Turkish Journal of Water Science & Management
ISSN: 2536 474X / e-ISSN: 2564-7334

Volume: 6 Issue: 1 Year: 2022

Research Article

A Comparative Evaluation of Automated Recession Extraction Procedures for Karst Spring Hydrographs

Otomatik Çekilme Eğrisi Seçim Prosedürlerinin Karstik Kaynak Hidrograflarında Karşılaştırılmalı Değerlendirilmesi

Kübra Özdemir Çallı[1*], Andreas Hartmann[2]
[1]*Republic of Turkey Ministry of Agriculture and Forestry General Directorate of Water Management, 06510, Yenimahalle-Ankara*
[1]*Department of Geological Engineering, Middle East Technical University, 06800 Çankaya/Ankara*
kubra.ozdemircalli@tarimorman.gov.tr (https://orcid.org/0000-0003-0649-6687)
[2]*Albert-Ludwigs-Universität Freiburg, Chair of Hydrological Modeling and Water Resources, Friedrichstrasse, 79098 Freiburg, Germany*
andreas.hartmann@hydmod.uni-freiburg.de (https://orcid.org/0000-0003-0407-742X)
Received Date: 03.05.2021, Accepted Date: 30.09.2021
DOI: 10.31807/tjwsm.930269

Abstract

Recession Curve Analysis is a common method to characterize karstic aquifers and their discharge dynamics. Although this technique provides crucial information on quantifying system hydrodynamic properties, the manually selected recession curves analysis is neither a practical technique to cover all candidate recession curves, nor it allows extracting the entire hydrological diversity of the recession behavior. This study aimed to comparatively evaluate the applicability of automated recession selection procedures to the late-time recession analysis of karst spring hydrograph. For the comparative evaluation of the three automated recession extraction methods (Vogel Method, Brutsaert Method, and Aksoy and Wittenberg Method), we quantified the late-time recession parameters of spring hydrographs by combining three extraction methods with four recession analysis methods (Maillet, 1905; Boussinesq, 1904; Coutagne, 1948; and Wittenberg, 1999). By applying our experimental design into the five karst springs located in Austria, we identified the possible weaknesses of the automated recession extraction procedures for the late-time recession analysis for spring hydrographs. To explore the value of the karst spring's physicochemical data (electrical conductivity and water temperature) as a completion data for the recession curve analysis, we carried out the hydro-chemograph analysis to examine the recession time and its duration. The research provides a research direction as to how the automated recession extraction procedures for the karst spring hydrographs could be improved by the physicochemical signatures of karst springs.

Keywords: *automated recession extraction methods (REMs), karst spring, hydrograph analysis, hydro-chemograph analysis, recession curve analysis*

Öz

Kaynak hidrograflarında Çekilme Eğrisi Analizi, karstik akifer sistemlerinin akım ve boşalım dinamiklerini karakterize etmek için kullanılan yaygın bir yöntemdir. Bu yöntem, akifer sisteminin hidrodinamik özelliklerinin tanımlanmasında önemli bilgiler sağlamasına karşın, aday bir çekilme eğrisi(leri)nin elle seçimi ne tüm çekilme eğrilerinin analizini kapsayacak şekilde pratik bir tekniktir, ne de hidrolojik bir değişiminin karstik kaynak çekilme davranışı üzerindeki etkisinin tanımlanmasına

* *Corresponding author*

izin vermektedir. Bu çalışmada, otomatik çekilme eğrisi seçim prosedürlerinin kaynak hidrografı geç-dönem çekilme analizlerinde uygulanabilirliği araştırılmıştır. Bu kapsamda, Vogel Metodu, Brutsaert Metodu ile Aksoy ve Wittenberg Metodu olmak üzere üç otomatik çekilme eğrisi seçim prosedürü dört adet çekilme eğrisi analizi metodu (Maillet, 1905, Boussinesq, 1904, Coutagne, 1948 ve Wittenberg, 1999) ile birleştirilerek karstik kaynaklarda geç-dönem kaynak çekilme (boşalım) katsayıları karşılaştırmalı olarak hesaplanmıştır. Çalışmada, Avusturya'da bulunan beş karstik kaynağın çekilme katsayıları belirlenmiş olup karstik kaynak fizikokimyasal verileri (elektriksel iletkenlik ve su sıcaklığı) hidro-kemograflar yardımıyla değerlendirilerek otomatik çekilme eğrisi seçim prosedürlerinin olası zayıf yönleri ortaya konmuştur. Bu araştırma, karstik kaynaklarda geç-dönem çekilme eğrisi analizlerinde çekilme başlangıcını ve süresini tamamlamak için otomatik çekilme eğrisi seçim prosedürlerinin uygulanabilirliği için bir araştırma yönü sağlamaktadır.

