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Challenges and Future Opportunities of Groundwater Resources for Drinking Water Use: A Case Study of Slatina nad Bebravou (Slovakia)

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Abstract: The interlinked issues of climate change and increasing water demand are creating high pressure on water resources. In Slovakia, groundwater is a principal resource for human consumption. Consequently, an analysis was conducted of the current water yields of three springs, river discharges and precipitation trends, from several points of view. As a case study, we selected the area around Slatina nad Bebravou (Slovakia), which has the most relevant database. Descriptive statistics, the Mann–Kendall test and Sen's slope were used for the trend analysis. The findings indicate that the current capacity of springs is sufficient to meet the present needs of water users. However, the downward trend in abundance, the increasing trend in water withdrawal, and the current poor state of infrastructure point to an early tipping point. Data analysis revealed a problem with the yield of springs, especially in the summer and autumn months.

Keywords: groundwater withdrawal; spring yield; flow rate; hydrological trend

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1. Introduction

Ongoing climate change, the energy crisis, industrial development and recreation are exerting pressure on the availability of sufficient water of the required quality. Rising average temperatures, changing distributions of annual rainfall and increasing weather extremes are resulting in decreasing water availability for people and the landscape. Consequently, there is an increasing discourse surrounding the retention of water in the landscape. To manage water resources effectively, it is necessary to ascertain their current status and utilization. Mainly, ground water is used to fulfil human needs.

In the context of escalating global demand and the increasingly prevalent phenomenon of drought in numerous regions worldwide, groundwater, stored within aquifers, has emerged as a critical water resource. This assertion is further substantiated by projections indicating a further exacerbation of water scarcity, attributable to both the expanding global population and the concomitant economic growth. Consequently, the value of groundwater is anticipated to rise in proportion to the diminishing water availability across various regions, a phenomenon compounded by the effects of climate change. This underscores the imperative for effective groundwater management to be recognized as a pivotal strategy [1]. Therefore, it is imperative that long-term groundwater recharge and exploitation be monitored to ensure current and future sustainable groundwater extraction in the context of climate change [2].

The sustainable utilization of groundwater is contingent upon the maintenance of optimal levels of groundwater recharge, a process that is anticipated to be subject to alteration in the context of climate change. However, the extent to which climate change will impact recharge remains uncertain, primarily due to the scarcity of measurements pertaining to global recharge trends [3]. The establishment of a comprehensive monitoring network has been identified as a potential solution to address this knowledge gap, with the capability to identify areas of preferential recharge. This approach facilitates the mapping of preferential groundwater flow paths, enabling the targeted replenishment of surface runoff during the rainy season [2].

The issue of groundwater depletion is exacerbated by overexploitation, particularly in cases where natural recharge is impaired. Recharge, a complex process influenced by various factors such as soil properties, rainfall intensity, water table depth, soil moisture, evaporation, area, geomorphology, and geology, and these factors play pivotal roles in determining the rate of infiltration. Infiltration, being the primary process for groundwater recharge, is subject to modification by land use change, which in turn affects the rainfall–runoff partitioning [4,5]. Topographic effects and vegetation cover can introduce uncertainties in recharge estimates derived from baseflow separation [2]. Furthermore, land use change impacts not only the soil water balance but also the occurrence of preferential flow by destroying preferential channels in soil, thereby causing changes in groundwater recharge rates [6].

Agriculture is the world's largest consumer of water, with water resources worldwide under pressure from rapidly growing demands (increasing food production, urban expansion and industrial development) as well as climate change. Concurrently, the escalating demand for water has been a substantial contributing factor to the contamination of existing water bodies [7].

Drought is one of the most serious consequences of climate and land use change. Climate change is expected to affect almost every environmental and social aspect. Socio-economic sectors, energy, services, ecosystems and water resources will face a clear increase in vulnerability to climate change. The water cycle is one of the most important components of the natural system and one of the most vulnerable in socio-economic terms. Already a large proportion of the world's population is suffering from water stress, and therefore, changes in water availability have a significant impact. Soil moisture is one of the most important water resources as it provides a large part of the world's food production [8].

Hydrological drought is primarily associated with water scarcity in hydrological systems, as evidenced by abnormally low flows or deficits in lake, reservoir or groundwater levels. These abnormal hydrological conditions can also affect other sectors, including aquatic and riparian habitat, water quality, domestic water supply, agricultural and industrial uses, river transport, and hydropower generation [9]. As a result of recent climate change and variability, as well as unprecedented rates of urbanization, industrialization, and population growth, these negative impacts have accelerated in recent decades [10]. Although drought is mainly caused by a lack of precipitation, other factors (e.g., demand for atmospheric evaporation, storage in ice and snow, land use change) may also play a role in the occurrence of hydrological drought [11]. To address hydrological drought, there are several measures that aim to improve water management. Increasing storage capacity or storing rainwater, equitable practices for water supply and distribution, river health, and watershed management can reduce the negative effects of climate change on the availability of water resources. Similarly, developing climate-resilient crops, water management for irrigation, adopting climate-smart agriculture approaches, and promoting local knowledge can ensure food security by increasing agricultural yields [12].

The aim of this study is to analyze the impact of climate change on the rainfall–runoff process in the landscape and on changes in spring yield in the study area over time. Based on this, the availability of water for the population in the future will be assessed.

2. Materials and Methods

2.1. Location

An important water supply system in the territory of Western Slovakian Water Company, Inc. is the Ponitrian Group Water Supply System, which supplies drinking water to Banovce nad Bebravou, Partizanske, Topolcany, Nitra and other smaller consumption localities. The system utilizes groundwater sources from the north-western part of the Banovce nad Bebravou district (water sources: Slatina, Cierna Lehota, Timoradza, Podluzany), as well as from the Trencin district (water source: Motesice) and other local water sources.

The area is located in central Slovakia, in the district of Banovce nad Bebravou, in the Trencin Region (see Figure 1). The Bebrava river flows through the territory, which rises in the Strazovske vrchy mountains on the south-western slopes of the Kremeniste hill at an altitude of about 770 m above sea level in the cadastral territory of the Cierna Lehota municipality [13]. In years of low precipitation, the section between Sipkov and Slatina nad Bebravou is known to lose the surface water connection, a phenomenon attributed to the influence of karst-volcanic development of the bedrock, as asserted by Toman and Dzúrik [14]. The catchment area of the Bebrava is 631 km^2, with the river's length being 47.2 km. The shape factor of the basin has a magnitude of 0.29, and the slope of the Bebrava basin is 10.9‰. The highest point of the basin is 1042 m above sea level, and the lowest is 165 m above sea level at the confluence of the Bebrava and the Nitra River near the village of Praznovce. From a hydrological perspective, the Bebrava can be characterized as a stream with a rain–snow runoff regime [13], which is characteristic of upland–lowland areas.

The water resources we analyze are found in the localities of Slatina nad Bebravou and Slatinka nad Bebravou and are included in the hydrogeological region MP 066 Mesozoic and Paleogene of the southern part of the Strazovske vrchy [15], and they also belong to the pre-Quaternary groundwater body SK200140KF—a body with dominant karst–fissure groundwater in the northern part of the Strazovske vrchy and Lucanska Mala Fatra mountains in the Vah River basin area, while the water source (Vrchoviste) in the Dolne Motesice locality belongs to the pre-Quaternary groundwater body SK2001300P—an intergranular groundwater of the Banovska basin in the Vah River basin area [16]. Based on the results of three geological wells, Bahnová et al. [17] determined the average value of the transmissivity coefficient T, calculated as the geometric mean, to be 1.48×10^{-3} m^2/s and the average value of the filtration coefficient k to be 4.78×10^{-5} m/s.

From a climatological perspective, most of the area is situated within a moderately warm region, with the upper part of the catchment falling within a cold area characterized by an average temperature in July of ≥12 °C and <16 °C [13].

The springs of *Pri mlyne* and *Pri moste* in Slatina nad Bebravou, and *Vrchoviste* in Slatinka nad Bebravou (Table 1) are springs connected to the Ponitrian group water supply system.

Table 1. General information related to springs.

Spring	Municipality	Type of the Spring	Permitted Withdrawal, L/s	Start of Operation
Pri moste	Slatina nad Bebravou	karst	71.9	1976
Pri mlyne	Slatina nad Bebravou	karst	37.0	1976
Vrchoviste	Slatinka nad Bebravou	karst	204.4	1968

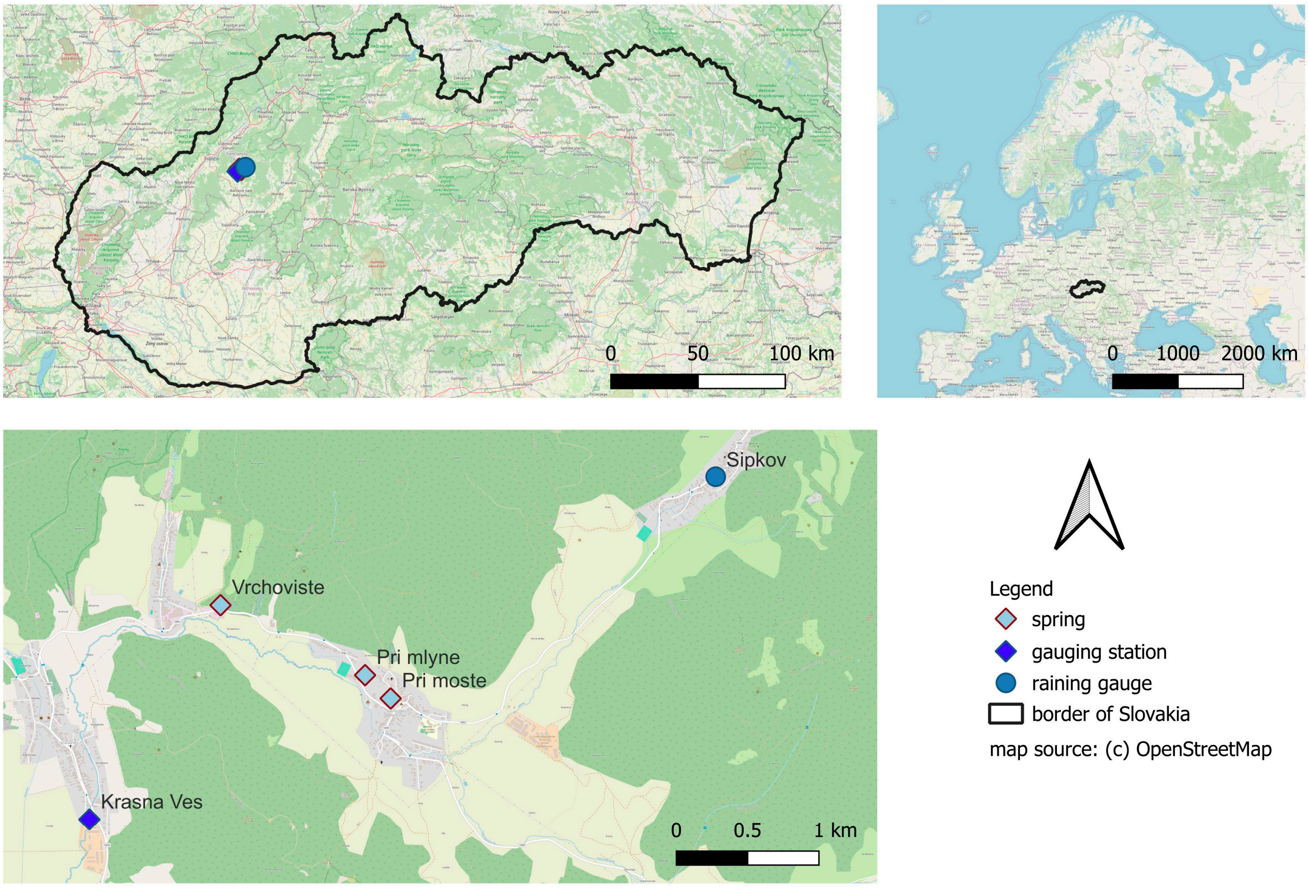


Figure 1. Location of study area within Europe, Slovakia and location of each spring, gauging station and rainfall gauge.

