

Article

Assessing the Effect of Conduit Pattern and Type of Recharge on the Karst Spring Hydrograph: A Synthetic Modeling Approach

Hadi Ostad ¹, Zargham Mohammadi ^{1,*} and Francesco Fiorillo ²¹ Department of Earth Sciences, Faculty of Sciences, Shiraz University, Shiraz P.O. Box 71348-14336, Iran² Department of Science and Technology, University of Sannio, Via dei Mulini 59/A, 82100 Benevento, Italy

* Correspondence: zmohammadi@shirazu.ac.ir

Abstract: It is widely accepted that spring hydrographs are an effective tool for evaluating the internal structure of karst aquifers because they depict the response of the whole aquifer to recharge events. The spring hydrograph is affected by various factors such as flow regime, geometry, type of recharge, and hydraulic properties of conduit. However, the effect of conduit network geometry received less attention and required more comprehensive research studies. The present study attempted to highlight the impact of the two most frequent patterns of karst conduits (i.e., branchwork and network maze) on the characteristic of the spring hydrograph. Therefore, two conduit patterns, branchwork and network maze, were randomly generated with MATLAB codes. Then, MODFLOW-CFP was used to quantify the effect of conduit pattern, conduit density, and diffuse or concentrated recharge on the spring hydrograph. Results reveal that peak discharge, fast-flow recession coefficient, and the return time to baseflow are mainly affected by conduit network pattern, conduit network density, and recharge, respectively. In contrast, the time to reach peak flow only reacts to recharge conditions. Large variations in conduit density produce tangible changes in the baseflow recession coefficient.

Keywords: spring hydrograph; conduit patterns; MATLAB code; MODFLOW-CFP; recession coefficient; baseflow



Citation: Ostad, H.; Mohammadi, Z.; Fiorillo, F. Assessing the Effect of Conduit Pattern and Type of Recharge on the Karst Spring Hydrograph: A Synthetic Modeling Approach. *Water* **2023**, *15*, 1594. <https://doi.org/10.3390/w15081594>

Academic Editor: Aizhong Ye

Received: 5 March 2023

Revised: 7 April 2023

Accepted: 13 April 2023

Published: 19 April 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Highlights:

1. The network maze conduit pattern is generated based on a newly developed code.
2. A synthetic modeling approach is applied to characterize the shape of the spring hydrograph.
3. The interaction of conduit patterns and recharge types mainly affects the spring hydrograph.
4. Peak discharge and time are controlled by conduit patterns and recharge events, respectively.
5. The recession coefficient is mainly affected by the density of conduits.

1. Introduction

Karst water resources play a crucial role on a worldwide scale since 20–25% of the world's population relies on water from these areas [1]. Karst aquifers are characterized by sinkholes, conduits, springs, and drainage systems due to dissolution, internal drainage, and collapse [2]. Karst systems are a complex and heterogeneous medium due to the simultaneous influence of various geological, hydrogeological, and chemical factors in their development and evolution [3,4]. Karst aquifers are complex due to their inherent heterogeneity, which has made it hard to determine their function [5]. However, karst aquifers have been considered a medium with double porosity (conduit and matrix) or triple porosity (conduit, fracture, and matrix). Their main characteristic is triple porosity, leading to different flow and storage in the matrix, channels, and fractures [6].

Moreover, the heterogeneity from developing the karst conduit network is not comparable to heterogeneous porous media and fractured limestone aquifers. As a result of karst development processes, several inception karst horizons, such as major discontinuities, joints, fractures, and bedding planes, create a hydraulic connection from the karst surface

features to discharging points, such as major springs. The heterogeneity of karst systems gradually organizes and develops, becoming an integrated drainage system similar to hierarchical river systems [7].

Due to the heterogeneity and complexity of karst aquifers, generalization of the information obtained locally and pointwise by conventional methods, such as pumping tests and tracing tests to the whole aquifer at a regional scale, may lead to misinterpretation of existing conditions [8]. Understanding and predicting the hydrological behavior of karst systems requires using various complementary and step-by-step methods [9]. Therefore, information from surface hydrology, hydrogeology, geochemistry, and geophysics methods must be combined at different scales to provide a more comprehensive and realistic description of the karst system [10]. So far, many indirect methods, such as hydrochemical analysis, time series analysis, hydrograph analysis of springs, well hydrograph analysis, and modeling techniques, have been frequently used to understand the conditions governing the karst aquifer and its characteristics. Karst aquifer's functions can be more precisely determined by examining the spring hydrograph recession curve than by any other approach [5]. The spring hydrograph reflects the response of the entire aquifer system to precipitation and recharge events and provides a reliable insight into the hydrogeology and hydraulics of the karst aquifer [8].

The overall response of the aquifer to each precipitation event appears as individual peaks in the hydrograph curve. Each peak has an ascending and a descending limb (Figure 1). The spring hydrograph recession curve runs from one peak to the start of the following ascending limb [11]. The falling segment is more stable than the rising part of the hydrograph and can express the hydraulic and geometric properties of the karst aquifer [12]. The descending limb of the hydrograph includes at least two parts with steep (i.e., flood recession) and mild (i.e., baseflow recession) slopes.

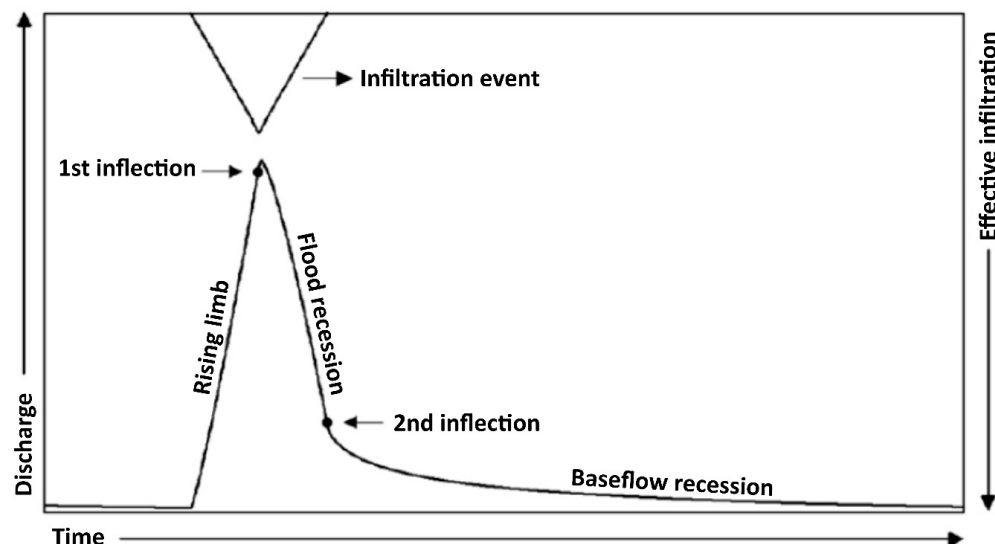


Figure 1. A graphical representation of spring hydrograph components. The first inflection point shows the maximum infiltration state, and the second inflection point represents the end of the infiltration event [13].

Fiorillo [12] provides a review of the several mathematical functions that have been suggested to characterize the recession limb. The spring hydrograph is affected by a wide variety of factors, such as flow regime [14], epikarst and unsaturated zone structure [15], type of recharge [11,16], amount of annual precipitation [16], frequency of precipitation events, the shape and size of catchment area [11], geometry and hydraulic properties of conduits [5,11], transfer flow between conduit and matrix [17], lithological characteristics of the aquifer [18], the thickness of the aquifer below the outlet [19], and the dominant conduit network pattern [20]. However, the effect of conduit network geometry on the

hydrograph of springs and observation wells has not been well studied and requires more comprehensive research. This present study attempted to investigate the effect of a few frequent karst conduit patterns and how they are connected to the spring hydrograph.

The most comprehensive classification of karst conduit patterns in carbonate rocks was suggested by Palmer [21] based on the interaction between the dominant initial porosity and the type/origin of the dissolution agent (Figure 2). Among the studied caves, the branch pattern with 57% frequency and network pattern with 17% are more frequent. In the branch type, the first-order branches (i.e., order 1) are fed by a separate recharge source. The second-order branches are formed when the branches with order 1 connect to each other. With increasing the order of conduits, the groundwater flow is concentrated downstream until drained through spring. In a well-developed branchwork conduit pattern, the number of conduits (i.e., the density of conduits) tends to decrease from the upstream to the discharge site but their diameter increases. This pattern is equivalent to dendritic river channels with rarely closed loops. Contrary to the branching pattern, closed loops are abundant in the network pattern, and it has a similar appearance to the streets of a city [21]. Since the map of actual conduit patterns is rarely known except by direct cave mapping and/or partly by indirect geophysical methods, a wide range of theoretical approaches has been introduced to generate the possible karst conduit patterns [22–24].

CAVE PATTERN		curvilinear branchwork	rectilinear branchwork	anastomotic maze	network maze	spongework maze	ramiform pattern
SOURCE OF AGGRESSIVE WATER	dolines	●	●	●	●	●	
	sinking streams	●	●	●	●	●	
	uniform seepage				●	●	
	mixing of 2 sources				●	●	●
	hypogenic			●	●	●	●
DOMINANT STRUCTURES	bedding - plane partings	●		●		●	●
	fractures		●		●		●
	matrix porosity					●	●

Figure 2. Common patterns of dissolution conduits in carbonate rocks. The size of the black circles shows the relative abundance of cave types in each of the listed categories [25].

Several methods have been proposed to generate a pattern of possible karst conduits, which in general, can be said to follow two approaches: structure-imitating and process-imitating. Reproducing the network of conduit structure by statistical methods that are not reliant on calculations from physical and chemical processes is the aim of structural imitation approaches [24,26–28]. How to generate realistic connection patterns using pure statistical tools is still an open question. On the contrary, the process-imitating approach attempted to produce a pattern of conduits based on speleogenesis principles [29–31]. Positive feedback between dissolution and flow leads to self-organization of the conduit network, consequently creating a realistic conduit pattern. However, the dependence of the produced conduit network on the model boundary conditions is one of the disadvantages of this approach [32,33]. To model the flow and particle transport in a hypothetical karst sys-

tem, Ronayne [28] used the invasion percolation algorithm to generate a conduit network, which is an example of a structure-imitating approach. This structural model (nonlooping invasion percolation model) was suggested to produce a branch conduit pattern and cannot run for creating other conduit patterns, such as network conduit patterns [32]. The current research used a structure-based approach to generate branchwork and network maze conduit patterns.

To compare the effect of different patterns of conduit networks on the spring hydrograph, a synthetic numerical modeling approach is considered. The lack of precise data on the pattern of conduits in real-field karst aquifers causes ambiguity in the interpretation of the effect of conduit pattern on the spring hydrograph. However, a synthetic numerical modeling approach can produce a spring hydrograph under a controlled setting in a karst aquifer that is allowed to host different conduit patterns. Numerical and laboratory karst models can potentially test new hypotheses [34,35] and analyze karst aquifer's spatial and temporal functions [34]. Despite the known challenges in applying mathematical models to karst aquifers due to the scarcity of required data, they are frequently implemented to sustain karst water resources [35]. Two general modeling approaches have been introduced in karst systems [36]: (1) spatially lumped models (i.e., global models) and (2) spatially distributed models. Two examples of lumped models are hydrograph–chemograph analysis and discharge–precipitation models [36].

Moreover, the equivalent porous medium (EPM) approach, dual porosity model (DPM), discrete fracture network approach (DFN), discrete channel network approach (DCN), and hybrid model (HM) are examples of spatially distributed models [37]. Hybrid models (HM) merge discrete (DFN and DCN) with equivalent porous medium models. These models simulate conduit and fracture as one-dimensional or two-dimensional elements in a three-dimensional matrix [36]. Insufficient knowledge of the conduit network geometry, position, distribution, and size poses significant limitations to applying numerical models in karst systems. These limitations have led to discrete–continuous numerical studies often performed on karst systems with simple conduit geometry. Yet, natural karst aquifers are typically quite heterogeneous and have complicated conduit networks. Due to the heterogeneity and influence of hydrodynamic characteristics of the aquifer, conduit networks are significant. An appropriate assessment of the state of the karst system's conduit network should be given to improve the accuracy of the modeling of the karst system [33].