Anahtar sözcükler: *otomatik çekilme eğrisi belirleme metotları, karstik kaynak, hidrograf analizi, hidro-kemograf analizi, çekilme eğrisi analizi*

Introduction

Recession curve analysis is a hydrogeological tool to characterize the karst aquifer internal hydraulic properties, catchment characteristics, and climate characteristics (Atkinson, 1977; Amit et al., 2002; Dewandel et al., 2003; Yüce, 2007; Fiorillo, 2014; Ford & Williams, 2013; Kovács & Perrochet, 2008; Padilla & Pulido-Bosch, 1995). For this reason, the structure of mathematical models for the recession curve analysis of karst spring hydrograph is studied in-depth with a particular focus on the quantification of the storage-discharge relationships in karstic aquifers.

Due to the dual-flow characteristics of the karstic aquifers, each segment on the recession curve is characterized by – at least – two flow components, each of which informs about the different sub-regimes in the hydrological system (Bonacci, 1993; Estrela & Sahuquillo, 1997; Fiorillo, 2014; Kovacs et al., 2005; Stevanović, 2015), thereby leading to several recession coefficients that characterize the distinct flow components on a single recession curve (Xu et al., 2018). To a certain extent, while the late-time recession segment on the recession curve represents the more stable part of the spring hydrograph, while indicating the maturity of the system's hydrological response, the early-time recession segment represents rather flashier characteristics of the system of interest (Birk & Hergarten, 2010; Tallaksen, 1995). Therefore, on a single recession curve, while the baseflow characteristics of the karstic system are mainly linked to the matrix-dominated flow component defined as the behavior of the late-time recession curve, the fractured and/or conduit-dominated flow is tracked by the early-time recession behavior. Furthermore, the transition flow between these distinct flow regions could develop, thereby resulting in more than two inflection points on the single recession curve.

The extraction of the candidate recession segment(s) from the recession curve is the first step to analyze the recession characteristics based on the recession parameters. Thus, the recession curve analysis inherently covers the identification of the recession time (or initial discharge value of the recession curve/segment) and recession length (or recession duration) of a candidate recession curve(s). For this reason, these two variables of the recession curve are of great importance to obtain the recession coefficients while covering the recession variability over the spring hydrograph analysis. Therefore, for the identification of the recession time and its duration in the recession curve, different methodological approaches have been proposed with a primary aim to eliminate the potential biases and uncertainties – mainly sourcing from the implementation procedure such as the single-event analysis and master recession curve analysis (Gregor & Malik, 2002; Nathan & McMahon, 1990).

As a traditional karst spring hydrograph analysis approach, the manual selection of a candidate recession curve/segment is the main step to define the recession parameters, followed by the implementation of an appropriate conceptual model for the candidate recession curve –under either the linear reservoir or non-linear reservoir model assumptions. Of all, the linear reservoir model – known as Millet exponential formula – is commonly used for the karst spring hydrograph analysis for the delineation of recession characteristics. This analysis simultaneously covers the matrix-dominated and conduit-dominated flow segments (Çelik & Çallı, 2021; Forkasiewicz & Paloc, 1967; Fu et al., 2016).

Despite the merit of the traditional recession curve analysis (Biswal & Marani, 2010; Shaw & Riha, 2012), the flow characteristics of any hydrological system cannot be only derived by an individual recession curve/segment (Fiorotto & Caroni, 2013). This is mainly because the structure of the recession curve (shape and degree of steepness) significantly varies from one hydrological event to another. Along with this, the manually selected recession curve procedure is neither a practical technique to cover all candidate recession curves, nor it allows extracting the entire hydrological diversity of the karst spring recession behavior (Calli & Hartmann, 2019). For that reason, the recession analysis should be collectively performed to capture the hydrological variability of discharge dynamics and its hydraulic properties considering a long data record (Chen & Krajewski, 2015; Jachens et al., 2019; Sánchez-Murillo et al., 2015; Stewart, 2015; Stoelzle et al., 2013). In this context, the framework of the automated recession curve extraction procedures for the streamflow hydrograph analysis has been gained attention as an alternative approach to objectively extract candidate recession curves(s) while delineating the catchment baseflow conditions (– or late-time recession characteristics) of the streamflow. Therefore, this framework provides an opportunity to eliminate the potential biases and uncertainties caused by the subjectivity of the manually selected curve procedure, thereby allowing to capture the hydrological diversity of the system of interest based on the recession behaviour.

Since the applicability of the recession curve extraction procedure is still not being evaluated for the recession curve analysis in karst spring hydrographs for the delineation of the late-time recession characteristics, the overall goal of this study is to investigate the applicability of the automated recession curve extraction procedures to the late-time recession parameters of the karst spring hydrograph. To achieve so, we applied three automated recession extraction methods (REMs), which are specifically developed to characterize the baseflow characteristics of the streamflow hydrographs. By coupling these three REMs – Vogel; Brutsaert; and Aksoy and Wittenberg Methods – with four recession analysis methods (RAMs) – Maillet (1905); Boussinesq (1904); Coutagne (1948); and Wittenberg (1999) Methods –we comparatively evaluated the applicability of each procedures for the estimation of the late-time recession parameters of each karst springs. Doing that, we simultaneously examined the variations in the range of recession parameters in response to the applied recession extraction procedure. Therefore, to reveal the possible weakness of REMs procedures, we carried out spring hydro-chemograph analysis for the identification of the late-time recession time and its duration considering the independent physicochemical data of spring discharge.

