

## Article

# Contrasting Hydrodynamic Behavior and Climate Sensitivity of Two Karst Springs in the Aggtelek Karst (NE Hungary): Evidence for System-Dependent Climate Responses

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## Abstract

Karst spring discharge is highly sensitive to climatic variability, but responses may differ markedly even within the same karst region. We compared long-term discharge dynamics and potential future changes of the Nagy-Tohonya and Jósza springs in the Aggtelek Karst (NE Hungary) using statistical analysis, flow duration curves, recession coefficients, periodicity analysis, and hydrological modelling driven by climate projections. The two springs exhibit contrasting hydrological behavior: Nagy-Tohonya shows high discharge variability and rapid responses to recharge, whereas Jósza exhibits a more buffered discharge regime with lower relative variability and more sustained low flows. Future simulations project decreasing mean discharge for both springs during 2022–2059, followed by contrasting late-century responses. Nagy-Tohonya remains highly variable but shows comparatively limited changes in its overall discharge distribution, whereas Jósza exhibits a widening discharge range, with increasing high flows and declining low flows. Model evaluation indicates that simulated discharge variability is generally damped, requiring caution when interpreting projected extremes. These results demonstrate that climate change impacts cannot be generalized across geographically close karst systems and emphasize the need for system-specific assessment, climate adaptation, and water management strategies addressing both future water availability and hydrological extremes.

**Keywords:** karst springs; discharge variability; hydrological modelling; climate projections; climate change; system-dependent response; groundwater management



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## 1. Introduction

Climate change represents one of the most significant environmental challenges of the 21st century and exerts substantial impacts on hydrological processes and water resources worldwide [1–3]. Rising air temperatures, changes in precipitation regimes, and the increasing frequency of extreme weather events influence both surface and groundwater systems

(e.g., [4] and references therein). These processes are particularly relevant in Central and Eastern Europe, where recent decades have been characterized by pronounced warming trends and increasing climatic variability (e.g., [5–8]).

In Hungary, a clear warming trend has been documented over the past century, with an acceleration since the 1980s [9]. While precipitation exhibits considerable temporal and spatial variability, several studies indicate a redistribution within the year, including more frequent summer droughts and increased interannual variability [5,10,11]. At the same time, extreme precipitation events have become more frequent across Europe, often occurring as short-duration, high-intensity storms that can trigger rapid hydrological responses. These changes are expected to affect not only surface water systems but also groundwater recharge and discharge dynamics (e.g., [12,13]), which is of particular importance in regions where groundwater represents a key water resource.

Karst aquifers are particularly sensitive to climatic variability due to their complex internal structure and the presence of well-developed fracture and conduit networks that enable rapid groundwater flow [14]. Consequently, karst springs often exhibit highly variable discharge regimes and rapid responses to precipitation inputs [15–18]. Changes in precipitation intensity, seasonal distribution, and evapotranspiration therefore directly influence recharge processes and groundwater flow dynamics in karst systems. Understanding the variability of karst spring discharge is thus essential for assessing groundwater sensitivity to climatic forcing [19], particularly in karst regions where springs contribute significantly to regional water supply.

A wide range of methods has been applied to analyze karst spring behavior, including statistical time series analysis, flow duration curves (FDC), and hydrological modelling (e.g., [17,18,20–24]). These approaches provide valuable insights into discharge variability and hydrological processes, and are widely used to evaluate potential future changes under different climatic conditions. Previous studies have addressed different components of karst hydrological behavior, but usually in isolation. For example, reservoir-based studies have successfully characterized the functioning and recession behavior of individual karst systems (e.g., [22,25]), while recent hydroclimatic studies have demonstrated substantial temporal and flow-regime variability across multiple catchments (e.g., [26]). Climate-impact modelling has also been applied to individual spring systems (e.g., [24]). However, comparatively few studies have explicitly examined whether two geographically close karst springs with contrasting hydrodynamic characteristics exhibit systematically different present-day discharge behavior and future responses to the same climatic forcing. This question remains particularly underexplored in Central European karst environments.

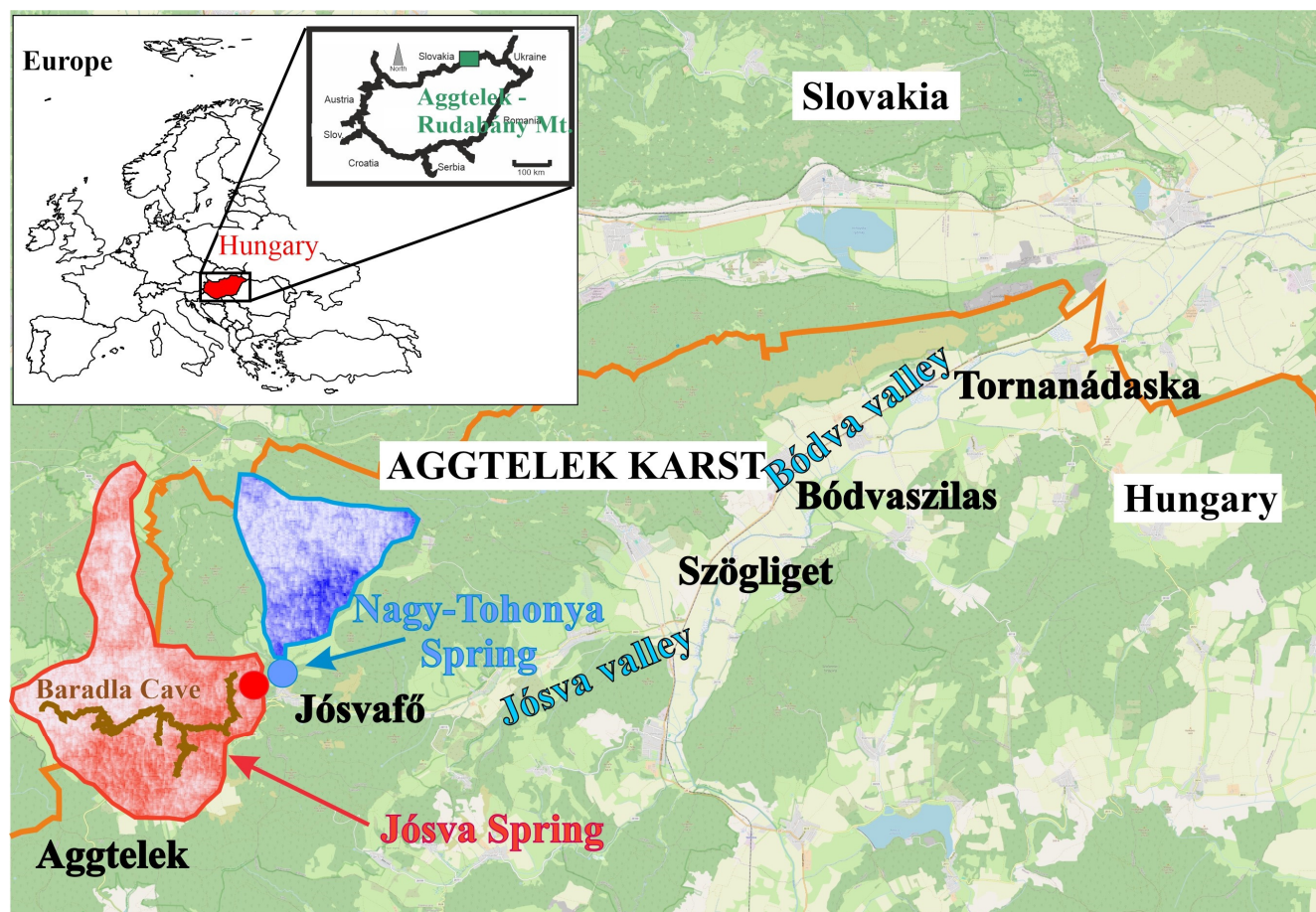
The Aggtelek Karst region in northern Hungary represents a well-studied transboundary karst system with complex hydrogeological conditions and numerous springs that play an important role in regional groundwater resources [27,28]. Long-term discharge records indicate considerable variability, reflecting both climatic forcing and the complexity of subsurface flow processes. This makes the region particularly suitable for investigating system-specific hydrological responses under changing climatic conditions.

In this study, two karst springs with contrasting hydrodynamic characteristics (Nagy-Tohonya and Jósfa) were analyzed to investigate how system-specific properties control discharge variability and response to climatic forcing. Long-term discharge time series were evaluated using statistical indicators, flow duration curve analysis, recession analysis, and periodicity assessment. In addition, hydrological simulations were performed using the Gardénia rainfall–runoff model [29] to assess potential future changes. This study provides a detailed regional assessment of discharge variability and future response of two karst springs in the Aggtelek Karst, contributing to improved understanding of groundwater

behavior under changing climatic conditions and supporting water resource management and groundwater protection in karst environments.

## 2. Geological and Hydrogeological Settings

The study area, including the Jósua and Nagy-Tohonya springs, is located in the Aggtelek Karst region in northeastern Hungary (Figure 1), extending partly into Slovakia. The region covers approximately 202 km<sup>2</sup> and forms part of the southern limestone belt of the Carpathians. Owing to its hydrogeological characteristics and extensive karstification, it represents one of the most significant karst regions in Central Europe [14,16,30]. The area is widely known for its large cave systems and diverse hydrogeological conditions [31–33].



**Figure 1.** Location of the investigated karst springs (Jósua and Nagy-Tohonya) in the Aggtelek Karst region, northeastern Hungary, and their approximate recharge areas. The red and blue dots indicate the locations of the Jósua and Nagy-Tohonya springs, respectively, while the red and blue shaded areas indicate the approximate recharge areas of the Jósua and Nagy-Tohonya springs, respectively. The orange line indicates the boundary of the Aggtelek Karst. The recharge-area boundaries represent preliminary, unpublished delineations and should be considered approximate because of the inherent uncertainty in defining groundwater catchment boundaries in karst systems. The map also shows the position of the study area within Europe and Hungary and the location of the Baradla Cave system. Base map source: Aggtelek National Park Directorate; modified by the authors.

The Hungarian side is characterized by east–west trending limestone plateaus situated at elevations of 400–600 m above sea level, incised by deep valleys whose floors typically occur between 200 and 260 m. Toward the Slovakian side, plateau elevations reach approximately 800 m, with a further northward increase in relief [30,31]. The geological structure of the Aggtelek Karst is dominated by Permian–Triassic sedimentary successions. The Lower

Triassic sequence consists mainly of siliciclastic and mixed marine deposits, including sandstone, claystone and marl, which generally act as aquitards. These are overlain by Middle–Upper Triassic carbonate formations that constitute the principal karst aquifer of the region. Carbonate sedimentation became dominant during the Middle Triassic, represented by the dark-grey, finely crystalline limestone of the Gutenstein Formation and the light-grey bioclastic limestone of the Steinalm Formation. These units are followed by the very thick (>1000 m) Ladinian–Carnian Wetterstein Formation, composed predominantly of platform carbonates and forming extensive karst plateaus in the region. The Middle–Upper Triassic carbonate succession is strongly karstified and hosts the major cave and groundwater-flow systems of the Aggtelek Karst. Younger Miocene deposits occur locally, particularly in the southern part of the study area [14,30].

The resulting karst aquifer is characterized by a well-developed underground drainage network and more than one hundred identified springs, including both permanent and temporary ones [30,34]. The low content of insoluble residues in the Middle- and Upper-Triassic limestones indicates high solubility, which promotes intensive karstification and the formation of extensive cave systems [14,31]. As a result, many major springs are hydraulically connected to conduit networks within the karst system.