This research addresses three basic inquiries: (1) how the randomly generated network maze conduit pattern compared to the branchwork pattern, (2) how the pattern and geometry of the karst conduits (i.e., branchwork and network maze patterns) affect the characteristics of the spring hydrograph, for example, the time to reach a peak discharge and baseflow discharge and recession coefficients, and (3) how the recharge types (i.e., concentrated and diffuse) alter the conduit pattern's impact on the spring hydrograph.

2. Methods

2.1. Generation of Conduit Networks

Two conduit patterns, branchwork and network, were generated to assess the effects of the pattern of conduits on the spring hydrograph. A series of MATLAB codes were utilized to create the patterns.

The curvilinear branchwork pattern was generated based on the MATLAB program (MATLAB code S1) introduced by Ronayne [38]. In the first step, a two-dimensional grid with normal distribution is created. Each square cell of the grid is randomly assigned a resistance value, indicating the cell's resistance to invasion. This resistance represents the combined effect of different physical properties of the karst media, such as limestone purity, stratigraphy, tectonics, etc. In the second step, one seed cell (as a spring) is defined in the lowest row of the grid area (i.e., lower boundary). In the third step, the conduit growth starts from the seed location and continues by attacking the neighboring cells with the least resistance. A maximum of two neighboring cells can be attacked in each iteration. The

newest conduit cells attacked at one growth stage are considered the source cells at the next stage. To prevent loops in the conduit network, the new cell is only attacked if all its neighbors except the source cell are not occupied. The conduit network continues to expand in this manner until there are no more sites to attack; usually, this happens when the conduit network reaches the boundary of the area (right, left, and upper boundary of the grid domain). In the fourth step, a number is assigned to the tributaries of the conduit network based on the ordering method proposed by Strahler [39]. Finally, all tributaries of the conduit network are numbered from order 1 to the largest order, which is allocated to the tributaries far from and close to the spring, respectively (Figure 3). The curvilinear branchwork pattern may be generated with different geometry in terms of length, density, tortuosity, and direction of tributaries by changing the anisotropy factor and assuming a threshold for the order of conduits [28].

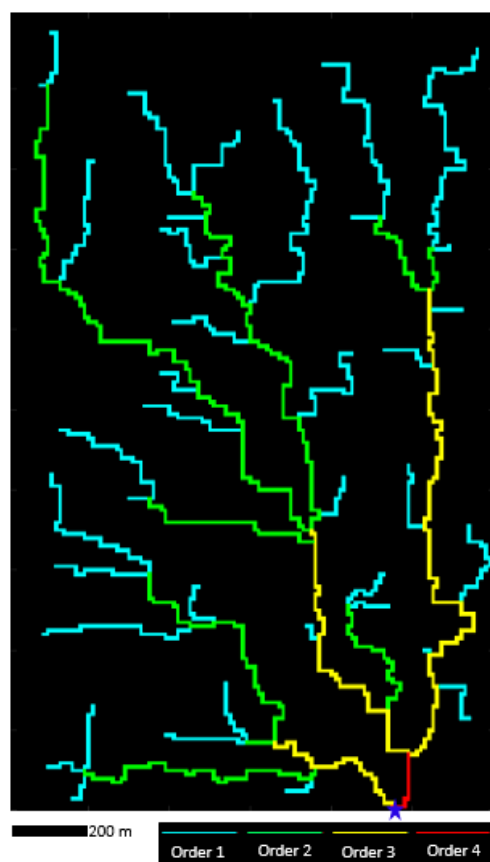


Figure 3. The branchwork pattern assuming different orders for conduits generated based on the invasion theory [38]. The blue star displays the location of the spring that initiates conduit formation.

A network conduit pattern (Figure 4b) was generated with the following steps: (1) a two-dimensional joint set (Figure 4a) was randomly generated using the ADFNE1.5 code (MATLAB code S2) [40], and (2) one seed cell (as a spring) is defined in the lower boundary, and the conduit growth starts from the seed location and continues along the joints. The neighbors that can be attacked are a maximum of three; for a new cell to be attacked, its neighbors do not need to be unoccupied. Such conditions enable the formation of loops in the conduit network because a cell can be attacked from different paths. Where the conduit network's growth reaches the joint intersection, it continues in shorter paths first, and (3) the conduit network was ranked using the algorithm proposed by Gleyzer et al. [41]. This algorithm allows a conduit to split into several downstream conduits, which can be reconnected at one point. The loops with the greatest distance from the starting point of the network (seed cell) are ranked first, and the order of conduits increases if independent tributaries join together [41].

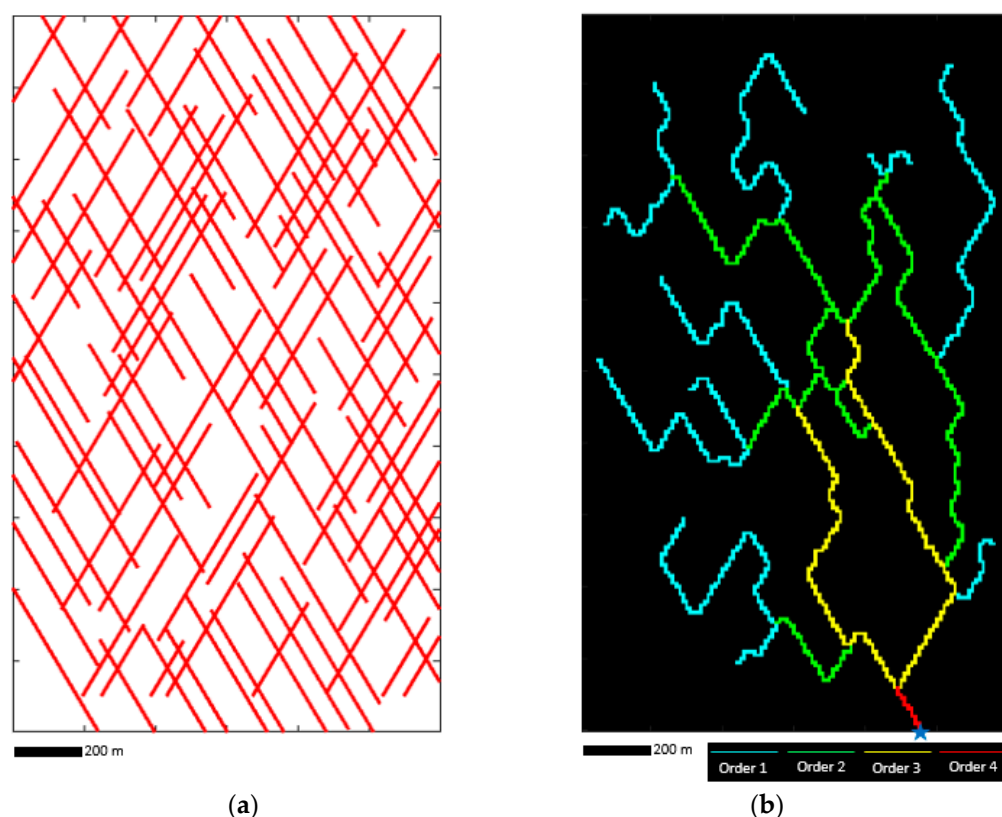


Figure 4. (a) The assumed random joint system and (b) the generated conduit network pattern with the order of conduits. The blue star is the seed cell (spring).

The generation of the rectilinear branchwork pattern is similar to the network maze pattern (MATLAB code S3), but the creation of closed loops in the conduit network is prevented.

2.2. Conceptual Model and Model Description

A conceptual model was created based on a synthetic karst aquifer to evaluate the impact of the conduit pattern on the karst spring hydrograph (Figure 6). Hypothetical karst conduits (i.e., generated branchwork and network patterns in Section 2.1) were transferred to ModelMuse v.4.2, and their hydrogeological parameters were defined. ModelMuse is an intuitive software package for running groundwater models, such as MODFLOW–2005, MODFLOW–CFP, etc. [42]. MODFLOW–CFP is a hybrid model that simulates flow in a karst aquifer with three modes. CFP-Model1 simulates the behavior of dual porosity in karst aquifers by coupling a linear flow model (MODFLOW–2005) with a network of discrete tubes/pipes (conduit system) [43]. MODFLOW–CFP employs the block-centered formulation, in which a node exists in each cell and is responsible for calculating the hydraulic head [43]. Each conduit is defined by a pipe that connects two nodes (the length of each pipe is equal to the distance between two nodes). Input parameters in CFP-Model1 include pipe height, pipe diameter, tortuosity, roughness coefficient, pipe wall permeability (exchange coefficient between pipe and matrix), and the upper and lower limit of Reynolds number.

The synthetic karst aquifer includes the conduit network hosted by a low permeability matrix, as assumed in previous studies (Chang et al. [5], Reimann and Hill [35], and Reimann et al. [44]). The matrix/fissured and conduit systems are coupled to represent the hydraulic system [45]. The model domain extends over 3000×1800 m, which is divided into cells with a length and width of 10 m. The synthetic karst aquifer was assumed to be an unconfined aquifer with a thickness of 400 m, and an elevation of zero was assigned to the bottom of the aquifer. The matrix is considered a homogeneous media with hydraulic

conductivity and a specific yield of 1×10^{-4} m/s, and 1×10^{-2} , respectively. The conduit wall permeability (i.e., k-exchange) was assumed to be 3.33×10^{-5} m/s. A karst spring with an elevation of 60 m was treated as the fixed head boundary. The initial head of the matrix was set to 60 m. Moreover, an elevation of 50 m was assigned to the elevation of conduits. The boundaries around the model were considered as no flow and fixed head boundaries (Figure 5).

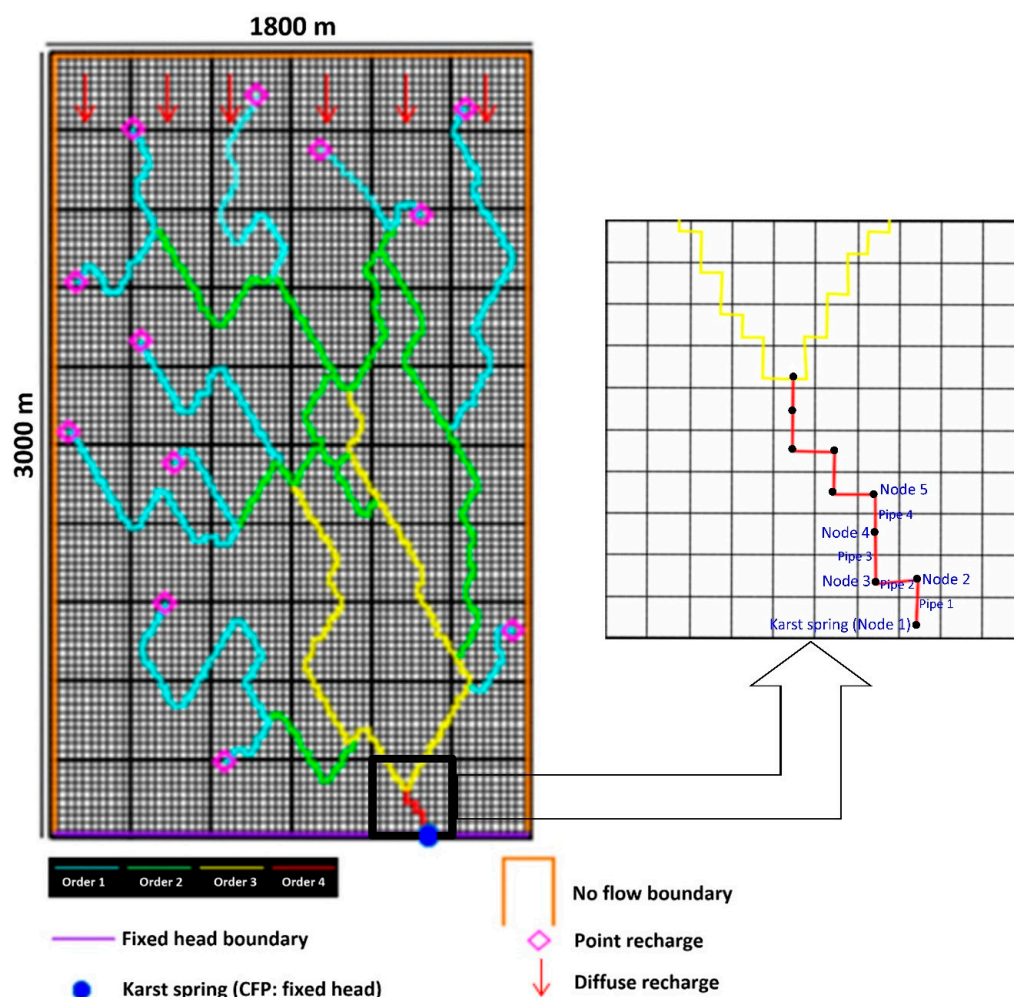


Figure 5. Plan view of the model used for the simulations.

