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Article

Trend Analysis of Precipitation, Runoff and Major Ions for the Russian Part of the Selenga River Basin

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Abstract: At present, the problem of climate change is becoming increasingly acute. This is especially pressing for Lake Baikal, a World Natural Heritage site. The Russian part of the Selenga watershed is a suitable site for climate change research. The study of changes in precipitation, runoff, and chemical runoff is important for sustainable water resources management. This study presents a trend analysis of precipitation and runoff at hydrological stations and weather stations in the Russian part of the Selenga River basin. A comparative analysis of the concentrations of major ions in the surface water of the Selenga River depending on water levels was also carried out. Analysis of the data series on precipitation revealed a slight negative trend at the Novoselenginsk, Ulan-Ude, and Kabansk stations, and a weak positive trend—at the Kyakhta station. Runoff analysis revealed negative trends at the two used stations (Novoselenginsk and Mostovoi). The hydrochemical regime of the Selenga River is characterized by an increase in major ions and salinity during winter low-water periods, and a decrease during high-water periods. Mineralization and major ion content are lower in the high-water period (2019–2021) than in the low-water period (2015–2017).

Keywords: Selenga River basin; precipitation; runoff; major ions; Mann Kendall test

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1. Introduction

In recent decades, global climate change has become an increasingly hot topic [1–3]. This problem is especially important for the basin of Lake Baikal, a world natural heritage site that contains about 19% of the world's freshwater. Intense industrial development has led to global warming, which can negatively affect the ecology of Lake Baikal [4,5]. In the Lake Baikal basin, warming has manifested itself much stronger than the Earth's average, especially for winter and spring periods [6–9]. An increase in air temperature leads to an increase in evaporation and, consequently, to a change in the amount of precipitation [2,3]. Also, global warming accelerates the hydrological cycle by increasing fluctuations in river runoff [10]. An integrated analysis of trends of hydrometeorological parameters for the period of 1946–2017 revealed baseline subperiod (1946–1975) and warming subperiod (1976−2017) with intensified anthropogenic pressure and natural processes [11].

An increase of 1.6 °C or 0.022 °C/year in the average annual temperature in the Selenga River basin (i.e., by almost twice the global average warming rate) during the historical period 1938−2009 was described previously [12].

The Selenga River basin is an important and relevant model area for climate change research [12,13]. The study of changes in precipitation, as shown in [14], and their spatial and temporal distribution, as well as their response to climate change, which can be calculated even with incomplete data [15], is especially important for the basin of the Selenga River (the main tributary of Lake Baikal), which carries up to 50% of the water runoff and over 50% of the chemical runoff [16,17].

Since the start of monitoring in 1930s, the annual average flow of the rivers of the Selenga basin has shown cyclicity, comprising high water phases (12–17 years) and low-water phases (about 7 years) [18].

The ongoing hydroclimatic changes in the Selenga River catchment have led to the increase in the frequency of moderate flows (Q = 750–1250 m^3/s) in the Selenga River during the past decades, and the decrease of high flows (Q > 1350 m^3/s) [19]. A significant decreasing trend of average and maximum river flow (up to −2.9%/year) was registered for the half of the gauges in the eastern part of the Selenga River basin [20].

The Selenga River basin area overlaps with the industrially developed and densely populated areas of Mongolia and Buryatia. Currently, more than 2.2 million people live in the Mongolian part of the Selenga basin, accounting for about 67% of the country's total population [21]. More than 85% of Buryatia's population also lives in the Selenga basin [22]. Anthropogenic activity affects water quality, runoff, and soil cover. Large cities and industrial centers are located in the Russian part of the Selenga River basin.

The Buryat Center for Hydrometeorology and Environmental Monitoring regularly monitors water levels and quality in the Selenga River basin. The chemical composition of the water of the Selenga and its tributaries, as well as the ionic discharge into Lake Baikal, were studied in detail in the 1950s and 1960s [23,24]. These data on water quality can be taken as background data.

There are many studies on atmospheric circulation, climate change and hydrological processes in the Selenga River basin. Trend analysis showed a noticeable change in the hydrological conditions of flow formation of the flow of the Selenga River and its tributaries. Also, a positive trend in annual temperature values and a negative trend in the runoff of the Selenga and its tributaries were revealed [25,26]. The main cause for the variations in the runoff is the variability of the summertime precipitation [27,28].

In the 1980s, the anthropogenic impact on the water and its chemical composition significantly increased, leading to a deterioration in water quality [29–31]. At present, the ionic composition of the Selenga water has changed along its entire length (compared to the background period) due to increased economic activity and a decrease in water levels [32–34]. Moreover, changes in the precipitation levels affect the hydrological regime, which, in turn, controls the concentration of substances in the water [35]. Precipitation and runoff in the Selenga River basin have decreased from the highest reported peak in 1992 to its lowest (2004–2008) [36].

In this study we described the correlation between changes in water levels and chemical indicators in the Selenga, conducted spatiotemporal and seasonal analyses of changes in salinity and major ions in the river waters.

This paper aims to analyze the trend of precipitation, runoff, and major ions in the Selenga River basin. To do this we need to solve the following tasks: (i) to analyze spatiotemporal changes in precipitation, (ii) to analyze spatiotemporal changes in runoff, and (iii) to identify trends in spatiotemporal changes in concentrations of major ions.

2. Materials and Methods

2.1. Study Area

We investigated trends in precipitation, runoff, and major ion data for the Russian part of the Selenga River basin downstream (toward the confluence with Lake Baikal). The Selenga is a transboundary river with a length of 1024 km, and 46% of its annual flow is formed on the territory of Mongolia. It brings about 30 km^3 of water to Lake Baikal on average per year, which is half of the total inflow to the lake. The catchment area of the river is 447,060 km^2, the Russian part accounts for 148,000 km^2. The average density of the Selenga River network in the Russian part of its basin reaches 0.47 km/km^2. The largest tributaries in the Russian part are the Khilok (840 km) and the Chikoi (769 km). The

Selenga River basin is located within the mountainous central part of the Asian mainland, stretching from southwest to northeast between 46°20′ and 53°00′ N, 96°50′ and 112°50′ E. In its Russian part, the watershed is bounded by Khamar-Daban and Ulan-Burgasy ridges; in the northeast, it passes through a poorly defined watershed of the headwaters of the Uda and Khilok rivers and further along Yablonovy ridge. In the east, the watershed continues along the ridges of the Khentei-Chikoi plateau. The southern boundary passes through the hills of Northern Khalkha (Mongolia) [37,38].

The climate of the region is sharply continental, with great annual and daily variations in air temperature and an uneven distribution of precipitation. The long-term average annual air temperature throughout the Selenga River basin has negative values, varying from −0.1 °C (Tsetserleg weather station) to −6.7 °C (Ikatsky Pereval weather station) [39,40]. January is the coldest month, while July is the warmest.

Air masses coming from the southeast bring the greatest amount of moisture to the Selenga River basin area, while the least amount—is from the north [41]. Air masses from the west and northwest bring significant but not extreme amounts of moisture. The average annual precipitation ranges from 230 to 700 mm [40].

2.2. Data Sources

Data on monthly and annual precipitation and runoff in the Russian part of the Selenga basin were retrieved from the Information System on Water Resources and Management in the Russian Rivers' basins, (http://gis.vodinfo.ru, accessed on 2 December 2022), World Meteorological Organization (http://climexp.knmi.nl, accessed on 2 December 2022), and web portal "Weather and Climate" (http://pogodaiklimat.ru, accessed on 2 December 2022). The locations of the selected meteorological stations and gauging stations in the Selenga River basin are shown in Figure 1.

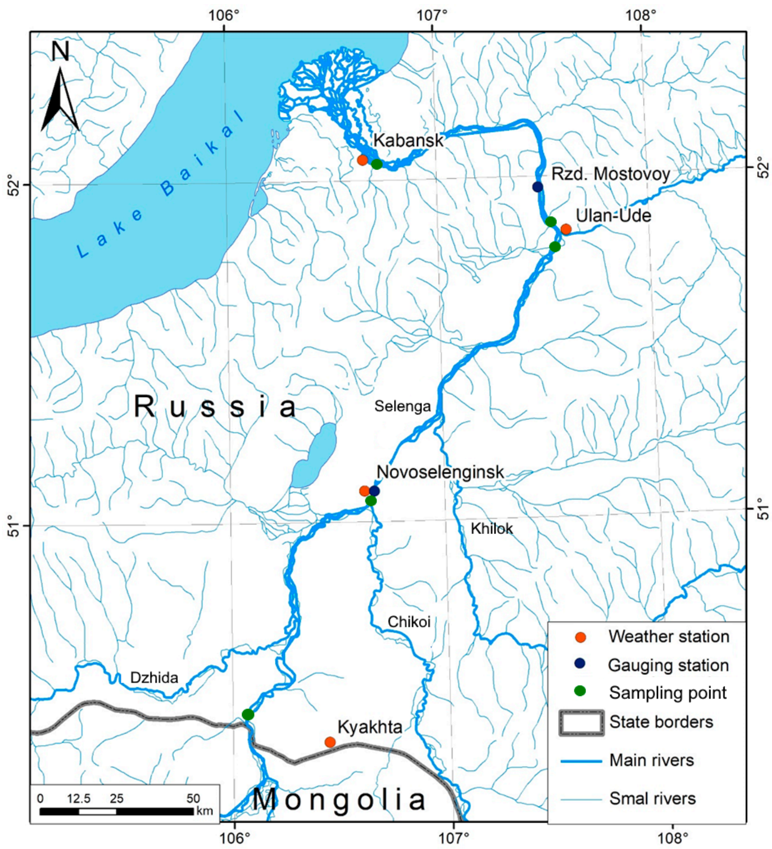

Figure 1. Location of the Selenga River basin, water gauge stations, meteorological stations, and sampling points on the territory of Russia.