2.2. Data Sources

Data connected to the yield of springs were processed from the database of the Western Slovakian Water Company, Inc., Nitra, Slovakia. The measurements were prepared in 7-day intervals for the period from 1 January 2000 to 31 December 2023. The same database was used for processing monthly water withdrawal from individual springs source, the volumes of we processed monthly. Mean monthly discharges at the Krasna Ves gauging station on the Bebrava River were obtained from the Slovak Hydrometeorological Institute yearbooks for the period 2000–2023.

The rainfall and other climate data were obtained from the E-OBS dataset from the Copernicus Climate Change Service (C3S, https://surfobs.climate.copernicus.eu, accessed on 30 January 2025) and the data providers in the ECA&D project (https://www.ecad.eu, accessed on 30 January 2025) in the form of daily gridded meteorological data for Europe from 1950 to present derived from in situ observations [18]. The station data are provided by 87 participating institutions, and the ECA&D dataset contains over 23,700 meteorological stations, according to its September 2024 status. Metadata of the time series, including the source and information about the meteorological stations, are provided through the ECA&D website. Data for the years 2000–2023 were selected.

2.3. Statistical Analysis

The datasets were analyzed by standard statistical methods and visualized using MS 365 Excel. The descriptive statistics, correlation and regression analysis and histograms were used to compare the two decades. Furthermore, the Mann–Kendall test, Sen's slope [19] and linear trend analysis were also used to perform the trend analysis. The histograms, normal and gamma distributions were created by HEC-SSP 2.3.

3. Results

3.1. Trends in Spring Yields

A consistent downward trend in abundance, accompanied by inter-annual variability, is evident across all three springs (Figure 2). There is variability in the yields of the springs (Appendix A: Table A1), with the absolute lowest values of daily discharge recorded in May 2021 in the spring *Pri moste* and in August 2021 in *Pri mlyne*, with a minimum recorded in December 2020 in the *Vrchoviste* spring. During the study period, the yield at *Pri moste* spring was 45.12% below the permitted water withdrawal. For the *Vrchoviste* spring, this value was almost 62%, while for the *Pri mlyne* spring it was less than 40%. The lowest values of yields were observed in the summer and autumn months (August to October), with maximum values recorded in the early spring months of March and April (Appendix B: Figure A1). The skewness values indicate that in all three springs, lower abundances prevail over higher ones, particularly in the *Vrchoviste* spring. This phenomenon is further substantiated by the kurtosis values, which, for the *Vrchoviste* spring, demonstrate a heightened prevalence of lower values closer to the mean.

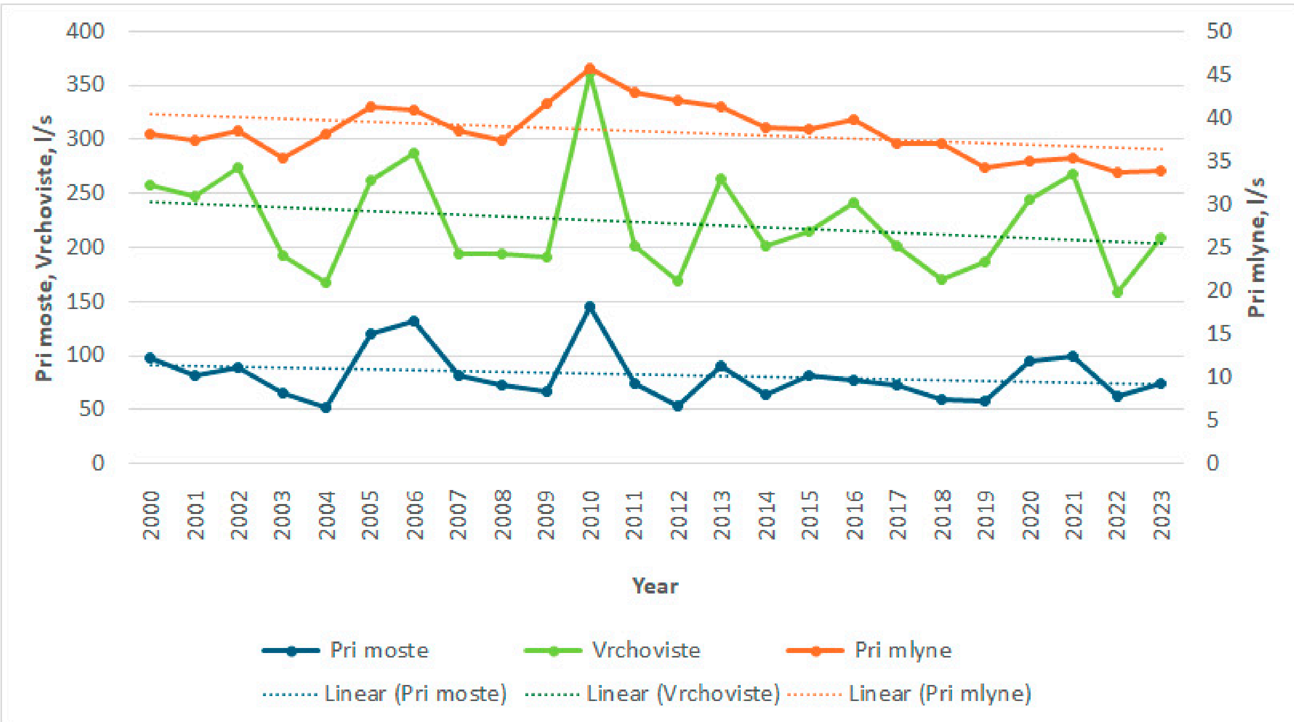
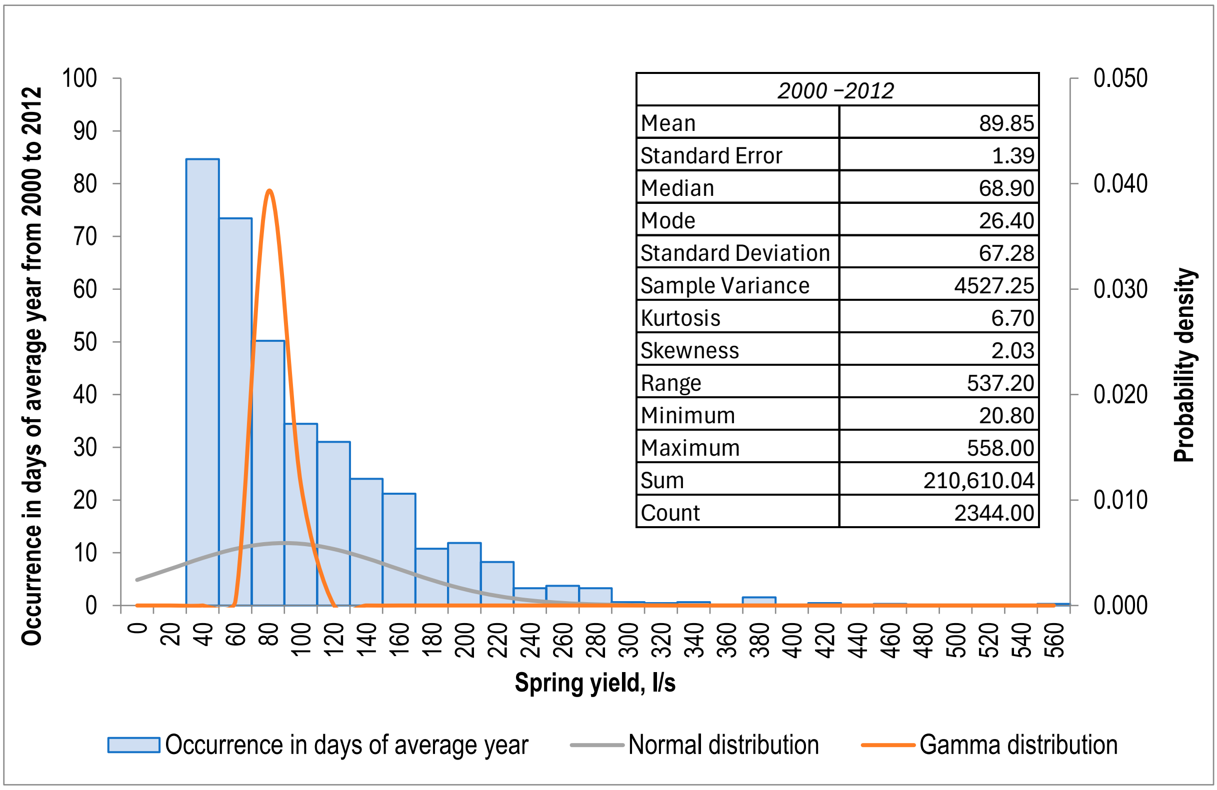


Figure 2. Trends in average annual spring yields in L/s between 2000 and 2023, with a linear overall trend.

The decreasing prevalence of yields is visible also from the results of the Mann–Kendall test for all three springs, with even values of −1.02 (confidence 85%) for *Pri moste* and −0.82 (confidence level 79%) for *Vrchoviste* showing a stable trend. However, spring *Pri mlyne* has a visibly decreasing trend (−2.01, confidence 98%). Also, all three springs have a negative value of Sen's slope: −0.695 (*Pri moste*), −0.198 (*Pri mlyne*), and −1.072 (*Vrchoviste*).