The largest springs in the region include the Jósfa and Nagy-Tohonya springs, both located in the northern part of the Aggtelek Karst. Based on the historical hydrological dataset compiled by Maucha [30], the mean discharge of the Jósfa Spring was approximately 0.166 m<sup>3</sup>/s for 1974–1993, whereas that of the Nagy-Tohonya Spring was approximately 0.106 m<sup>3</sup>/s for the available 1964–1993 record. Smaller springs generally exhibit considerably lower average discharges, ranging from approximately 0.002 to 0.035 m<sup>3</sup>/s [30]. Despite their geographical proximity, the Jósfa and Nagy-Tohonya springs differ markedly in both the extent and geological composition of their recharge areas. The estimated recharge area of the Nagy-Tohonya Spring is approximately 13 km<sup>2</sup> based on water-balance calculations [35], although earlier estimates range between 13.5 and 22.5 km<sup>2</sup> [35,36], reflecting the uncertainty inherent in delineating karst groundwater catchments. In comparison, the Jósfa–Baradla system is associated with a larger catchment. Gruber et al. [37] reported a total investigated karstic and non-karstic drainage area of 29.83 km<sup>2</sup>, whereas Borbás et al. [38] reported a catchment area exceeding 34 km<sup>2</sup> for the Baradla cave system, and a recent study reported an aquifer area of 34.4 km<sup>2</sup> for the Jósfa Spring [39]. The Nagy-Tohonya recharge area is mainly associated with dolomitic members of the Wetterstein Formation together with the Gutenstein Formation, whereas the larger Jósfa recharge area is predominantly developed in massive limestone units of the Wetterstein Formation (Figure S1) [33,40–42]. These differences in catchment size and lithological setting provide an important geological and hydrogeological context for the contrasting discharge dynamics of the two springs.

### 3. Hydrometeorological Data and Climate Projections

To investigate the hydrological behavior of the studied karst springs, an integrated methodological approach combining statistical analysis and hydrological modelling was applied. The analysis was based on long-term discharge records of the springs together with meteorological observations describing the climatic conditions of the recharge area. The variability and statistical characteristics of the discharge time series were evaluated using descriptive statistical indicators and flow duration curve (FDC) analysis. In addition, hydrological simulations were performed using the conceptual Gardénia rainfall–runoff model to reproduce the observed discharge dynamics and to explore potential changes in spring discharge under different climatic conditions. The following chapters present

the hydrological and meteorological datasets used in the study, the applied climate model projections, and the statistical and modelling methods used in the analysis.

### 3.1. Spring Discharge Data

Daily discharge time series were used for two major karst springs, the Jósza Spring and the Nagy-Tohonya Spring. The discharge data were obtained from the North Hungarian Water Directorate and the General Directorate of Water Management. The available datasets cover the period 1974–2020. Most of the discharge measurements were available at a daily temporal resolution, although hourly measurements were also available for certain shorter periods. For the purposes of the hydrological analysis and modelling, daily mean discharge values were used consistently throughout the study.

### 3.2. Meteorological Observations

Meteorological data used in the study were provided by the Hungarian Meteorological Service (HungaroMet, formerly OMSZ). The datasets included daily precipitation and reference evapotranspiration ( $ET_0$ ), which were used as input variables for the hydrological modelling. The  $ET_0$  data provided by HungaroMet were calculated using the FAO-56 Penman–Monteith method. This standardized, physically based approach accounts for both radiative and aerodynamic controls on evapotranspiration and is widely used for estimating reference evapotranspiration. The evapotranspiration calculation method was therefore not independently selected or implemented in the present study; instead, the  $ET_0$  dataset supplied by HungaroMet was used directly as model input. The same  $ET_0$  dataset and methodology were applied consistently to both the reference and future climate simulations, ensuring methodological consistency across the simulation periods. Reliable climate analyses require long-term, quality-controlled, and spatially representative observational datasets. Changes in measurement conditions, such as station relocation, modifications in measurement frequency, or instrument replacement, may introduce artificial discontinuities into meteorological time series. To minimize these effects, the meteorological datasets were homogenized using the MASH (Multiple Analysis of Series for Homogenization) method [43,44]. Following the homogenization procedure, the station data were interpolated onto a  $0.1^\circ$  regular grid covering the entire territory of Hungary. The interpolation was performed using the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) system [45], which was specifically developed for the spatial interpolation of meteorological variables.

### 3.3. Climate Model Projections

Future climatic conditions were represented using meteorological projections provided by the Hungarian Meteorological Service (HungaroMet, formerly OMSZ). The projections were based on the EURO-CORDEX modelling framework, using the IPSL-CM5A-MR global climate model dynamically downscaled with the SMHI-RCA4 regional climate model. Climate projections were considered under the RCP4.5 greenhouse gas concentration scenario. The available model outputs included daily precipitation and reference evapotranspiration ( $ET_0$ ) for the period 2022–2100, which were used as input to the hydrological simulations. The projected precipitation data were bias-corrected prior to their application in the GARDÉNIA model [46], thereby reducing systematic differences between the climate-model simulations and the corresponding observations. For the future simulations, the calibrated GARDÉNIA model structure and parameter values were kept unchanged, so that differences between the reference and future simulations reflect changes in the applied meteorological forcing.

## 4. Methods

Conceptual hydrological models represent the functioning of a catchment using simplified interconnected reservoirs that simulate the main processes of the hydrological cycle, including infiltration, storage and runoff generation. In this approach, the catchment is treated as a single spatial unit characterized by averaged parameters. Such models are particularly suitable for karst aquifers, where strong heterogeneity, preferential flow paths and complex subsurface structures limit the applicability of physically based distributed models [16,18]. Despite their simplified structure, they are capable of reproducing the main dynamic characteristics of spring discharge and the overall hydrological response of karst systems.

In the present study, the Gardénia [29] rainfall–runoff model was applied to simulate the discharge dynamics of the investigated karst springs. The model represents the hydrological functioning of the catchment using a system of interconnected conceptual reservoirs and has been successfully applied in hydrological modelling and water resources assessments [29].

### 4.1. Hydrological Modelling Using the Gardénia Model

The simulation of spring discharge was carried out using the Gardénia hydrological model developed by the Bureau de Recherches Géologiques et Minières (BRGM). Gardénia is a conceptual rainfall–runoff model that represents catchment behavior through a cascade of interconnected reservoirs. It describes the main components of the hydrological cycle (precipitation, evapotranspiration, infiltration and groundwater flow) using simplified storage and transfer processes [29,47]. The model uses meteorological time series, primarily precipitation and evapotranspiration, to simulate discharge at the catchment outlet and, when required, groundwater levels within the aquifer system. Within this framework, the catchment is conceptualized as a system of reservoirs representing the principal storage components and flow pathways. Conceptual reservoir models are widely used in karst studies, as the highly heterogeneous structure of karst aquifers often limits the applicability of physically based distributed models. Although subsurface processes are represented in a simplified manner, such models can adequately reproduce the main dynamics of spring discharge and the overall hydrological response of karst catchments.

### 4.2. Model Calibration

The Gardénia model includes an automatic calibration procedure based on the Rosenbrock optimization algorithm [48]. During calibration, model parameters are adjusted to minimize the difference between simulated and observed discharge time series. Since the automatic calibration optimizes the hydrograph as a whole, additional manual adjustments were applied to improve the representation of individual hydrograph components. In karst aquifers, discharge variability is typically governed by two main components: a rapid flow component associated with conduit flow, and a slower baseflow component related to diffuse flow from the rock matrix [15,49–53]. Accordingly, the calibration was carried out in two steps. First, parameters controlling the rapid response of the system were adjusted to reproduce peak discharge events. In the second step, the recession behavior of the hydrograph was refined by tuning parameters related to the baseflow component. Recession characteristics were derived from the falling limbs of the observed hydrographs following the approach described by Tallaksen [54].

Model performance was evaluated by comparing simulated and observed discharge time series. The goodness of fit was assessed using statistical indicators, including the Nash–Sutcliffe efficiency coefficient and the correlation coefficient [55].

Following model calibration and performance evaluation, bias correction was applied to the simulated discharge to account for systematic differences between the observed discharge and the discharge simulated by GARDÉNIA using climate-model-derived meteorological inputs. The correction was performed using monthly flow-duration-curve quantile mapping (MFDC-QM), following the approach of Sanchez Lozano et al. [56]. For the historical reference period (1981–2020), monthly empirical distributions were constructed separately from the observed daily discharge series and the discharge series simulated by GARDÉNIA using the climate-model-derived meteorological data. For each calendar month, simulated discharge values were mapped to the corresponding quantiles of the observed discharge distribution based on their non-exceedance probabilities. The month-specific transfer relationships derived from the 1981–2020 reference period were subsequently applied to the corresponding calendar months of the future simulated discharge series. The resulting bias-corrected daily discharge series were used for the subsequent flow-duration-curve analysis.

The principal hydrologically relevant GARDÉNIA parameters and their adopted values for the two spring systems are summarized in Table S1. The reported parameters represent the main processes controlling soil–water storage, rapid-flow versus groundwater-recharge partitioning, recharge transfer, groundwater recession, and discharge-response propagation. Only one groundwater reservoir was active in both model configurations.

#### 4.3. Hydrograph Decomposition and Recession Analysis

Hydrograph decomposition was applied to support the calibration and interpretation of the hydrological model. The method allows the estimation of recession coefficients ( $\alpha$ ), which provide information on aquifer drainage behavior and the hydraulic and geometric characteristics controlling the recession process. Discharge time series of karst springs typically exhibit a characteristic hydrograph shape characterized by a rapid increase in discharge following precipitation events and a subsequent gradual decline. The decreasing part of the hydrograph, referred to as the recession limb, reflects the drainage of groundwater storage within the aquifer. The mathematical description of spring recession was originally proposed by Maillet [57], according to which the temporal decrease in discharge can be approximated by an exponential function [53]:

$$Q(t) = Q_0 e^{-\alpha t}$$

where  $Q(t)$  is the discharge at time [ $L^3T^{-1}$ ] while  $Q_0$  is the discharge [ $L^3T^{-1}$ ] at the beginning of the recession period,  $t$  is time, and  $\alpha$  is the recession coefficient, typically expressed in units of days.

When the exponential recession equation is plotted on a semi-logarithmic scale, it appears as a straight line with slope  $\alpha$ . This representation is generally suitable for characterizing baseflow conditions in karst systems during low-flow periods. However, in the earlier phases of baseflow recession, the discharge commonly departs from Maillet's [57] simple exponential model. Forkasiewicz and Paloc [58] demonstrated that the recession limbs of hydrograph peaks can generally be decomposed into several (typically three) exponential segments. They introduced the concept of hydrograph decomposition, in which exponential components are fitted to the flattest part of a spring hydrograph and then successively subtracted from the residual hydrograph. They further assumed that the different segments of a spring hydrograph peak represent distinct, parallel reservoirs, each contributing to the overall discharge of the spring.

$$Q(t) = Q_1 e^{-\alpha_1 t} + Q_2 e^{-\alpha_2 t} + Q_3 e^{-\alpha_3 t}$$

Schoeller [59] proposed that the successive exponential segments observed along the recession limbs of spring hydrographs reflect transitions between different flow regimes, such as shifts from turbulent to laminar flow. Kovács et al. [60] derived an exact analytical solution for baseflow recession. Subsequently, Kovács and Perrochet [61] demonstrated that baseflow recession can be represented as the sum of an infinite series of exponential terms. Their results indicate that these exponential components do not necessarily correspond to distinct permeability zones; rather, they capture transient processes associated with the gradual release of water from low-permeability matrix blocks.

$$Q(t) = \sum_{i=1}^{\infty} Q_i e^{-\alpha_i t}$$

Recession analysis and hydrograph decomposition are widely used approaches in karst hydrology to characterize aquifer drainage behavior [16,61,62]. Representative flood events were selected from the observed and simulated discharge time series of both investigated springs, and recession segments following precipitation events were identified and analyzed. Hydrograph decomposition was performed using semi-logarithmic discharge–time plots, where exponential recession terms appear as linear segments. Exponential functions were fitted to the identified recession segments using least-squares regression in MS Excel, based on the semi-logarithmic transformation of the discharge time series. The goodness of fit was evaluated visually and by assessing the linearity of the semi-logarithmic plots. When a fitted exponential term adequately represented a recession segment, it was subtracted from the original hydrograph, and the residual discharge series was analyzed iteratively to identify subsequent exponential terms. This procedure was repeated until no further exponential term could be reliably identified. Most analyzed hydrographs could be decomposed into two or three exponential recession terms (for further methodological details, see Kovács [63], Kovács et al. [60], and Kovács and Perrochet [61]).