2.3. Rainfall and Runoff Trend Analysis in the Selenga River basin Using the Mann Kendall Statistic

Trend analyses of precipitation and runoff data were conducted using Mann Kendall (MK) test and Sen's slope (SS) estimators. Data on average monthly precipitation (from 4 stations) and runoff (from 2 stations) in the study basin were analyzed. Monthly precipitation data are available for Kyakhta, Novoselenginsk, Ulan-Ude, and Kabansk monitoring stations from 1936 to 2021. Monthly runoff data for hydrological gauging stations Novoselenginsk and Mostovoi are available from 1990 to 2017. The nonparametric MK test, first proposed in 1945 and suitable for samples with outlying values [42], can be used to analyze hydrometeorological data [43]. To study seasonal and monthly fluctuations, we used Seasonal Kendall Test [44], which was well suited to determine trends in hydrometeorological data over the seasons [45]. The Seasonal Kendall test (S_k) accounts for seasonality by combining the results of individual MK tests (S_i) for each of m seasons (it compares the data of each season separately—January with Januaries, February with Februaries, etc.) [44,46].

$$S_k = \sum_{i=1}^{m} S_i \tag{1}$$

The Standard Normal Test Statistic:

$$Z_{Sk} = \begin{cases} \frac{S_k - 1}{\sigma_{Sk}} & if\ S_k > 0 \\ 0 & if\ S_k = 0, \\ \frac{S_k + 1}{\sigma_{Sk}} & if\ S_k < 0 \end{cases} \tag{2}$$

where

$$\mu_{Sk} = 0 \tag{3}$$

Positive values of ZS indicate increasing trends, while negative ZS values show decreasing trends. Testing trends is done at specific significance levels. When $|ZS| < Z1 - \alpha/2$, the null hypothesis is rejected and a significant trend exists in the time series. $Z1 - \alpha/2$ is obtained from the standard normal distribution table. In this study, significance levels $\alpha = 0.01$ and $\alpha = 0.05$ were used. At the 5% significance level, the null hypothesis of no trend is rejected if $|ZS| > 1.96$ and rejected if $|ZS| > 2.576$ at the 1% significance level.

Variance

$$\sigma_{Sk} = \sqrt{\sum_{i=1}^{m} \left(\frac{n_i}{18}\right)(n_i - 1)(2n_i + 5)}, \tag{4}$$

where n_i = number of data points for the ith season.

The Sen Slope Estimation method was then used to show the slope of the trend for the pairs of data (n) as suggested by Silva et al. [30].

$$Q_i = \frac{X_j - Y_k}{j - k}, \tag{5}$$

where X_j and X_k were the data values at times j and k respectively, while $j > k$. When there was one datum in each period,

$$N = n(n - 1)/2, \tag{6}$$

n was the number of periods.

When there were multiple observations during one or more periods—

$$N < n(n - 1)/2 \tag{7}$$

Then the n values of Q_i were arranged in ascending order. The median of slope otherwise known as Sen's slope estimator was calculated as follows [43]:

$$Q_{med} = \begin{cases} Q_{[(n+1)/2]} & if\ n\ is\ odd \\ \frac{Q_{[n/2]}+Q_{[(n+2)/2]}}{2} & if\ n\ is\ even \end{cases} \tag{8}$$

The Q_{med} sign indicated the trend while the value or magnitude indicated steepness of that trend [36]. The confidence interval was computed as follows:

$$C_\alpha = Z_{1-\alpha/2}\sqrt{Var(S)}, \tag{9}$$

where $Var(S)$ was as in Equation (4) above.

$Z_{i-\alpha/2}$ was taken from standard normal distribution table [43]. M_1 and M_2 indices were calculated as follows:

$$M_1 = \frac{n - C_\alpha}{2} \tag{10}$$

$$M_2 = \frac{n + C_\alpha}{2} \tag{11}$$

Therefore, the lower and upper limits of the confidence interval (Q_{min} and Q_{max}) were the M_1th largest and $(M_2 + 1)$th largest slope estimates arranged in a chronological order. The following hypotheses were considered: null hypothesis (H_0)—there is no trend in the data series; alternative hypothesis—there is a trend in the data series.

2.4. Field Sampling

The surface water of the Selenga was sampled at monitoring points, beginning from the border with Mongolia (Naushki settlement) to the Kabansk settlement: Naushki, Novoselenginsk, Ulan-Ude up stream, Ulan-Ude down stream and Kabansk (Figure 1). The sampling was conducted in different hydrological seasons (February–March, May, July, and September–October) during 2015−2021. A total of 124 samples of surface water were taken. The samples were preserved for further study in the laboratory.

Laboratory Analyses

We performed chemical analyses at the Laboratory of Nature Systems Chemistry (Baikal Institute of Nature Management SB RAS, Siberia, Russia) using Russian National standard methods (GOST). Concentrations of F^-, major anions (Cl^-, SO_4^{2-}), and cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) were analyzed by ion chromatography (Dionex 1600, Thermo Fisher Scientific Inc., New York, NY, USA), with a 2–5% error. The reliability of the data obtained was controlled by evaluating the ionic balance error evaluation and comparing the calculated and measured specific conductivity [47].

3. Results

3.1. Rainfall Trend Analysis

Precipitation data trends were analyzed for the Kyakhta, Novoselenginsk, Ulan-Ude, and Kabansk stations. At three weather stations, precipitation data were continuous within the investigated time range, only at the Kabansk station, there was a small gap. Mean monthly precipitation data were presented in millimeters (mm).

3.1.1. Analysis of Rainfall Data for the Kyakhta Station

We used data on average monthly precipitation for the period from 1936 to 2021. The main statistical characteristics of the data set are presented in Table 1. In 5 of 12 months, the minimum amount of precipitation was 0 mm. The greatest amount of precipitation was recorded in August (231.0 mm), and the least—was in January and February (11.1 mm). An MK test (p < 0.05) performed over the 12-month season showed that the p-values were higher than the significance (alpha) level of 0.05 for 9 months, as shown in Table 2. The

p-values were below the significance level (p = 0.008; 0.047; 0.032) for May, October, and November, respectively. Monthly precipitation data from the Kyakhta station showed no trend for 10 months, but only in two months (October, November), the data indicated a significant trend. The twelve-month MK test result was 5.019, which was above the significance level of 0.05, hence no significant trend was found in the data series.

Table 1. Basic statistical characteristics of the Kyakhta rainfall data.

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	0.000	11.000	3.808	2.544
February	0.000	11.000	3.236	2.570
March	0.000	17.000	4.640	4.030
April	0.200	54.000	11.676	11.037
May	4.000	91.000	28.471	19.657
June	9.000	187.000	58.082	34.761
July	17.000	213.000	82.941	38.339
August	26.000	231.000	78.753	35.728
September	4.000	87.000	39.847	18.539
October	0.200	39.000	13.446	8.901
November	0.000	24.000	6.833	4.862
December	0.000	15.000	4.835	3.121

Table 2. SS and MK test results for the Kyakhta station.

Variable (Month)	SS	Kendall tau (t)	MK	Variance	p-Value	Alpha	Interpretation
January	0.000	−0.011	−36.000	67,581.333	0.893	0.05	Accept H_0
February	0.000	−0.029	−100.000	68,214.000	0.705	0.05	Accept H_0
March	0.011	0.086	298.000	68,856.000	0.258	0.05	Accept H_0
April	0.035	0.095	331.000	69,155.667	0.210	0.05	Accept H_0
May	0.214	0.198	703.000	69,348.333	0.008	0.05	Accept H_0
June	0.000	0.008	29.000	69,371.000	0.915	0.05	Accept H_0
July	−0.133	−0.068	−243.000	69,382.333	0.358	0.05	Accept H_0
August	0.020	0.009	31.000	69,395.000	0.909	0.05	Accept H_0
September	0.125	0.097	342.000	69,338.000	0.195	0.05	Accept H_0
October	0.075	0.149	524.000	69,248.667	0.047	0.05	Reject H_0
November	0.041	0.163	565.000	68,895.000	0.032	0.05	Reject H_0
December	0.000	0.053	182.000	68,458.667	0.489	0.05	Accept H_0
Sum	0.388	0.750	2626.000	827,244.000	5.019	0.05	Accept H_0

SS test showed no change for four months and an upward trend in the remaining six months. For one month a small negative value was calculated. The sum value of 0.388 indicates that there is a weak upward trend in precipitation at this station (Table 2).