A consistent downward trend in abundance is visible also from the comparison of decades. While during the years 2000–2012, 52.63% of yields were below the available withdrawal, in the decade 2013–2023, this value was 57.5% for the *Pri moste* spring. Similarly, the springs *Pri mlyne* and *Vrchoviste* had increased values in the second decade (2000–2012: 17.86% and 50.79%; 2013–2023: 60.57% and 61.43%, respectively).

The comparison of the frequency distribution curves of the spring yields for the *Pri moste* site in the periods 2000–2012 (Figure 3) and 2013–2023 (Figure 4) shows a decrease in the average yield value from 89.85 to 75.96 L/s, while the mode value increased from 26.40 to 45.70. This was also reflected in the decreased standard deviation (from 67.28 to 45.66). The frequency distribution of yield values for the period 2013–2023 tended to better follow the normal distribution (decreasing of kurtosis from 6.70 to 4.14).



2000 −2012	
Mean	89.85
Standard Error	1.39
Median	68.90
Mode	26.40
Standard Deviation	67.28
Sample Variance	4527.25
Kurtosis	6.70
Skewness	2.03
Range	537.20
Minimum	20.80
Maximum	558.00
Sum	210,610.04
Count	2344.00

Figure 3. Histogram and frequency distribution curves for the *Pri moste* spring yields, 2000–2012.

The comparison of the frequency distribution curves of the spring yields for the *Pri mlyne* site in the periods 2000–2012 (Figure 5) and 2013–2023 (Figure 6) shows a slight decrease in the average yield value from 40.76 to 36.82 L/s. Also, the mode value decreased from 37.90 to 33.90, with the standard deviation decreasing from 4.45 to 3.36. The frequency distribution of yield values for the period 2013–2023 is very close to following the normal distribution (with a decrease in kurtosis from 6.19 to 2.92).

The comparison of the frequency distribution curves of the spring yields for the *Vrchoviste* site in the periods 2000–2012 (Figure 7) and 2013–2023 (Figure 8) shows a decrease in the average yield value from 229.67 to 216.18 L/s, while the mode value increased from 114.00 to 198.00. This was also reflected in the decreased standard deviation (from 177.62 to 139.37). The frequency distribution of yield values for the period 2013–2023 tended to better follow the normal distribution (with a decrease in kurtosis from 3.67 to 2.83).

3.2. Trends in Water Withdrawals from Springs

The data indicate a general upward trend in water withdrawals at all three springs, with the annual withdrawals since 2021 reaching the highest levels observed over the entire period. In contrast, from 2007 to 2019, total water withdrawals were at their lowest, with a local increase from 2013 to 2017 (see Figure 9). The highest monthly flow withdrawals were observed in May and June at all springs, and the lowest in October, apart from *Pri moste* spring, where the lowest total withdrawals were recorded in September (Appendix B: Figure A2). The increase in extractions from the springs can be attributed to infrastructure development and the connection of new customers to the network, as well as water losses within the network.

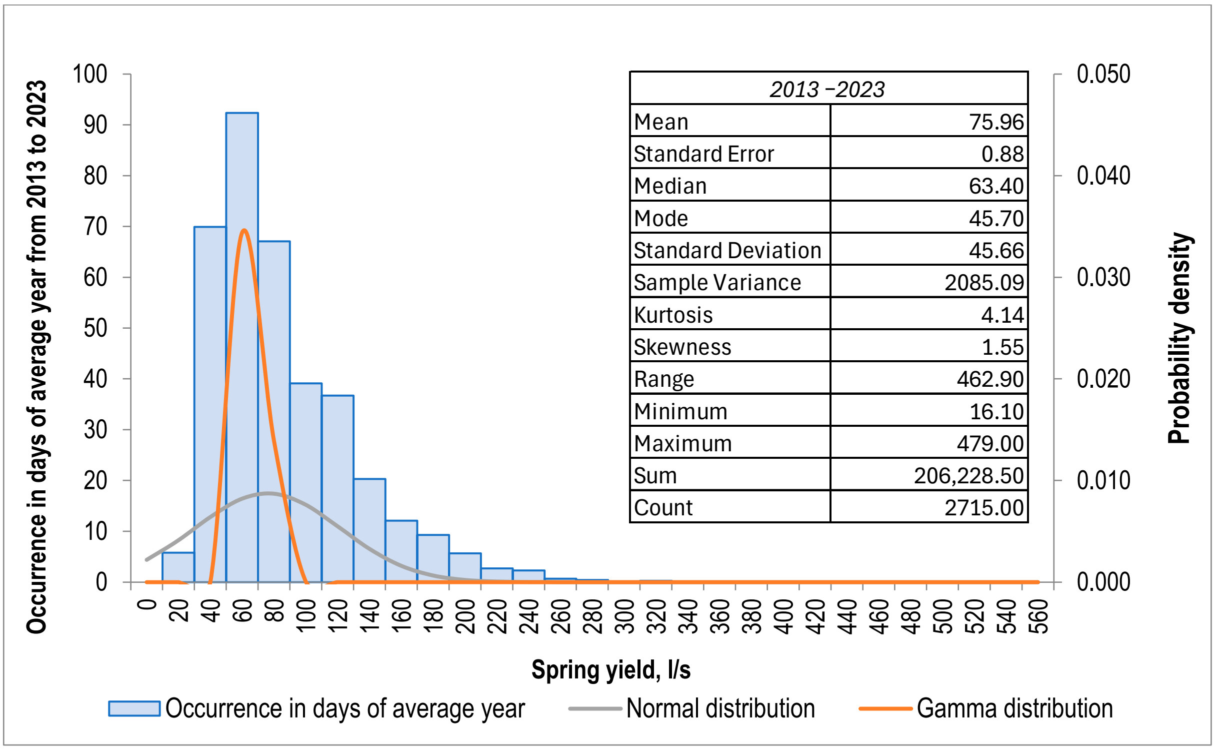


Figure 4. Histogram and frequency distribution curves for the *Pri moste* spring yields, 2013–2023.

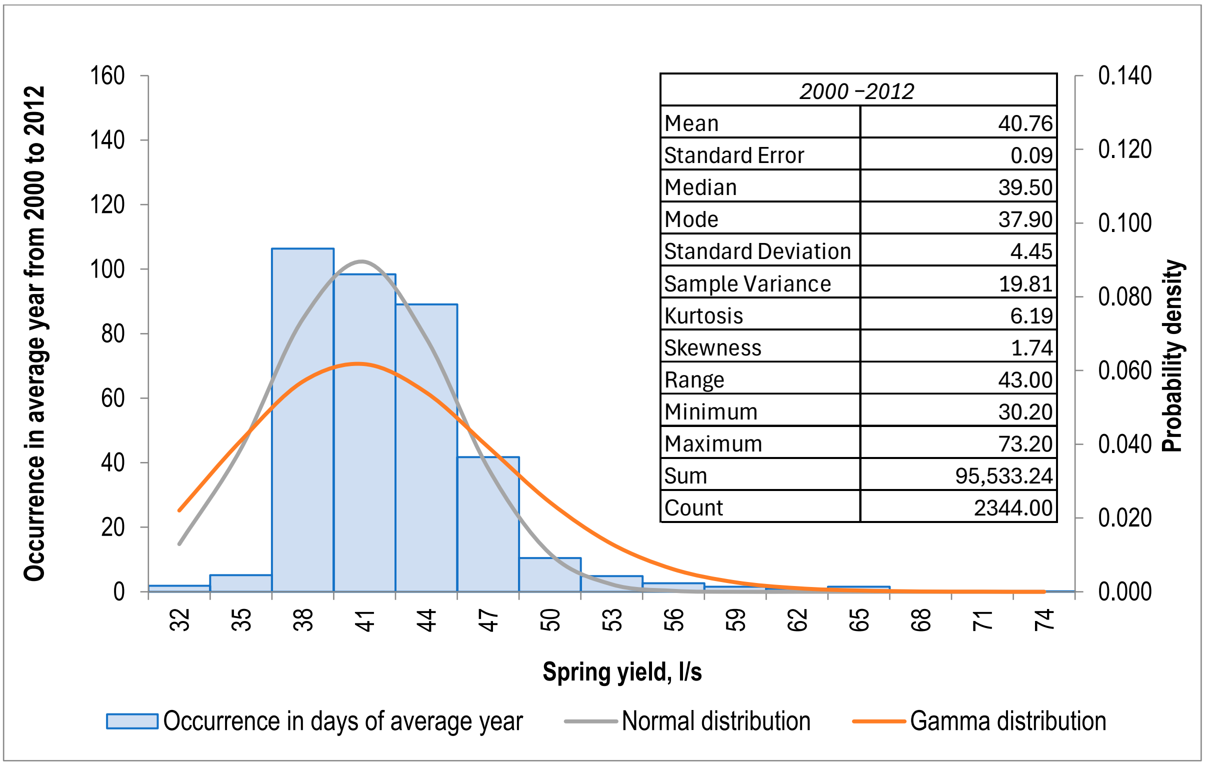


Figure 5. Histogram and frequency distribution curves for the *Pri mlyne* spring yields, 2000–2012.