Method

Data Sets

To reveal to what extent the REMs is applicable for the characterization of spring hydrograph's late-time characteristics we selected five karst springs in Austria. Each spring reflects the different hydrological flow regimes (Figure 1). The main properties of the springs are provided in Table 1. The recession curve analysis was performed daily over the 10 years (01/01/2002–31/12/2012). Daily precipitation, spring discharge, and physicochemical dataset including electrical conductivity and water temperature were obtained from https://ehyd.gv.at/#.

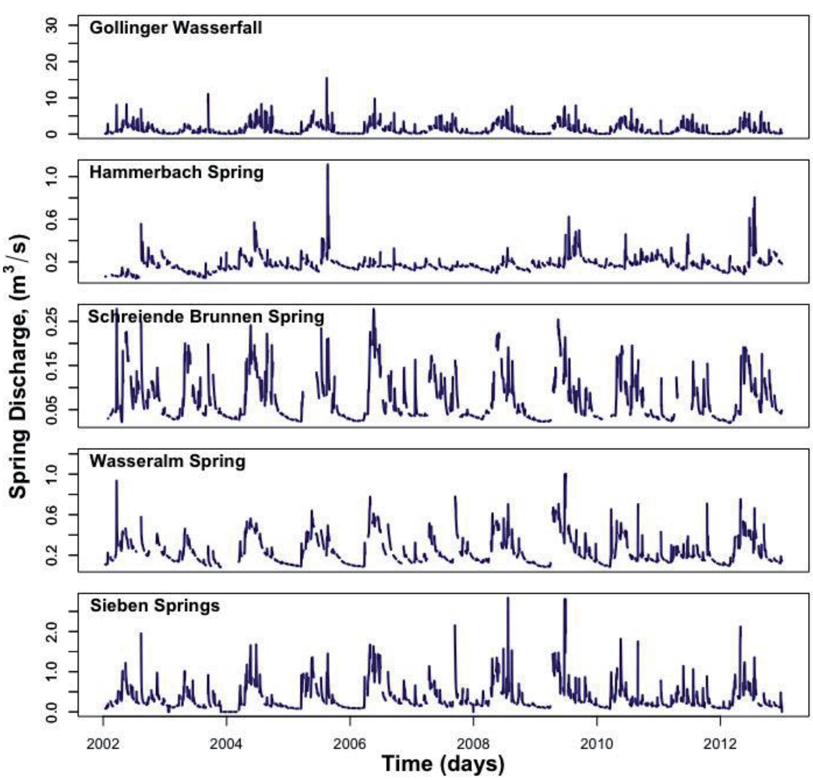
Table 1

Metadata of the Selected Karst Springs in Austria

Spring Name	Elevation (m.asl)	Geology	Mean Annual Discharge (m^3/s)
Gollinger Wasserfall	555	Cretaceous Limestone	1.25
Hammerbach Spring	410	Paleozoic carbonate rocks	0.19
Schreiende Brunnen	980	Limestone	0.08
Wasseralm Spring	802	Triassic Limestone and dolomites	0.24
Sieben Springs	797	Triassic Limestone and dolomites	0.37

Figure 1

The Karst Spring Hydrographs in Austrian Site Over the Period of 01/01/2002 – 31/12/2012



Applied Procedure to Define Late-time Recession Characteristics of Hydrographs

To define the late-time recession characteristics of the karst springs we used the HYDRORECESSION toolbox developed by Arciniega-Esparza et al. (2017) in MATLAB environment while R-Studio was used for the post-processing analysis of the obtained recession parameter sets.

For the estimation of hydrograph recession parameters, we first applied three automated REMs to extract the candidate recession segments from each recession curve from spring hydrographs during the period of 01/01/2002 - 31/12/2012. The REMs procedures are the Vogel Method (Vogel & Kroll, 1992); Brutsaert Method (Brutsaert & Nieber, 1977; Brutsaert, 2008), and Aksoy and Wittenberg Method (Aksoy & Wittenberg, 2011). After the extraction of each recession segment from the 10-year data record, four RAMs including Maillet (1905); Boussinesq (1904); Coutagne (1948); and Wittenberg (1999) were applied to the hydrographs for the estimation of the late-time recession parameters. Then, we compared each parameter estimation procedure by referring to the different combinations of REMs and RAMs. Furthermore, to reveal the variations in the value of estimated parameters due to the applied parameter-fitting techniques (PFTs), the linear regression, lower envelope, and data binning methods were used for the estimation of the recession parameters.

Recession Curve Analysis and Recession Plots

To comparatively evaluate the automated recession curve methods, we performed the automated recession extraction procedures to the karst spring hydrographs. All methods are already successfully applied to the streamflow hydrographs to analyze the baseflow characteristics of the catchment hydrology while discarding the influence of the storm events on the early-time response of the recession curve to capture the late-time hydrological response (baseflow characteristics) of the catchment.