The conduit networks include 774 nodes and 773 pipes, which are classified into 4 orders of diameter. The conduit Node 1 was set to a fixed head boundary representing a karst spring (Figure 5). To assign a reliable diameter to the conduits, conceptual and physical processes in developing different conduit patterns are considered. In particular, we know that the curvilinear branchwork pattern is generally developed along the bedding planes with dominant point recharge. In contrast, the rectilinear branchwork pattern combines joint and fracture structures and point recharge conditions [25]. However, the porosity of joints and fractures under diffuse recharge is responsible for developing a network maze conduit pattern. Therefore, since a uniform recharge through joints and fractures causes similar karst development in the network maze conduit pattern, the diameters of the conduits are assumed to be equal in the whole flow domain (Table 1). However, conduits enlarge hierarchically in the branchwork pattern. The conduit's diameter tends to be larger, close to the discharging spring, compared to the recharge area far from the spring location [25]. The assumed specifications (i.e., order and diameter) for the three patterns of conduit are shown in Table 1.

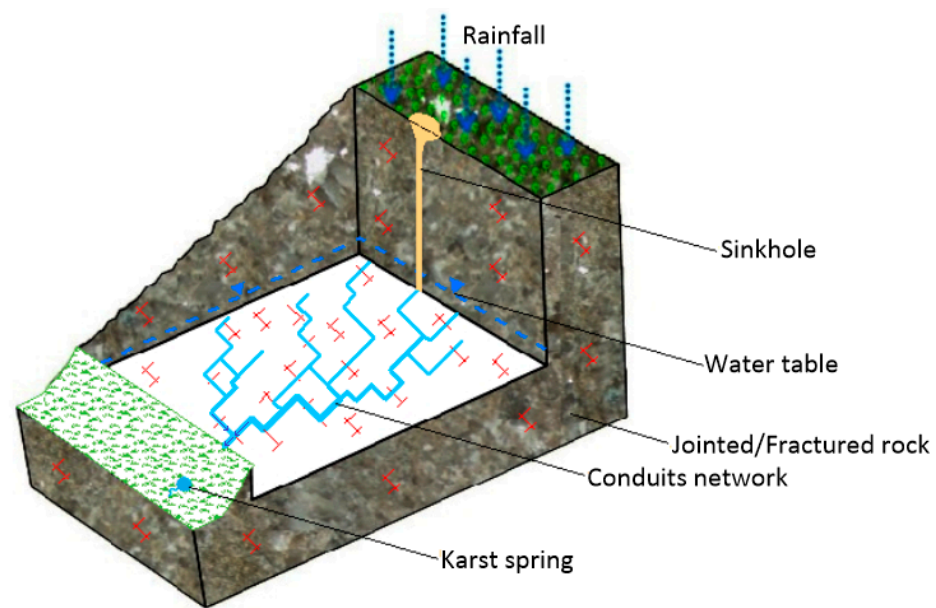


Figure 6. Schematic presentation of the synthetic karst aquifer (modified from Hubinger and Birk [46]).

Table 1. The assumed specifications for different conduit networks.

Conduit Pattern Characteristics		Diameter of Conduit (m)		
Order	Conduit Node	Curvilinear Branchwork	Rectilinear Branchwork	Network Maze
1	371	0.5	0.7	0.8
2	246	1	0.9	0.88
3	147	1.5	1.2	1
4	10	2	1.5	1.25

The entire model domain is supplied with constant diffuse recharge of 1×10^{-8} m/h. Additionally, the diffuse recharge caused by a multi-hour precipitation event was applied to all model cells (Figure 7). Moreover, in a few scenarios (Section 2.3), part of recharge is applied directly to the conduits through sinkholes as point recharge.

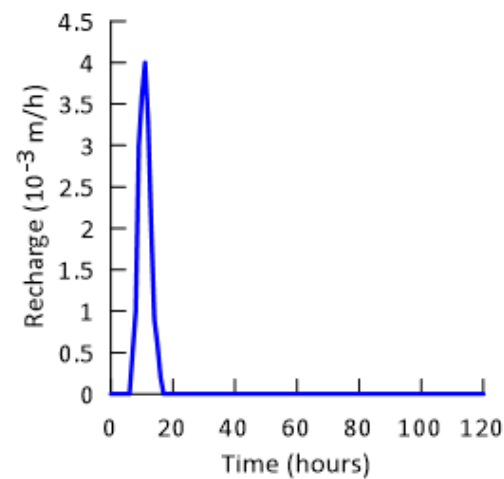


Figure 7. The amount of hypothetical recharge applied to the model.

A numerical model using MODFLOW-CFP [43] was set up based on the assumed synthetic karst model (Figure 5). A period of 120 h with a time step of 1 h was assumed for simulating flow and producing the spring hydrograph.

2.3. Simulation Scenarios

In order to assess the effect of conduit network geometry (e.g., curvilinear and rectilinear branchwork patterns versus network maze pattern), conduit density, and recharge type (e.g., diffuse versus point recharge) on the spring hydrograph, three sets of scenarios were considered (Table 2).

Table 2. Description of the assumed scenarios.

Scenario	Constant Parameters	Variable Parameters	Assumed Conduit Network	Recharge Type		The Number of Models Run
Scenario A	Hydrogeological characteristics of the aquifer (K, T, and S), K-exchange, Volume of conduit network, Boundary conditions (No flow boundary, Fixed head boundary, Karst spring), and Type of recharge	Conduit pattern	A1: Curvilinear branchwork	Diffuse Recharge (100%)	Point Recharge (0%)	3
			A2: Rectilinear branchwork			
			A3: Network maze			
Scenario B	Hydrogeological characteristics of the aquifer (K, T, and S), K-exchange, Conduit pattern, Boundary conditions (No flow boundary, Fixed head boundary, Karst spring), and Type of recharge	Conduit density	B1: the base model, including A1, A2, and A3	Diffuse Recharge (100%)	Point Recharge (0%)	9
			B2: 25% reduction in the length of the base model, including A1, A2, and A3			
			B3: 50% reduction in the length of the base model including A1, A2, and A3			
			B4: 75% reduction in the length of the base model, including A1, A2, and A3			
Scenario C	Hydrogeological characteristics of the aquifer (K, T, and S), K-exchange, Volume of conduit network, Boundary conditions (No flow boundary, Fixed head boundary, Karst spring), and Conduit pattern	Recharge type and amount	C1 (same as A1 or A2 or A3)	Diffuse Recharge (100%)	Point Recharge (0%)	6
			C2 (A1 or A2 or A3)	Diffuse Recharge (75%)	Point Recharge (25%)	
			C3 (A1 or A2 or A3)	Point Recharge (50%)	Diffuse Recharge (50%)	

The conduit pattern is the only variable assessed in scenario A (CFP input files S1). Other variables include hydrogeological characteristics of the aquifer (K, T, and S), exchange coefficient between matrix and conduits (K-exchange), the volume of conduit network, boundary conditions (no flow boundary, fixed head boundary, karst spring), and the type of recharge are the same in the three models of the scenario A (Table 2). The diffuse recharge type is considered in scenario A, and none of the conduit nodes receives the point recharge. Three conduit patterns (i.e., curvilinear branchwork, rectangular branchwork, and network maze) were used in scenario A to compare their effect on the spring hydrograph (Figure 8).

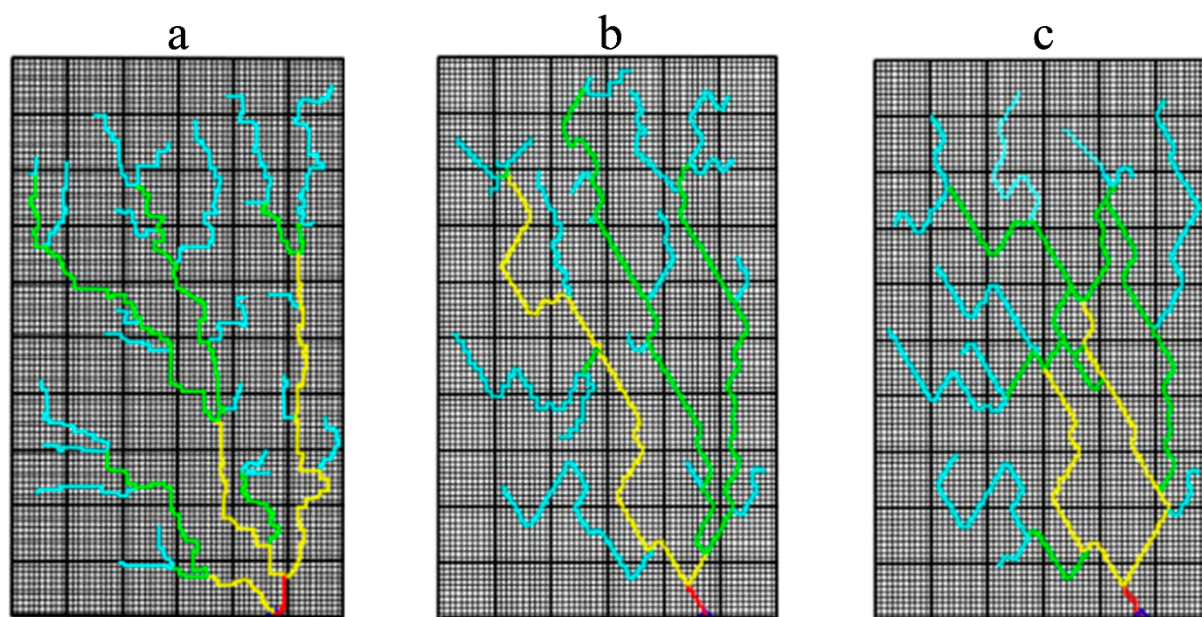


Figure 8. Three types of conduit patterns used in scenario A. (a) Curvilinear branchwork. (b) Rectilinear branchwork. (c) Network maze.

Scenario B evaluated the effect of conduit density on the spring hydrograph based on stepwise reduction of the number of conduits in three models introduced in scenario A (CFP input files S2). Therefore, for each pattern of conduits (i.e., three models in scenario A in Figure 8), three models were generated based on the reduction of conduit length by 25%, 50%, and 75% compared to the original model in Figure 8. The assumed density of conduits in curvilinear branchwork, rectangular branchwork, and network maze patterns are presented in Figure 9, Figures S1 and S2, respectively. Except for the volume of the conduits, all scenario B variables remained the same as in scenario A (Table 2). Moreover, the type and amount of recharge in scenario B are similar to scenario A.