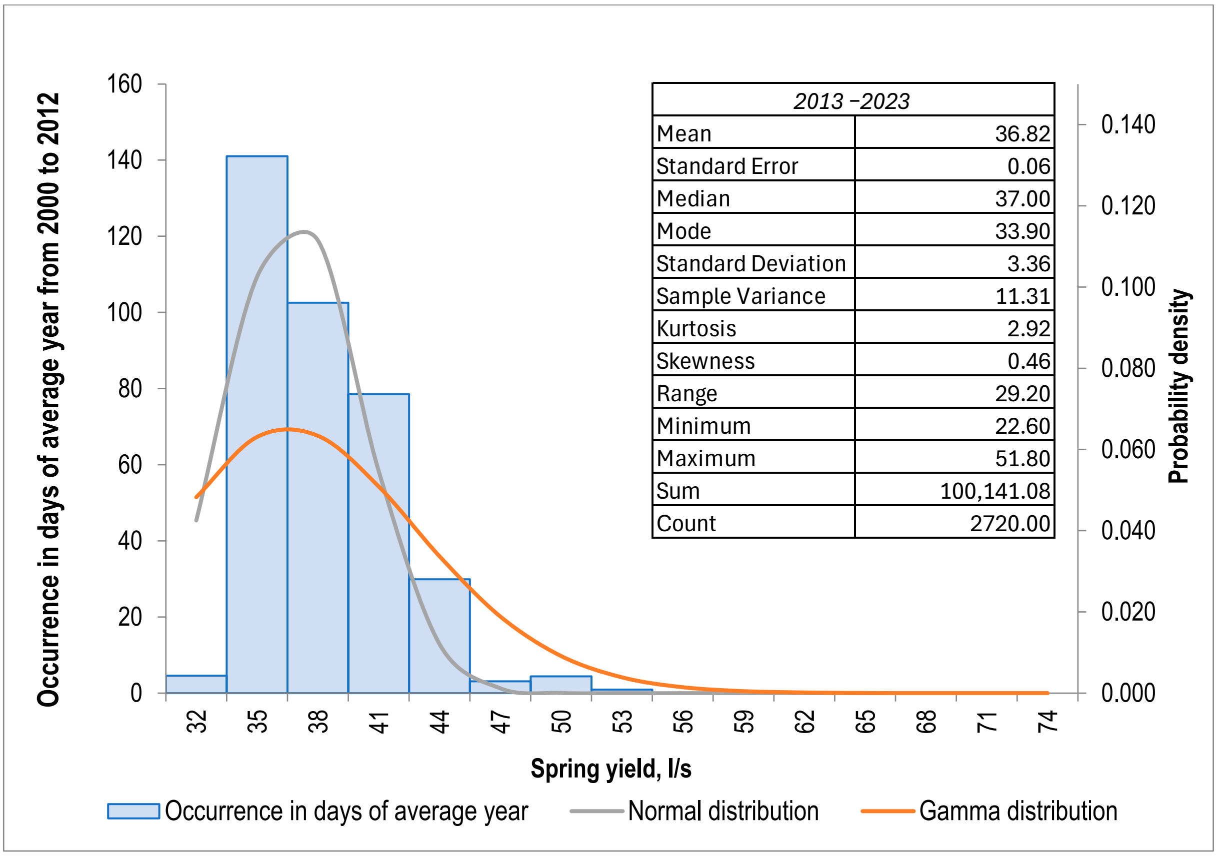


Figure 6. Histogram and frequency distribution curves for the *Pri mlyne* spring yields, 2013–2023.

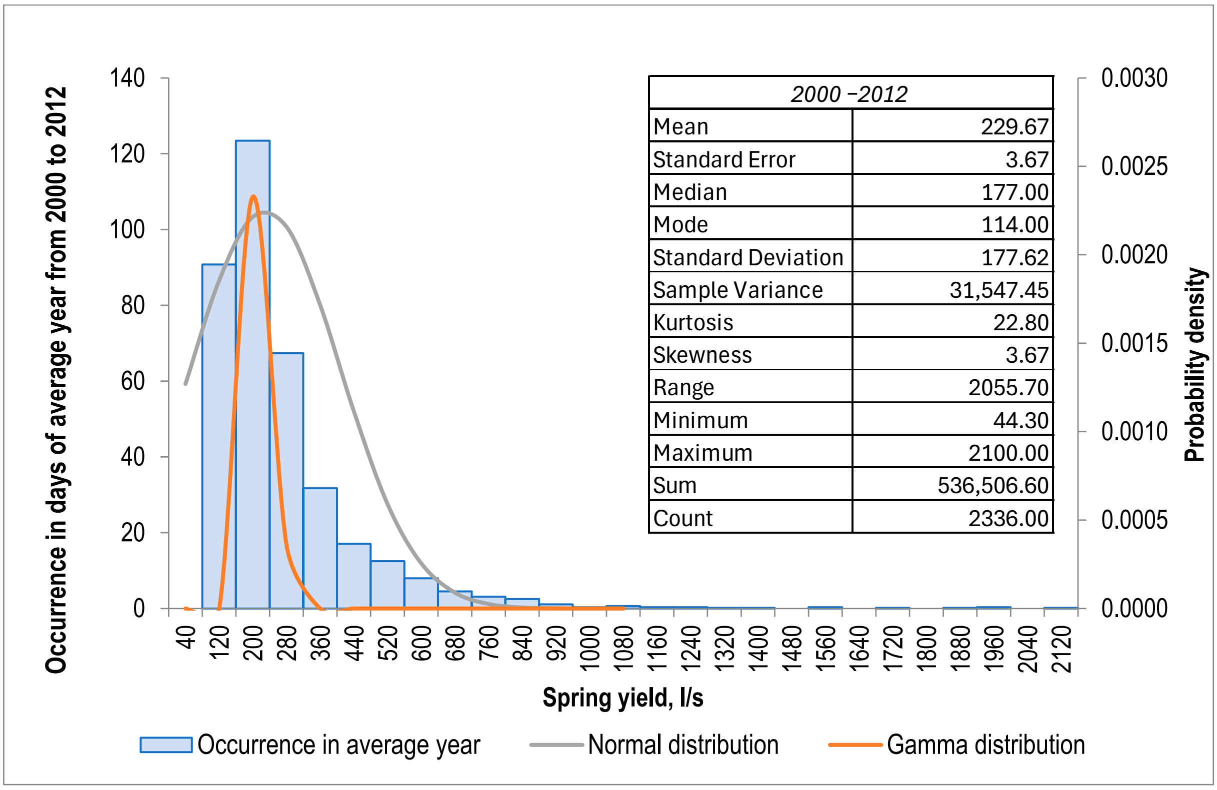


Figure 7. Histogram and frequency distribution curves for the *Vrchoviste* spring yields, 2000–2012.

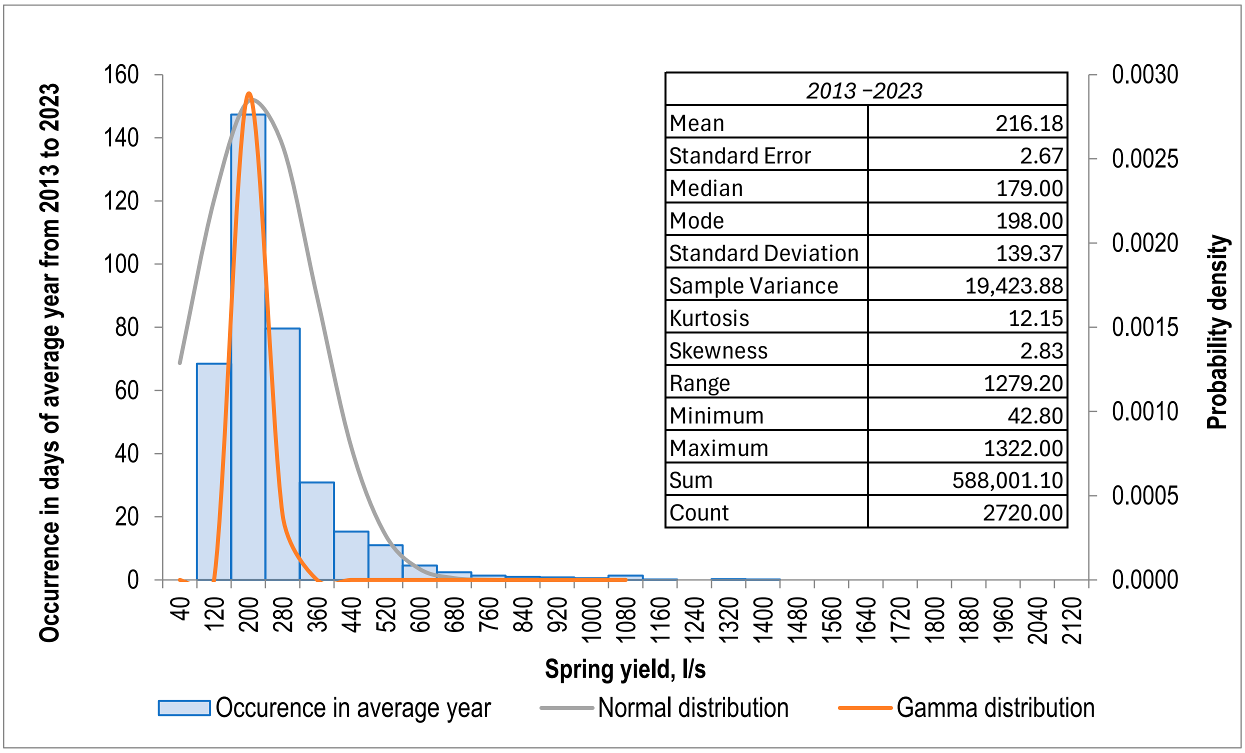


Figure 8. Histogram and frequency distribution curves for the *Vrchoviste* spring yields, 2013–2023.

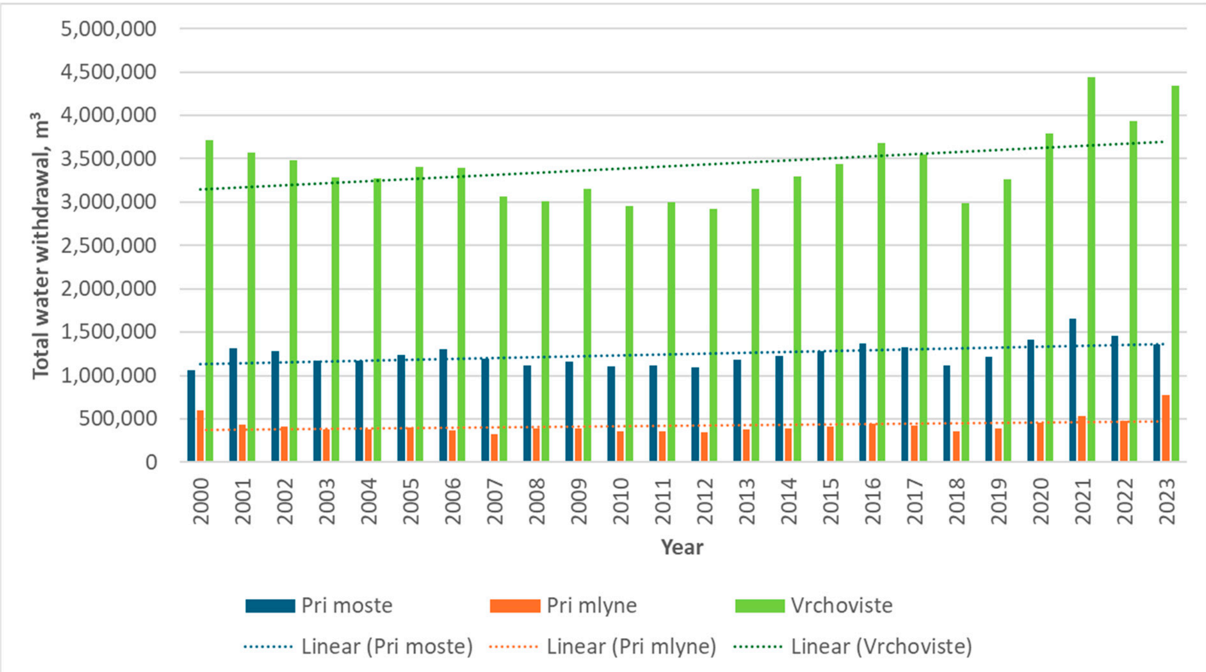


Figure 9. Sum of annual water withdrawals from individual springs in m^3 in 2000–2023, with the overall linear trend.