Figure 2 shows the general trend of precipitation recorded at the Kyakhta station from 1936 to 2021. The plot shows the tendency for a slow increase in precipitation near Kyakhta. This is consistent with the SS and MK values, which also indicate a positive trend in precipitation at the station (Figure 2).

3.1.2. Analysis of Rainfall Data for the Novoselenginsk Station

Precipitation data at the Novoselenginsk station also covered the period of 1936–2021. The minimum precipitation was the same (0.100 mm) for eight months (October through May); in the remaining four months (June through September) the minimums were 0.8 mm, 8.0 mm, 6.0 mm, and 2.0 mm, respectively. Precipitation was highest in the summer months, with the maximum in July at 171.0 mm (Table 3).

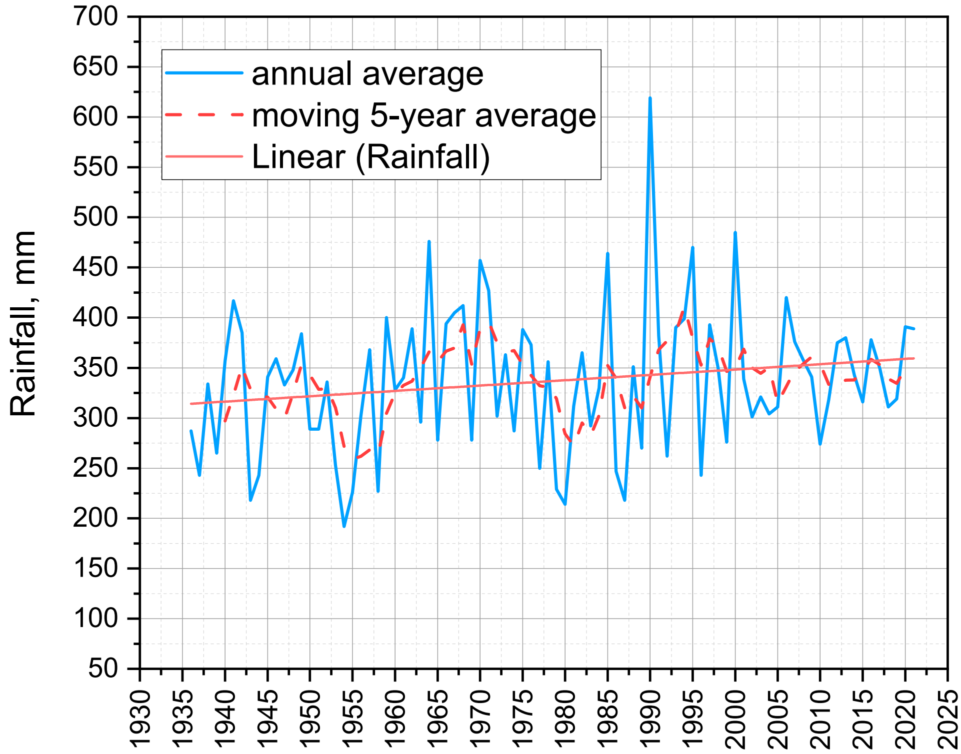

Figure 2. Rainfall trend at the Kyakhta station for the period of 1936–2021.

Table 3. Basic statistical characteristics of the Novoselenginsk rainfall data.

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	0.100	19.000	3.142	3.158
February	0.100	38.000	2.115	4.339
March	0.100	20.000	1.452	2.455
April	0.100	46.000	5.378	6.905
May	0.100	101.000	14.189	13.454
June	0.800	106.000	37.009	22.633
July	7.000	151.000	64.059	30.585
August	6.000	171.000	58.600	29.002
September	2.000	77.000	25.659	16.060
October	0.100	81.000	6.326	9.547
November	0.100	21.000	4.160	3.845
December	0.100	33.000	4.680	4.868

The MK and SS test values for precipitation data from the Novoselenginsk station are presented in Table 4. The *p*-value for August was the only one that was below the significance level of 0.05, indicating a trend in the data series. However, the overall *p*-value of 7.491 was well above the significance level of 0.05, indicating no significant trend.

The SS results showed no change for six months within a year, and downward trends—for four months. A slight positive trend was observed in March (0.011) and May (0.031). The overall SS value of −0.406 indicates a slight downward trend.

Precipitation recorded at the Novoselenginsk station from 1936 to 2020 shows a tendency to insignificant decrease (Figure 3), which is confirmed by the MK and SS calculations (Table 4).

Table 4. SS and MK test results for the Novoselenginsk station.

Variable (Month)	SS	Kendall tau (t)	MK	Variance	*p*-Value	Alpha	Interpretation
January	0.000	−0.013	−43.000	65,723.000	0.870	0.05	Accept H_0
February	0.000	0.009	32.000	68,202.667	0.906	0.05	Accept H_0
March	0.011	−0.031	−107.000	68,394.333	0.685	0.05	Accept H_0
April	−0.007	−0.081	−278.000	68,721.333	0.291	0.05	Accept H_0
May	0.031	0.061	213.000	69,213.667	0.420	0.05	Accept H_0
June	0.000	−0.008	−30.000	69,352.000	0.912	0.05	Accept H_0
July	−0.260	−0.131	−466.000	69,366.667	0.077	0.05	Accept H_0
August	−0.160	−0.092	−0.092	−0.092	−0.092	−0.092	Accept H_0
September	−0.021	−0.031	−110.000	69,316.667	0.679	0.05	Accept H_0
October	0.000	−0.001	−4.000	68,970.000	0.991	0.05	Reject H_0
November	0.000	−0.004	−14.000	68,368.667	0.960	0.05	Reject H_0
December	0.000	−0.021	−70.000	68,300.667	0.792	0.05	Accept H_0
Sum	−0.406	−0.343	−877.092	753,929.600	7.491	0.05	Accept H_0

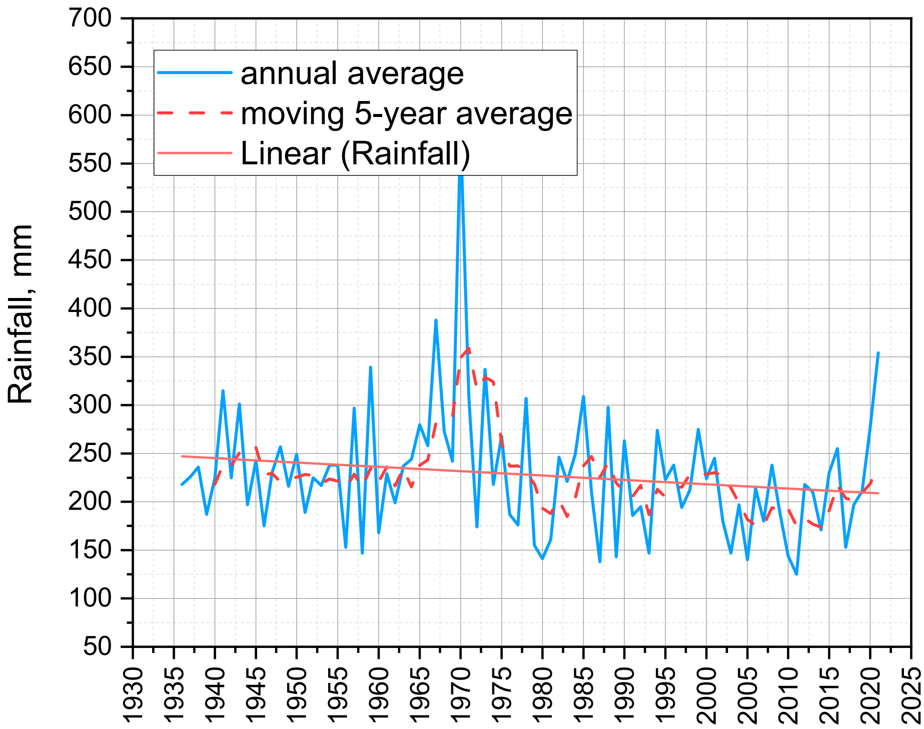

Figure 3. Rainfall trend at the Novoselenginsk station for the period of 1936–2021.

3.1.3. Analysis of Rainfall Data for the Ulan-Ude Station

Data on average monthly precipitation covered the period from 1936 to 2021 (statistical data in Table 5). In 4 of 12 months the minimum amount of precipitation was 0 mm. The highest amount of precipitation was recorded in July (162 mm).

The MK test data ($p < 0.05$) showed that the p values for January and April were below the significance level (0.027 and 0.019, respectively); and for the other 10 months the p values were above alpha 0.05. The cumulative p value for the twelve months was 4.904, which was also above the significance level, hence there was no distinct trend for this data series (Table 6). The SS value for eight months had negative values, and for the remaining four months—zero values, demonstrating no trend.