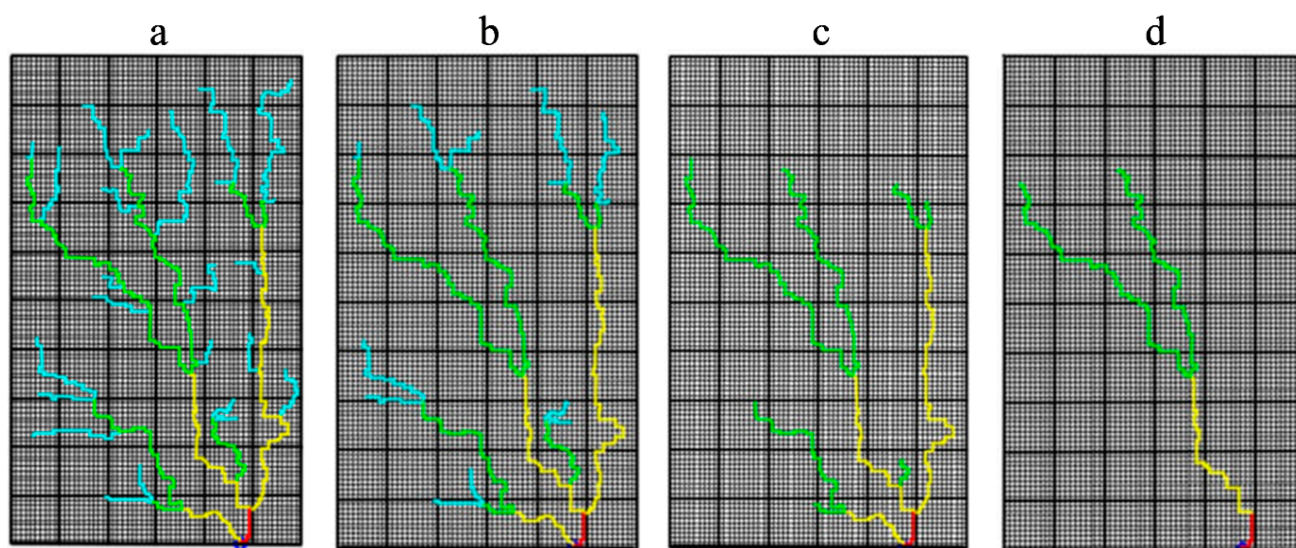


Figure 9. Curvilinear branchwork patterns with different conduit densities in scenario B. (a–d) represent the base curvilinear branchwork model, with 25%, 50%, and 75% reduction in the length of conduits, respectively. Rectilinear branchwork and network maze patterns with different conduit densities in scenario B can be found in the Supplementary Materials (Figures S1 and S2, respectively).

In scenario C, the effect of recharge type (i.e., the contribution of the diffuse and point recharge) on the spring hydrograph was investigated (CFP input files S3). Three conduit patterns introduced in scenario A (Figure 8) were considered to compare the effect of stepwise reduction of the diffuse recharge by 25% and 50% and allocating these values to the point recharge. However, the rest of the variables and conditions of scenario C models remain the same as scenario A (Table 2). The pattern of conduits and the assumed location of point recharge (i.e., sinkholes) in scenario C is presented in Figures 10 and S3.

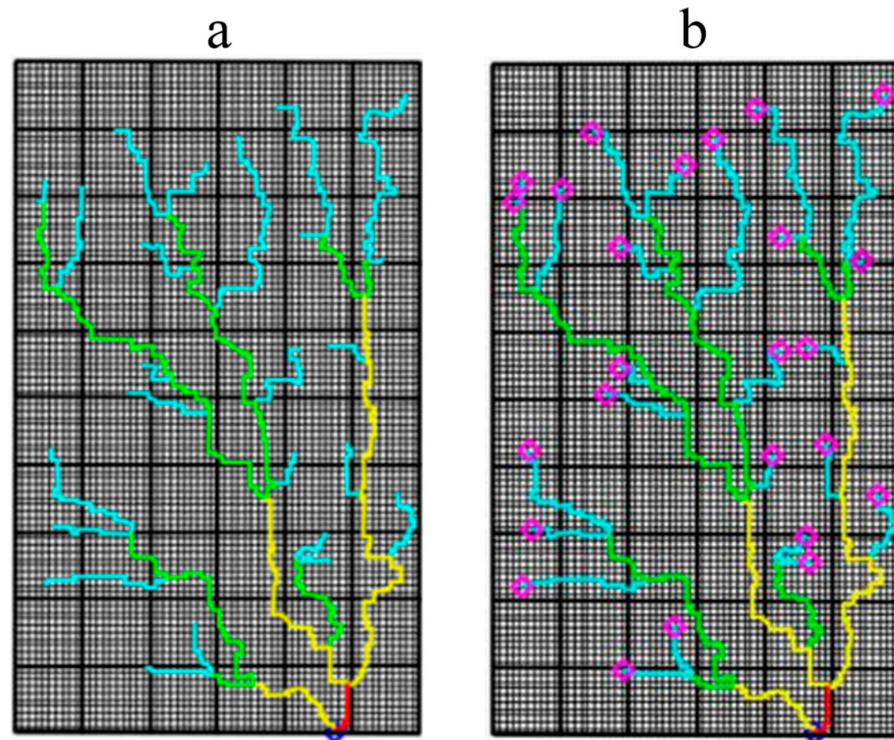


Figure 10. The conduit pattern (curvilinear branchwork) used in scenario C. (a) Model runs only under diffuse recharge. (b) In addition to the diffuse recharge, two different point recharge modes are also applied to the model. The purple squares represent the location of point recharge as sinkholes. Other conduit patterns (rectilinear branchwork and network maze) in scenario C can be found in the Supplementary Materials (Figure S3).

3. Results and Discussion

To compare the hydrographs obtained from modeling in each scenario, the parameters of peak discharge (Q_P), the lag time between the peaks of recharge and discharge (t_P), baseflow discharge (q_0^b), the return time to baseflow discharge (t_b), the fast-flow recession coefficient (α_f), the intermediate recession coefficient (α_i), the baseflow recession coefficient (α_b), the fast flow volume (V_f), the intermediate flow volume (V_i), and the baseflow volume (V_b) from the spring hydrograph curve were extracted and evaluated (Figure 11).

The entire discharge–time relationship of the recession and the total volume of water drained across the recession from $t = 0$ to $t = \infty$ is expressed based on Equations (1) and (2), respectively [47,48].

$$Q_t = \begin{cases} Q_0 e^{-\alpha_f t} & (t_0 \leq t \leq t_i) \\ q_0^i e^{-\alpha_i t} & (t_i \leq t \leq t_b) \\ q_0^b e^{-\alpha_b t} & (t_b \leq t \leq \infty) \end{cases} \quad (1)$$

$$V_T = \begin{cases} V_f = \int_0^{t_i} (Q_0 e^{-\alpha_f t} - q_0^i e^{-\alpha_i t}) dt \\ V_i = \int_0^{t_b} (q_0^i e^{-\alpha_i t} - q_0^b e^{-\alpha_b t}) dt \\ V_b = \int_0^{\infty} q_0^b e^{-\alpha_b t} dt \end{cases} \quad (2)$$

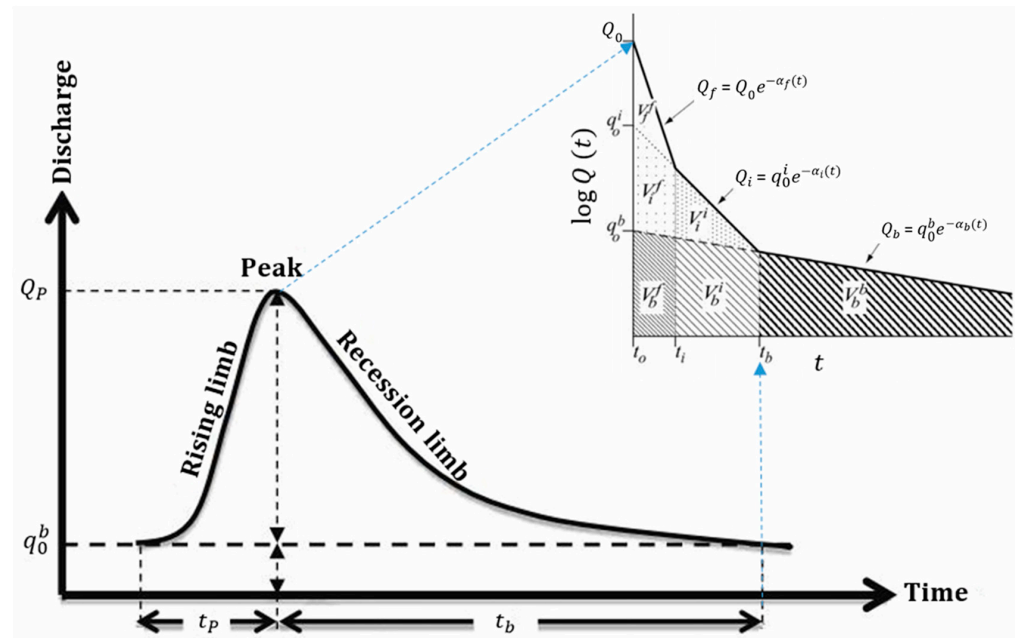


Figure 11. Schematic representation of karst spring hydrograph [49] and recession curve [47]. Q_P is the peak discharge of spring, q_0^b is the base discharge, t_P is the time duration to reach the peak discharge, and t_b represents the return time from the peak discharge to the baseflow. In the recession curve, Q or q is the flow rate, V is the discharge volume, α is the recession coefficient, and t is time. Index 0 indicative beginning points, and indices of f , i and b are the abbreviation of fast, intermediate, and baseflow, respectively.

Although just two types of hydraulic conductivity and storativity (matrix and conduits) were considered in the synthetic karst aquifer, the recession curve can show multiple segments with different recession coefficients in the semilogarithmic plot. Kira'ly and Morel [50] and Eisenlohr et al. [11] attributed the appearance of the intermediate exponential section to transient phenomena near the conduit network with high hydraulic conductivity.

Each recession segment has also been explained as the drainage of sinkholes, the first, and drainage of the saturated zone, the following, under different hydraulic laws [51,52].

3.1. The Effect of the Conduit Pattern

In order to assess the effect of conduit patterns in scenario A, three models that differ only in their conduit patterns are compared. The modeling results show that Q_P changes under the influence of the pattern of conduits. The increase in Q_P is attributed to the relatively larger diameter of the conduits close to the spring and the higher degree of conduit connections in the branchwork patterns compared to the network pattern. Since the rising limb of the hydrograph curve is more affected by the recharge condition [53,54], and in scenario A, the type and amount of recharge was assumed to be the same for all three models, t_P is similar for different patterns of conduits (Figures 12 and 13; Table S1). However, t_b and q_0^b are different in the three models, indicating the slower water transfer in the maze pattern than in the branched patterns (Figures 12 and 13; Table S1).