The percentage distribution of water withdrawal in each month ranges from 6.84 to 9.37% for the *Pri Moste* spring, from 7.13 to 9.24% for the *Pri mlyne* spring and from 6.82 to 9.33% for the *Vrchoviste* spring. The distribution of withdrawal over the year is comparable for all three springs, showing a strong linear dependence. The increased water withdrawal observed during the spring and summer months is attributable to the irrigation of gardens and recreational activities, such as filling swimming pools. The water withdrawals from the *Pri mlyne* spring are predominantly lower than average, while the *Pri moste* spring is characterized by higher than average water withdrawal. At the *Pri mlyne* spring, the values are more concentrated around the mean; however, for the other springs, the distribution of values is more evenly distributed to either side of the mean (see Appendix A: Table A2).

Sen's slope of all springs has an increasing trend (8921 for *Pri moste*, 3174 for *Pri mlyne* and 15,577 for *Vrchoviste*). The Mann–Kendall test shows an increasing trend in water withdrawal from springs *Pri moste* (2.11, confidence 98%) and *Pri mlyne* (1.41, confidence 92%), while for the spring *Vrchoviste*, the trend was not significant, and more data are needed to distinguish a trend.

3.3. Trends in Water Flow in the Bebrava River

The mean annual flows in the Bebrava river range from 0.21 to 0.75 m^3/s (see Figure 10). The highest mean flows were recorded in March (0.95 m^3/s) and the lowest in September (0.21 m^3/s), which corresponds to the rain–snow runoff regime (see Appendix B: Figure A3). The mean monthly flows tend to increase in the autumn and winter months (October–December and February), while they reach increasingly lower values in the spring and summer months. Despite the variability of flows from year to year, a decreasing trend in annual average flows can be observed. In the second half of the period under consideration, the variability and dispersion of the annual mean flows were lower than in the first half. While the maximum annual flows demonstrate a downward trend, the minimum annual flows exhibit an upward trend, thereby leading to a flattening of the extremes.

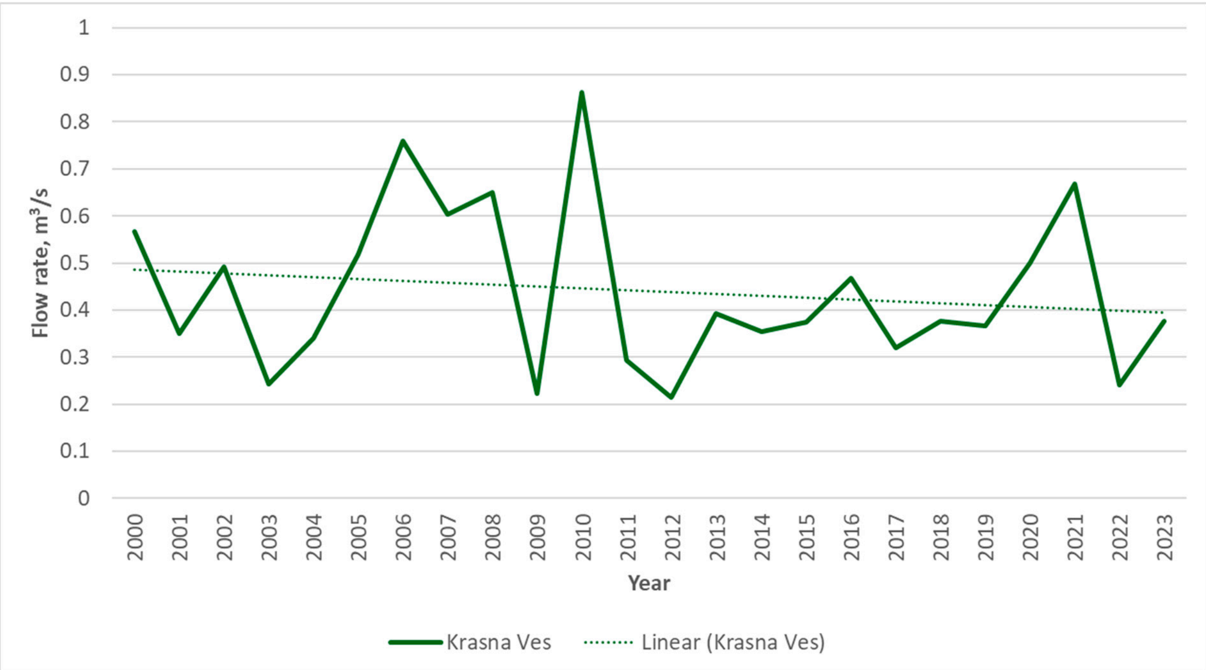


Figure 10. Mean annual flows in the Bebrava river at the *Krasna Ves* water gauging station in m^3/s in 2002–2023.

Even though the confidence level of the Mann–Kendall test is low (about 61%) and shows a stable trend, the negative value −0.27 indicates a somewhat more negative trend. Also, the negative Sen's slope (−0.002) indicates a decreasing trend.

3.4. Precipitation Trends at the Sipkov Station

The long-term precipitation trend is balanced, with the lowest recorded rainfall occurring in 2003 (547.16 mm), followed by 2011 and 2022 (634.44 and 639.6 mm, respectively). On the other hand, the highest recorded rainfall totals were observed in 2010 (1053.41 mm), 2020 (960.51 mm), and 2023 (960.15 mm) (Figure 11). The months of April and July experienced the lowest and highest rainfall, respectively, with the late spring and summer months demonstrating the highest monthly rainfall totals, and the autumn to April period exhibiting a decreasing trend (Appendix B: Figure A4). A decline in precipitation totals is evident in the months of March, June, and July, suggesting a decrease in precipitation in these months. In contrast, January, May, August to October and December have higher monthly totals. The remaining months show more or less balanced totals. Significant decreases in maximum rainfall totals are evident in July, while May and September show increases, with the two highest totals in May being the highest in the last five years. The period of 26 October 2011 to 2 December 2011 (38 days) is noteworthy for its uninterrupted rainless status, while the maximum daily precipitation recorded was 52.13 mm on 1 June 2021. The values of skewness (3.25) and kurtosis (15.5) demonstrate the predominance of low rainfall values, a phenomenon that is further exacerbated by the number of rainless days.

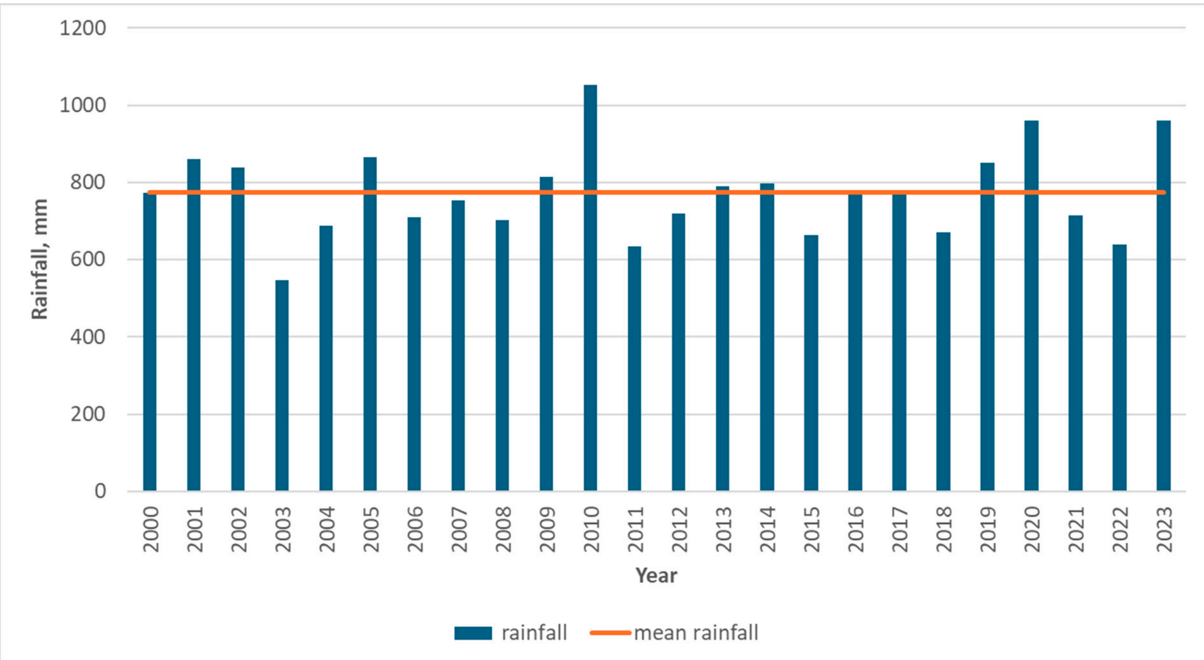


Figure 11. Annual precipitation at the rain gauge station Sipkov in mm, in the years 2000–2023.

4. Discussion

A comparison of the trend in the average monthly yield with the sum of the monthly withdrawals from the springs in each year does not demonstrate a linear dependence. Similarly, the dependence between rainfall, flow and yield is low to moderate. However, a comparison of average monthly discharge and average monthly streamflow values in each year demonstrates a strong linear dependence at the *Pri moste* and *Vrchoviste* springs (R = 0.82 and R^2 = 0.7584, and R = 0.77 and R^2 = 0.7466, respectively). The *Pri mlyne* spring exhibited a comparatively negligible relationship (R = 0.26 and R^2 = 0.2131) with flows (see Table 2, Appendix B: Figure A3).

Table 2. Correlation coefficients based on annual data (mean discharge, mean flow, rainfall).