According to the analytical framework developed by Kovács et al. [60] and Kovács and Perrochet [61], the exponential terms identified during recession analysis should not be interpreted as direct representations of discrete permeability domains or separate matrix, fracture, and conduit flow components. Multiple exponential terms may arise from the transient drainage of a single low-permeability block. Their occurrence therefore reflects the transient nature of aquifer drainage rather than the presence of an equivalent number of physically distinct flow domains. The recession coefficients are related to the hydraulic and geometric properties governing this drainage process, particularly the hydraulic diffusivity and characteristic geometry of the low-permeability blocks under matrix-restrained flow conditions. In the present study, the derived recession coefficients were therefore used to compare the recession behavior of the Nagy-Tohonya and Jósfa springs and to assess whether the observed and simulated hydrographs exhibit comparable drainage characteristics.

#### 4.4. Statistical Analysis

The hydrological behavior of the discharge time series was characterized using descriptive statistical indicators calculated for both the observed and simulated datasets. The applied parameters included mean discharge, standard deviation, coefficient of variation (CV = standard deviation/mean), as well as skewness and kurtosis describing the shape of the discharge distribution. These indicators provide quantitative information on the magnitude, variability and distribution characteristics of the discharge series.

In addition to the descriptive statistics, the performance of the hydrological model was evaluated using the Pearson correlation coefficient and the Nash–Sutcliffe efficiency coefficient (NSE). The Pearson correlation coefficient describes the strength of the linear

relationship between observed and simulated discharge values, while the NSE assesses the relative magnitude of residual variance compared to the variance of the observed data, thereby providing a measure of model performance. These statistical indicators are widely used in hydrological time series analysis and model performance evaluation [55,64,65].

#### 4.5. Flow Duration Curve and Variability Index Analysis

To further analyze the variability and frequency characteristics of spring discharge, flow duration curve (FDC) analysis was also applied. The FDC describes the relationship between discharge magnitude and exceedance probability, allowing the identification of high-, medium- and low-flow conditions and their persistence. Indeed, the FDC is a widely used hydrological tool that describes the percentage of time during which a given discharge is equaled or exceeded, providing a comprehensive representation of the entire discharge distribution and enabling comparison of hydrological behavior among different catchments [20,21]. To construct the FDC, daily discharge values were arranged in descending order and assigned a rank. The exceedance probability was calculated using a standard plotting position formula:

$$P = 100 \, m / (n + 1)$$

where  $P$  is the exceedance probability (%),  $m$  is the rank of the discharge value, and  $n$  is the total number of observations.

The discharge values were plotted against exceedance probability to obtain the FDC. The upper part of the curve reflects high-flow conditions and the system's response to recharge events, while the lower part represents low-flow conditions and the contribution of stored groundwater. Therefore, the shape of the FDC provides important information about storage characteristics and groundwater flow processes within the catchment. Several FDC-based indices can be used for hydrological characterization and comparison of catchments, particularly in studies investigating hydrological variability and flow regime dynamics [20,21,66].

To quantify discharge variability, the FDC slope index was calculated from the mid-segment of the curve:

$$S_{FDC} = \frac{\log(Q_{33}) - \log(Q_{66})}{0.66 - 0.33}$$

where  $Q_{33}$  and  $Q_{66}$  correspond to discharge values at 33% and 66% exceedance probabilities, representing the intermediate flow regime.

In addition, a dimensionless variability index ( $VI$ ) was calculated to characterize the contrast between high and low flows:

$$VI = \frac{Q_{10}}{Q_{90}}$$

where  $Q_{10}$  represents high-flow conditions and  $Q_{90}$  low-flow conditions. Higher “ $VI$  values” indicate a more variable discharge regime, whereas lower values suggest more stable hydrological behavior.

## 5. Results

In the following, the characterization of the Nagy-Tohonya and Jóska springs is presented based on the results of time series analyzes, statistical evaluations, and flow duration curve (FDC) analysis. In addition, a comparison of the observed and simulated discharge time series is provided using both statistical indicators and FDC analysis for the investigated periods. Finally, the results of future simulations (for the periods 2022–2060 and 2060–2100) are presented for both springs.

### 5.1. Characterization of the Nagy-Tohonya and Jósua Springs

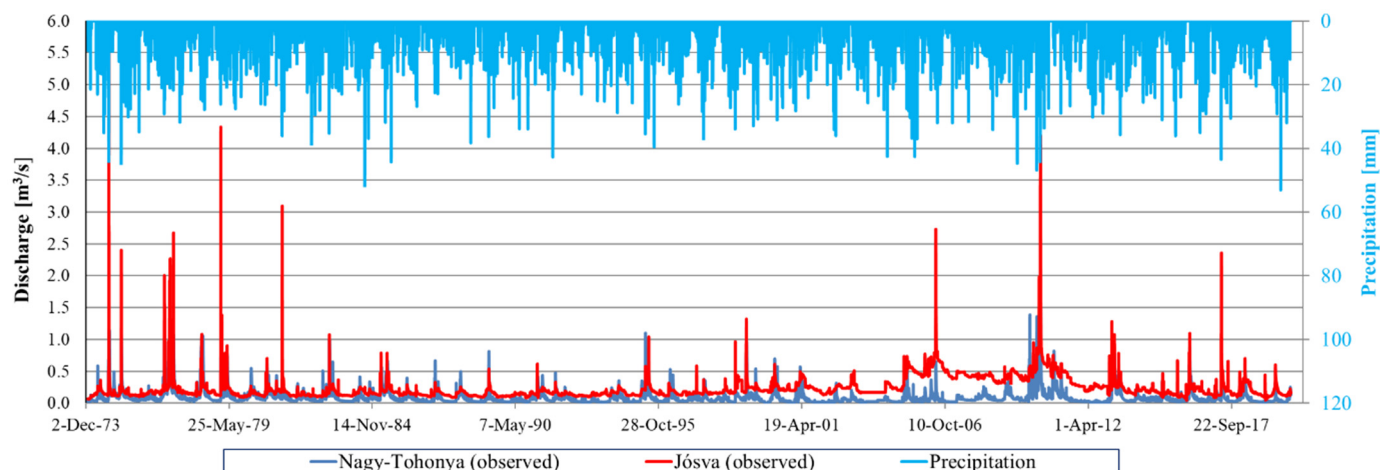
To establish the fundamental hydrological characteristics of the two springs, the statistical properties of the observed discharge time series (1974–2020) were first analyzed. The descriptive statistical characteristics of the Nagy-Tohonya and Jósua springs are summarized in Table 1.

**Table 1.** Characterisation of the Nagy-Tohonya and Jósua springs.

| Statistical Characteristics            | Nagy-Tohonya Observed 1974–2020 | Jósua Observed 1974–2020 |
|----------------------------------------|---------------------------------|--------------------------|
| Number of observations                 | 17,167                          | 17,167                   |
| Mean [m <sup>3</sup> /s]               | 0.077                           | 0.239                    |
| Standard deviation [m <sup>3</sup> /s] | 0.102                           | 0.166                    |
| Minimum [m <sup>3</sup> /s]            | 0.001                           | 0.042                    |
| Maximum [m <sup>3</sup> /s]            | 1.492                           | 4.187                    |
| Range [m <sup>3</sup> /s]              | 1.491                           | 4.145                    |
| Skewness                               | 5.049                           | 5.042                    |
| Kurtosis                               | 40.530                          | 67.770                   |
| Coefficient of variation (%)           | 131.630                         | 69.280                   |
| $\alpha_1$ [day <sup>−1</sup> ]        | 0.04–0.05                       | 0.02–0.03                |
| $\alpha_2$ [day <sup>−1</sup> ]        | 0.12–0.14                       | 0.07–0.08                |
| $\alpha_3$ [day <sup>−1</sup> ]        | 0.25–0.30                       | 0.16–0.18                |

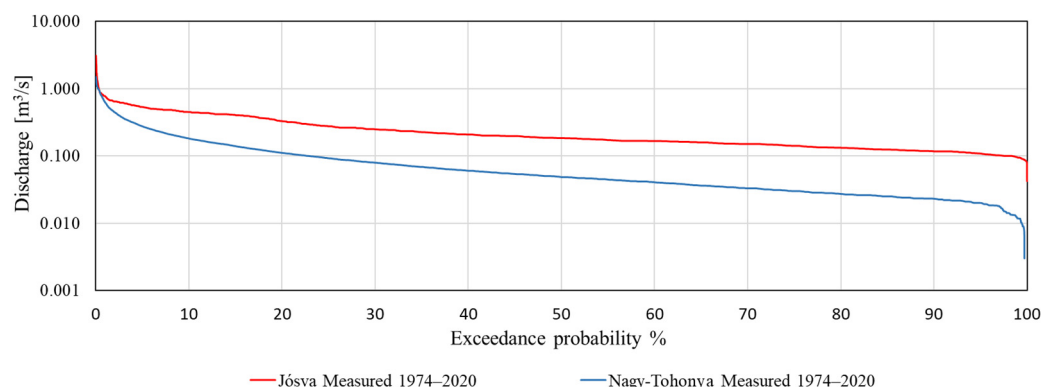
Both datasets consist of 17,167 daily observations. The descriptive statistics reveal clear differences between the discharge characteristics of the two springs (Table 1). The Jósua Spring exhibits a higher mean discharge and a substantially wider absolute discharge range, whereas the Nagy-Tohonya Spring shows considerably greater relative variability, as indicated by its higher coefficient of variation. Both discharge distributions are strongly positively skewed and leptokurtic, with the Jósua Spring exhibiting the higher kurtosis.

The observed discharge time series and precipitation data are shown in Figure 2. The Jósua Spring consistently exhibits higher discharge values throughout the investigated period, whereas the Nagy-Tohonya Spring is characterized by lower baseflow conditions and more abrupt discharge peaks. Differences are evident not only in absolute discharge magnitude but also in the temporal variability of the time series. Based on the hydrograph analysis, the recession coefficients reveal further characteristics. The recession limb exhibits a gradual decline in discharge, reflecting the transient drainage of the karst aquifer. Semi-logarithmic analysis of the recession segments reveals that the recession curves of both springs can be represented by three exponential terms. In accordance with the analytical framework described above, these terms are treated as mathematical components of transient aquifer drainage rather than as direct representations of physically distinct flow or storage domains. The comparison of recession coefficients between the Jósua and Nagy-Tohonya springs reveals systematic differences in their recession behaviour (Table 1). For all three recession coefficients, the Nagy-Tohonya Spring consistently exhibits higher  $\alpha$  values than the Jósua Spring. Within the theoretical framework of Kovács et al. [60] and Kovács and Perrochet [61], these differences may reflect differences in the effective hydraulic and geometric properties controlling the transient drainage of the low-permeability blocks.



**Figure 2.** Combined representation of the observed discharge time series of the Nagy-Tohonya and Jóska springs together with the corresponding precipitation data for the investigated period (1974–2020).

To further characterize the distribution of discharge values, flow duration curves (FDC) were constructed. The FDCs of the observed discharge time-series are shown in Figure 3. The curve of the Jóska Spring lies above that of the Nagy-Tohonya Spring across the entire exceedance probability range, indicating consistently higher discharge values. In contrast, the Nagy-Tohonya curve is positioned at lower discharge values and exhibits a steeper slope. Differences between the two curves are most pronounced in the low-flow domain, where the Nagy-Tohonya curve shows a rapid decline, whereas the Jóska curve displays a flatter and more gradual decrease. In the medium- and high-flow ranges, differences remain present, although their magnitude is less pronounced.