Table 5. Basic statistical characteristics of the Ulan-Ude rainfall data.

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	0.400	16.000	5.266	3.572
February	0.000	8.000	2.928	1.994
March	0.000	15.000	3.013	3.275
April	0.000	31.000	6.695	6.106
May	0.400	49.000	16.187	12.551
June	3.000	117.000	37.153	24.177
July	11.000	162.000	68.612	32.422
August	10.000	146.000	62.353	32.713
September	7.000	70.000	27.682	14.682
October	0.000	33.000	8.024	6.071
November	1.000	29.000	9.318	5.226
December	2.000	47.000	11.047	6.729

Table 6. SS and MK test results for the Ulan-Ude station.

Variable (Month)	SS	Kendall tau (t)	MK	Variance	*p*-Value	Alpha	Interpretation
January	−0.032	−0.170	−582.000	68,746.667	0.027	0.05	Reject H_0
February	0.000	−0.040	−135.000	67,579.000	0.606	0.05	Accept H_0
March	0.000	−0.036	−123.000	68,365.000	0.641	0.05	Accept H_0
April	−0.044	−0.179	−618.000	68,910.000	0.019	0.05	Reject H_0
May	0.000	0.009	30.000	69,212.667	0.912	0.05	Accept H_0
June	−0.083	−0.066	−235.000	69,367.667	0.374	0.05	Accept H_0
July	−0.255	−0.134	−478.000	69,379.333	0.070	0.05	Accept H_0
August	−0.139	−0.067	−238.000	69,384.000	0.368	0.05	Accept H_0
September	−0.027	−0.031	−110.000	69,316.667	0.679	0.05	Accept H_0
October	−0.035	−0.120	−415.000	68,988.333	0.115	0.05	Accept H_0
November	0.000	−0.020	−69.000	68,937.667	0.796	0.05	Accept H_0
December	−0.023	−0.079	−275.000	69,049.667	0.297	0.05	Accept H_0
Sum	−0.638	−0.933	−3248.000	827,236.700	4.904	0.05	Accept H_0

The plot of precipitation at the Ulan-Ude station for the period of 1936–2021 shows a decreasing trend (Figure 4), which is also confirmed by the total SS value of 1.256.

3.1.4. Analysis of Rainfall Data for the Kabansk Station

Data on average monthly precipitation at the Kabansk station covered the period of 1936−2021. Over the entire study period, the minimum amount of precipitation (0 mm) was recorded in 7 months; the maximum—in August (451 mm) (Table 7).

Table 7. Basic statistical characteristics of the Ulan-Ude rainfall data.

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	0.000	171.000	11.732	19.445
February	0.000	23.000	5.933	4.865
March	0.000	50.000	8.591	7.605
April	0.000	105.000	18.389	15.369
May	0.000	88.000	30.427	20.073
June	0.000	189.000	48.720	36.219
July	10.000	307.000	83.110	48.727
August	11.000	451.000	82.110	61.347

Table 7. *Cont.*

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
September	10.000	148.000	49.195	27.882
October	0.300	105.000	22.845	15.878
November	3.000	73.000	18.927	12.317
December	0.000	68.000	18.480	12.030

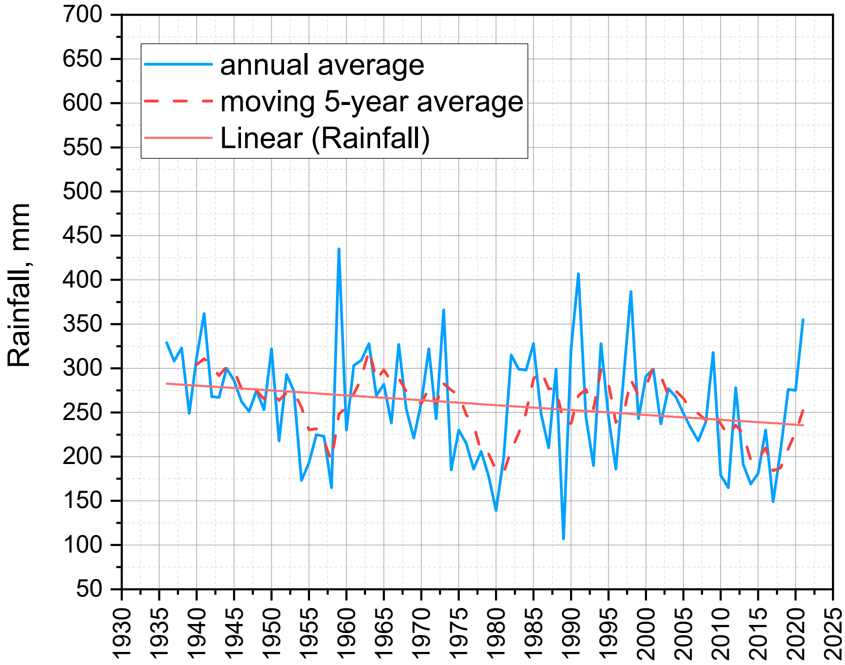

Figure 4. Rainfall trend at the Ulan-Ude station for the period of 1936–2021.

The MK data ($p < 0.05$), showed that p values for six months were below the significance level of 0.05, the remaining months had higher values (Table 8). The sum of p-values for the twelve months was 2.101, which was above the alpha level, hence no significant trend was found. The SS data showed a downward trend in all months. The overall SS value of −1.428 indicates a slight downward trend (Figure 5).

Table 8. SS and MK test results for the Ulan-Ude station.

Variable (Month)	SS	Kendall tau (t)	MK	Variance	p-Value	Alpha	Interpretation
January	−0.045	−0.156	−504.000	61,932.667	0.043	0.05	Reject H_0
February	−0.053	−0.204	−657.000	61,889.667	0.008	0.05	Reject H_0
March	−0.071	−0.207	−668.000	61,957.333	0.007	0.05	Reject H_0
April	−0.182	−0.270	−887.000	62,246.333	0.000	0.05	Reject H_0
May	−0.038	−0.033	−108.000	62,281.333	0.668	0.05	Accept H_0
June	−0.200	−0.122	−402.000	62,308.667	0.108	0.05	Accept H_0
July	−0.407	−0.159	−526.000	62,342.667	0.035	0.05	Reject H_0
August	−0.050	−0.024	−81.000	62,327.000	0.749	0.05	Accept H_0
September	−0.143	−0.105	−348.000	62,307.333	0.164	0.05	Accept H_0
October	−0.035	−0.114	−376.000	62,285.888	0.133	0.05	Accept H_0
November	−0.065	−0.103	−336.000	62,142.000	0.179	0.05	Accept H_0
December	−0.139	−0.206	−678.000	62,264.667	0.007	0.05	Reject H_0
Sum	−1.428	−1.703	−5571.000	746,285.600	2.101	0.05	Accept H_0

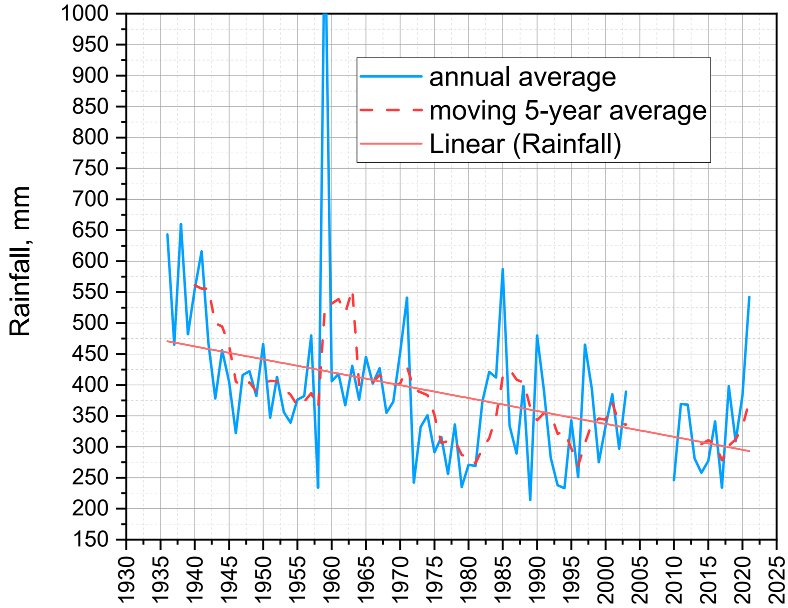

Figure 5. Rainfall trend at the Kabansk station for the period of 1936–2021.

The plot of precipitation recorded at Kabansk station from 1936 to 2021 shows a slight downward trend, which is consistent with the SS and MK data.

3.2. Runoff Data Analysis

Runoff trends were analyzed at two gauging hydrologic stations downstream of the Selenga River. The Novoselenginsk hydrologic station is located 140 km upstream of the Mostovoi station. Initial runoff data were presented in cubic meters per second (m^3/s).