	Pri Moste	*Pri Mlyne*	*Vrchoviste*	*Krasna Ves*	**Rainfall**
Pri moste	1				
Pri mlyne	0.45	1			
Vrchoviste	0.92	0.45	1		
Krasna Ves	0.82	0.26	0.77	1	
Rainfall	0.47	0.16	0.57	0.41	1

The distribution of annual data as a percentage over the course of the year reveals a clear relationship between spring discharge and streamflow's (R = 0.93–0.95; Table 3, Figure 12). Although the *Pri mlyne* spring has more or less equilibrated throughout the year, a slight increase and decrease can be observed in the same months as for the other springs and water flow. The distribution of rainfall during the year exhibits a reverse pattern to that of discharge and flow, with the increase in discharge and flow commencing at the minimum rainfall and reaching its minimum in the months with the highest rainfall. This is also supported by the findings of Chang et al. [20] that the shape of the recession curve changed under different rainfall conditions.

Table 3. Correlation coefficients based on monthly data (average discharge, average flow, rainfall).

	Pri Moste	*Pri Mlyne*	*Vrchoviste*	*Krasna Ves*	**Rainfall**
Pri moste	1				
Pri mlyne	0.97	1			
Vrchoviste	0.99	0.98	1		
Krasna Ves	0.95	0.93	0.95	1	
Rainfall	−0.40	−0.34	−0.40	−0.59	1

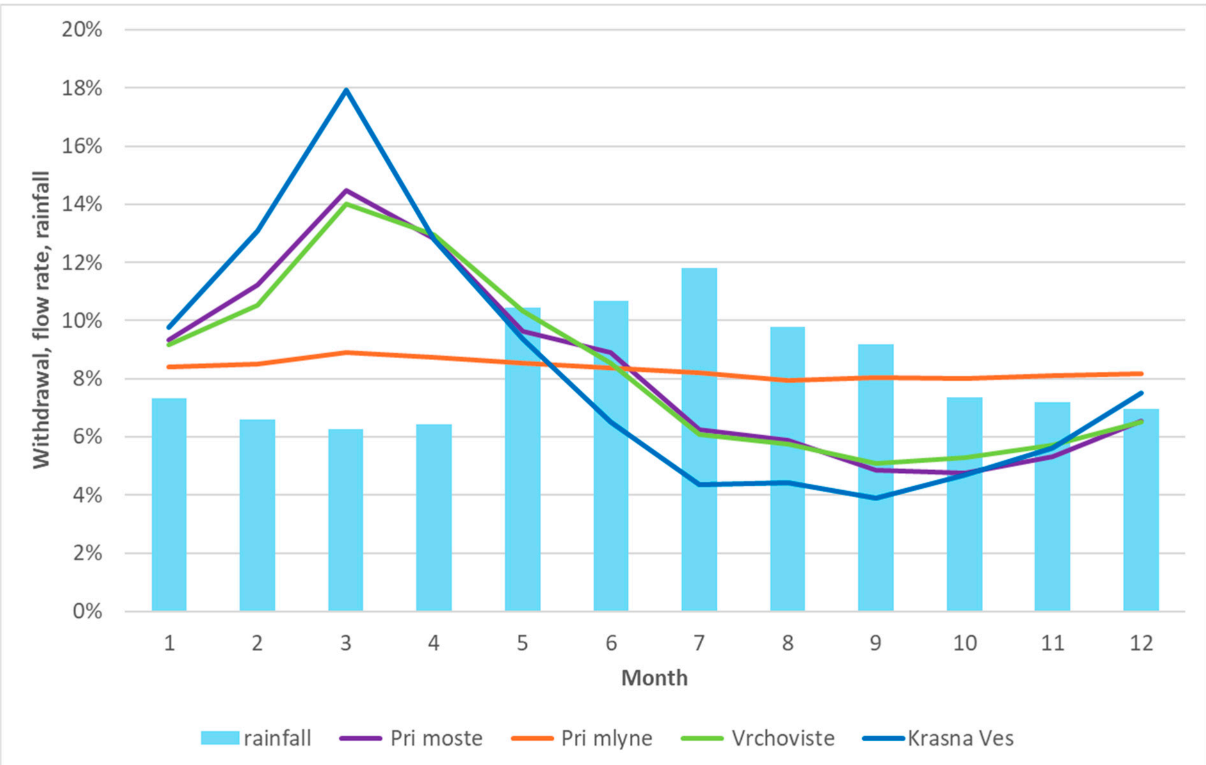


Figure 12. Percentage of average monthly discharge, average monthly flow and average monthly rainfall for the years 2000–2023.

All the evaluated springs showed a tendency to have decreased average yield values and variability when comparing the two reference periods (2000–2012 and 2013–2023). This is in accordance with the findings of Ferencz et al. [21], who analyzed the changes in the yields of springs in a research area consisting of two physic-geographical units, the Lublin Upland and Roztocze Region in Poland. Frequency distributions for the period 2013–2023 tended to more closely follow a normal distribution.

Our results did not confirm the findings of Worthington and Foley [22] that annual groundwater levels, and consequently the spring discharge, in carbonate aquifers show a strong correlation with precipitation. It is a well-established fact that a significant proportion of limestone rock springs exhibit considerable variations in yield, with rapid responses to alterations in hydrometeorological parameters being a common feature. It is evident from the ratio of minimum-to-maximum discharge that these springs are predominantly unstable to quite unstable [23]. Of course, there will be differences year by year; however, the trend will continue to decrease.

Our findings of close correlations between the discharge in the Bebrava river and particular springs (R^2 are in the interval from 0.93 to 0.95) confirm the findings of Ferencz et al. [21] that riverbank and slope springs are the most sensitive to changes in supply. In the alluvial floodplains of rivers near surface streams, and in the mountains of lower altitudes, as is the case of the selected springs, the groundwater level regime reflects fluctuations in water levels in streams with shorter or longer lags [24]. Based on the models, diminished levels of natural water resources are to be anticipated in the majority of European basins when considering the most unfavorable scenario and the long-term predictions of mean annual runoff. These reductions will inevitably lead to a decrease in water availability [25]. Therefore, we also expect decreases in groundwater levels.

Of the total number of springs under the management of the Western Slovakian Water Company, Inc. that were evaluated in the years 2000–2023, up to 53% showed a balanced stable yield without significant change, 4% showed yield increases in the long term, 27% showed a gradually decreasing yield, 14% a significantly decreasing deviation in the long term, and 2% showed an extreme decrease in the years, with almost zero deviation [26]. Generally, springs localized in karst and fractured limestone rocks demonstrate increased yield [4].

Providing a complete picture of groundwater response to a changing climate is even more challenging given that climate change impacts are often influenced by human and indirect factors such as land use change and groundwater overexploitation [27]. A second-level protection zone was delineated for all springs in the area around Slatina nad Bebravou in 1989. Therefore, strict rules apply for the river basin management in the locality. Especially, land use changes are regulated by legislation and relevant local decrees. Therefore, during the selected period of study, no land use changes were made, and none had been made for several decades before. The basin is mostly covered by deciduous and coniferous forests and meadows. The urban area is located only in the valley surrounding the Bebrava river. Therefore, the impact of land use on the spring yield variability in this area is low.

Decades 2010 and 2020 were warmer by 2 °C than the entire 20th century in Slovakia. Furthermore, it is expected that the country will be affected by severe drought episodes almost every year. There are no exceptions to the precipitation totals, but the rain will fall in the warmer and drier seasons. In particular, the rainfall in the warm period of the year occurs mainly in the form of showers and thundery downpours [28]. These do not gradually infiltrate and percolate into the groundwater but instead result in rapid direct surface runoff. Therefore, we can see the disproportion and low correlation between spring yields, river flow and precipitation in the mean monthly (Figure 12) and yearly steps (Appendix B: Figure A5).

The trend in withdrawals is highly affected by the connection of new residents, water losses in the water supply system and the price. Currently, due to the decrease in the yield of several other springs in the operation of the Western Slovakian Water Company, Inc., there is higher demand and pressure on the water withdrawal from the springs *Pri moste*, *Pri mlyne* and *Vrchoviste*. Since the springs have been operated for almost 50 years (*Vrchoviste* spring for about 57 years), the water supply system is nearing the end of its service life. In 2023, the total water losses in the water supply system were 26.63% of total water production in Slovakia [29]. However, previous years the water losses in the water supply system in the selected systems were about 32.6% [30], so almost third of the withdrawals were "lost" in the soil without being delivered to the people. This is one of the reasons for the price increase in the last years. Generally, these price increases have led to decreases in water use and withdrawal (Figure 13). The water demand and withdrawal are not affected by the water yield from the springs. Only during the dry years are the water withdraws from the springs lower (Appendix B: Figure A6). In such years, people are informed about the lower water resource capacities and are asked to decrease their water consumption.

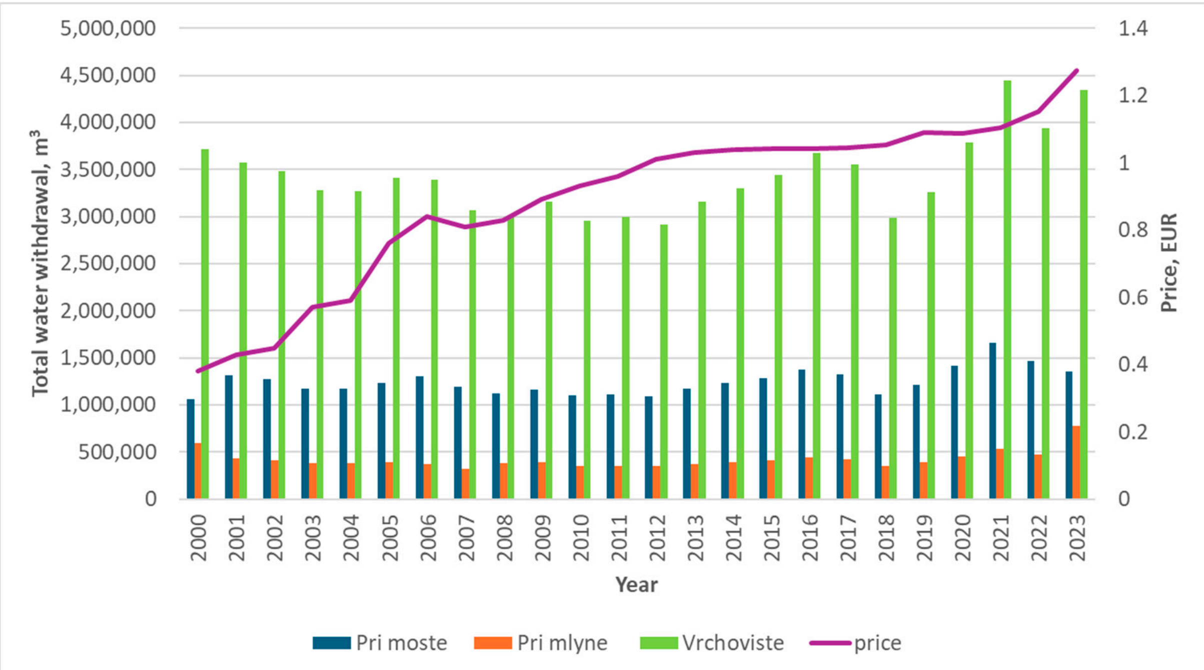


Figure 13. Trends in yearly water withdrawal from springs in m^3 and water price in Slovakia in EUR.