**Figure 3.** Flow duration curves (FDC) of the observed discharges of the Nagy-Tohonya and Jóska springs.

Autocorrelations have also been conducted on both time series (Figure S2) in order to reveal the extent to which these time series depend on their own past values. Figure S2 illustrates that the Nagy-Tohonya Spring curve approaches zero rapidly (in 150 days), in contrast with Jóska Spring curve which decreases slowly. Based on this, the Nagy-Tohonya Spring is less autocorrelated, than the Jóska Spring is strongly autocorrelated. These differences reinforce the distinct characteristics of both springs.

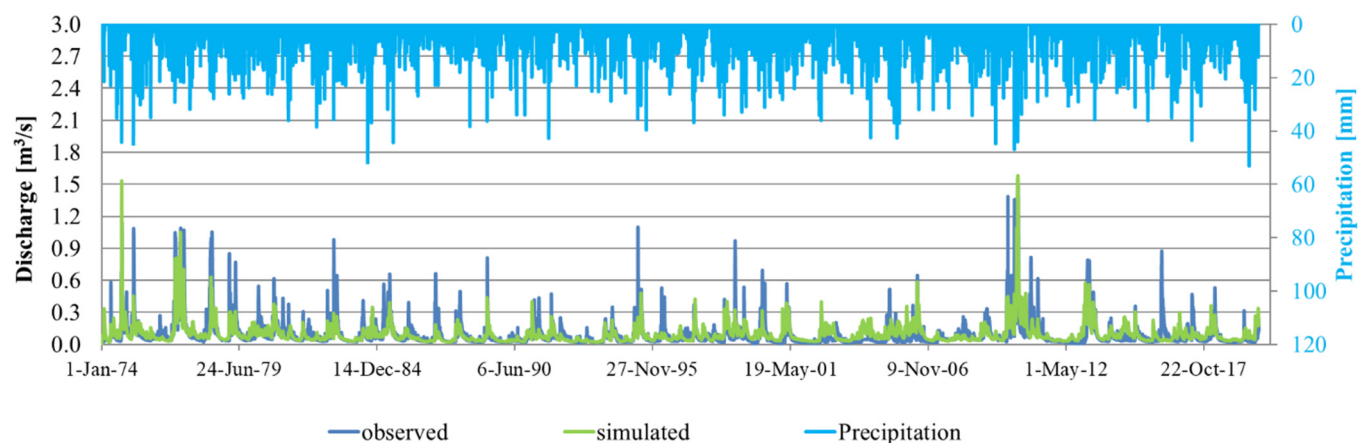
In order to identify periodicities, the discharge times series for both springs were analyzed using two different methods: spectral analysis (with the discrete Fourier transform) and wavelet analysis (Figure S3). Based on the results of the periodogram, the annual period (~365 days) is clearly detectable for Nagy-Tohonya and Jóska springs as

well. However, in addition to the annual cycle, longer-term components are also present in both springs. Peaks appear in the ~3–5-year and ~10–15-year ranges. Nevertheless, significant differences between the two springs can already be observed at the level of spectral analysis. In the case of the Nagy-Tohonya spring, the annual period remains clearly dominant, and the multi-year components play only a secondary role. In contrast, at the Jósza Spring, longer periods, particularly components on a multi-decade scale, appear more strongly, which suggests a different hydrodynamic behavior of the system. Wavelet analysis further refines this picture by revealing the temporal variation of different periods. The results show that the annual cycle is consistently present in both sources, confirming its dominant role. At the same time, the multi-year components are not constant over time: they strengthen during certain periods and weaken during others.

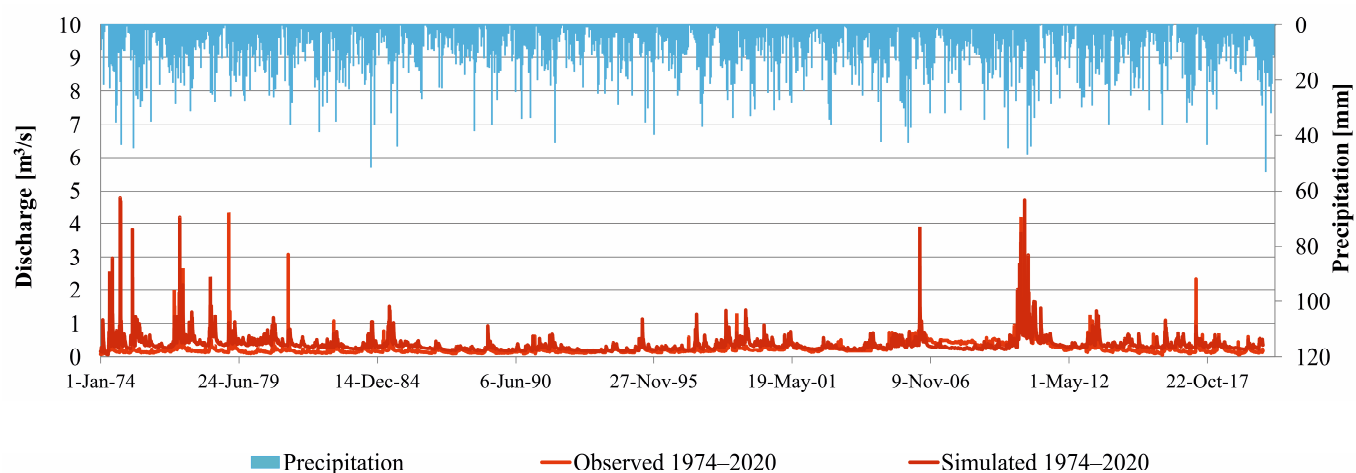
### 5.2. Comparison of the Observed and Simulated Discharge Time Series

For the model simulations, the parameterization and calibration of the Gardénia conceptual hydrological model were first completed. The model was then run using the observed meteorological dataset for the period during which observed discharge data were available (1974–2020). In addition, the model was also run using the meteorological dataset obtained from the climate model for the period 1981–2020, as the climate model was only available from 1981. In the following, we refer to the simulation based on the observed meteorological dataset as ‘simulated’, while the simulation based on the climate model dataset is referred to as ‘CM-simulated’. The simulated discharge time series were subsequently compared with the observed spring discharge data to evaluate the model’s ability to reproduce the hydrological behavior of the karst springs. The evaluation of the model results was carried out in several steps. First, a graphical comparison of the observed and simulated hydrographs was performed to assess overall model performance. Next, hydrograph decomposition was applied to the recession segments of selected flood events to determine the recession coefficients associated with different storage components. To further characterize both the hydrological behavior of the springs and the model performance, the discharge time series were also evaluated using statistical indicators and flow duration curve (FDC) analysis.

The comparison between the observed and simulated discharge time series of the Nagy-Tohonya and Jósza springs is shown in Figures 4 and 5, which illustrate the precipitation and discharge conditions over the investigated period (1974–2020). The simulated discharge time series follow the general temporal pattern of the observed hydrographs, and the major increases in discharge following precipitation events are also reflected in the simulations. However, the simulated hydrographs exhibit a smoother response compared to the observed data. The statistical characteristics of the observed and simulated time series were also compared. The results for the Nagy-Tohonya Spring are shown in Table 2, while those for the Jósza Spring are presented in Table 3. The statistical characteristics of discharge for the Nagy-Tohonya and Jósza springs show that the simulated and climate model-simulated (CM-simulated) datasets exhibit similar overall patterns to the observed time series, despite some differences. In both cases, the simulated and observed mean discharge values and standard deviations are of similar magnitude, although differences are observed in the minimum and maximum values. Moreover, it is important to note that the differences between the two springs are consistently reflected across all datasets. Nagy-Tohonya is characterized by lower mean discharge and higher relative variability, while Jósza exhibits higher discharge and lower variability. These contrasts are preserved in both the “simulated” and “CM-simulated” datasets.



**Figure 4.** Observed and simulated discharge time series of the Nagy-Tohonya Spring and the corresponding precipitation data for the investigated period (1974–2020).



**Figure 5.** Observed and simulated discharge time series of the Jósza Spring and the corresponding precipitation data for the investigated period (1974–2020).

**Table 2.** Descriptive statistical characteristics of the observed and simulated discharge timeseries of the Nagy-Tohonya Spring.

| Statistical Characteristics                  | Nagy-Tohonya Observed (1974–2020) | Nagy-Tohonya Simulated (1974–2020) | Nagy-Tohonya Simulated CM (1981–2020) |
|----------------------------------------------|-----------------------------------|------------------------------------|---------------------------------------|
| Number of observations                       | 17,167                            | 17,167                             | 14,246                                |
| Mean [ $\text{m}^3/\text{s}$ ]               | 0.077                             | 0.073                              | 0.070                                 |
| Standard deviation [ $\text{m}^3/\text{s}$ ] | 0.102                             | 0.080                              | 0.072                                 |
| Minimum [ $\text{m}^3/\text{s}$ ]            | 0.001                             | 0.001                              | 0.001                                 |
| Maximum [ $\text{m}^3/\text{s}$ ]            | 1.492                             | 1.540                              | 1.689                                 |
| Range [ $\text{m}^3/\text{s}$ ]              | 1.491                             | 1.539                              | 1.688                                 |
| Skewness                                     | 5.049                             | 5.464                              | 5.864                                 |
| Kurtosis                                     | 40.530                            | 60.080                             | 72.080                                |
| Coefficient of variation (%)                 | 131.630                           | 103.620                            | 105.620                               |

**Table 3.** Descriptive statistical characteristics of the observed and simulated discharge series of the Jósua Spring.

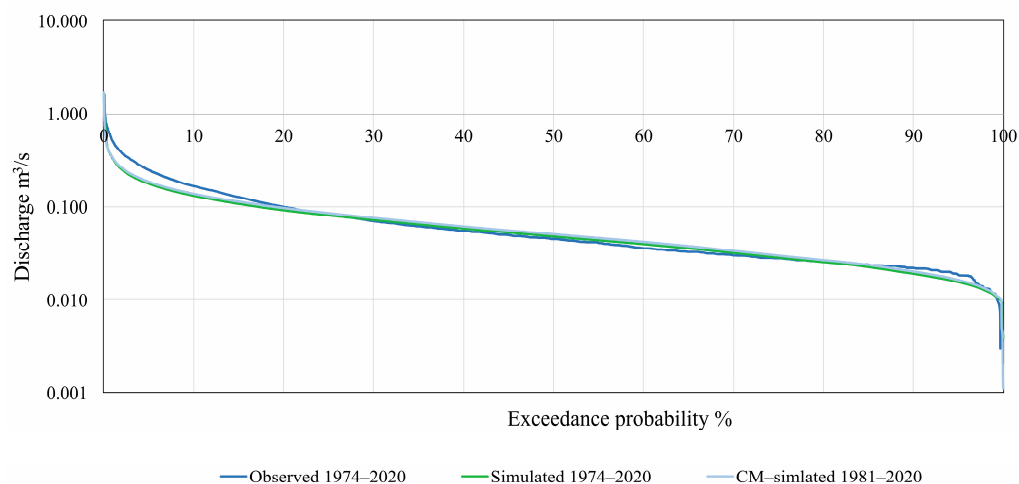
| Statistical Characteristics            | Jósua Observed<br>(1974–2020) | Jósua Simulated<br>(1974–2020) | Jósua Simulated CM<br>(1981–2020) |
|----------------------------------------|-------------------------------|--------------------------------|-----------------------------------|
| Number of observations                 | 17,167                        | 17,167                         | 14,246                            |
| Mean [m <sup>3</sup> /s]               | 0.239                         | 0.235                          | 0.231                             |
| Standard deviation [m <sup>3</sup> /s] | 0.166                         | 0.161                          | 0.156                             |
| Minimum [m <sup>3</sup> /s]            | 0.042                         | 0.062                          | 0.091                             |
| Maximum [m <sup>3</sup> /s]            | 4.187                         | 3.953                          | 3.871                             |
| Range [m <sup>3</sup> /s]              | 4.145                         | 3.869                          | 3.780                             |
| Skewness                               | 5.042                         | 4.860                          | 4.532                             |
| Kurtosis                               | 67.770                        | 61.120                         | 60.760                            |
| Coefficient of variation (%)           | 69.280                        | 65.130                         | 64.710                            |

To investigate recession characteristics, some flood events were analyzed in detail of the simulated time series for both springs and compared with the observed values. The recession coefficients for the Nagy-Tohonya Spring were found to be  $\alpha_1 = 0.06 \text{ day}^{-1}$ ,  $\alpha_2 = 0.14 \text{ day}^{-1}$ , and  $\alpha_3 = 0.25 \text{ day}^{-1}$ . These values are fairly similar to those obtained from the observed time series (Table 4). The recession coefficients obtained from the hydrograph decomposition of the Jósua Spring data are summarized in Table 4 together with the values derived from observed time series. The recession coefficients showed generally good agreement between the observed and simulated hydrographs. For the Jósua Spring,  $\alpha_2$  and  $\alpha_3$  showed close agreement between the observed and simulated hydrographs, whereas the simulated  $\alpha_1$  ( $\sim 0.05 \text{ day}^{-1}$ ) was higher than the observed value ( $\sim 0.025 \text{ day}^{-1}$ ). This discrepancy may reflect limitations of the lumped conceptual model in reproducing the long-term recession behavior of the karst system, which is influenced by aquifer hydraulic properties and geometry. Nevertheless, the close agreement of  $\alpha_2$  and  $\alpha_3$  indicates that the other identified recession characteristics were reproduced well.

