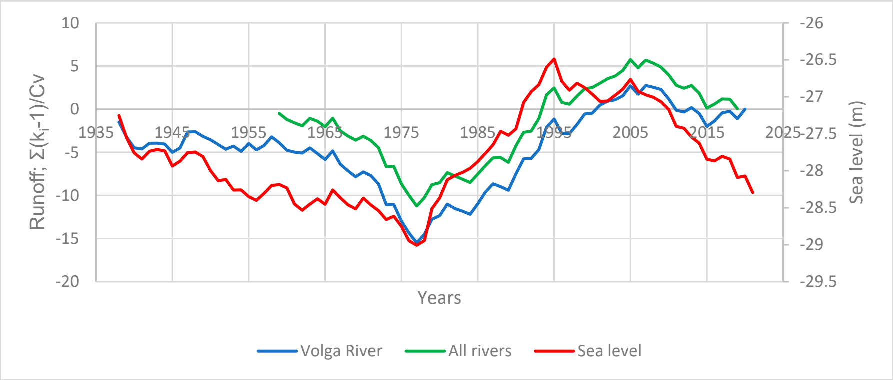

Figure 9. Multiyear changes in the annual runoff of the Volga River (1938–2020) and all rivers flowing into the Caspian Sea (1959–2020), as well as sea level (1938–2020).

As is known, the difference integral curve gives a more visual representation of the flow fluctuation cycles, which can be compared with sea level fluctuations. The difference integral curves for the Volga River runoff and the total runoff of all rivers flowing into the sea were constructed using Formula (1) based on contact observations (Figure 9).

As can be seen from Figure 9, the curves of the Volga River runoff and the total runoff of all rivers flowing into the sea are almost parallel, and the correlation coefficient between them is close to 1 (0.994). This is understandable because the dynamics of the total runoff is mainly determined by the dynamics of the Volga River runoff, which accounts for 80–90% of the former [15,21,38].

In most cases, the dynamics of the sea level are similar to the Volga River runoff and the total runoff of all rivers. The minimum (1977) and maximum (1995) of the sea level coincide with the minimums and maximums of the Volga River runoff and the total runoff with rather high accuracy (Figure 9). However, since 1996, the situation has started to change. As can be seen from Figure 9, over the period 1996–2001, despite the increase in the Volga River runoff and total runoff, the sea level continued to decline. Further, until 2005, the coincidence of sea level and runoff dynamics was temporarily restored, but then the sea level started to decline rapidly, even in years of high-water availability.

To understand the reason for this situation, we can refer to the water balance of the Caspian Sea, which consists of the volume of water flowing into the sea by rivers, the amount of evaporation from the sea surface, and the amount of precipitation falling into its surface [6].

As is known, the average annual precipitation falling on the sea surface is about 200 mm and does not vary greatly [43]. Therefore, a sharp decrease in the Caspian Sea level after 2005 with relatively stable river discharge may indicate an increase in evaporation from the sea surface. And this, in turn, can be associated with an increase in air and sea surface temperature, with a decrease in relative humidity over the sea and an increase in wind speed over the water area. As is known, air temperature and sea surface temperature (SST) are mainly increasing against the background of global warming [13,44–47].

According to [45], the linear positive trend in average air temperature for the period 1980–2020 was +0.030 °C/year, i.e., air temperature during this period increased by 1.2 °C. However, this linear trend of the air temperature is lower than the previously obtained value of +0.067/year for the period 1979–2011 [48]. The smaller value of the trend in the period 1980–2020 indicates a slowdown (or absence) of the air temperature growth in the Caspian region in the second decade of the 2000s. I.e., in this case, the course of air temperature change over the Caspian Sea water area cannot be the main reason for the increase in evaporation from the sea surface. A similar pattern was found with the sea surface temperature, which confirms the conclusion about the slowing down of Caspian Sea warming in the second decade of the 2000s [49].

Thus, in contrast to the Volga River basin, where the temperature increase is more significant than in the Caspian Sea area, the dynamics of air and water surface temperature cannot be the main reason for the increase in evaporation from the sea water surface.

What, then, can affect evaporation from the sea surface so much? As mentioned above, the intensity of evaporation also depends on wind speed and its direction.

Studies conducted by various authors show that over the Caspian Sea, wind speed and direction change periodically [17,50]. These studies show that during periods of decreasing Caspian Sea level, the wind speed was greater than during periods of increase [17]. On the other hand, during periods of sea level decrease, the eastern component of the wind direction prevailed, and during periods of sea level rise, the northern component prevailed [50].

In general, the physical mechanism of the effect of wind speed on the evaporation rate is clear because an increase in wind speed enhances the evaporation process. As for the wind direction, it should be noted that since the eastern winds blow from Central Asia, unlike the northern winds, they bring drier and hotter air masses, which, in turn, increase the intensity of evaporation.

6. Conclusions

A comprehensive study of the Volga River flow for the period 1938–2020 showed that, in general, the annual flow of the river depends on the annual amount of precipitation in its basin. On average, periods of high values of river flow corresponded to high values of precipitation in the river basin. However, the runoff coefficient, which expresses the degree to which precipitation is converted into runoff, was found to be decreasing over the period under consideration, especially after 2005. Using the values of runoff coefficients for different periods of sea level rise and fall, it is shown that for the period 1977–2020, against the background of anthropogenic factors, the share of climate warming in the reduction in the Volga River runoff amounted to 492.2 km^3. This is equivalent to a sea level decrease of 132.7 cm.

Comparison of the time curve of the Caspian Sea level with the curve of the difference integral of the annual runoff of the Volga River mainly showed their similarity, i.e., large values of the river runoff corresponded to large values of the sea level. However, starting from 2005, the sea level began to rapidly decline, even in years of relatively high-water availability. A comparative analysis of this situation with the results obtained by a number of authors [17,50] shows that in recent years, the sharp decrease in sea level is associated with a sharp increase in evaporation from the sea surface as a result of changes in the wind regime over the Caspian Sea.

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