A decreasing trend in spring yields has also been confirmed in the Czech Republic. There it was also concluded that there is no direct connection between groundwater withdrawal and spring yield [31]. The current capacity of the springs is sufficient to meet the present needs of water users. Nevertheless, the downward trend in abundance, the increasing trend in population connectivity, and the current poor state of infrastructure point to an early tipping point, i.e., equivalence of spring abundance and water demands. Especially the summer months can be more affected by the drought, which was also concluded by several other authors [4,20,26,31]. Of course, the variability in the spring yield during the decades is high, but in general, decreasing trends are more common than increasing trends [31,32]. Therefore, increased awareness in the population and improvements in the technical water supply system conditions must be the main focus for sustainable water use in the future.

5. Conclusions

In the forthcoming years, a decline in the yield and quantity of springs is to be anticipated, which will result in reductions in water availability for the population. This phenomenon will be particularly pronounced during the summer and autumn months, resulting in significant alterations to the demand patterns of water users.

The springs studied here exhibit a high correlation with the development of the flow in the river, indicating that they are valley springs more influenced by the flow in the watercourse than by rainfall events in the catchment. All three springs are thus dependent on the flow regime of the Bebrava River which also tends to dry in the summer and autumn months. Considering the strict rules related to protected areas for land use in the spring's basins, the only human impact on the spring's water availability is water withdrawal.

Our analysis of the current status and future security of water resources has identified a need to improve the protection, monitoring and, above all, efficiency of water use. This is to ensure sufficient and clean drinking water for present and future generations. It is also important to take measures to protect water resources from pollution and the impacts of climate change, and to increase investment in infrastructure to ensure sufficient capacity with minimal water losses in the distribution network. Effective communication with the public and collaboration with neighboring communities are recognized as pivotal to the successful implementation of these measures.

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Conflicts of Interest: Author Peter Lukac was employed by Western Slovakian Water Company, Inc. Author Andrej Valek was employed by Slovak Water Management Enterprise. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Selected statistics of spring yields in L/s for the period 2000–2023.

Statistics	*Pri Moste*	*Pri Mlyne*	*Vrchoviste*
Mean	82.40	38.64	221.58
Standard Error	0.80	0.06	2.21
Mode	45.7	37.9	198
Standard Deviation	57.13	4.37	156.85
Sample Variance	3263.95	19.11	24,600.76
Kurtosis	7.90	5.19	21.75
Skewness	2.10	1.27	3.50
Range	541.9	50.6	2057.2
Minimum	16.1	22.6	42.8
Maximum	558	73.2	2100

Table A2. Selected statistics of water withdrawal in m^3 for the period 2000–2023.

Statistics	*Pri Moste*	*Pri Mlyne*	*Vrchoviste*
Mean	103,927.84	35,246.78	285,010.26
Standard Error	1280.04	629.29	3445.36
Median	103,512	33,597	283,613
Standard Deviation	21,722.97	10,679.44	58,469.74
Sample Variance	471,887,509.4	1.14×10^8	3,418,710,896
Kurtosis	0.75	4.07	0.18
Skewness	−0.20	1.73	0.31
Range	142,048	62,615	300,458
Minimum	19,544	17,602	147,420
Maximum	161,592	80,217	447,878

Appendix B

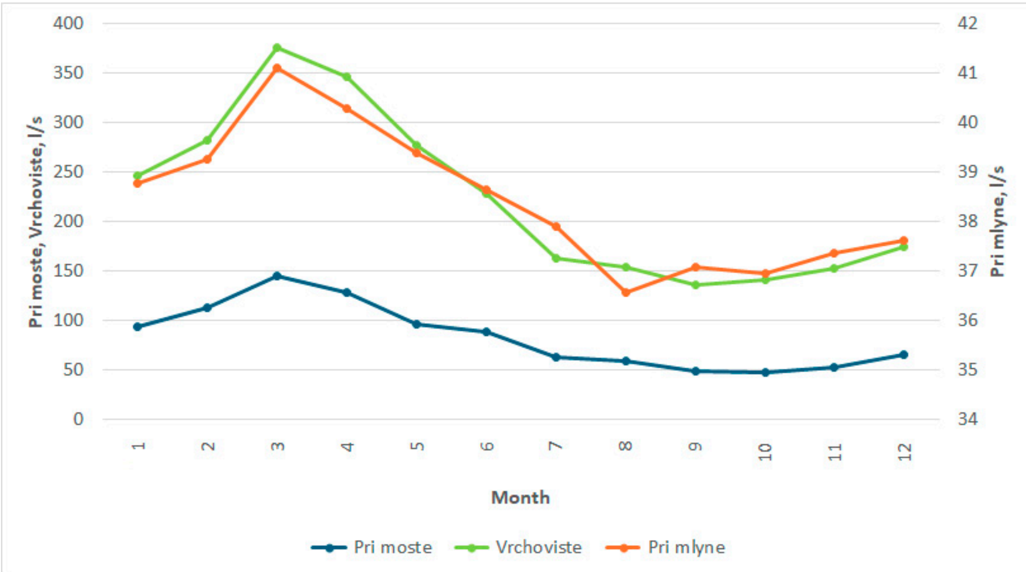

Figure A1. Trends in average monthly spring yields in L/s for the period 2000–2023.

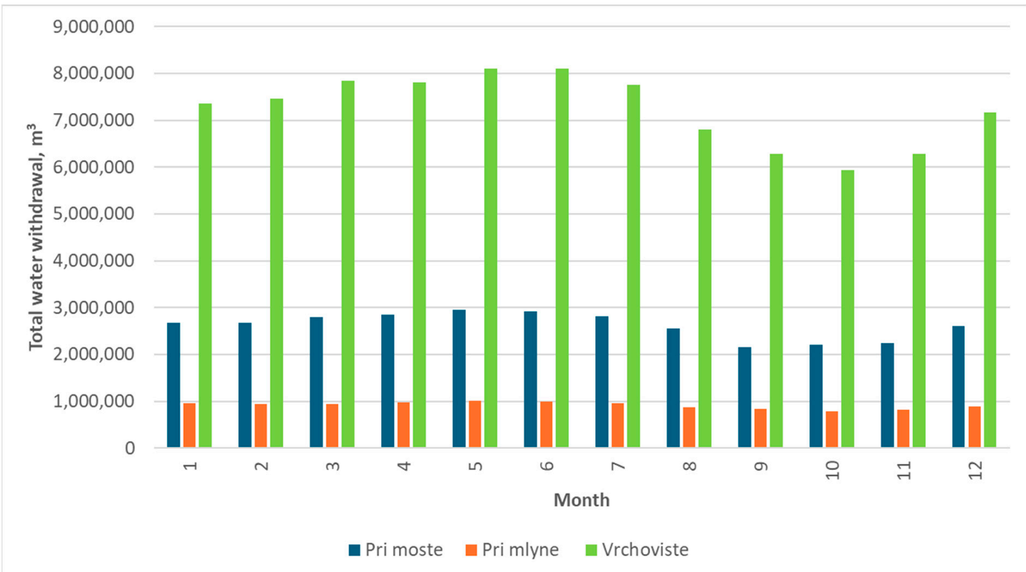

Figure A2. Sum of monthly water withdrawals from individual springs in m^3 in 2000–2023.

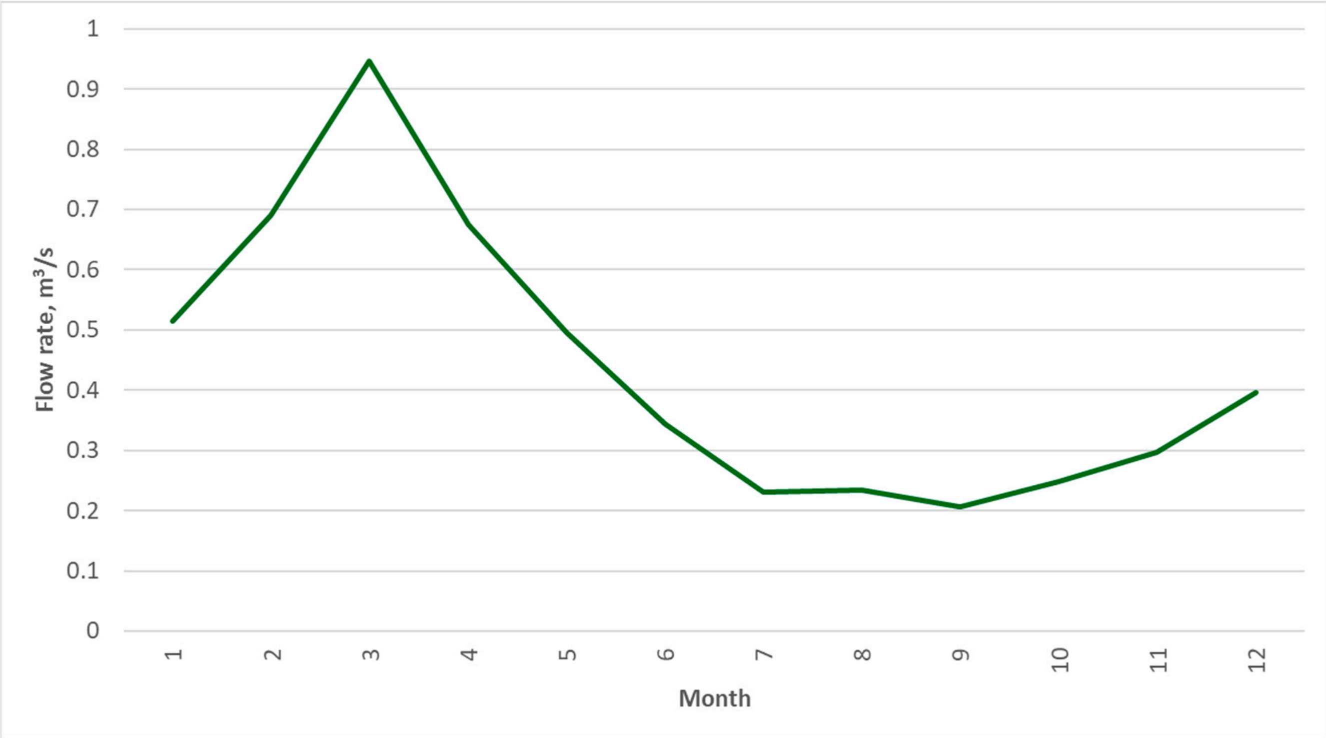

Figure A3. Mean monthly flows in the Bebrava river at the Krasna Ves water gauging station in m^3/s in 2002–2023.