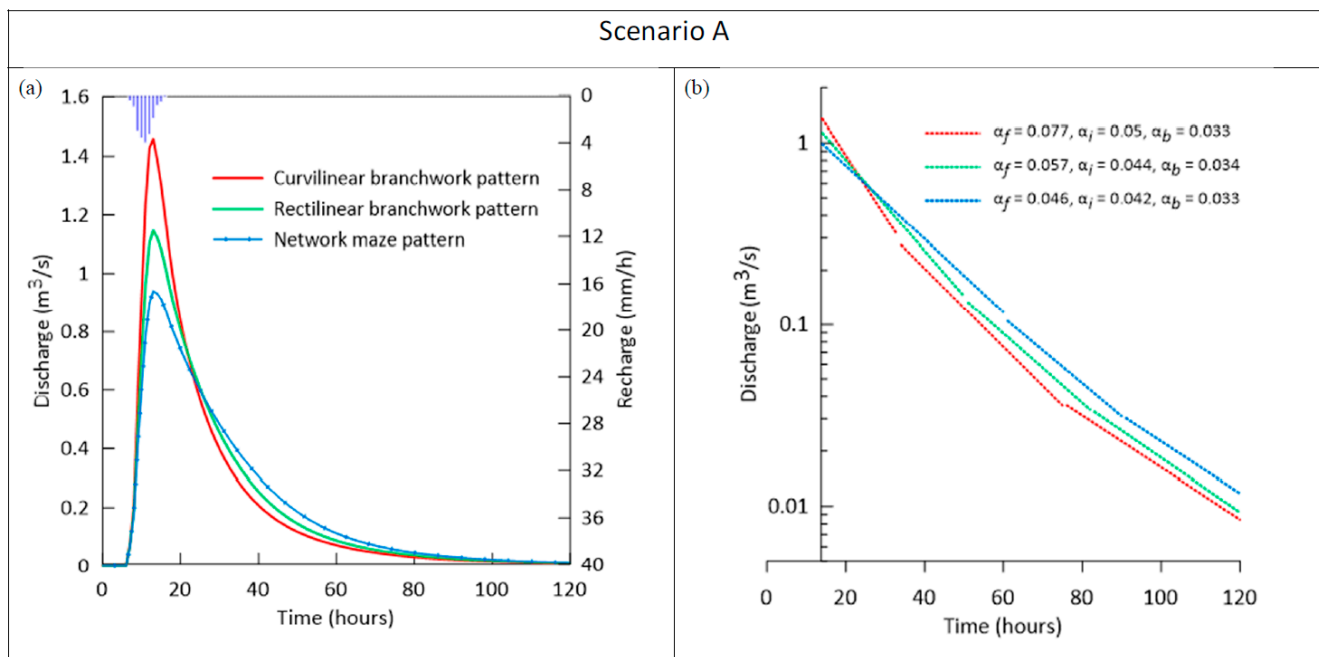


Figure 12. (a) The spring hydrographs were obtained from the different conduit network patterns in diffuse recharge (scenario A). (b) Recession curves (α_f , α_i , and α_b are the fast flow, intermediate flow, and baseflow recession coefficients, respectively). The blue lines at top of graph (a) indicate recharge.

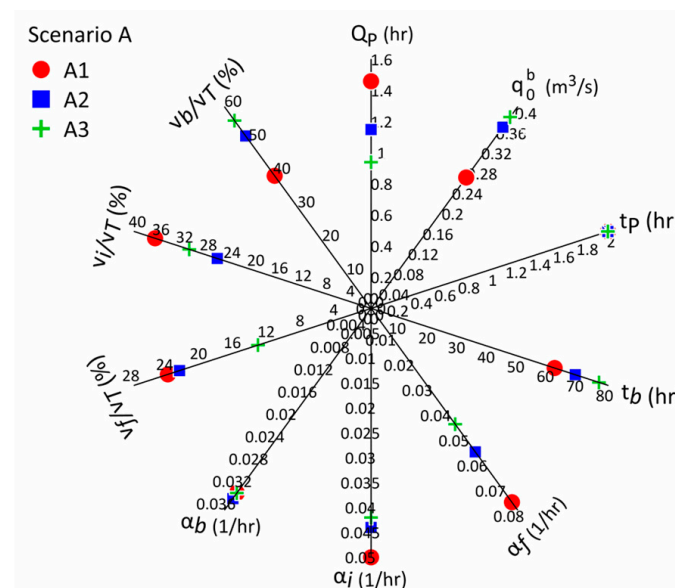


Figure 13. Comparison of different spring hydrograph characteristics in scenario A.

Although the recession coefficient depends on a reservoir's permeability, storage, and geometric properties [55], scenario A was designed to assess the effect of conduit pattern only. Since α_f represents the most rapid drainage of the karst network by the largest conduits [47], a larger value of 0.077 is estimated for the branchwork conduit pattern compared to 0.046 in the network pattern. However, α_b is almost similar in three assumed conduit patterns (Figures 12b and 13; Table S1). Assigning similar aquifer characteristics (such as aquifer shape, hydraulic conductivity, storage coefficient, and boundary conditions) for models in scenario A caused similar α_b for three models. Theoretically, the baseflow recession coefficient (α_b) depends on not only the hydraulic properties of the low hydraulic conductivity volumes but also the area and form of the whole aquifer geometry, the hydraulic conductivity, and the density of the conduit network with high

hydraulic conductivity [11]. Results of scenario A suggest no considerable effect of the conduit patterns on α_b .

Comparison of the percentage of volume drained by fast flow, intermediate flow, and baseflow to the total initial volume (V_f/V_T , V_i/V_T , V_b/V_T) revealed a larger V_f and smaller V_b in branchwork patterns related to the network pattern. In the network maze pattern, V_f/V_T is less than the branching patterns, while V_b/V_T is higher. This means the geometry and pattern of conduits influence water transfer in the karst aquifer (Figure 13 and Table S1).

3.2. The Effect of the Conduit Density

Scenario B includes nine models to examine the conduit density effect on the spring hydrograph characteristics. The scenario B model results, which assume a stepwise reduction in conduit density, revealed that Q_P decreased with decreasing density of the conduit network compared to the base model (Figures 14 and 15; Table S2). The result suggests a direct relationship between the length of the conduit network and the amount of spring discharge. The greater conduit density (i.e., the total length of the conduit network) causes a higher water transfer rate and, consequently, a more significant peak discharge. In scenario B, t_P is similar in all models due to assuming similar recharge conditions in all models (Figures 14 and 15; Table S2).

Generally, decreasing the density of the conduit network reduced the values of q_0^b , t_b , and α_f due to the reduction in conduit volume and the slow transfer of water from the matrix to the conduits. There are a few exceptions that seem to be affected by the reverse exchange of water between the conduits and matrix (Figures 14b,d,f and 15; Table S2).

In all models implemented in Scenario B, the baseflow recession coefficient has decreased with decreasing conduit network density. Since the other factors affecting the value of α_b (hydraulic properties of the matrix, area and form of the whole aquifer, and the hydraulic conductivity of conduits) remain constant in all models; the simulation results prove the effect of conduit network density and geometry on α_b . Results elucidate that the percentage of volume drained by fast flow, intermediate flow, and baseflow to the total initial volume correlates to the proportion to the density of the conduit network. In particular, decreasing the density of conduits causes a decreasing and increasing trend in V_f/V_T and V_b/V_T , respectively (Figures 14b,d,f and 15; Table S2).

3.3. The Effect of Recharge Type

Different contributions of point and diffuse recharge in six scenario C models were assumed to assess the effect of recharge type on the characteristics of the spring hydrograph. The results of scenario C indicate that an increased proportion of point recharge compared to diffuse recharge decreases t_P and t_b (Figures 16 and 17; Table S3). Moreover, increasing the role of point recharge increased and decreased Q_P and q_0^b , respectively, in three patterns of conduits (Figure 17 and Table S3), as mentioned by Kovács and Perrochet [56].

Values of α_f increase with increasing point recharge ratio but α_b values do not noticeably change, except in one case (Figures 16b,d,f and 17; Table S3). Based on investigations by Kovács and Perrochet [56] and Kovács et al. [55], α_b is exclusively dependent on the hydraulic characteristics of the matrix and the total extent of the aquifer; thus, a different proportion between concentrated and diffuse recharge does not influence the value of α_b . However, in the presence of point recharge, if the diameter of conduits is not large enough to quickly transfer the recharge water, the excess volume of water could enter the matrix and affects the α_i and α_b . It is also possible that the conduit network connections in response to a point recharge or diffuse recharge play a different role and influence the baseflow recession that needs more research under different hydraulic conditions.

Results reveal that the percentage of volume drained by fast flow, intermediate flow, and baseflow to the total initial volume changes depending on the type and amount of recharge. In particular, by increasing the point recharge portion, V_f/V_T increases while V_b/V_T decreases (Figure 17 and Table S3).

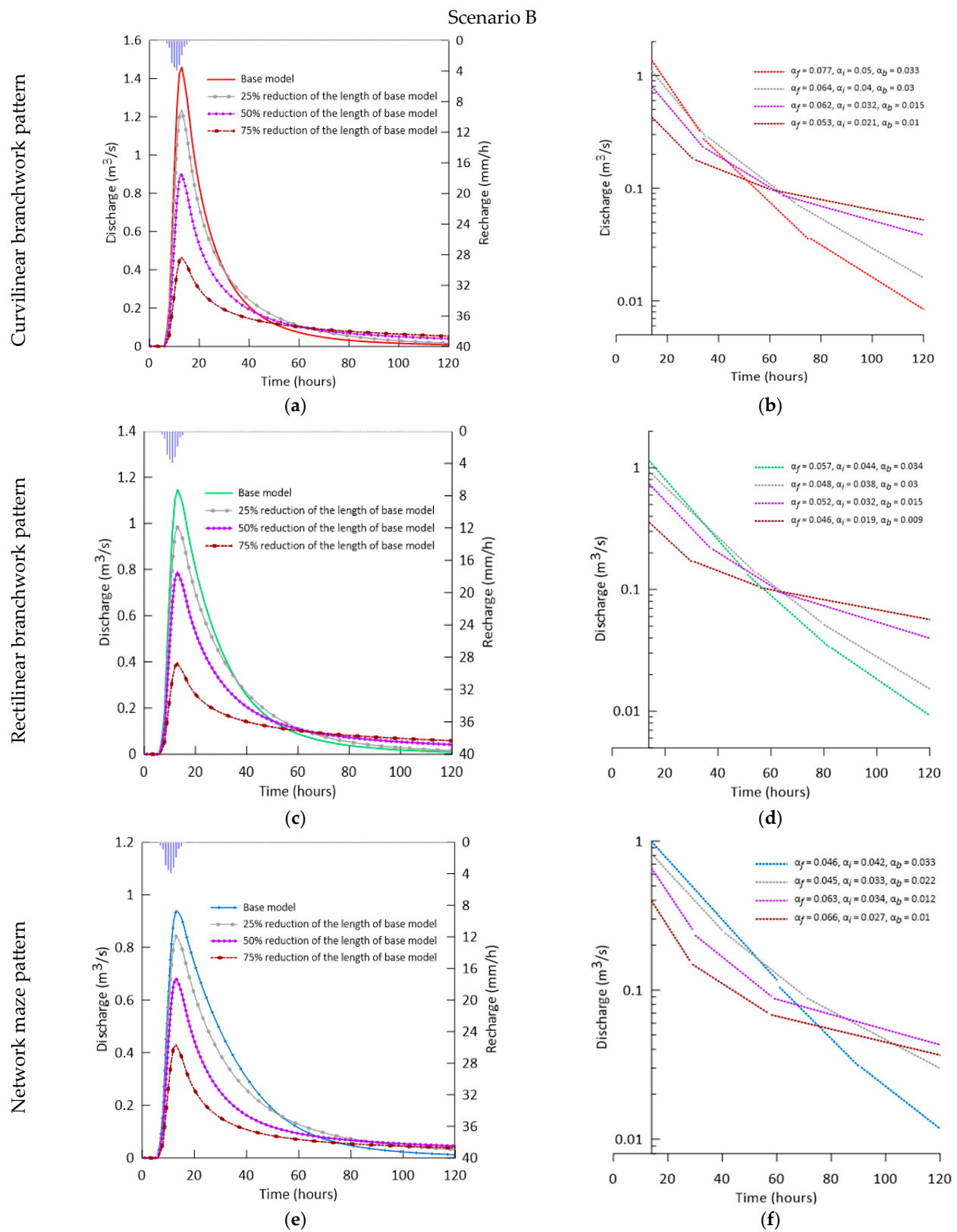


Figure 14. (a,c,e) The spring hydrographs were obtained from curvilinear branchwork patterns, rectilinear branchwork patterns, and network maze patterns with different conduit network density (scenario B). (b,d,f) Recession curves (α_f , α_i , and α_b are the fast flow, intermediate flow, and baseflow recession coefficients, respectively). The blue lines at top of graphs indicate recharge.