As an analytical model parameterization method, the late-time recession analysis is performed based upon the recession slope curve (hereinafter referred to as hydrograph recession plot) analysis. This analysis involves the selection/extraction of a candidate recession segment(s) and plotting the log – log graph of the recession rate (dQ/dt) as a function of the discharge (Q). This linking approach based on the Boussinesq equation is proposed by Brutsaert and Nieber (1977) to eliminate time dependencies on recession curve analysis (Rupp & Selker, 2005).

The hydrograph recession plot defines the storage-discharge relationship by the slope of the hydrograph (- dQ/dt, (LT^{-2})) and discharge (Q, (LT^{-1})) using a power law of form of storage-discharge relationship expressed by;

$$\frac{-dQ}{dt} = aQ^b \quad (1)$$

where *b* and *a* are the recession parameters, referring to the power coefficient (–) and recession coefficient (T^{-1} or $(L^3/T)^{1-b}$), respectively. These parameters vary from catchment to catchment (Brutsaert & Nieber, 1977), thus indicating the instinct properties of the hydrological system (Rimmer & Hartmann, 2012). In Eq. 1, the discharge rate (- dQ/dt) is computed by the differences of two consecutive points on the extracted recession segment ($dQ/dt = (Q_{i+1} - Q_i)/\Delta t$) while Q is calculated as a mean value of these discharge values ($Q = (Q_{i+1} + Q_i)/2$).

In general, the exponent b (–) ranges from less than 1 to larger than 3 (Chapman, 1999; Harman et al., 2009; Kirchner, 2009; Wittenberg, 1999), which is attributed to the catchment heterogeneities (Clark et al. 2009; Tague & Grant, 2004). As a special case, when the exponent *b* (–) is equal to 1, the hydrological system acts as a linear reservoir, referring to the main concept formula for the recession curve analysis in the karst spring hydrograph analysis – known as the Maillet's exponential formula by Maillet (1905):

$$Q_t = Q_0 e^{-\alpha t} \quad (2)$$

where Q_0 and Q_t are the initial discharge and the discharge at the time, *t*, respectively. α is the recession coefficient (T^{-1}) indicating the intrinsic hydraulic properties of aquifer system.

To obtain late-time recession parameters of the karst spring hydrograph we used the recession plot approach (- dQ/dt vs. Q) which overlaps the multiple individual recession segments extracted by four REMs. Each procedure for the parameter estimation is detailed in Table 2 and Table 3. After applying the recession plot to estimate the recession parameters of b *(–)* and a *(T^{-1})*, to assess model performance on late-time flow analysis and the quality fit of the recession plots the performance metrics of Nash Suffice Efficiency, NS and Coefficient of Determination, R^2 were performed.

$$NS = 1 - \frac{\sum_{i=1}^{N} |Q_{sim,i} - Q_{obs,i}|}{\sum_{i=1}^{N} |Q_{obs,i} - \overline{Q_{obs}}\ |} \quad (3)$$

$$R^2 = \left(\frac{\sum_{i=0}^{N} (Q_{obs,i} - \overline{Q_{obs}})(Q_{sim,i} - \overline{Q_{sim}})}{\sqrt{\sum_{i=0}^{N} (Q_{obs,i} - Q_{obs})^2} \sqrt{\sum_{i=0}^{N} (Q_{sim,i} - \overline{Q_{sim}})^2}} \right)^2 \quad (4)$$

where $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and simulated spring discharges at time, *i,* while $\overline{Q_{obs}}$ and $\overline{Q_{sim}}$ represent the mean values of the corresponding variables.

Procedure for the Estimation of Recession Parameters

For the estimation of recession parameters of five karst springs in Austria, we used three REMs and four RAMs provided in the HYDRORECESSION software toolbox. The algorithms of the recession curve extraction and recession analysis methods are summarized in Table 2 and Table 3.

To comparatively assess the REMs, the recession coefficients were only calculated by the Maillet exponential formula as it is the most preferable recession analysis method for spring hydrograph recession analysis. Additionally, we used PFTs which are broadly used for the model fitting techniques over the hydrograph recession plot [log (- dQ/dt) vs. log (Q)].

For the sake of simplicity, we used the abbreviations of VG, BRU, and AWM for the Vogel Method, Brutsaert Method, and Aksoy and Wittenberg Method, respectively. Similarly, the abbreviations of MAI, BOU, and WIT were used for the Maillet (1905), Boussinesq (1904), and Wittenberg (1999) Methods. During the recession analysis, the PFTs including the linear regression, lower envelope, and data binning were also shortened by LR, LE, and BIN, reciprocally.

To refer to the dual combination of REMs and RAMs for the procedure of recession parameter estimation we used the mathematical symbol of the intersection “∩”. For instance, we called VG ∩ MAI to combine the Vogel recession extraction method with the Maillet recession analysis method.