3.2.1. Analysis of Runoff Data for the Novoselenginsk Hydrological Gauging Station

The monthly runoff data from the Novoselenginsk hydrological station for the period of 1990–2017 were used for analysis. Due to the lack of available data on the average monthly river flow for the previous and subsequent years, the Mann Kendal trend analysis was carried out in this time interval.The minimum monthly runoff values at the station were recorded during the winter months and March: 56.571, 32.114, and 33.826 m^3/s in January, February, and March, respectively (Table 9). Maximum absolute and mean runoff values were recorded from May through September. The high difference between the minimum and maximum flow values for June, July, August, and September resulted in high mean values and standard deviations for this period.

Table 9. Basic statistical characteristics of the Novoselenginsk runoff data (1990–2017).

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	56.571	301.565	134.996	55.177
February	32.114	248.782	91.814	45.217
March	33.826	824.911	116.297	144.643
April	124.214	895.381	371.848	212.061
May	345.903	1659.000	788.890	300.897
June	416.733	1993.786	900.974	389.413
July	398.161	3966.932	1175.082	766.570
August	635.000	3324.974	1448.708	684.632
September	510.585	2619.793	1229.337	567.326
October	377.572	1407.050	790.555	279.546
November	198.233	890.623	385.294	180.023
December	100.990	633.042	205.639	105.873

The MK results for the data from the Novoselenginsk hydrological station are presented in Table 10. Eight of the 12 hydrological months had p-values below the significance level of 0.05, demonstrating a trend, while the remaining four months showed no trend. However, the overall p-value of 1.619 indicated no significant trend in the data series.

Table 10. SS and MK test results for the Novoselenginsk station.

Variable (Month)	SS	Kendall tau (t)	MK	Variance	p-Value	Alpha	Interpretation
January	−4.254	−0.538	−203.000	2561.000	<0.0001	0.05	Reject H_0
February	−3.010	−0.481	−182.000	12.000	0.000	0.05	Reject H_0
March	−3.152	−0.444	−168.000	12.000	0.001	0.05	Reject H_0
April	1.321	0.026	10.000	12.000	0.860	0.05	Accept H_0
May	−9.174	−0.159	−60.000	12.000	0.247	0.05	Accept H_0
June	−6.971	−0.132	−50.000	12.000	0.337	0.05	Accept H_0
July	−20.999	−0.206	−78.000	12.000	0.130	0.05	Accept H_0
August	−42.180	−0.434	−164.000	12.000	0.001	0.05	Reject H_0
September	−35.459	−0.339	−128.000	12.000	0.011	0.05	Reject H_0
October	−15.887	−0.302	−114.000	12.000	0.025	0.05	Reject H_0
November	−10.337	−0.381	−144.000	12.000	0.004	0.05	Reject H_0
December	−4.286	−0.400	−151.000	2561.000	0.003	0.05	Reject H_0
Sum	−154.388	−3.790	−1432.000	5242.000	1.619	0.05	Accept H_0

SS for all months indicated a downward trend, except for April. The highest values of changes were observed in July, August and September.

The general trend of runoff at the hydrological gauging station Novoselenginsk is shown in Figure 6. During the period, the monthly runoff varied little from year to year and was less than 3000 m^3/s, except for the month in 1992. The trend line shows a decrease in runoff at a low rate, which is confirmed by negative values of SS and MK.

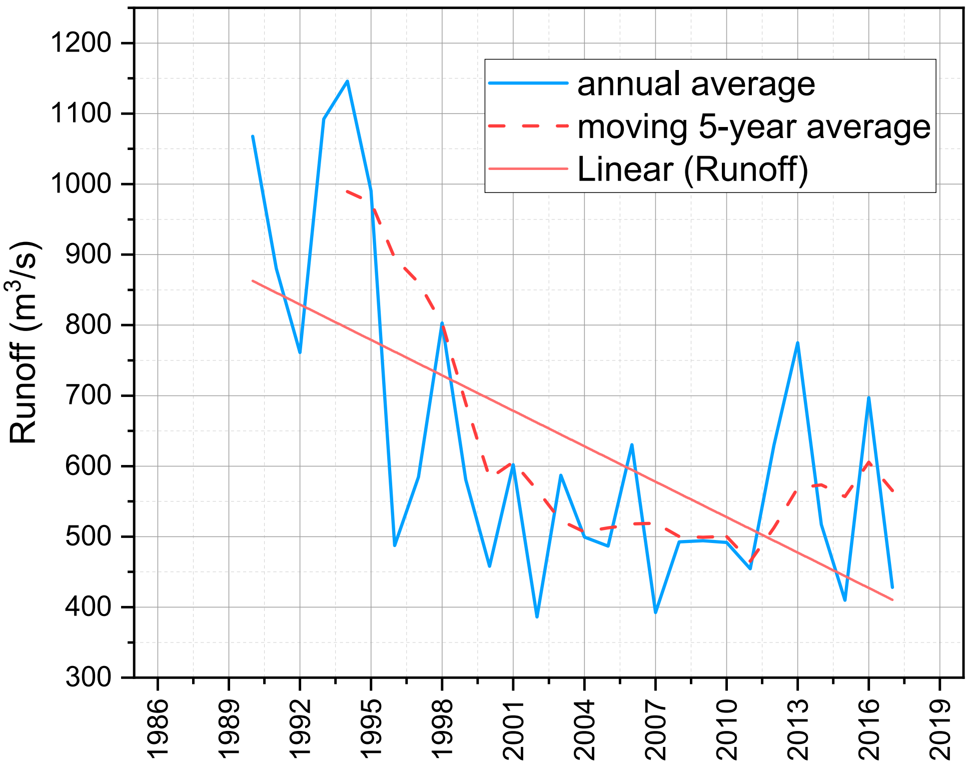

Figure 6. Runoff trend at the Novoselenginsk station for the period of 1990–2017.

3.2.2. Analysis of Runoff Data for the Mostovoi Hydrological Station

The Mostovoi hydrological station is located on the Selenga River, downstream of the Novoselenginsk station. The runoff trend at the Mostovoi station was analyzed from 1990 to 2017. The lowest runoff values were in January, February, and March (as at the Novoselenginsk station), and the highest rates were observed in the summer and fall months (Table 11). August had the highest values of mean monthly runoff and standard deviation.

Table 11. Basic statistical characteristics of the Mostovoi runoff data (1990–2017).

Variable (Month)	Minimum	Maximum	Mean	Std. Deviation
January	71.371	271.000	143.473	49.618
February	42.014	204.000	100.551	39.862
March	42.474	239.000	112.390	44.004
April	176.000	1356.000	538.796	262.639
May	566.000	1755.806	1074.043	313.077
June	606.967	2065.000	1124.700	331.473
July	556.806	2142.000	1250.298	446.843
August	752.000	4356.000	1803.969	959.009
September	533.000	3875.000	1595.908	873.952
October	379.000	2587.000	1136.551	593.913
November	224.600	1248.000	549.032	299.622
December	105.000	426.000	241.111	81.809

The results of the SS and MK tests are shown in Table 12. The *p*-values for the six months were below the significance level, and above it for the remaining months. The sum of the MK *p*-values for the twelve months was 2.05, (above the significance level), demonstrating no significant trend. The SS and MK data had negative values, indicating a downward trend in the data series.

Table 12. SS and MK test results for the Mostovoi runoff data (1990–2017).

Variable (Month)	SS	Kendall tau (t)	MK	Variance	*p*-Value	Alpha	Interpretation
January	−2.735	−0.312	−118.000	0.000	0.020	0.05	Reject H_0
February	−1.679	−0.236	−89.000	2559.000	0.082	0.05	Accept H_0
March	−1.669	−0.239	−90.000	2560.000	0.079	0.05	Accept H_0
April	5.381	0.143	0.143	0.143	0.143	0.143	Accept H_0
May	2.053	0.032	12.000	12.000	0.830	0.05	Accept H_0
June	−8.157	−0.116	−44.000	12.000	0.400	0.05	Accept H_0
July	−7.993	−0.101	−38.000	12.000	0.469	0.05	Accept H_0
August	−57.194	−0.407	−154.000	12.000	0.002	0.05	Reject H_0
September	−56.333	−0.349	−132.000	12.000	0.009	0.05	Reject H_0
October	−42.263	−0.368	−139.000	2561.000	0.006	0.05	Reject H_0
November	−29.183	−0.529	−200.000	12.000	<0.0001	0.05	Reject H_0
December	−5.929	−0.344	−130.000	12.000	0.010	0.05	Reject H_0
Sum	−205.701	−2.826	−1121.86	7764.143	2.05	0.05	Accept H_0

The overall runoff trend for the Mostovoi station is shown in Figure 7. It shows a decreasing trend in runoff (the same is observed at the upstream station). The linear trend line and predictive runoff model indicate a decreasing trend in runoff at the hydrologic station.

3.3. Summary of Trends

The direction of trends in precipitation and runoff levels relative to the altitudes of the study region is shown in Figure 8. The green up triangle shows a positive non–significant trend in precipitation, while the green down triangle indicates a negative non–significant trend. The blue down triangle represents a negative non-significant trend in runoff levels.