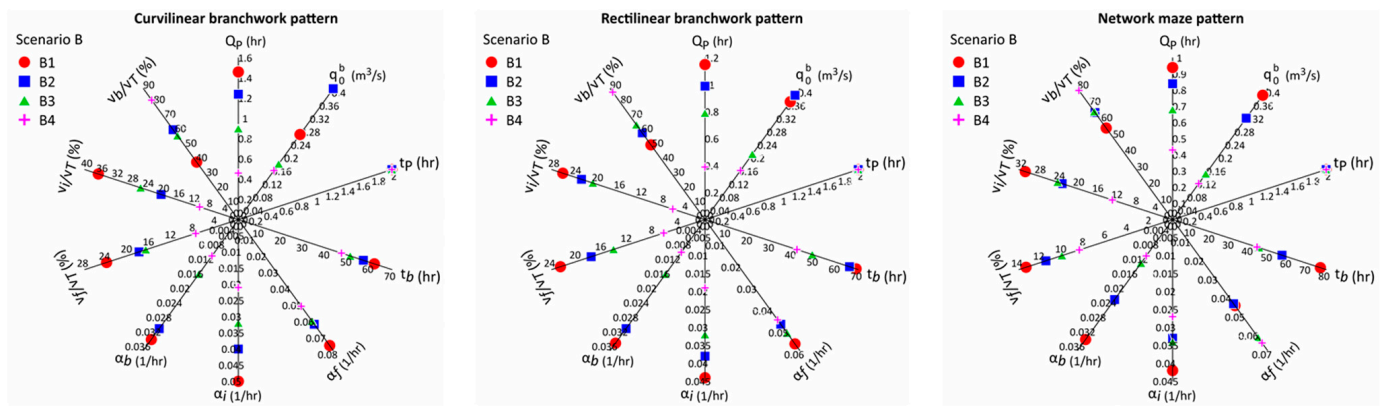


Figure 15. Comparison of different spring hydrograph characteristics in scenario B.

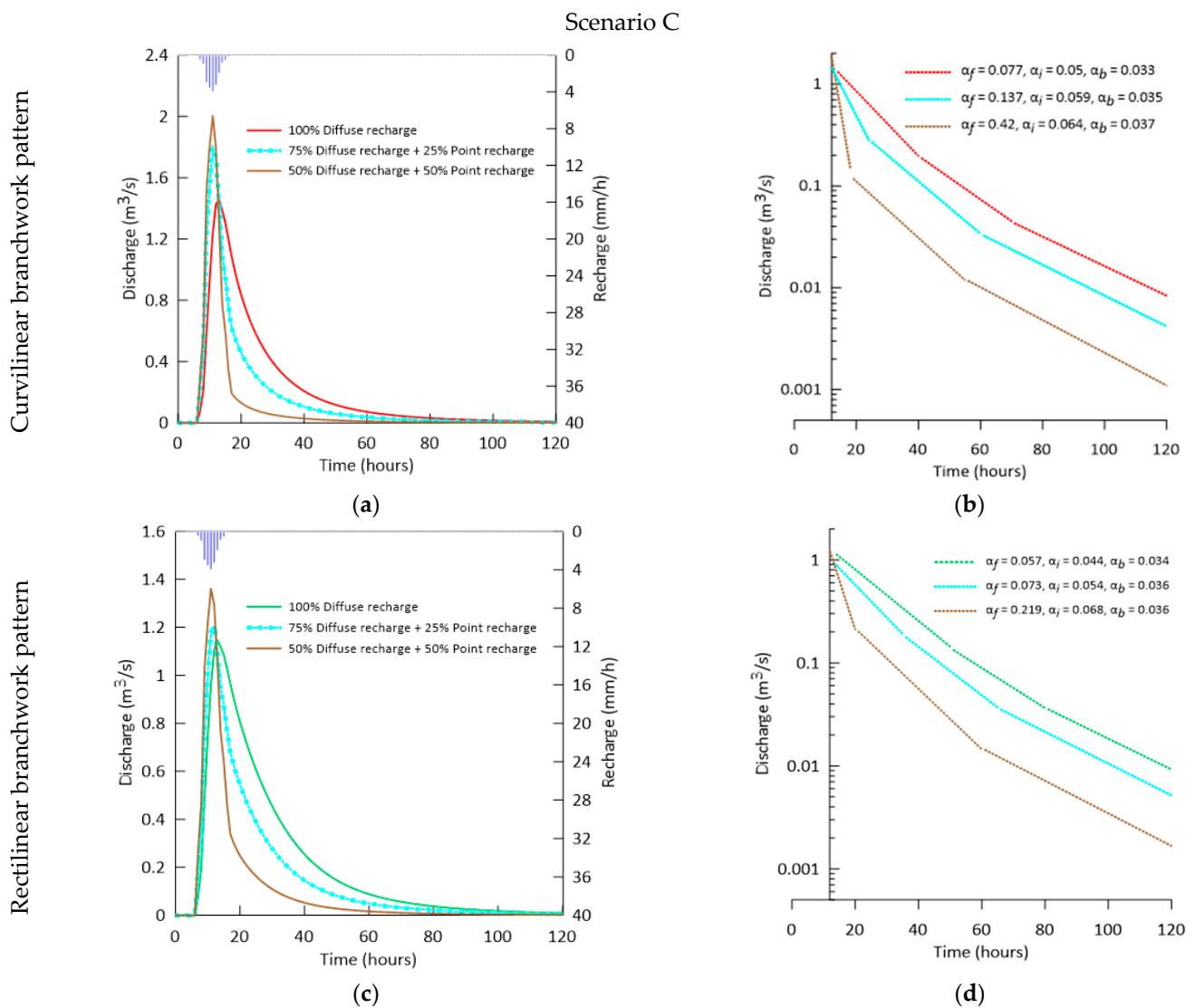


Figure 16. Cont.

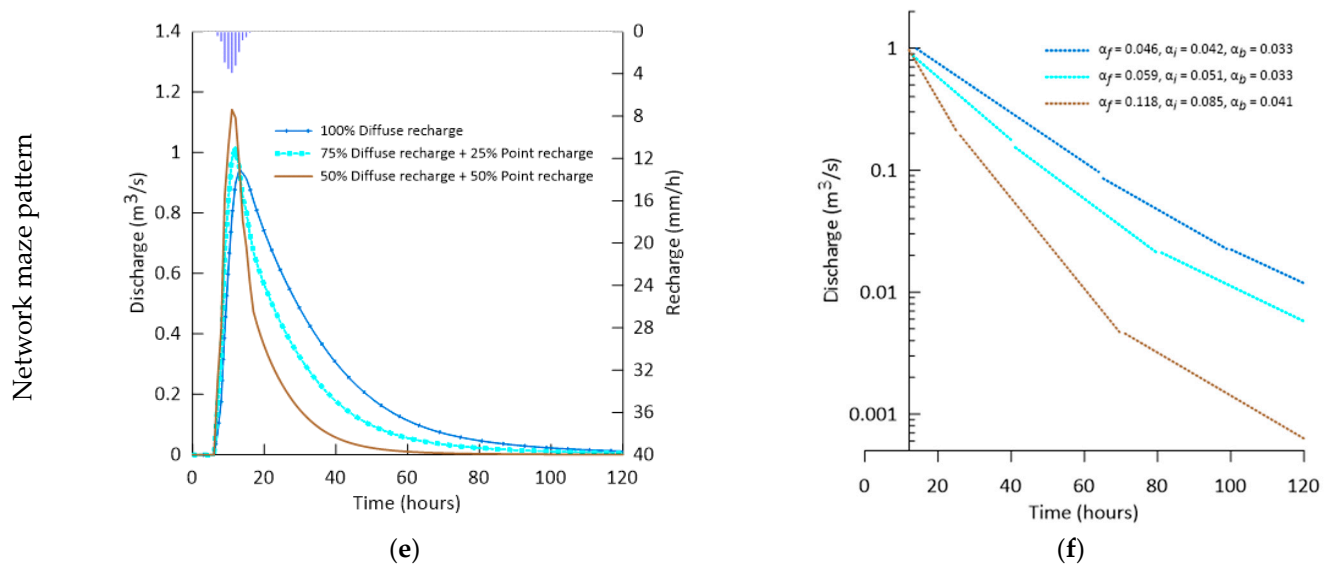


Figure 16. (a,c,e) The spring hydrographs were obtained from curvilinear branchwork, rectilinear branchwork, and network maze patterns under different recharge types (scenario C). (b,d,f) Recession curves (α_f , α_i , and α_b are the fast flow, intermediate flow, and baseflow recession coefficients, respectively). The blue lines at top of graphs indicate recharge.

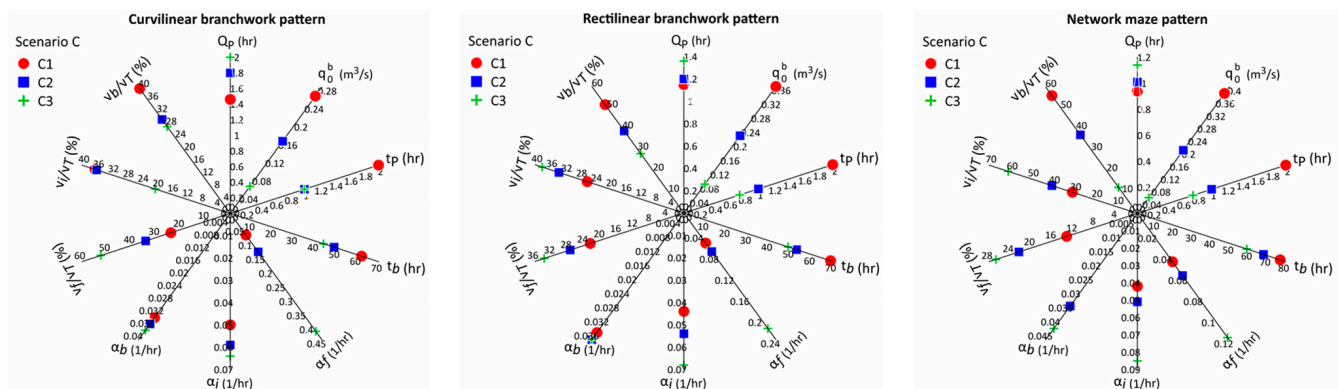


Figure 17. Comparison of different spring hydrograph characteristics in scenario C.

4. Field Examples to Verify the Results

Understanding the relationship between springs and conduit patterns is vital in groundwater resource management of karst systems because it contributes to delineating both the area of recharge that contributes to spring flow and the potential for rapid groundwater/surface water exchange [57]. Kaufmann [58] studied flow evolution in a karst aquifer by numerical simulation based on chemical dissolution over time to enlarge fractures and generate the conduit network. The results of this study have shown that the response of karst spring changes based on the development of conduit patterns (Figure 18). The graphs in Figure 18, which are the results of a simulation of the development of karst conduits, show that as more time passes and the length and size of the conduits increase, the shape of the spring hydrograph changes significantly. Somehow, this conclusion confirms the results of scenario B, which investigates the effect of conduit network density on the shape of the spring hydrograph.