Table 2

Recession Extraction Methods (REMs)

Recession Extraction Methods	Criterion	Minimum Duration* (days)	Filter Criterion* (removed days)	Exclusion of Anomalous Recession Decline*
Vogel and Kroll, 1992	Decreasing 3-day moving average	10	First 30 %	$\frac{Q_i - Q_{i+1}}{Q_{i+1}} > 30\ \%$
Brutsaert and Nieber, 1977	$\frac{dQ}{dt} < 0$	6-7	First 3-4 Last 2	$\frac{Q_i - Q_{i+1}}{Q_{i+1}} > \frac{dQ}{dt}$
Aksoy and Wittenberg, 2011	$\frac{dQ}{dt} < 0$	5	First 2	$CV > 0.20$

*Editable features provided by the HYDRORECESSION Toolbox. We used the same properties as provided.

Table 3

Recession Analysis Methods (RAMs)

Recession Analysis Methods	Storage-Discharge Relationship	Recession Curve Equation	Parameter-Fitting Techniques
Maillet, 1905	$S = \frac{Q}{\alpha}$	$Q_t = Q_0 e^{-\alpha t}$	Mean Square Error
Boussinesq, 1904	$S = \int f(Q) dt$	$Q_t = \frac{Q_0}{(1 + nt)^2}$	Least Squares
Coutagne, 1948	$\frac{dQ}{dt} = -\alpha Q^b$	$Q_t = \frac{1}{\left[{Q_0}^{1-b} - (1-b)\alpha t\right]^{1-b}}$	Linear Regression Lower Envelope Data Binning
Wittenberg, 1999**	$S = cQ^d$	$Q_t = Q_0 \left[1 + \frac{(1-d)Q_0}{cd}\right]^{\frac{1}{(d-1)}}$	Mean Square Error

**provided by the HYDRORECESSION Toolbox. In the paper, the recession parameters, c and d, of the Wittenberg Method are referred to a and b, respectively.

Incorporation of Hydro-Chemographs into Late-time Recession Curve Analysis

To reveal the late-time recession time and its duration based on the physicochemical response of the karstic aquifers we examined spring hydro-chemographs by relating this process-based knowledge with the aquifer internal flow dynamics. To do so, we considered the dynamic hydrological response of the karstic aquifer considering karst spring physicochemical data including electrical conductivity (*EC)* and water temperature (*T)* in response to variations of spring discharge (Q). This, therefore, allowed us to examine to what extent the late-time recession time and its duration could be captured by the hydro-chemograph analysis.

Results and Discussions

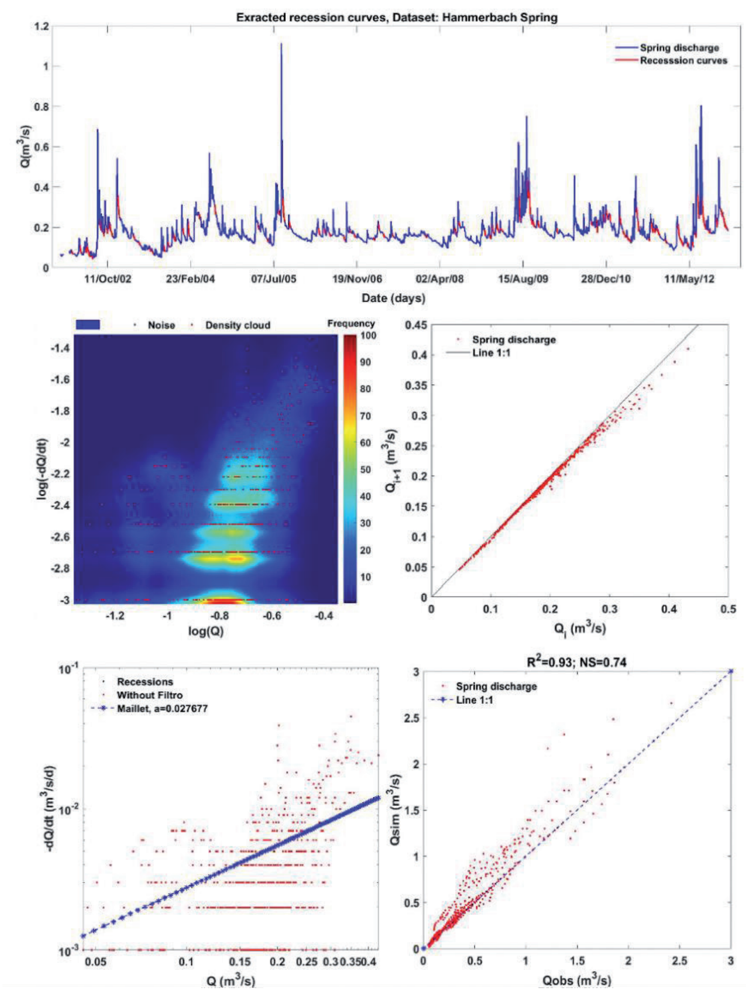
Extraction of Late-time Recession Curves

Figure 2 and Figure 3 demonstrate how an automated REM was implemented into the spring hydrograph recession curve analysis while collectively analyzing the recession parameters over the 10-year discharge data. In both figures, the spring hydrographs are also accompanied by the recession plots [log (- dQ/dt) vs. log (Q)] in which the aggregation of all candidate recession curves (hereinafter referred to the 'point cloud') and the plot of linearity of the selected points (Q_{i+1} vs. Q_i) are provided. Here, the model results for the Hammerbach spring and Gollinger Wasserfall are particularly given for the comparison of the main differences between the automated recession curve analysis, which are only resulted from the hydrological regimes of both springs. The BRU recession extraction method was used to exemplify the implementation procedure of the REMs in each spring while the Maillet method was selected as a reservoir model. Furthermore, Appendix Figure A1 demonstrates the model results for the Gollinger Wasserfall spring with the selection of three REMs over the period of 01/01/2002 – 31/12/2012.