3.4. Trend Analysis of Major Ions (Correlation of Water Level Change with Chemical Runoff)

To analyze the correlation between changes in water levels and chemical indicators in the Selenga, we conducted spatiotemporal and seasonal analyses of changes in salinity and major ions in the river waters from the border with Mongolia (Naushki settlement) and to the river delta (Kabansk settlement). The analysis was conducted for a range of data from 2015 (with extremely low water levels), to 2021, when water levels were close to their maximum, and during the summer rainfall flooding, the river was observed reaching the floodplain at all observation stations.

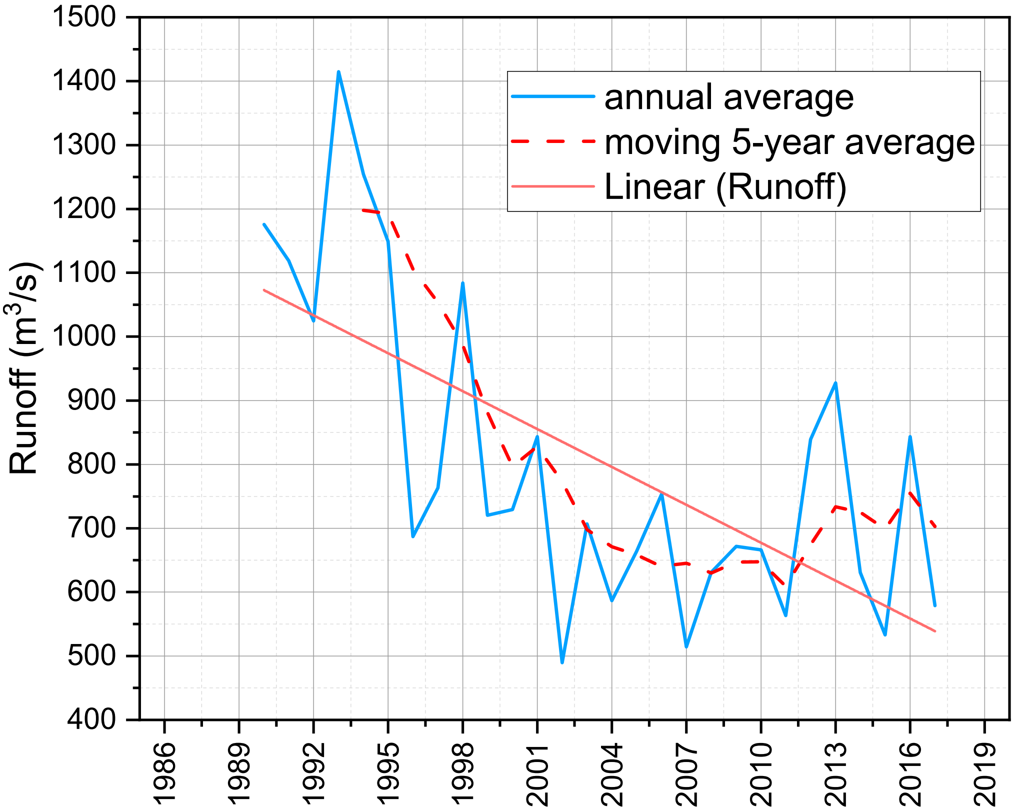

Figure 7. Runoff trend at the Mostovoi station for the period 1990–2017.

A comparative analysis was performed at 5 stations from Naushki to the delta of the Selenga (Naushki, Novoselenginsk, 2 stations above and below Ulan-Ude, Kabansk). Figure 8 shows that the water level in the river was low in 2015 and 2017; starting from 2018, the water level began to increase. Mineralization of the Selenga water in the period of low water level was 158–268 mg/L. The increase in water level was accompanied by a decrease in salinity to 107–201 mg/L (Figure 9a,b), with the highest values being typical for the Naushki–Novoselenginsk section of the river. The decrease in salinity is insignificant downstream of the Selenga River, from Naushki to Novoselenginsk: the tributary flowing in here (the Dzhida River) has no effect due to the close values of salinity. Moving even further downstream, from Novoselenginsk to Kabansk, the Selenga water shows a decrease in salinity due to dilution by less saline waters of tributaries—the Chikoi, Khilok, and Uda rivers. As for seasonal changes, the maximum values of salinity are observed in the subglacial period when there is no runoff from the watershed, the minimum—is during the spring floods and summer rainfall floods.

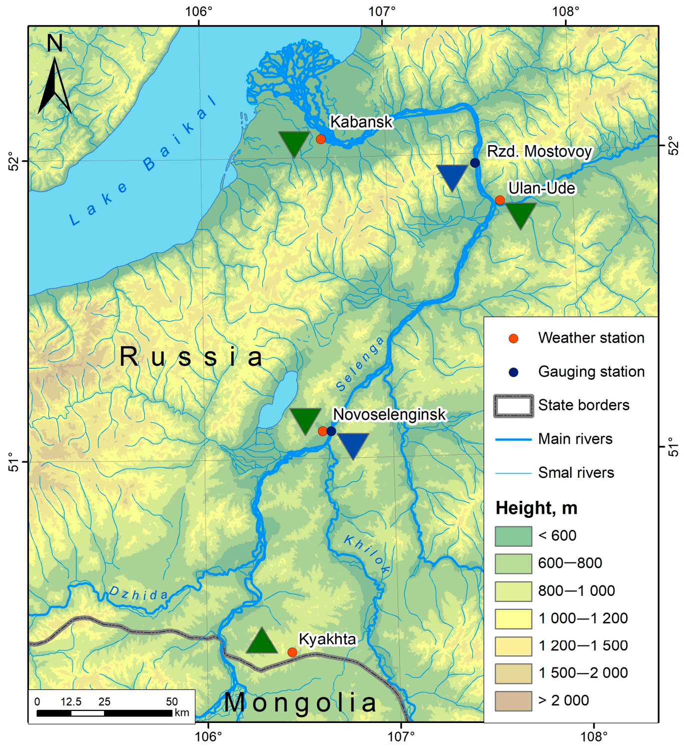

Figure 8. Summary of rainfall and runoff trends.

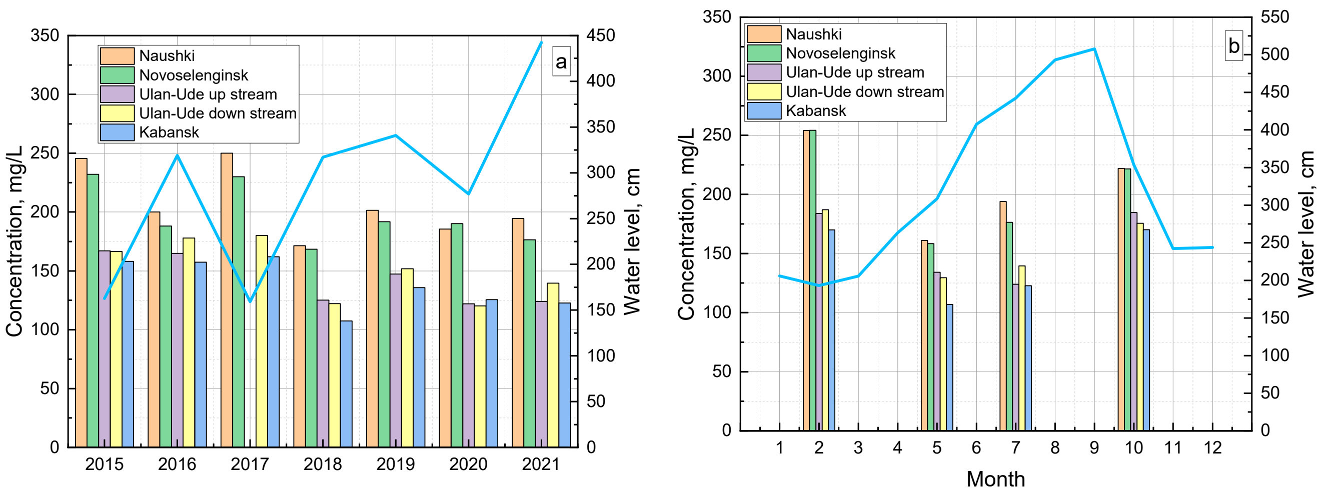

Figure 9. Spatiotemporal (**a**) and seasonal (**b**) changes in water salinity in the Selenga.

Concentrations of major ions HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+ in the Selenga River water during 2015–2021 varied in the intervals (mg/L): 72—184; 6.3—17.8; 0.8—1.9; 17.4—41.2; 3.6—11.2; 4.3—9.4 and 1.0—2.1, respectively. The maximum concentrations of all components were observed in the subglacial period of 2015–2017. The spatial and seasonal dynamics of HCO_3^-, Ca^{2+}, Mg^{2+}, and K^+ ion concentrations correspond to the dynamics of total mineralization. The seasonal dynamics of SO_4^{2-}, Cl^-, and Na^+ ions are close to that for total mineralization, while the spatial dynamics are different and more complex (Figures 10 and 11).