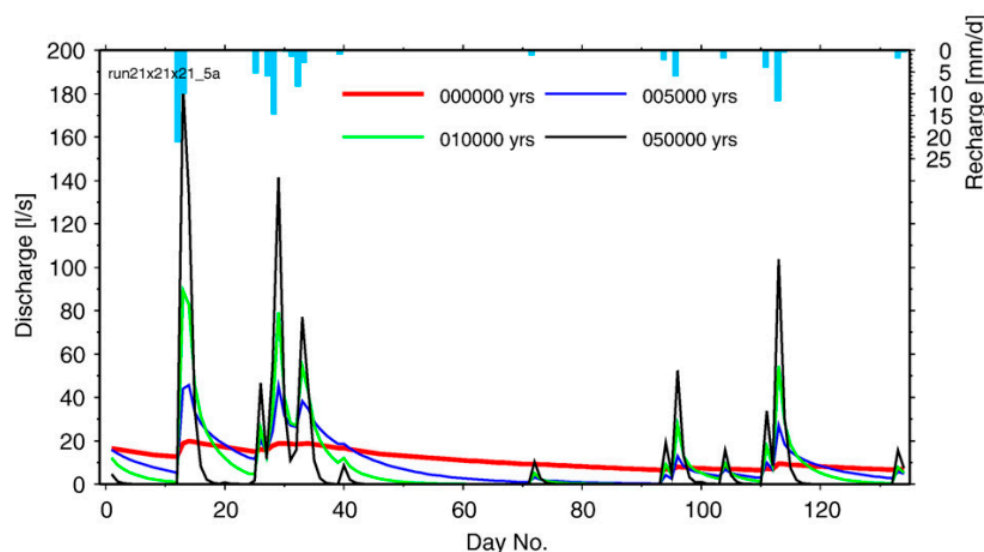


Figure 18. Short-term spring response in the stationary model: recharge and discharge time series for different evolution times. Yrs is the abbreviation of years. For example, 005000 yrs shows the evolution of channels after this time. Run21 × 21 × 21_5a shows the model domain that is discretized into 21 × 21 × 21 nodal points. 5a indicates the fifth uplift of the basin [58].

According to the length of mapped conduits, Wakulla–Leon Sinks Cave System (51,484 m) and Sally Ward Cave (2090 m) are 2 of the largest mapped caves in the Woodville Karst Plain (WKP). In the WKP, the dissolution process leads to dendritic (branchwork pattern) cave systems that originate from large single conduits at springs, towards the upstream of the basin, and away from the springs; they are divided into numerous and smaller conduits [59]. Hydrographs of Wakulla and Sally Ward Springs show that both springs have a similar flow pattern [60]. Since the pattern of conduits connected to Wakulla and Sally Ward Springs and other hydrogeological conditions are alike, the difference in peak discharge, baseflow discharge, and other hydrograph characteristics can be attributed to the difference in conduit network density (i.e., similar to scenario B). The length of mapped conduits of Wakulla Cave and Sally Ward Cave is approximately 10 and 1.2 miles, respectively [61,62].

Measured and simulated spring discharge for Oje de Agua and Oje de Guillo springs are plotted versus the average amount of rain that has fallen each day at the Manati rain gauge station over 33 months (Figure 19). The Oje de Guillo spring responds more strongly (more sudden and sharper) to severe short-term rainfall events (e.g., 11/93 and 8/95) than the Oje de Agua spring. Its baseflow, which ranges from 1500 to 3000 m³/d, is much lower than the Oje de Agua spring (5000–10,000 m³/d). The recession limb of this spring has a much steeper slope compared to Oje de Agua spring, denoting a relatively short residence time in the conduit network [3,63]. Although Rodriguez-Martinez [63] classified Oje de Agua spring and Oje de Guillo spring as diffuse-type and conduit-type springs, respectively, Ghasemizadeh et al. [3] believe that conduits feed both springs. The discrepancies in their responses are mostly due to the recharge differential, with the Ojo de Guillo spring having a greater share of concentrated recharge at sinkholes and dolines. These conclusions are based on the results of scenario C.

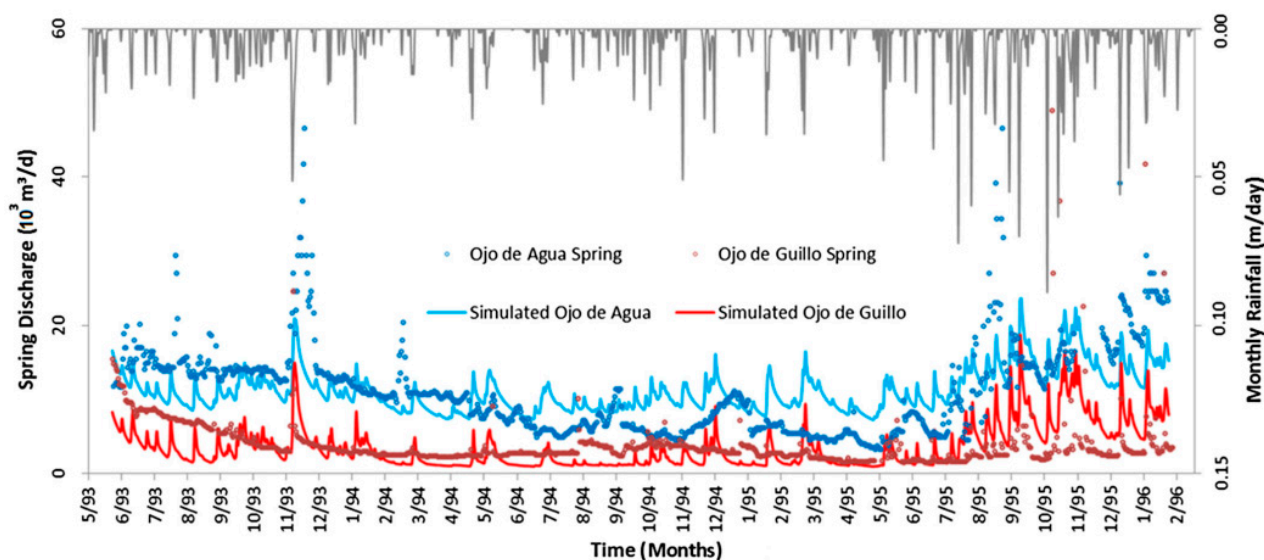


Figure 19. A comparison of the daily rainfall hydrograph with the daily mean discharge hydrograph, both simulated and observed, for the Ojo de Agua spring in Vega Baja and the Ojo de Guillo spring in Manati between June 1993 and February 1996 [3].

5. Conclusions

The influence of conduit pattern, conduit density, and recharge type on the spring hydrograph in a synthetic karst aquifer was investigated. The simulation results revealed that Q_P , q_0^b , α_f , and t_b are mainly affected by the conduit network pattern, conduit network density, and recharge type, respectively. Larger values of Q_P and α_f , and smaller values of t_b , belongs to scenarios with higher conduit density, branchwork conduit patterns, and greater point recharge rates. Branchwork patterns, the lower density of the conduit network, and the increasing proportion of point recharge are mainly responsible for the reduction of q_0^b .

Results suggest no influence of the pattern and density of the conduits on t_P . However, in most cases, t_P is reduced by increasing the proportion of point recharge. A comparison of results revealed that although α_b has no significant dependency on the conduit network pattern and proportion of point recharge, it decreases with decreasing conduit network density. Moreover, V_f/V_T and V_b/V_T increased and decreased in response to branchwork patterns (compared to network maze pattern), higher density of conduit network, and increase in the proportion of point recharge, respectively. Finally, a few real field examples were reviewed to confirm the results of synthetic modeling scenarios. Despite the scarcity of suitable field data, comparing the results is promising. Although this research was a preliminary insight into the effect of conduit patterns on the spring hydrograph, it seems that further studies are required to clarify the role of conduit patterns in the hydrogeological processes of karst aquifers. The authors recommend developing subsequent modeling studies to compare the results of this research with considering the vertical zones of a typical karst aquifer and/or conducting inverse modeling to optimize the characteristics of conduit pattern based on the characteristics of spring hydrograph.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w15081594/s1>, Figure S1: Rectilinear branchwork patterns with different conduit densities in scenario B. a, b, c, and d represent the base rectilinear branchwork model, 25%, 50%, and 75% reduction in the length of conduits, respectively; Figure S2: Network maze patterns with different conduit densities in scenario B. a, b, c, and d represent the base network maze model, 25%, 50%, and 75% reduction in the length of conduits, respectively; Figure S3: The conduit patterns (a, b: rectilinear branchwork; c and d: network maze) used in scenario C. Models b and d run under two different modes of the point recharge. The purple squares represent the location

of point recharge as sinkholes; Table S1: The characteristics of the spring hydrograph in scenario A; Table S2: The characteristics of the spring hydrograph in scenario B; Table S3: The characteristics of the spring hydrograph in scenario C.

Author Contributions: Methodology, H.O. and Z.M.; Software, H.O.; Validation, Z.M. and F.F.; Formal analysis, H.O.; Writing—original draft, H.O.; Writing—review & editing, Z.M. and F.F.; Supervision, Z.M. All authors have read and agreed to the published version of the manuscript.

Funding: The first and second authors would like to acknowledge the support from the Iran National Science Foundation (INSF) [Grant Number: 4012713] and Shiraz University.

Data Availability Statement: The data presented in this study are available in the article and supplementary material.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ford, D.; Williams, P.D. *Karst Hydrogeology and Geomorphology*; John Wiley & Sons: Hoboken, NJ, USA, 2007; ISBN 0-470-84997-5.
2. White, W.B. *Geomorphology and Hydrology of Karst Terrains*; Oxford University Press: Oxford, UK, 1988.
3. Ghasemizadeh, R.; Yu, X.; Butscher, C.; Padilla, I.Y.; Alshawabkeh, A. Improved regional groundwater flow modeling using drainage features: A case study of the central northern karst aquifer system of Puerto Rico (USA). *Hydrogeol. J.* **2016**, *24*, 1463. [[CrossRef](#)] [[PubMed](#)]
4. Andriani, G.F.; Parise, M. On the applicability of geomechanical models for carbonate rock masses interested by karst processes. *Environ. Earth Sci.* **2015**, *74*, 7813–7821. [[CrossRef](#)]
5. Chang, Y.; Wu, J.; Liu, L. Effects of the conduit network on the spring hydrograph of the karst aquifer. *J. Hydrol.* **2015**, *527*, 517–530. [[CrossRef](#)]
6. Worthington, S.R. Groundwater residence times in unconfined carbonate aquifers. *J. Cave Karst Stud.* **2007**, *69*, 94–102.
7. Bakalowicz, M. Karst groundwater: A challenge for new resources. *Hydrogeol. J.* **2005**, *13*, 148–160. [[CrossRef](#)]
8. Padilla, A.; Pulido-Bosch, A.; Mangin, A. Relative importance of baseflow and quickflow from hydrographs of karst spring. *Groundwater* **1994**, *32*, 267–277. [[CrossRef](#)]
9. Mohammadi, Z.; Raeisi, E.; Bakalowicz, M. Method of leakage study at the karst dam site. A case study: Khersan 3 Dam, Iran. *Environ. Geol.* **2007**, *52*, 1053–1065. [[CrossRef](#)]
10. Jourde, H.; Massei, N.; Mazzilli, N.; Binet, S.; Batiot-Guilhe, C.; Labat, D.; Steinmann, M.; Bailly-Comte, V.; Seidel, J.-L.; Arfib, B.; et al. SNO KARST: A French network of observatories for the multidisciplinary study of critical zone processes in karst watersheds and aquifers. *Vadose Zone J.* **2018**, *17*, 1–18. [[CrossRef](#)]
11. Eisenlohr, L.; Király, L.; Bouzelboudjen, M.; Rossier, Y. Numerical simulation as a tool for checking the interpretation of karst spring hydrographs. *J. Hydrol.* **1997**, *193*, 306–315. [[CrossRef](#)]
12. Fiorillo, F. The recession of spring hydrographs, focused on karst aquifers. *Water Resour. Manag.* **2014**, *28*, 1781–1805. [[CrossRef](#)]
13. Kovács, A.; Perrochet, P. A quantitative approach to spring hydrograph decomposition. *J. Hydrol.* **2008**, *352*, 16–29. [[CrossRef](#)]
14. Bonacci, O. Karst springs hydrographs as indicators of karst aquifers. *Hydrol. Sci. J.* **1993**, *38*, 51–62. [[CrossRef](#)]
15. Kiraly, L.; Perrochet, P.; Rossier, Y. Effect of the epikarst on the hydrograph of karst springs: A numerical approach. *Bull. Cent. Hydrogéol.* **1995**, *14*, 199–220.
16. Mohammadi, Z.; Shoja, A. Effect of annual rainfall amount on characteristics of karst spring hydrograph. *Carbonates Evaporites* **2014**, *29*, 279–289. [[CrossRef](#)]
17. Shirafkan, M.; Mohammadi, Z.; Sivel, V.; Labat, D. The effects of exchange flow on the Karst spring hydrograph under the different flow regimes: A synthetic modeling approach. *Water* **2021**, *13*, 1189. [[CrossRef](#)]
18. Amit, H.; Lyakhovsky, V.; Katz, A.; Starinsky, A.; Burg, A. Interpretation of spring recession curves. *Groundwater* **2002**, *40*, 543–551. [[CrossRef](#)]
19. Dewandel, B.; Lachassagne, P.; Bakalowicz, M.; Weng, P.; Al-Malki, A. Evaluation of aquifer thickness by analysing recession hydrographs. Application to the Oman ophiolite hard-rock aquifer. *J. Hydrol.* **2003**, *274*, 248–269. [[CrossRef](#)]
20. Florea, L.J.; Vacher, H. Springflow hydrographs: Eogenetic vs. telogenetic karst. *Groundwater* **2006**, *44*, 352–361. [[CrossRef](#)]
21. Palmer, A.N. Origin and morphology of limestone caves. *Geol. Soc. Am. Bull.* **1991**, *103*, 1–21. [[CrossRef](#)]
22. Al-Halbouni, D.; Watson, R.A.; Holohan, E.P.; Meyer, R.; Polom, U.; Dos Santos, F.M.; Comas, X.; Alrshdan, H.; Krawczyk, C.M.; Dahm, T. Dynamics of hydrological and geomorphological processes in evaporite karst at the eastern Dead Sea—a multidisciplinary study. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 3351–3395. [[CrossRef](#)]
23. Jeannin, P.-Y.; Groves, C.; Häuselmann, P. Speleological investigations. *Methods Karst Hydrogeol. Int. Contrib. Hydrogeol. IAH* **2007**, *26*, 25–44.
24. Pardo-Igúzquiza, E.; Dowd, P.A.; Xu, C.; Durán-Valsero, J.J. Stochastic simulation of karst conduit networks. *Adv. Water Resour.* **2012**, *35*, 141–150. [[CrossRef](#)]
25. Palmer, A.N. Speleogenesis in carbonate rocks. In *Evolution of Karst: From Prekarst to Cessation*; Inštitut za Raziskovanje Krasa, ZRC SAZU: Ljubljana, Slovenia, 2002; pp. 43–59.