Overall, the recession extraction procedure does not necessarily capture the late-time recession behavior of Hammerbach spring (Figure 2), instead mainly extracting the early-time recession characteristics. By comparison, the late-time recession segments are, in general, represented by the extracted curves from the Gollinger Wasserfall during the 10 years (Figure 3). Considering the recession plots – indicated as the point cloud in both figures – the point space for the Gollinger Wasserfall is more consistent, providing a denser space for the point cloud than that of Hammerbach spring. Overall, the dependency of the recession rate (- dQ/dt) on the discharge of the Gollinger Wasserfall is higher to obtain the storage-discharge relationship, thus defining the late-time flow characteristics. However, the extracted segments do not ensure a condensed space for the Hammerbach spring hydrograph, thereby resulting in a rather noise for the estimation of recession parameter, despite the better model performance (NS: 0.74 and R^2: 0.93).

Figure 2

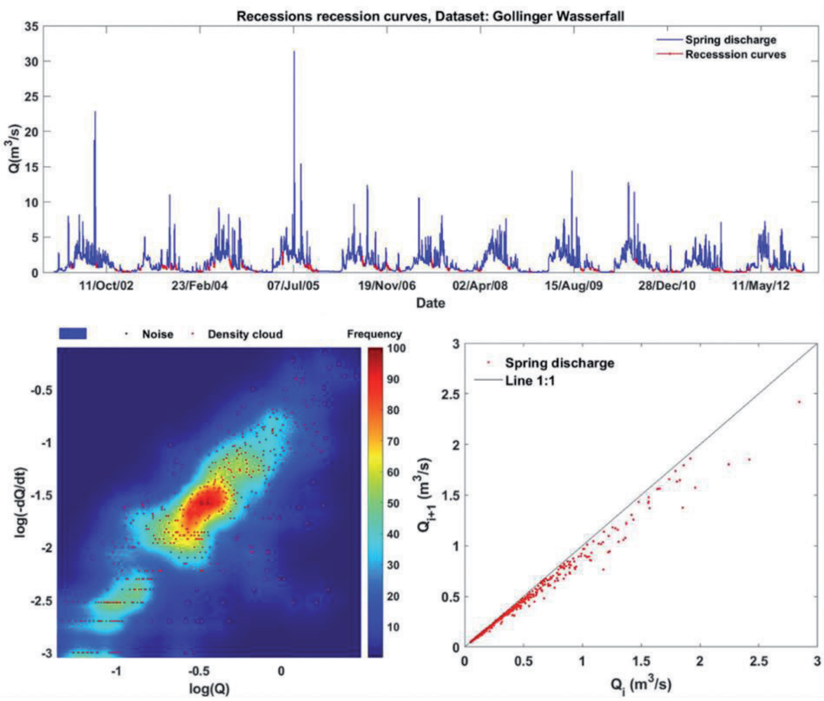
Model Results Obtained from HYDRORECESSION



Note. Upper Panel: Extracted recession curves of Hammerbach spring hydrograph over 10 years. Lower Panel (1): (Left) Hydrograph recession plot is demonstrated as a form of a cloud of points, which indicates the noise reduction from log (- dQ/dt) vs. log (Q). Lower Panel: (Right) Linearity of the dataset based on the simulation with the Maillet method. Lower Panel (2): (Left) Hydrograph recession plot is demonstrated as a form of a cloud of points, which indicates the noise reduction from log (-dQ/dt) vs. (Q). The Lowest Panel: (Right) Model performance on the late-time flow analysis based on the with the Maillet method, and the quality fit of the recession plots demonstrated by the model performance metrics.