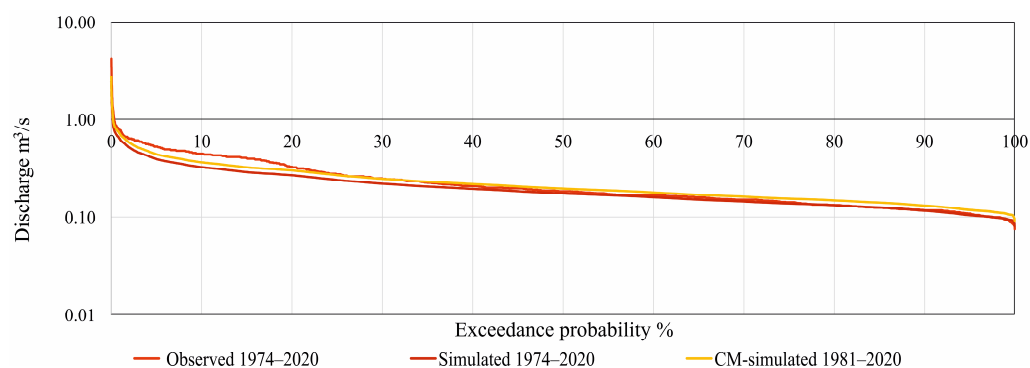
**Table 4.** Recession coefficients derived from the hydrograph decomposition of the investigated karst springs.

| Component  | Nagy-Tohonya<br>Observed (day <sup>−1</sup> ) | Nagy-Tohonya<br>Simulated (day <sup>−1</sup> ) | Jósua Observed<br>(day <sup>−1</sup> ) | Simulated Jósua<br>(day <sup>−1</sup> ) |
|------------|-----------------------------------------------|------------------------------------------------|----------------------------------------|-----------------------------------------|
| $\alpha_1$ | $\sim 0.045$                                  | $\sim 0.06$                                    | $\sim 0.025$                           | $\sim 0.05$                             |
| $\alpha_2$ | $\sim 0.13$                                   | $\sim 0.14$                                    | $\sim 0.07$                            | $\sim 0.08$                             |
| $\alpha_3$ | $\sim 0.27$                                   | $\sim 0.25$                                    | $\sim 0.16$                            | $\sim 0.16$                             |

To further evaluate the distributional characteristics of the “simulated” and “CM-simulated” with the observed discharge series, flow duration curves were also compared. The results are shown in Figures 6 and 7. In general, the simulated and CM-simulated curves are fairly similar for both springs. Comparing these with the observed FDC curves shows that they follow each other closely over most of the exceedance probability range, with deviations primarily occurring in the extreme flow domains. The model’s estimation of lower high-range and higher low-range discharges is slightly lower than the actual figures, but this difference is negligible.



**Figure 6.** Comparison of the observed, the simulated and the CM-simulated FDC curves of the Nagy-Tohonya Spring.



**Figure 7.** Comparison of the observed, the simulated and the CM-simulated FDC curves of the Jósua Spring.

Model performance metrics are presented in Table 5. In case of the Nagy-Tohonya Spring, the Pearson correlation coefficient for simulated and CM-simulated are 0.71 and 0.70, respectively, while the Nash–Sutcliffe efficiency is 0.54 and 0.51. In case of the Jósua Spring, higher values are obtained ( $r_{\text{simulated}} = 0.89$  and  $r_{\text{CM-simulated}} = 0.88$  and  $\text{NSE} = 0.69$ ). Overall, it can be concluded that the models for both spring and both cases perform well.

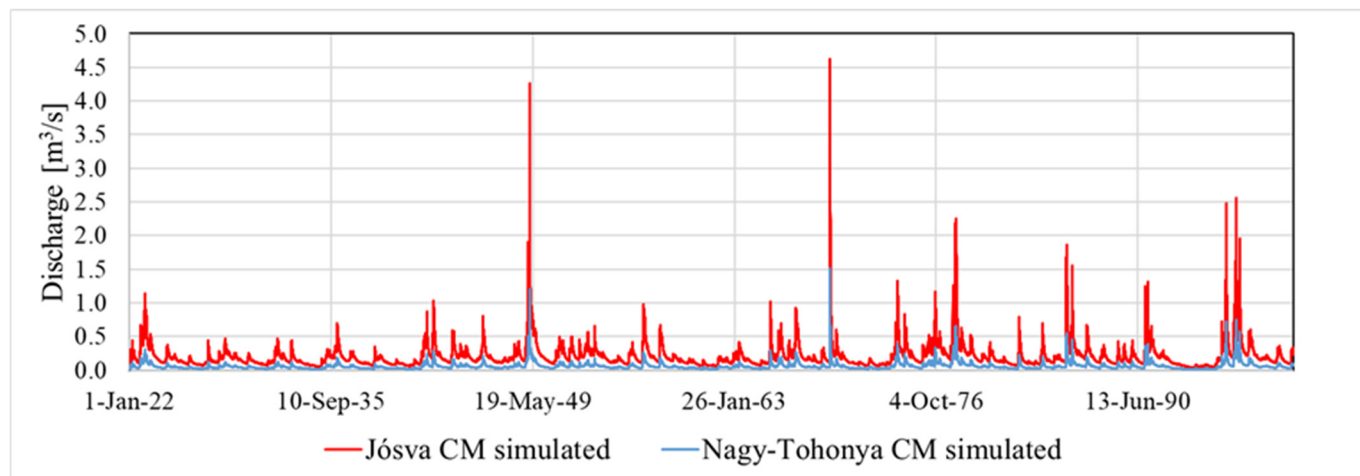
**Table 5.** Model performance metrics for the investigated springs, including the Pearson correlation coefficient ( $r$ ) and the Nash–Sutcliffe efficiency (NSE) calculated for the observed and simulated discharge time series.

| Spring       | Simulated (1974–2020)                   |                                 | Simulated CM (1981–2020)                |                                 |
|--------------|-----------------------------------------|---------------------------------|-----------------------------------------|---------------------------------|
|              | Pearson Correlation Coefficient ( $r$ ) | Nash–Sutcliffe Efficiency (NSE) | Pearson Correlation Coefficient ( $r$ ) | Nash–Sutcliffe Efficiency (NSE) |
| Nagy-Tohonya | 0.72                                    | 0.54                            | 0.70                                    | 0.51                            |
| Jósua        | 0.89                                    | 0.69                            | 0.88                                    | 0.65                            |

### 5.3. Discharge Predictions

The hydrological model was applied to projected meteorological time series to simulate future spring discharge for the period 2022–2100. During the simulations, previously calibrated model parameters were kept unchanged, while precipitation and temperature time series derived from regional climate model projections were used as input data. Prior

to further analysis, bias correction was applied to the simulated discharge time series similar to other studies (e.g., [19]). The predictive results are presented for future in Figure 8. The time series exhibit pronounced temporal variability throughout the simulated period, with alternating high- and low-discharge conditions reflecting the variability of the meteorological forcing. The Jósva Spring consistently displays higher discharge values, while the Nagy-Tohonya Spring is characterized by lower baseflow conditions and more abrupt fluctuations. Periods of elevated discharge appear intermittently in both time series, while low-flow conditions are also clearly identifiable. To quantify these changes, descriptive statistical indicators were calculated for the reference and future periods. The results for the Nagy-Tohonya and Jósva springs are presented in Tables 6 and 7, respectively.



**Figure 8.** CM-simulated discharge time series of the Nagy-Tohonya Spring (blue) and Jósva Spring (red) for the period 2022–2100 based on the Gardénia hydrological model.

**Table 6.** Statistical characteristics of the simulated discharge series of the Nagy-Tohonya spring for the reference period (1981–2020) and the future periods (2022–2059 and 2060–2100).

| Statistical Characteristics                  | Nagy-Tohonya Simulated<br>CM (1981–2020) | Nagy-Tohonya Simulated<br>CM (2022–2059) | Nagy-Tohonya Simulated<br>CM (2060–2100) |
|----------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Number of observations                       | 14,246                                   | 14,300                                   | 14,975                                   |
| Mean [ $\text{m}^3/\text{s}$ ]               | 0.070                                    | 0.060                                    | 0.065                                    |
| Standard deviation [ $\text{m}^3/\text{s}$ ] | 0.072                                    | 0.048                                    | 0.066                                    |
| Minimum [ $\text{m}^3/\text{s}$ ]            | 0.001                                    | 0.032                                    | 0.009                                    |
| Maximum [ $\text{m}^3/\text{s}$ ]            | 1.689                                    | 0.977                                    | 1.514                                    |
| Range [ $\text{m}^3/\text{s}$ ]              | 1.688                                    | 0.946                                    | 1.505                                    |
| Skewness                                     | 5.864                                    | 5.063                                    | 5.832                                    |
| Kurtosis                                     | 72.080                                   | 49.660                                   | 71.340                                   |
| Coefficient of variation (%)                 | 105.620                                  | 95.270                                   | 106.420                                  |

**Table 7.** Statistical characteristics of the simulated discharge series of the Jósva spring for the reference period (1981–2020) and the future periods (2022–2059 and 2060–2100).