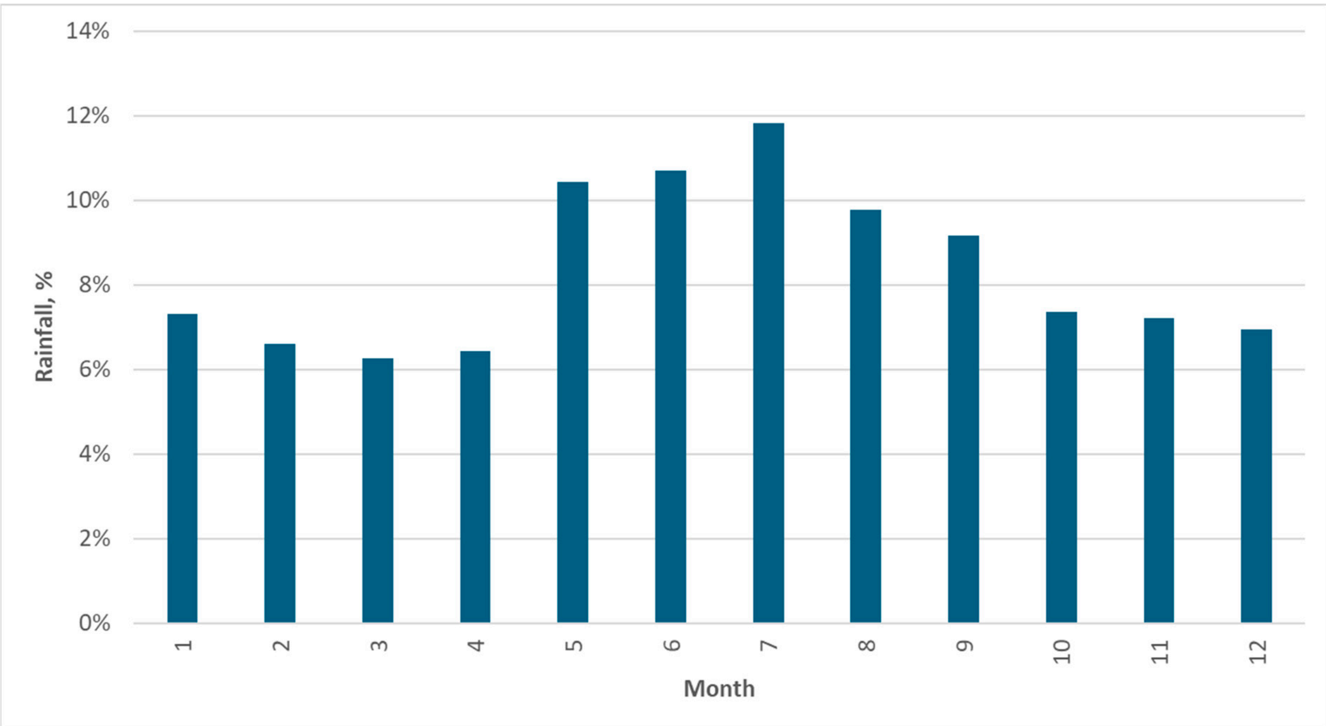

Figure A4. Percentage of monthly precipitation during the year at the Sipkov rain gauge station in 2000–2023.

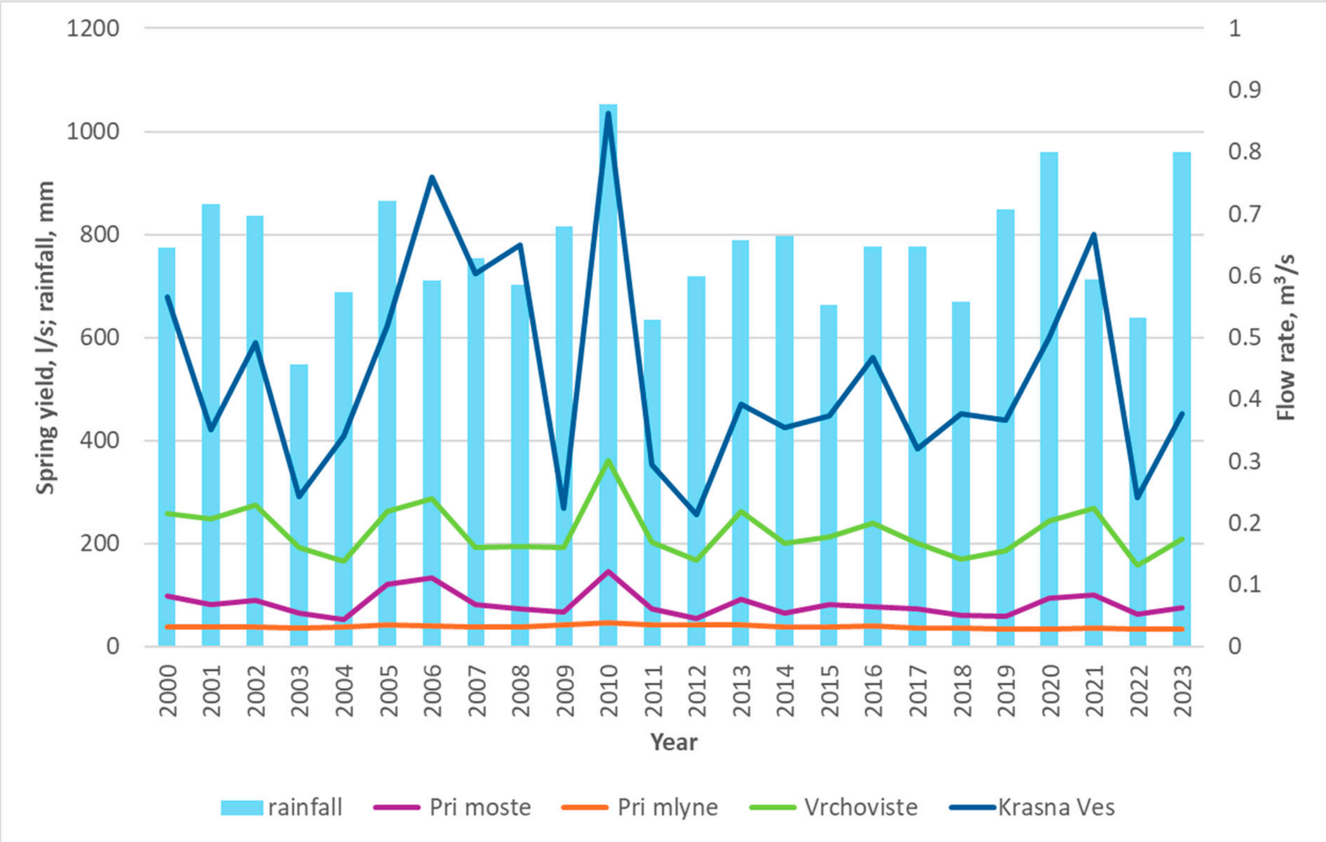

Figure A5. Yearly average spring yield in L/s, yearly rainfall in mm and yearly average flow rate in m^3/s for the years 2000–2023.

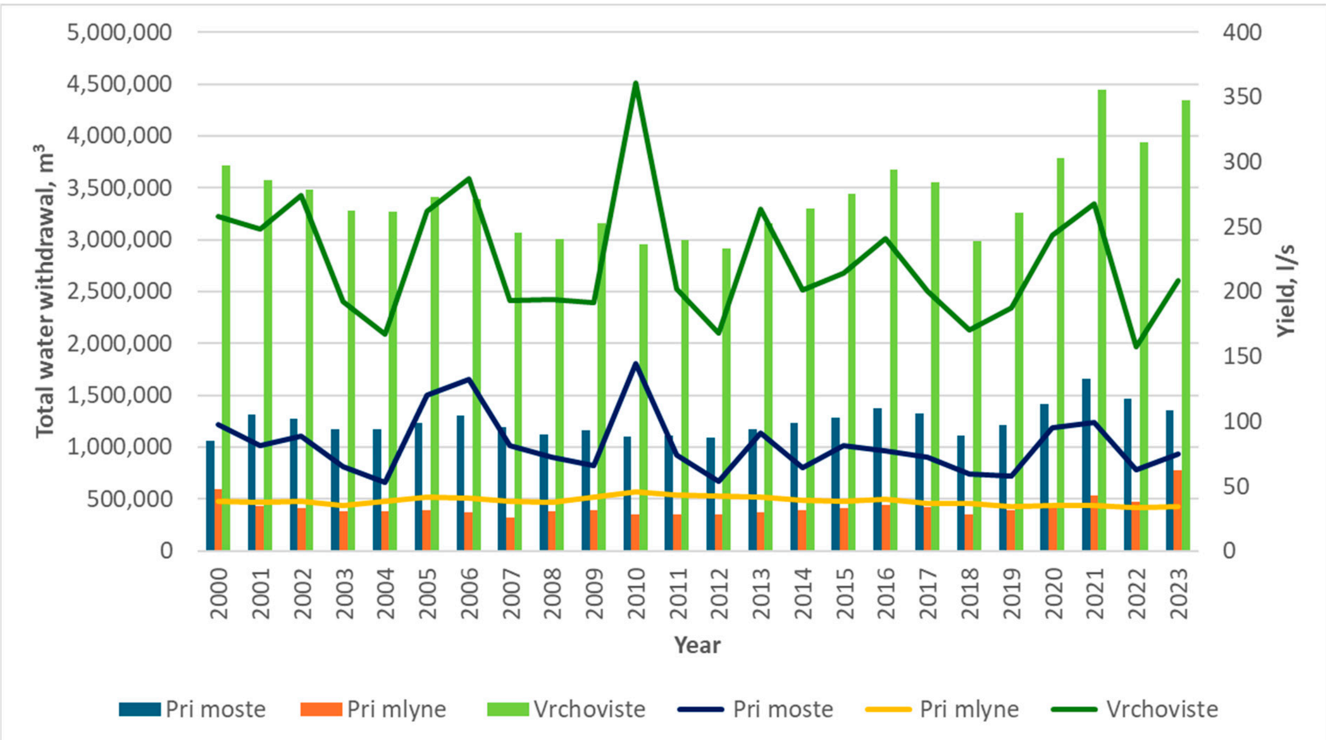

Figure A6. Yearly average spring yield in L/s and yearly water withdrawals from individual springs in m^3 for the years 2000–2023.

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