Figure 3

Model Results obtained from HYDRORECESSION



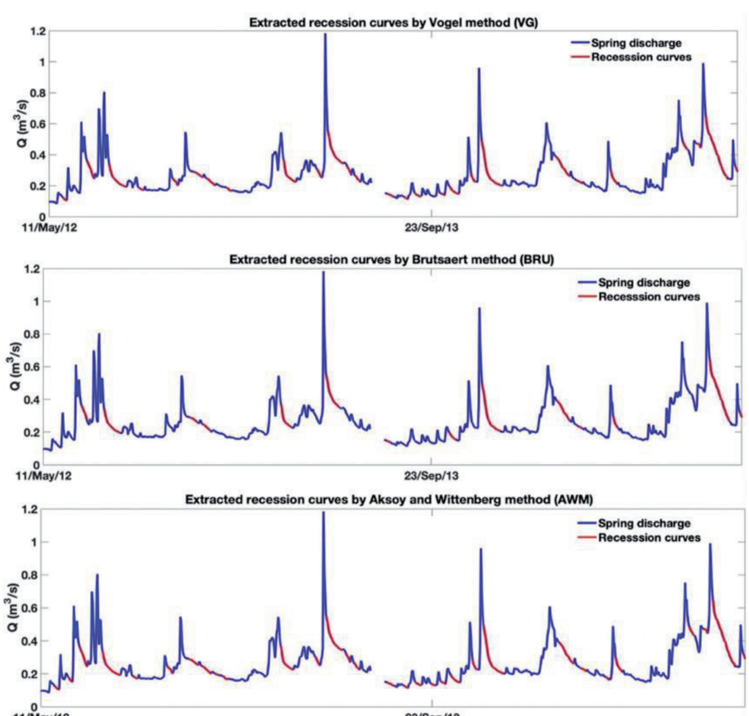
Note. Upper Panel: extracted recession curves of Gollinger Wasserfall for 10 years (01/01/2002 – 31/12/2012). Lower Panel: (Left) Hydrograph recession plot is demonstrated as a form of a cloud of points, indicating the noise reduction from log (- dQ/dt) vs. log (Q). *Here, the red points correspond to the clouds with higher frequency.* Lower Panel: (Right) Linearity of the dataset based on the model simulation with the Maillet method.

For the comparison of three REMs, Figure 4 exemplifies the extracted curves from the Hammerbach spring hydrograph over a one-year time-window. Overall, the BRU method extracted the 14 recession segments (a = 0.039 day^{-1}, NS = 0.71, R^2 = 0.91) during which the VG method extracts 27 segments (a = 0.035 day^{-1}, NS = 0.75, R^2 = 0.93) whereas the AWM method selected more segments with 31 segments, in total (a = 0.020 day^{-1}, NS = 0.89, R^2 = 0.98). Figure 4 also reveals that some extracted recession segments were interrupted by a sudden - but rather small – increment in the spring discharge, which limits to obtain the longer recession curves. This ultimately led to the extraction of a rather short recession segment. For that reason, it is not necessarily possible to cover a long recession curve when the recession rate

(- dQ/dt) is exposed to a small increment over the recession curve. Therefore, considering the flow characteristics of the extracted segment(s), the REMs procedures mainly captured the transition-time and late-time recession characteristics. This implies that all three methods do not necessarily correspond to the late-time recession characteristics in the spring hydrograph in each level of the recession curve analysis. Figure 4 confirms that the AWM method extracts more recession segments while capturing the recession variability much better, thereby providing with candidate recession segments for the spring hydrograph recession curve analysis.

Figure 4

The Comparison of the REMs during the Automated Recession Curve Extraction Procedure for the Hammerbach Spring

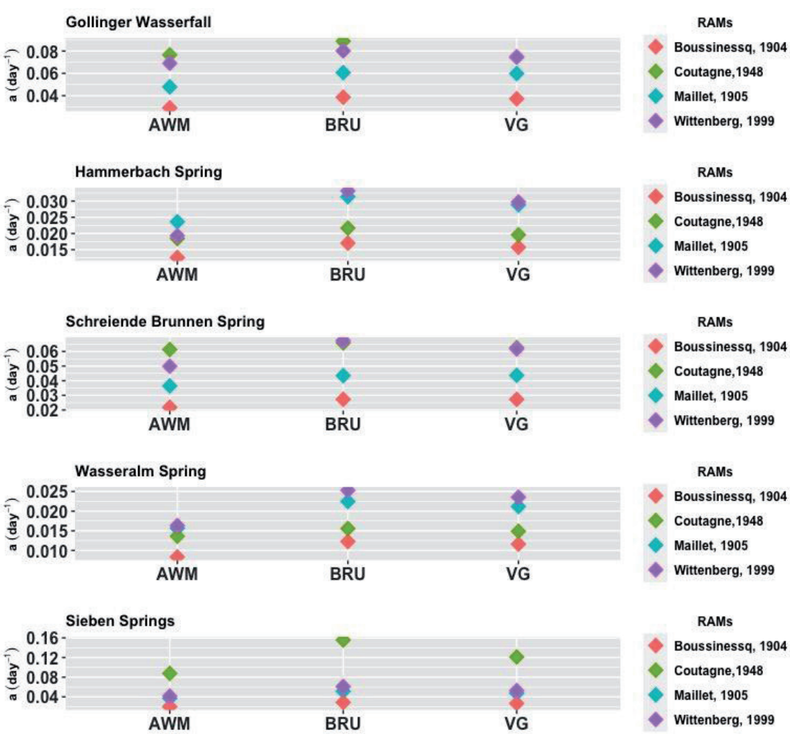


Variations in Obtained Recession Coefficients Due to the Implementation Procedure

The variations in the obtained late-time recession coefficients, *a* (day^{-1}) of the karstic springs are indicated in Figure 5. Overall, the estimated values were mainly influenced by which parameter estimation procedure was applied into the spring hydrograph analysis, thereby bringing in a wide range of parameter range. Of all dual combinations with RAMs, the AWM method consistently provided the lowest recession coefficients, followed by the VG and BRU methods, respectively. Similarly, as a reservoir model, the Boussinesq method ensured the estimation of the lowest recession coefficient by all dual combinations with three REMs regardless of which type and shape of the spring hydrograph were under the examination. Therefore, the results in Figure 5 are also supported by the previous findings about the streamflow hydrograph recession curve analysis (Stewart, 2015; Chen & Krajewski, 2016) such that the parameter estimation is strongly influenced by which procedure is implemented into the recession curve analysis. Yet here, the only exception would be the Boussinesq method which delivered the lowest values in the parameter range among all dual combinations by REMs and RAMs.