26. Collon, P.; Bernasconi, D.; Vuilleumier, C.; Renard, P. Statistical metrics for the characterization of karst network geometry and topology. *Geomorphology* **2017**, *283*, 122–142. [\[CrossRef\]](#)
27. Hendrick, M.; Renard, P. Subnetworks of percolation backbones to model karst systems around Tulum, Mexico. *Front. Phys.* **2016**, *4*, 43. [\[CrossRef\]](#)
28. Ronayne, M.J. Influence of conduit network geometry on solute transport in karst aquifers with a permeable matrix. *Adv. Water Resour.* **2013**, *56*, 27–34. [\[CrossRef\]](#)
29. Borghi, A.; Renard, P.; Jenni, S. A pseudo-genetic stochastic model to generate karstic networks. *J. Hydrol.* **2012**, *414*, 516–529. [\[CrossRef\]](#)
30. Jaquet, O.; Siegel, P.; Klubertanz, G.; Benabderrhamane, H. Stochastic discrete model of karstic networks. *Adv. Water Resour.* **2004**, *27*, 751–760. [\[CrossRef\]](#)
31. Lafare, A. Modélisation Mathématique de la Spéléogénèse: Une Approche Hybride à Partir de Réseaux de Fractures Discrets et de Simulations Hydrogéologiques. Ph.D. Thesis, Université Montpellier II, Montpellier, France, 2011.
32. De Rooij, R.; Graham, W. Generation of complex karstic conduit networks with a hydrochemical model. *Water Resour. Res.* **2017**, *53*, 6993–7011. [\[CrossRef\]](#)
33. Henson, W.R.; de Rooij, R.; Graham, W. What Makes a First-Magnitude Spring?: Global Sensitivity Analysis of a Speleogenesis Model to Gain Insight into Karst Network and Spring Genesis. *Water Resour. Res.* **2018**, *54*, 7417–7434. [\[CrossRef\]](#)
34. Kaufmann, G.; Romanov, D.; Hiller, T. Modeling three-dimensional karst aquifer evolution using different matrix-flow contributions. *J. Hydrol.* **2010**, *388*, 241–250. [\[CrossRef\]](#)
35. Reimann, T.; Hill, M.E. MODFLOW-CFP: A new conduit flow process for MODFLOW–2005. *Groundwater* **2009**, *47*, 321–325. [\[CrossRef\]](#)
36. Ghasemizadeh, R.; Hellweger, F.; Butscher, C.; Padilla, I.; Vesper, D.; Field, M.; Alshawabkeh, A. Groundwater flow and transport modeling of karst aquifers, with particular reference to the North Coast Limestone aquifer system of Puerto Rico. *Hydrogeol. J.* **2012**, *20*, 1441. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Sauter, M.; Geyer, T.; Kovács, A.; Teutsch, G. Modellierung der hydraulik von karstgrundwasserleitern—eine übersicht. *Grundwasser* **2006**, *11*, 143–156. [\[CrossRef\]](#)
38. Ronayne, M.J. Understanding Groundwater Dynamics in Structurally Heterogeneous Aquifers. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2008.
39. Strahler, A.N. Quantitative analysis of watershed geomorphology. *Eos Trans. Am. Geophys. Union* **1957**, *38*, 913–920. [\[CrossRef\]](#)
40. Alghalandis, Y. *DFNE Practices with ADFNE*; Alghalandis Computing: Toronto, ON, Canada, 2018.
41. Gleyzer, A.; Denisyuk, M.; Rimmer, A.; Salingar, Y. A Fast Recursive Gis Algorithm for Computing Strahler Stream Order in Braided and Nonbraided Networks 1. *JAWRA J. Am. Water Resour. Assoc.* **2004**, *40*, 937–946. [\[CrossRef\]](#)
42. Winston, R.B. ModelMuse Version 4: A graphical user interface for MODFLOW 6. In *Scientific Investigations Report-US Geological Survey*; US Department of the Interior, US Geological Survey: Reston, VA, USA, 2019.
43. Shoemaker, W.B.; Kuniansky, E.L.; Birk, S.; Bauer, S.; Swain, E.D. *Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005*; US Department of the Interior, US Geological Survey: Reston, VA, USA, 2008; Volume 6.
44. Reimann, T.; Rehl, C.; Shoemaker, W.B.; Geyer, T.; Birk, S. The significance of turbulent flow representation in single-continuum models. *Water Resour. Res.* **2011**, *47*, W09503. [\[CrossRef\]](#)
45. Liedl, R.; Sauter, M.; Hückinghaus, D.; Clemens, T.; Teutsch, G. Simulation of the development of karst aquifers using a coupled continuum pipe flow model. *Water Resour. Res.* **2003**, *39*, 1057. [\[CrossRef\]](#)
46. Hubinger, B.; Birk, S. Influence of initial heterogeneities and recharge limitations on the evolution of aperture distributions in carbonate aquifers. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 3715–3729. [\[CrossRef\]](#)
47. Doctor, D.H.; Alexander, E.C., Jr. Interpretation of water chemistry and stable isotope data from a karst aquifer according to flow regimes identified through hydrograph recession analysis. In *US Geological Survey Karst Interest Group Proceedings, Rapid City, South Dakota*; BiblioGov: Singapore, 2005; pp. 82–92.
48. Jakada, H.; Chen, Z.; Luo, M.; Zhou, H.; Wang, Z.; Habib, M. Watershed characterization and hydrograph recession analysis: A comparative look at a karst vs. non-karst watershed and implications for groundwater resources in Gaolan River Basin, Southern China. *Water* **2019**, *11*, 743. [\[CrossRef\]](#)
49. Şen, Z. General modeling of karst spring hydrographs and development of a dimensionless karstic hydrograph concept. *Hydrogeol. J.* **2020**, *28*, 549–559. [\[CrossRef\]](#)
50. Király, L.; Morel, G. Remarques sur l’hydrogramme des sources karstiques simulé par modèles mathématiques: Avec 15 figures. *Bull. Cent. Hydrogéol.* **1976**, *1*, 37–60.
51. Fiorillo, F. Tank-reservoir drainage as a simulation of the recession limb of karst spring hydrographs. *Hydrogeol. J.* **2011**, *19*, 1009. [\[CrossRef\]](#)
52. Abirifard, M.; Birk, S.; Raeisi, E.; Sauter, M. Dynamic volume in karst aquifers: Parameters affecting the accuracy of estimates from recession analysis. *J. Hydrol.* **2022**, *612*, 128286. [\[CrossRef\]](#)
53. Geyer, T.; Birk, S.; Liedl, R.; Sauter, M. Quantification of temporal distribution of recharge in karst systems from spring hydrographs. *J. Hydrol.* **2008**, *348*, 452–463. [\[CrossRef\]](#)
54. Kovács, A.; Perrochet, P.; Darabos, E.; Lénárt, L.; Szűcs, P. Well hydrograph analysis for the characterisation of flow dynamics and conduit network geometry in a karst aquifer, Bükk Mountains, Hungary. *J. Hydrol.* **2015**, *530*, 484–499. [\[CrossRef\]](#)

55. Kovács, A.; Perrochet, P.; Király, L.; Jeannin, P.-Y. A quantitative method for the characterisation of karst aquifers based on spring hydrograph analysis. *J. Hydrol.* **2005**, *303*, 152–164. [[CrossRef](#)]
56. Kovács, A.; Perrochet, P. *Well Hydrograph Analysis for the Estimation of Hydraulic and Geometric Parameters of Karst and Connected Water Systems*; Springer: Berlin/Heidelberg, Germany, 2014; ISBN 3-319-06138-0.
57. Kincaid, T.R. *Morphologic and Fractal Characterization of Saturated Karstic Caves*; University of Wyoming: Laramie, WY, USA, 1999; ISBN 0-599-44583-1.
58. Kaufmann, G. Modelling karst geomorphology on different time scales. *Geomorphology* **2009**, *106*, 62–77. [[CrossRef](#)]
59. Kincaid, T.; Werner, C.L.; GeoHydros, L. Karst Hydrogeology of the Woodville Karst Plain Florida. In *Sinkholes and the Engineering and Environmental Impacts of Karst, Edition: Geotechnical Special Publication*; Geo-Institute: Fairfax, VA, USA, 2008.
60. Gilbert, D. *Nutrient (Biology) TMDL for the Upper Wakulla River (WBID 1006)*; Florida Department of Environmental Protection Technical Report; Florida Department of Environmental Protection: Tallahassee, FL, USA, 2012.
61. Kincaid, T.R.; Hazlett, T.J.; Davies, G.J. Quantitative groundwater tracing and effective numerical modeling in karst: An example from the Woodville Karst Plain of North Florida. In *Sinkholes and the Engineering and Environmental Impacts of Karst*; Geo-Institute: Fairfax, VA, USA, 2005; pp. 114–121.
62. DeHan, R.; Loper, D. *Hydrogeologic Characterization and Modeling of the Woodville Karst Plain, North Florida Report of Investigations: 2005–2006*; Hazlett-Kincaid, Inc.: Reno, NV, USA, 2007.
63. Rodríguez-Martínez, J. *Characterization of Springflow in the North Coast Limestone of Puerto Rico Using Physical, Chemical, and Stable Isotopic Methods*; US Geological Survey: Reston, VA, USA, 1997.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.