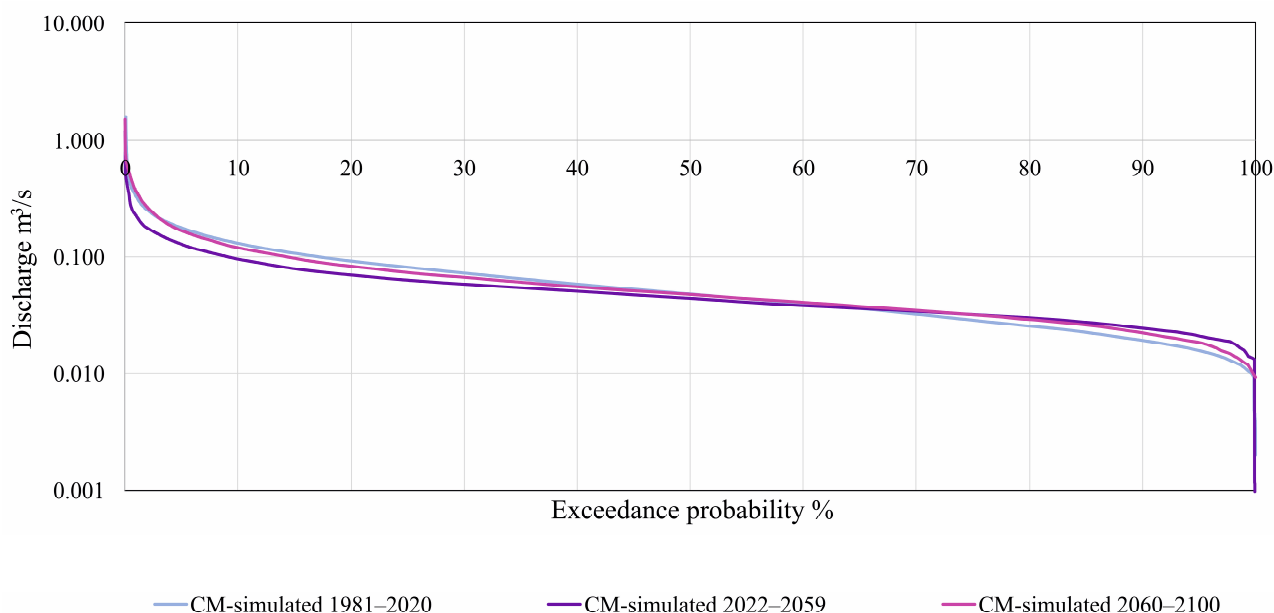
| Statistical Characteristics                  | Jósva Simulated CM<br>(1981–2020) | Jósva Simulated CM<br>(2022–2059) | Jósva Simulated CM<br>(2060–2100) |
|----------------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Number of observations                       | 14,246                            | 14,300                            | 14,975                            |
| Mean [ $\text{m}^3/\text{s}$ ]               | 0.231                             | 0.198                             | 0.224                             |
| Standard deviation [ $\text{m}^3/\text{s}$ ] | 0.156                             | 0.159                             | 0.227                             |
| Minimum [ $\text{m}^3/\text{s}$ ]            | 0.091                             | 0.048                             | 0.032                             |
| Maximum [ $\text{m}^3/\text{s}$ ]            | 3.871                             | 4.268                             | 4.457                             |
| Range [ $\text{m}^3/\text{s}$ ]              | 3.780                             | 4.220                             | 4.426                             |
| Skewness                                     | 4.532                             | 4.063                             | 4.632                             |
| Kurtosis                                     | 60.760                            | 58.660                            | 62.340                            |
| Coefficient of variation (%)                 | 64.710                            | 80.270                            | 101.420                           |

The statistical characteristics of the simulated discharge series reveal distinct future trends for the two springs. For the Jósva Spring, the mean discharge decreases from  $0.232 \text{ m}^3/\text{s}$  in the reference period (1981–2020) to  $0.198 \text{ m}^3/\text{s}$  in the near future (2022–2059), followed by a partial increase to  $0.224 \text{ m}^3/\text{s}$  in the late-century period (2060–2100), although it remains slightly below the reference value. At the same time, variability increases considerably. The standard deviation rises from  $0.156 \text{ m}^3/\text{s}$  to  $0.159 \text{ m}^3/\text{s}$  and further to  $0.227 \text{ m}^3/\text{s}$ , while the coefficient of variation increases from 64.71% to 80.27% and reaches 101.42% by the end of the century. Changes in extreme values further emphasize this trend. The minimum discharge decreases from  $0.091 \text{ m}^3/\text{s}$  to  $0.048 \text{ m}^3/\text{s}$  and further to  $0.032 \text{ m}^3/\text{s}$ , indicating worsening low-flow conditions. In contrast, maximum discharge increases from  $3.953 \text{ m}^3/\text{s}$  to  $4.268 \text{ m}^3/\text{s}$  and  $4.457 \text{ m}^3/\text{s}$ , resulting in a widening discharge range. Skewness (4.532–4.063–4.632) and kurtosis (60.76–58.66–62.34) remain high, indicating a strongly positively skewed and leptokurtic distribution throughout all periods.

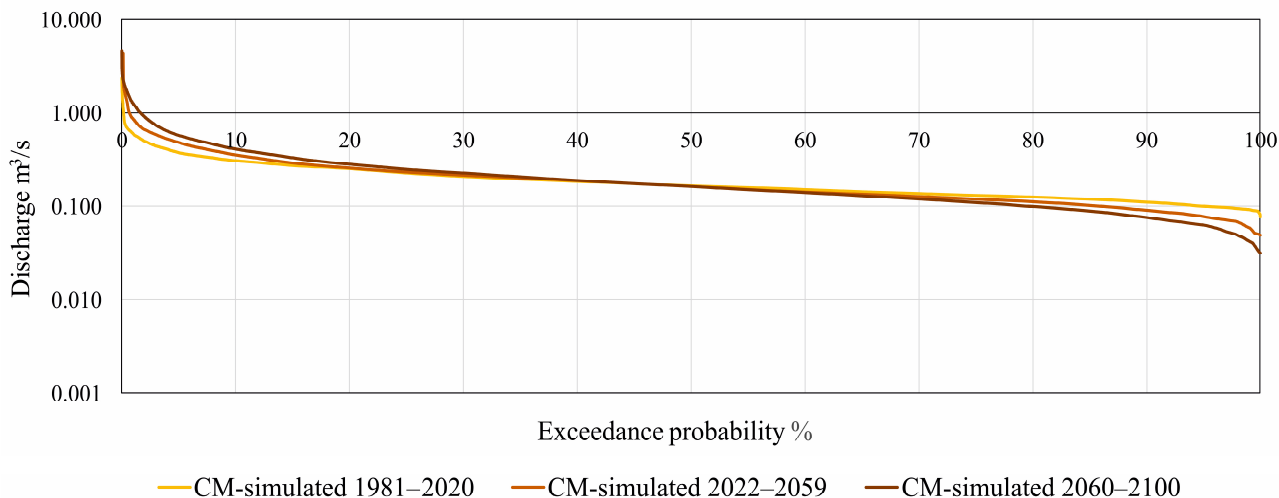
In contrast, the Nagy-Tohonya Spring shows a different pattern. The mean discharge decreases from  $0.070 \text{ m}^3/\text{s}$  in the reference period to  $0.060 \text{ m}^3/\text{s}$  in the near future, followed by a slight increase to  $0.065 \text{ m}^3/\text{s}$  in the late-century period, remaining below the reference value. Variability initially decreases, with the standard deviation dropping from  $0.072 \text{ m}^3/\text{s}$  to  $0.048 \text{ m}^3/\text{s}$ , and the coefficient of variation from 105.62% to 95.27%, indicating a temporary smoothing of discharge fluctuations. However, both indicators increase again by the end of the century (standard deviation:  $0.066 \text{ m}^3/\text{s}$ ; coefficient of variation: 106.42%). Extreme values follow a similar pattern. The minimum discharge remains very low but increases slightly in the near future ( $0.001$ – $0.032 \text{ m}^3/\text{s}$ ), while the maximum discharge decreases from  $1.689 \text{ m}^3/\text{s}$  to  $0.977 \text{ m}^3/\text{s}$ , followed by an increase to  $1.514 \text{ m}^3/\text{s}$  in the late-century period. Skewness (5.864–5.063–5.832) and kurtosis (72.08–40.66–71.34) indicate a persistently highly skewed distribution with pronounced extremes.

The flow duration curves (FDCs) of the simulated discharge series for the reference (1981–2020) and future periods (2022–2059 and 2060–2100) are shown in Figures 9 and 10 for both springs. The Flow Duration Curves (FDCs) of the Nagy-Tohonya Spring show clear differences between the reference period (1981–2020) and the simulated future periods. Across most of the exceedance probability range, the near-future curve (2022–2059) lies below the reference curve, indicating lower discharge values in this period. This difference is particularly visible in the high- to medium-flow range ( $Q_0$ – $Q_{50}$ ), where the separation between the curves becomes more pronounced. In the low-flow range ( $Q_{90}$ – $Q_{100}$ ), the near future curve (2022–2059) is above the reference period (1981–2020). In the late-century

period (2060–2100), the future curve shifts closer to the reference condition in most of the sections, especially in the medium-flow range ( $Q_{10}$ – $Q_{80}$ ). However, in the low-flow domain ( $Q_{90}$ – $Q_{100}$ ) the future curves show higher discharge values than the reference period.



**Figure 9.** Flow duration curves (FDC) of the CM-simulated discharge time series for the Nagy-Tohonya spring during the reference period (1981–2020) and the future periods (2022–2059 and 2060–2100).



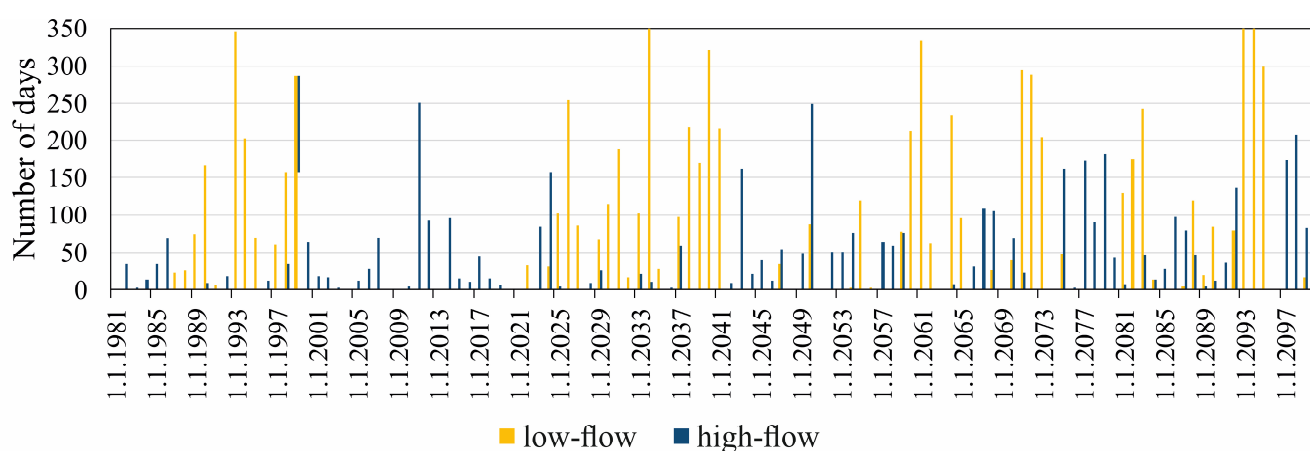
**Figure 10.** Flow duration curves (FDC) of the CM-simulated discharge time series for the Jósza spring during the reference period (1981–2020) and the future periods (2022–2059 and 2060–2100).

The Flow Duration Curves of the Jósza Spring also show distinct differences between the reference and future periods, although the pattern differs from that observed for the Nagy-Tohonya Spring. In the high-flow range ( $Q_0$ – $Q_{10}$ ), the future curves are above the reference curve, particularly in the late-century period (2060–2100), indicating similar or somewhat higher discharge values in this range. In the medium-flow range ( $Q_{10}$ – $Q_{50}$ ), the curves follow a very similar pattern across all periods, with only minor deviations. In the low- to medium-flow range ( $Q_{50}$ – $Q_{90}$ ), the future curves lie slightly below the reference curve, indicating somewhat lower discharge values in this section. In the low-flow domain ( $Q_{90}$ – $Q_{100}$ ), the differences become more pronounced, and the future curves, especially

for the period 2060–2100, show lower discharge values compared to the reference period. Overall, the curves indicate that differences between the reference and future periods are more evident in the low-flow range, while the high-flow and medium-flow ranges remain relatively similar.

To further examine changes in discharge conditions, a threshold-based analysis was carried out using percentile values derived from the reference period. The annual number of extreme discharge days was determined using  $Q_{10}$  and  $Q_{90}$  thresholds, where days exceeding  $Q_{10}$  represent wet (high-flow) conditions, and days below  $Q_{90}$  represent dry (low-flow) conditions. The number of days in each category was calculated annually for the period 2022–2100.