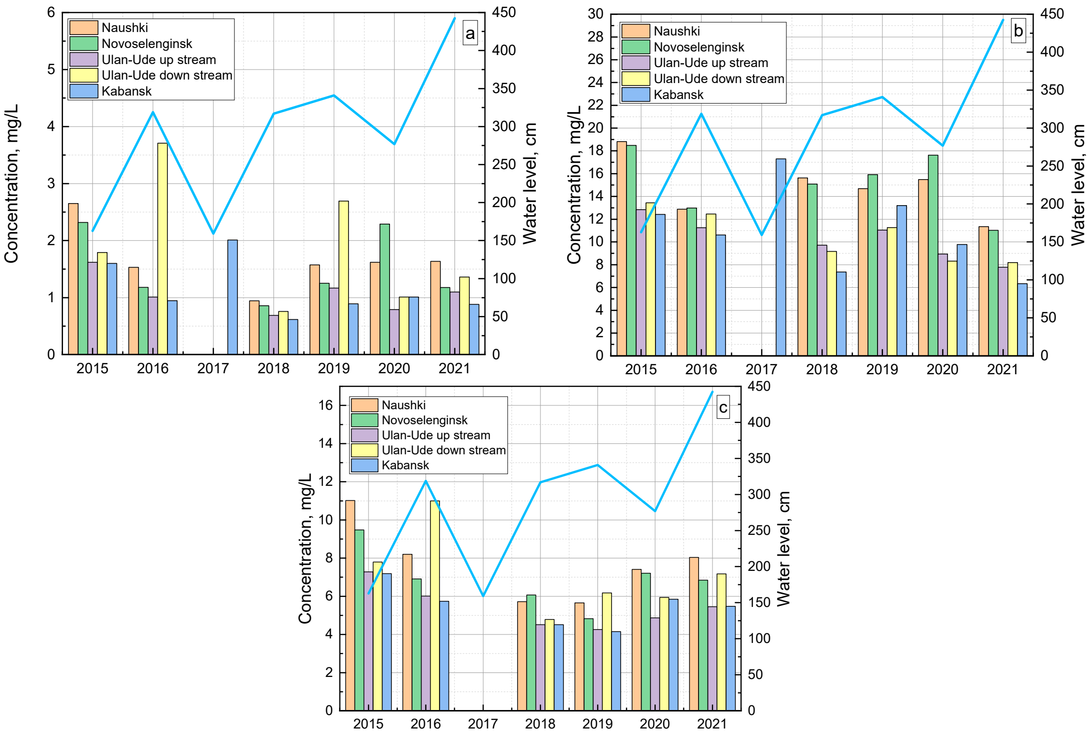

Figure 10. Spatiotemporal changes in the content of major ions in the Selenga water ((**a**)—Cl^-, (**b**)—SO_4^{2-}, (**c**)—Na^+). (Data on Na^+ ion content for 2017 are not available).

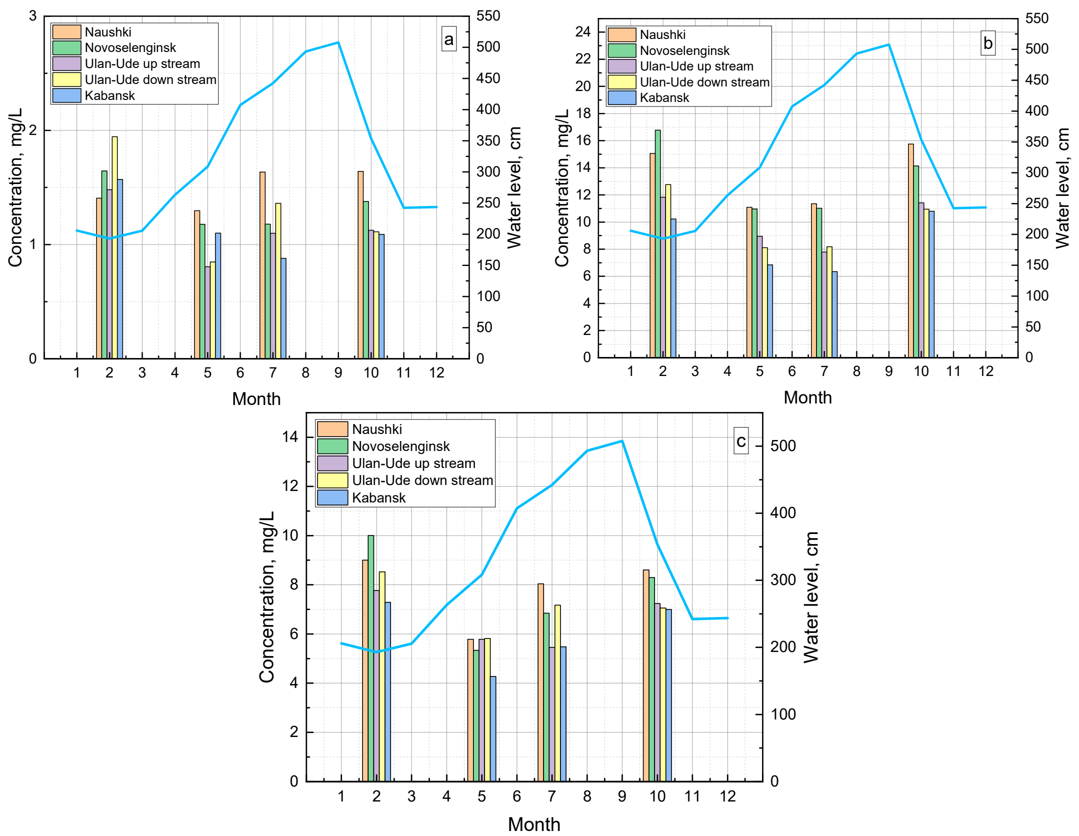

Figure 11. Seasonal changes in the content of major ions in the Selenga water ((**a**)—Cl^-, (**b**)—SO_4^{2-}, (**c**)—Na^+).

4. Discussion

The distribution of precipitation in the Selenga River basin is determined by atmospheric circulation conditions and the terrain [48]. In winter, the area of the river basin is affected by the Siberian anticyclone and therefore receives very little precipitation, which agrees with our findings. Analysis of the precipitation trend shows that most of it fall in the second half of summer and the first half of fall [49,50]. This is explained by the change of continental polar air to tropical sea air, which causes abundant precipitation. Up to 80−90% of the annual precipitation falls as rain [37,51]. Analysis of precipitation data for three weather stations shows a slight downward trend. Only one weather station shows a slightly positive trend. Overall, there is a slight negative trend throughout the Selenga River basin, which is consistent with the results of earlier studies [52]. The downward trend in the amount of precipitation can be related to changes in air temperature [53]. The global air temperature has increased by 1.2 °C since the beginning of industrialization [54], with a change in the atmospheric circulation, which in turn affects the amount of precipitation. During the period from 1936 to 2021, the mean annual air temperatures at the Kyakhta and Kabansk stations were 0.3 °C and −0.2 °C, respectively. The maximum 2.1 °C and the minimum 1.8 °C were recorded at the Kyakhta station in 2020 and 1947, respectively. The maximum value of 1.9 °C in 2007 and the minimum −2.2 °C in 1947 were recorded at the Kabansk station. Based on the graph, the air temperature began to rise sharply after 1980 (Figure 12). The consequence of such a sharp temperature rise can be climate change.

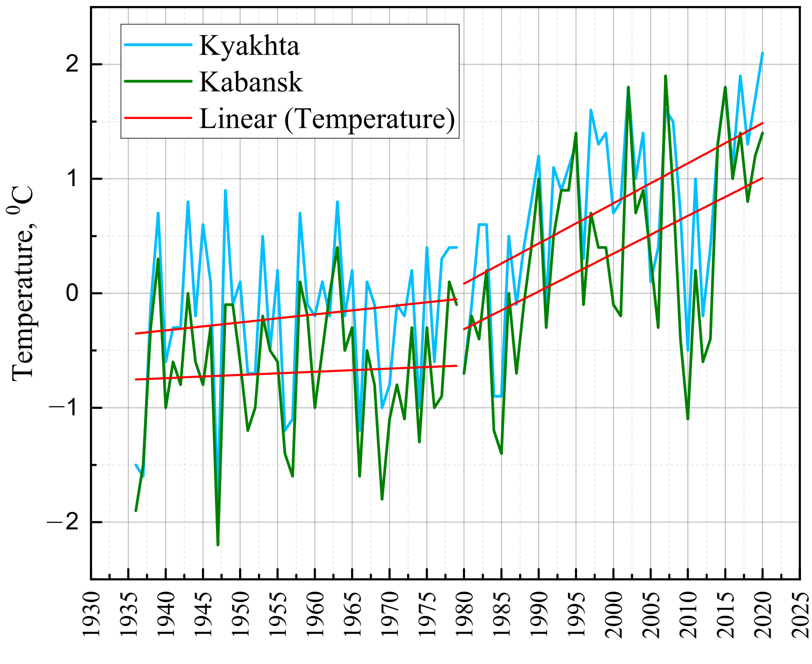

Figure 12. Changes in air temperature for the period of 1936–2020.