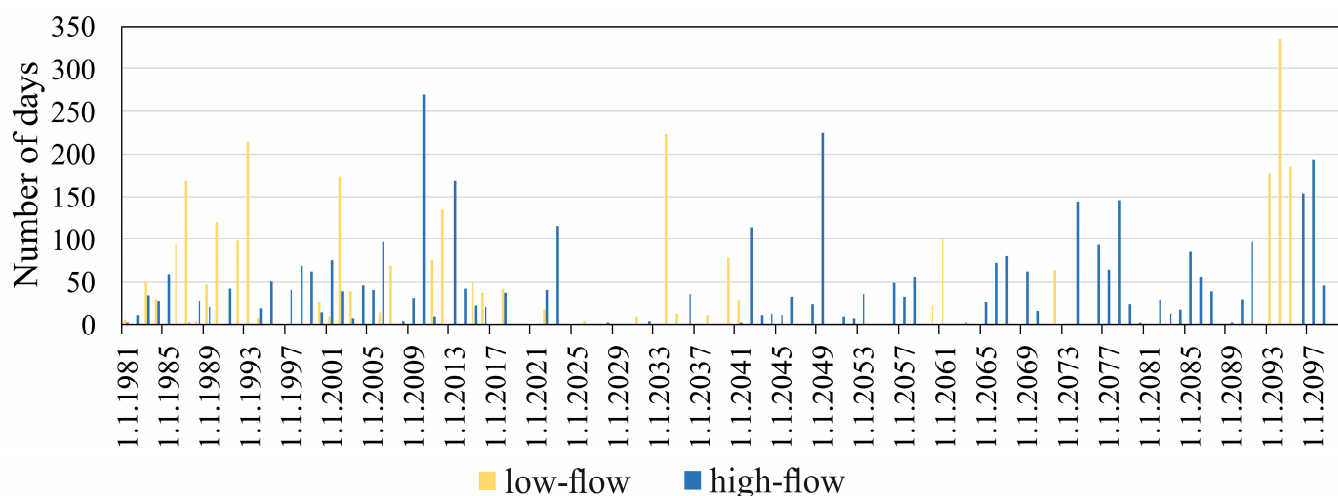
The results of Jósfa Spring reveal pronounced interannual variability in both dry and wet conditions (Figure 11). The number of dry days exhibits a wide range, with several years showing no dry days, while in other years extremely high values occur. Indeed, multiple years show prolonged dry periods exceeding 200 days (e.g., 2026, 2038, 2040, 2061, 2071–2073), indicating persistent low-flow dominance. In contrast, wet days occur more episodically and are generally less frequent. Several years show no wet days at all, while in other years exceptionally high values are observed (e.g., 2023: 156 days, 2042: 162 days, 2049: 248 days, 2076–2078: 172–181 days, 2096–2097: 174–206 days). Overall, the system is characterized not by clear monotonic trends but by strong variability and alternating extreme years. Particularly notable is the frequent occurrence of prolonged dry periods, including years dominated entirely by low-flow conditions, as well as the episodic clustering of wet events. This behavior suggests an increasing extremity in the discharge regime of the spring.



**Figure 11.** Annual number of low-flow and high-flow days for the Jósfa Spring during the reference and future periods. Low-flow days (yellow) were defined as days with daily discharge below the  $Q_{90}$  threshold, whereas high-flow days (blue) were defined as days with daily discharge above the  $Q_{10}$  threshold. Both thresholds were derived from the reference-period discharge distribution and applied consistently to the reference and future periods.

For the Nagy-Tohonya Spring, the annual occurrence of extreme-flow days is dominated by high-flow ( $Q_{10}$ ) days throughout most of the simulated future period, whereas low-flow ( $Q_{90}$ ) days occur less frequently and more episodically (Figure 12). From the 2070s onward, wet periods in the range of 50–150 days become increasingly frequent, indicating a rapid and pronounced system response to precipitation events. In contrast, dry days occur less frequently and show a more episodic pattern. In most years, no  $Q_{90}$  events are observed; however, some years exhibit exceptionally high values particularly in the late century. These events reflect prolonged low-flow conditions but are less persistent compared

to those observed at the Jósfa Spring. Overall, the discharge regime of the Nagy-Tohonya Spring is primarily controlled by rapid and intense responses to precipitation events, occasionally interrupted by longer dry periods. Thus, the system is characterized not by a clear long-term trend but by strong temporal clustering and alternation of extreme events.



**Figure 12.** Annual number of low-flow and high-flow days for the Nagy-Tohonya Spring during the reference and future periods. Low-flow days (yellow) were defined as days with daily discharge below the  $Q_{90}$  threshold, whereas high-flow days (blue) were defined as days with daily discharge above the  $Q_{10}$  threshold. Both thresholds were derived from the reference-period discharge distribution and applied consistently to the reference and future periods.

## 6. Discussion

### 6.1. Hydrological Differences Between the Nagy-Tohonya and Jósfa Karst Systems

The statistical characteristics of the discharge time series and the results of the Flow Duration Curve (FDC) analysis of springs together with other investigated parameters (recession coefficients, periodicity) can reveal clear differences in the hydrological behavior within the karst area. Analyzing the FDC and recession of distinct flood events can help us to understand the responses for rain events and provide information on differences in aquifer drainage, hydrological responsiveness and buffering behavior, as well as potential implications for karst vulnerability (e.g., [25,51,62,67,68]).

The combined results consistently indicate contrasting hydrological behavior of the two karst springs. The Nagy-Tohonya Spring is characterized by a highly variable and rapidly responding discharge regime with limited hydrological buffering, whereas the Jósfa Spring exhibits lower relative variability, more sustained low flows, and a more buffered hydrological response. Several independent indicators support this distinction. The coefficient of variation is substantially higher for Nagy-Tohonya (131%) than for Jósfa (69%), while the FDC of Nagy-Tohonya is steeper than that of Jósfa, particularly toward the low-flow domain (Figure 3), indicating greater discharge variability. The minimum discharge of Nagy-Tohonya is also markedly lower ( $0.001 \text{ m}^3/\text{s}$ ) than that of Jósfa ( $0.042 \text{ m}^3/\text{s}$ ). Although the difference in absolute discharge partly reflects the larger recharge area of the Jósfa Spring, its higher minimum discharge together with its lower relative variability is consistent with more sustained discharge under dry conditions. The  $Q_{10}/Q_{90}$  ratio similarly indicates greater relative discharge variability at Nagy-Tohonya. Temporal analyses provide independent support for this interpretation: the autocorrelation of Nagy-Tohonya decreases more rapidly (Figure S2), whereas Jósfa retains a longer hydrological memory. In addition, the consistently higher recession coefficients of Nagy-Tohonya indicate more rapid drainage, whereas the lower values of Jósfa are consistent

with its more buffered hydrological response. Within the theoretical framework of recession analysis, these differences may reflect differences in the effective hydraulic and geometric properties controlling transient aquifer drainage. Together, these independent indicators demonstrate that the two geographically close springs differ substantially in the way recharge variability is transmitted and buffered within their respective karst systems.

The shape of the discharge distributions provides further insight into system behavior (Table 1). Both distributions exhibit strong positive skewness (skewness  $\approx 5$ ), indicating that low and moderate discharges dominate, while high-flow events occur less frequently. However, kurtosis differs markedly between the two springs: approximately 40 for the Nagy-Tohonya Spring and about 71 for the Jósza Spring. This later high value reflects the presence of rare but very large discharge events and point to pronounced flood peaks. Such positively skewed and leptokurtic discharge distributions are characteristic of highly variable karst spring regimes, where relatively infrequent high-flow events produce pronounced upper tails and discharge variability reflects both recharge conditions and the hydraulic characteristics of the aquifer and its drainage system [69]. Hydraulic constraints within karst conduit networks may further influence extreme discharges. Bonacci [70] showed, based on several Central European karst springs, that maximum spring discharge may be controlled by the hydraulic capacity of conduits, depending on their geometry, roughness, and possible constrictions. Under extreme recharge conditions, spring discharge may therefore approach a physical limit imposed by the karst drainage network.

Based on these statistical indicators, the Nagy-Tohonya Spring can be interpreted as a fast-responding karst system with limited hydrological buffering, characterized by pronounced discharge variability and rapid responses to recharge events. This results in pronounced variability and short, high-amplitude flood peaks. Similar behavior has been documented in conduit-dominated systems such as the Fontaine de Vaucluse and Ombla springs [16,70]. In contrast, the Jósza Spring exhibits a more buffered hydrological response, with lower relative discharge variability and more sustained discharge under low-flow conditions. This buffering reduces the amplitude of discharge fluctuations and leads to a more stable regime. At the same time, the very high kurtosis suggests that rare but extreme events may still occur under saturated conditions, reflecting episodic activation of conduit flow.

The contrasting hydrological characteristics of the two systems also influence their responses to meteorological and climatological conditions, which are clearly reflected in the detectable periodicities of both the Jósza and Nagy-Tohonya springs (Figure S3). Periodogram analysis reveals a well-defined annual periodicity ( $\sim 365$  days) in both cases, indicating a strong seasonal climatic control of the hydrological systems. This suggests that discharge variations are primarily governed by the annual distribution of precipitation and temperature-driven evapotranspiration processes. In addition, periodicities in the multi-year range ( $\sim 3$ – $5$  years) point to interannual climatic variability, while peaks in the  $\sim 10$ – $20$  year range can be linked to larger-scale regional climatic processes. For the Nagy-Tohonya Spring, the annual periodicity remains clearly dominant, with multi-year components playing only a secondary role. In contrast, at the Jósza Spring, longer periodicities, particularly those on decadal scales, are more pronounced, indicating differences in hydrodynamic functioning between the two systems. In both springs, the annual cycle is continuously present, confirming its dominant role. However, the multi-year components are not temporally stable: their intensity varies over time, strengthening during certain periods and weakening in others. This suggests that, in addition to the seasonal cycle, the hydrological behavior is also influenced by multi-year climatic effects with variable intensity. The results of the spectral and wavelet analyzes clearly demonstrate that the Nagy-Tohonya and Jósza springs represent two karst systems with fundamentally dif-

ferent hydrodynamic characteristics, which strongly control their responses to climatic variability. The Nagy-Tohonya spring can be characterized as a fast-responding system with limited hydrological buffering, where discharge dynamics are primarily driven by direct precipitation events. Consequently, it exhibits a rapid hydrological response with high amplitude fluctuations and strong sensitivity to short-term changes. In contrast, the Jósza Spring exhibits a more buffered hydrological response, in which the influence of short-term recharge variability is less pronounced and longer-term variations are more clearly preserved in the discharge signal.

All these findings together suggest that the contrasting hydrological functioning of the two systems may result in different sensitivities to climatic variability, which is particularly relevant when interpreting potential future changes in spring discharge. Overall, the results emphasize the key role of the internal karst structure, including its geology (type of rock, geological formations) and storage capacity in controlling spring discharge behavior, even within the same regional karst environment. Indeed, the catchment area of Nagy-Tohonya Spring is mainly associated with the dolomitic members of the Wetterstein Formation together with the Gutenstein Formation, whereas the recharge area of Jósza Spring is dominantly linked to the massive limestone units of the Wetterstein Formation (Figure S1) [33,40–42]. The dolomitic Wetterstein units and the Gutenstein Formation generally form a more heterogeneous and structurally controlled karst aquifer system, where fracture permeability and preferential flow paths dominate groundwater circulation. Although dolomite is typically less intensively karstified than massive limestone, however tectonic fracturing can facilitate rapid infiltration and higher matrix permeability, which may contribute to the highly dynamic hydrological response observed in the Nagy-Tohonya system. This results in discharge time series with high positive skewness and kurtosis, reflecting frequent low-flow conditions interrupted by sharp flood peaks, as noted above. In contrast, the limestone-dominated Wetterstein Formation feeding Jósza Spring consists predominantly of well-karstified massive platform carbonates capable of storing and transmitting substantial amounts of groundwater through an integrated fracture-conduit network. The more buffered hydrological response of the Jósza Spring dampens short-term discharge variability, resulting in a more stable discharge regime, consistent with its lower coefficient of variation and less pronounced fluctuations compared with the Nagy-Tohonya Spring.

Overall, the statistical characteristics of the discharge time series reveal clear differences in the hydrological functioning of the two karst systems which ultimately related to the geology and size of the catchment area, as well as provided a robust basis for evaluating model performance.