The analysis revealed an insignificant downward runoff trend at two hydrological stations in the Russian part of the Selenga basin. The maximum runoff and precipitation levels were recorded in the summer months and the first half of autumn. The lowest runoff values were in the winter period. Analysis of precipitation and runoff data in the Mongolian part of the Selenga River basin, performed by scientists from different countries, also showed a negative trend at some hydrological stations [15]. To assess the correlation between precipitation and runoff, we calculated Spearman rank correlation coefficients of the average annual data for two stations—Novoselenginsk and Mostovoi (Figure 13), for which a weak (r = 0.37) and a moderate correlation (r = 0.53) was identified, respectively.

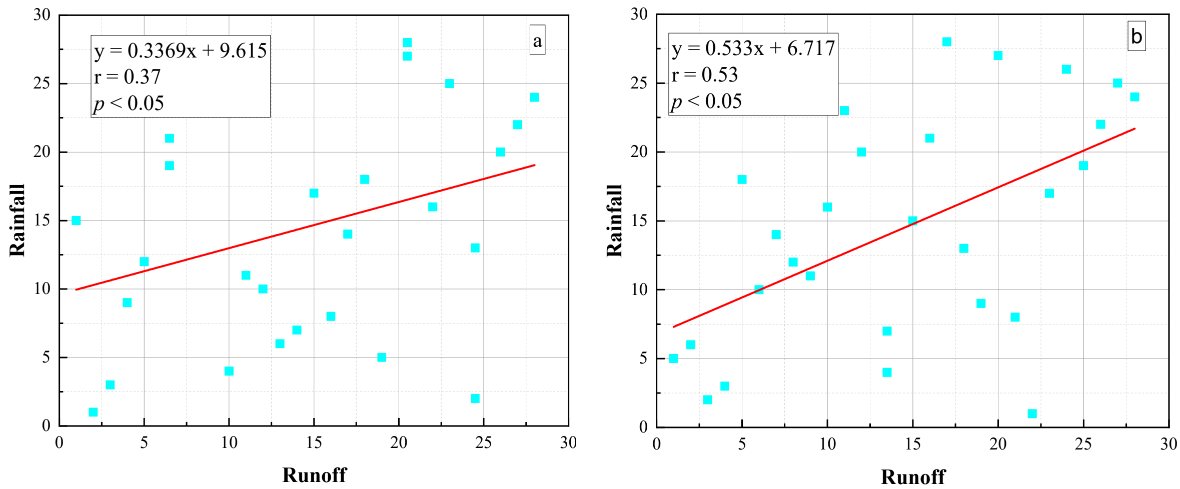

Figure 13. Spearman rank correlation coefficient for the rainfall and the runoff average annual data: (**a**)—Novoselenginsk station, and (**b**)—Mostovoi station.

We also carried out the correlation tests for air temperature and precipitation over the past 50 years, and calculated the Spearman rank correlation coefficient of the average annual data for the two stations (Figure 14). At the Novoselenginsk station, the rank correlation coefficient showed a moderate positive relationship (0.45), and strong relationship at the Ulan-Ude station (0.65).

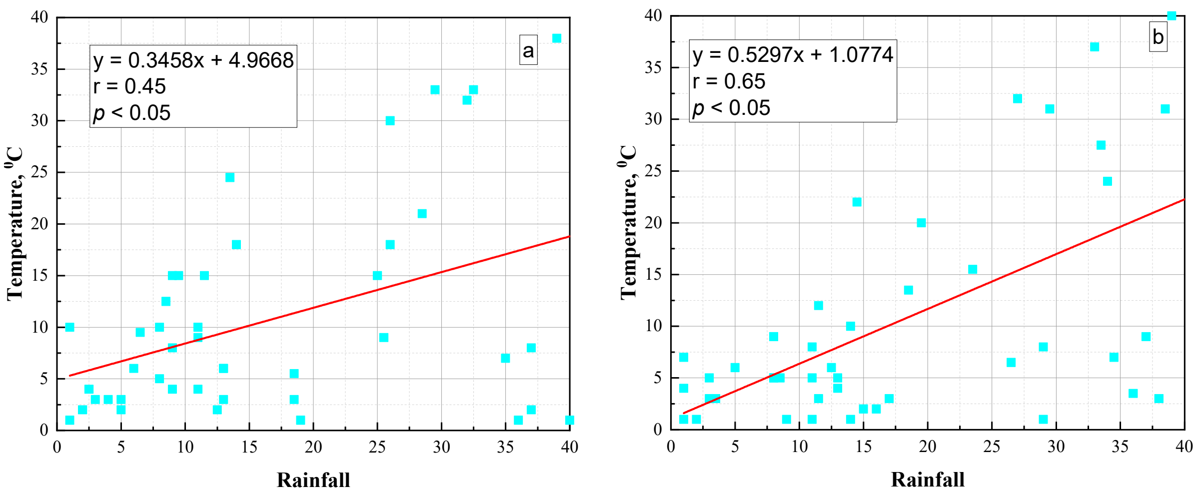

Figure 14. Spearman rank correlation coefficient for the air temperature and the rainfall average annual data: (**a**)—the Novoselenginsk station, and (**b**)—the Ulan-Ude station.

The weak correlation between the Selenga runoff and precipitation for the weather stations located in close proximity to the river may be due to the strong dependence of the Selenga runoff on the runoff of its tributaries (especially large rivers—Chikoi and Khilok), which in turn are determined by precipitation in their watershed. In other words, the Selenga runoff depends on the amount of precipitation that falls throughout its watershed.

The water of the Selenga by chemical composition belongs to the hydrocarbonate class (the calcium group, the first type), according to O.A. Alekin's classification. It has low mineralization, which varies depending on multi–year and seasonal fluctuations in water level [32,33]. The hydrochemical regime of the Selenga is characterized by an increase in major ions and salinity during the subglacial period, and a decrease during the spring flood and summer rainfall floods. Downstream of the Selenga (from Naushki settlement to the delta) salinity decreases by an average of 20–35% due to changing landscape conditions in the watershed, seasonal meteorological patterns, and the inflow of less saline tributaries that have a diluting effect. The spatial dynamics of SO_4^{2-}, Cl^-, Na^+ concentrations are influenced not only by the water level, but also by local sources of ions, such as meltwater or rainwater flushing from adjacent areas (ones with saline soils) and wastewater from the industrial complex in Ulan-Ude.

Comparison of these results with earlier observations (from the 1960s) showed a significant increase in sulfate concentrations in the water throughout the Russian section of the Selenga River, which is largely due to increased anthropogenic load. The increase in sulfate concentrations (especially in winter) is associated with both an increase in the proportion of underground feeding of the river in conditions of reduced water levels, as well as with the intensification of economic activity, mainly in the territory of Mongolia. The sulfate content has more than doubled in the waters coming from Mongolia. Compared to the pre–industrial period, the range of current SO_4^{2-} concentrations in the Selenga water in winter increased from 7.2–10.4 mg/L [25] to 7.6–18.7 mg/L in 2010–2012. The sulfate concentrations we determined in winter 2018–2020 were in the range of 10.6–20.7 mg/L, confirming the increasing trend noted earlier [55].

5. Conclusions

Trend analysis of precipitation data for the Kyakhta, Novoselenginsk, Ulan-Ude, and Kabansk stations, as well as runoff data for the Novoselenginsk and Mostovoi hydrological stations, was performed using Mann Kendal and Sen's slope statistical tests. We identified a slight downward trend at the Novoselenginsk, Ulan-Ude, and Kabansk weather stations, while a slight increase in precipitation was observed at the Kyakhta station. The results of the Mann Kendall test ($p < 0.05$) show that the data from the four weather stations show no significant changes in precipitation levels. The results of the Mann Kendal test at the Novoselenginsk and Mostovoi hydrological stations showed a downward trend in the runoff. The mean annual precipitation and runoff values shoed a direct positive correlation. Average annual air temperatures and precipitation levels showed a positive strong correlation. Analysis of runoff data for the Selenga for the period of 1990−2017 using the Mann-Kendal test showed a downward trend at the Novoselenginsk and Mostovoi stations (as well as for precipitation.

The hydrochemical regime of the Selenga is determined by the water level in the river and is characterized by an increase in major ions and salinity during the subglacial period and a decrease—during the open water period. An increase in water runoff is accompanied by a decrease in salinity and the content of major ions. Concentrations of sulfate, chloride, and sodium ions are also affected by local sources of their natural and anthropogenic origin. Communities living in the watershed of the Selenga River—the main tributary of Lake Baikal—should use water rationally and conserve the environment in the face of global climate change. Continuous monitoring of the basin's water quality and anthropogenic impacts is also recommended.

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