## 6.2. Performance and Limitations of the Hydrological Model

The performance of the hydrological model was evaluated by analyzing the relationship between measured and simulated discharge time series using several statistical indicators. For the Nagy-Tohonya Spring, the Pearson correlation coefficient is 0.72, while the Nash–Sutcliffe efficiency coefficient is 0.54, indicating an acceptable level of model performance in hydrological applications. This suggests that the model is capable of reproducing the main trends of the discharge time series, although its ability to capture the detailed dynamics of the hydrological response remains limited. A more detailed analysis of the statistical characteristics of Nagy-Tohonya Spring reveals systematic differences between the observed and simulated time series. The simulated mean discharge ( $0.073 \text{ m}^3/\text{s}$ ) is a bit lower than the observed value ( $0.077 \text{ m}^3/\text{s}$ ) (Table 2), indicating a slight underestimation of average discharge. The reduced standard deviation and lower coefficient of variation further suggest that the model slightly dampens the amplitude of discharge

fluctuations, resulting in a smoother representation of the hydrological response in the simulated series. The comparison of extreme values provides additional insight into model behavior (Table 2). While the minimum discharge is identical in both datasets ( $0.001 \text{ m}^3/\text{s}$ ), the maximum value is higher in the simulation ( $1.540 \text{ m}^3/\text{s}$ ) than in the observations ( $1.492 \text{ m}^3/\text{s}$ ), indicating that the model may overestimate certain rare extreme events in case of Nagy-Tohonya Spring. At the same time, exceedance probability-based indicators show that the Q10 value is lower in the simulation, suggesting that more frequent high-flow events are generally underestimated. This dual behavior indicates that the model tends to attenuate moderate flood events while occasionally producing exaggerated peak values for rare extremes.

These discrepancies are consistent with the structural characteristics of the Gardénia model, which represents catchment hydrological processes using a system of conceptual storage components. This modelling approach has limited capability to explicitly represent rapid conduit flow processes typical of karst systems; instead, their effects are incorporated in an aggregated manner. Consequently, the model tends to smooth the hydrological response, particularly in the case of high-amplitude, fast-flow events. This effect is less pronounced for Jósza Spring, which is associated with a high-storage, slower responding karst system. Therefore, for the Jósza Spring, the model shows better agreement between observed and simulated time series. Indeed, the Pearson correlation coefficient is 0.89, and the Nash–Sutcliffe efficiency coefficient is 0.69 for Jósza Spring, which can be considered good model performance in hydrological modelling. This indicates that the model adequately reproduces both the main trends and the variability of the discharge time series, supporting the reliability of future simulations.

The comparison of observed and simulated discharge series for both springs indicates that, in the present period, the model reproduces discharge variability in a more subdued manner than observed. In general, the simulated discharge distributions are confined to a narrower range, suggesting that the Gardénia model smooths discharge variability and shows limitations in reproducing rapid high-flow responses. We interpret this behavior as a consequence of the simplified conceptual representation of catchment processes in the model; however, whether this limitation is specific to the present karst systems or represents a more general feature of Gardénia applications to karst springs requires further investigation. Consequently, the model may partially underestimate hydrological variability and the amplitude of extreme events, which directly affects the interpretation of future projections. Accordingly, the results of future simulations should primarily be interpreted in terms of the direction and relative magnitude of changes, while absolute values, especially those related to extreme events, should be treated with greater caution.

An additional source of uncertainty is associated with the future climate forcing. The projections presented here are based on a single global–regional climate model chain (IPSL-CM5A-MR/SMHI-RCA4) under the RCP4.5 scenario and therefore do not represent the full range of uncertainty associated with alternative climate models or emission scenarios. Furthermore, future simulations assume that the calibrated model structure and parameters remain applicable under future climatic conditions. Consequently, the projected discharge series should be regarded as scenario-based estimates rather than deterministic predictions. The results are therefore most robust for comparing the relative responses of the two spring systems under the same climatic forcing, rather than for predicting exact future discharge values or individual extreme events.

### 6.3. Comparison of Future Changes for the Two Springs

The projected discharge behavior of the Jósza and Nagy-Tohonya springs highlights that the hydrological response to climatic changes is strongly system-dependent, influ-

enced by differences in aquifer geometry, hydraulic properties, and the resulting degree of hydrological buffering. The differences between the two systems become particularly evident when examining the evolution of discharge amplitudes and the distribution of extreme events.

For the Jósua Spring, future simulations suggest a clear widening of the discharge range, with higher peak flows and lower minimum discharges compared to the reference period. This indicates an increase in absolute amplitude and a progressive separation of low- and high-flow conditions. Such behavior may seem unexpected for a system characterized by relatively large storage capacity, where a buffering effect would typically be assumed. However, the results suggest that this buffering capacity becomes state-dependent under changing climatic conditions. During periods of intense recharge, the system approaches saturation more frequently, limiting its ability to store additional water. This behavior is consistent with a hydrologically buffered karst system in which water storage and drainage occur over different timescales. Consequently, instead of simply damping variability, the system may redistribute the effects of climatic forcing over time and, under certain conditions, amplify hydrological extremes. This is also reflected in the flow duration curves, where the divergence between reference and future conditions is visible in both the high-flow ( $Q_0$ – $Q_{10}$ ) and low-flow ( $Q_{90}$ – $Q_{10}$ ) ranges, indicating a shift towards more extreme discharge conditions. This pattern is consistent with broader evidence that hydrological change may be expressed differently across flow regimes rather than through uniform changes in mean discharge (e.g., [23,24,26,71]).

In contrast, the Nagy-Tohonya Spring exhibits a more constrained response. Although interannual variability remains high, no clear long-term trend is observed in the frequency of wet ( $Q_{10}$ ) and dry ( $Q_{90}$ ) days. This suggests that the system response is primarily event-driven rather than controlled by long-term storage dynamics. The limited hydrological buffering inferred from the discharge characteristics reduces the persistence of climatic signals in the spring response. Recharge variability is therefore more rapidly reflected in discharge, and changes are expressed primarily through the response to individual recharge events rather than through persistent shifts in discharge behavior. This explains why threshold-based indicators such as  $Q_{10}$  and  $Q_{90}$  show limited sensitivity, despite noticeable variability in the time series. The flow duration curves support this interpretation, as only minor deviations are observed between reference and future conditions, suggesting that the overall distribution of discharge remains relatively stable, even if the short-term dynamics fluctuate.

Overall, the comparison of the two springs indicates that their contrasting degrees of hydrological buffering strongly influence how climatic forcing is expressed in spring discharge. In the more buffered Jósua system, climatic signals are integrated over longer timescales, while the Nagy-Tohonya system responds more directly to short-term recharge variability. These contrasting responses may result in different patterns of change in discharge variability and extremes under future climatic conditions.

#### 6.4. Implications for Climate Adaptation and Water Management

The system-dependent responses identified in this study have direct implications for climate adaptation and water-resource management in karst regions. Our results demonstrate that regional climate projections alone may not be sufficient for assessing future groundwater availability, because karst systems exposed to similar climatic forcing may exhibit markedly different discharge responses depending on their hydrological characteristics. This highlights the importance of incorporating system-specific hydrodynamic information into climate-adaptation strategies and long-term water-resource planning.

In rapidly responding systems with limited hydrological buffering, such as the Nagy-Tohonya Spring, management should particularly consider vulnerability to persistent low-flow conditions and the limited ability of the system to maintain discharge during prolonged dry periods. In contrast, the more buffered Jósza Spring may maintain a more stable discharge regime under average conditions, while the projected widening of its discharge range indicates the increasing relevance of both high- and low-flow extremes.

The projected increase in high-flow extremes, particularly in the Jósza Spring, also has implications for flood management. Although increased spring discharge does not necessarily translate directly into downstream flooding, more pronounced high-flow events may increase short-term hydraulic loads on receiving streams and associated water-management infrastructure. Climate-adaptation strategies should therefore consider both sides of the projected hydrological extremes: maintaining water availability during prolonged low-flow periods and managing potentially increasing high-flow conditions.

Integrating long-term monitoring with climate-informed, system-specific hydrological modelling can therefore provide a scientific basis for identifying vulnerable periods, evaluating future water availability, and supporting adaptive groundwater management. Such an approach can strengthen the science–management interface by translating climate and hydrological information into evidence that can support water-resource planning, groundwater protection, flood-risk management, and climate-resilience strategies.

## 7. Conclusions

This study demonstrates that geographically close karst springs exposed to similar regional climatic forcing can exhibit markedly different hydrological responses due to differences in aquifer geometry and hydraulic properties. The combined evaluation of long-term discharge records, flow duration curves, recession behavior, periodicity, and hydrological modelling consistently distinguishes the rapidly responding and highly variable Nagy-Tohonya system from the more buffered Jósza system. This comparative approach provides evidence that system-specific hydrological characteristics strongly influence not only present-day discharge dynamics but also how climatic changes are translated into future spring discharge.

The main novelty of this study lies in demonstrating, through a direct comparative analysis, that two geographically close karst systems exposed to the same regional climatic forcing can translate climatic change into distinctly different discharge responses as a consequence of their contrasting hydrodynamic characteristics. Although mean discharge decreases at both springs during the near-future period (2022–2059), their subsequent responses diverge. At Nagy-Tohonya, the discharge regime remains characterized by pronounced temporal variability and persistent low-flow conditions, whereas at Jósza the discharge distribution progressively widens, with decreasing low flows accompanied by increasing high flows toward the end of the century. These results demonstrate that similar regional climatic forcing does not translate into a uniform hydrological response, even for neighboring karst systems.

These findings are consistent with previous studies showing that hydrological responses to future climatic forcing can vary substantially between individual catchments and hydrological systems [23,62]. In karst environments, this variability may be further influenced by aquifer hydraulic and geometric characteristics. The present comparison demonstrates that these controls may lead to contrasting responses to future climatic forcing even within the same regional karst setting. This has direct implications for climate adaptation and water management: regional climate projections alone are insufficient to assess future groundwater availability, and system-specific evaluations should consider not only changes in mean discharge but also the persistence of low-flow conditions and

the magnitude and frequency of high-flow events. Long-term monitoring combined with climate-informed hydrological modelling can therefore provide an important basis for adaptive groundwater management, water-resource planning and flood-risk management in karst regions. Modelled extremes should nevertheless be interpreted with caution, given the observed tendency of the Gardénia model to damp discharge variability in the investigated systems.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18192422/s1>. Figure S1: Geological and hydrogeological setting of the Jósza and Nagy-Tohonya spring systems in the Aggtelek Karst region. The red and blue outlines indicate the approximate recharge areas of the Jósza and Nagy-Tohonya springs, respectively. The recharge-area boundaries represent preliminary, unpublished delineations and should be considered approximate because of the inherent uncertainty in defining groundwater catchment boundaries in karst systems. The map shows the major geological formations and structural features of the Aggtelek–Rudabánya Mountains, the location of the Baradla Cave system, and the position of the study area within Hungary. The Nagy-Tohonya system is predominantly associated with the part of the Wetterstein Formation that includes dolomitic units, whereas the Jósza–Baradla system is mainly developed within the limestone-dominated part of the Wetterstein Formation. Geological map modified after Less (1997) [72]; Figure S2: Autocorrelation functions of the Jósza (red curve) and Nagy-Tohonya (blue curve) spring-discharge time series. Figure S3: Wavelet spectra and periodograms of the Jósza (left) and Nagy-Tohonya (right) spring-discharge time series. In the wavelet spectra, warmer colors indicate higher spectral power and cooler colors lower spectral power; the black line denotes the cone of influence. In the periodograms, crossed-out periods indicate periodicities that do not occur at least twice within the analyzed time series; Table S1: The principal hydrologically relevant GARDÉNIA model parameters used to represent the Nagy-Tohonya and Jósza spring systems. The selected parameters describe the main processes controlling recharge generation, rapid-flow partitioning, groundwater transfer, and the slower groundwater-storage component.

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