Figure 5

Variations of the Estimated Recession Coefficients for the Austrian Site Springs



Note. The recession parameters for the karstic springs are obtained from the 10-year spring discharge data records (01/01/2002 – 31/12/2012).

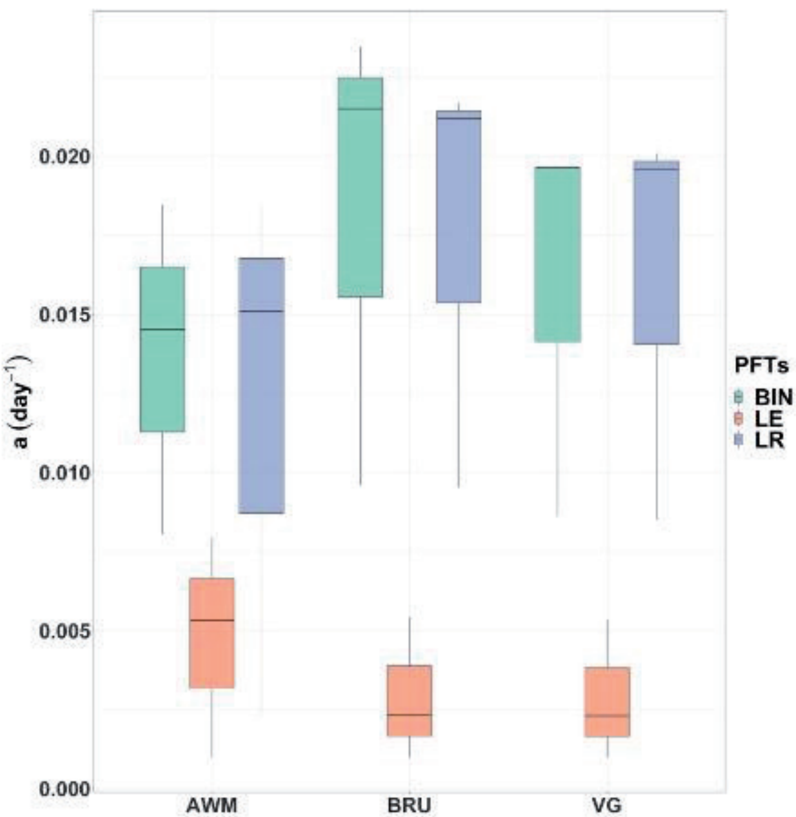
The box-and-whisker plots in Figure 6 demonstrate the sensitivity of the annual recession coefficient, a (day^{-1}) to the selection of the PFTs. The recession analysis results are also provided in Appendix Figure A2 for the Hammerbach spring over 01/01/2002 – 31/12/2012. Here, the Coutagne method was used to estimate the recession coefficients as it mainly gives insight into the non-linearity of a hydrological system due to the different b (–) values. Overall, the lower envelope (LE) with all REMs provided the lowest parameter values while ensuring a strictly confined parameter space with a lower interquartile range (IQR). This, therefore, gave less uncertain parameter estimation. Similarly, the AWM method enabled to obtain the lower recession coefficients as compared to the BRU and VG methods, particularly allowing a larger interquartile range with the linear regression (LR) method. As opposed to the AWM method, the higher values of the recession coefficient obtained by the combination of BRU ∩ LE and BRU ∩ LR amplified the parameter uncertainty, as indicated by the wider IQRs. Furthermore, the LE naturally contributed to the lower values with all dual combinations by each REM, thereby providing a less uncertain parameter range. Hence, Figure 6 confirms that the selection of PFTs inherently designs the estimation of the recession parameter(s) as much as the implementation of the REMs and RAMs procedures. From this point of view, it would be possible to infer that the dual combination procedure of the recession parameter estimation would serve to obtain different parameter ranges depending on the research target – preferably to estimate either lower or higher recession coefficients.

Incorporation of Hydro-Chemograph Analysis into Late-Time Recession Curve Analysis

Figure 7 and Figure 8 exemplify the main difference between the physicochemical response of Sieben springs and Hammerbach spring, accompanied by the spring hydrographs. In general, the temporal variations in *EC* for both springs did not have the same behavior during certain time-periods, particularly over the summer during which the young water came into the hydrological system via the storm event(s). The same hydrological response could also be tracked over the 10-year period (2002-2012) (see Appendix Figure A3-A4).

Figure 6

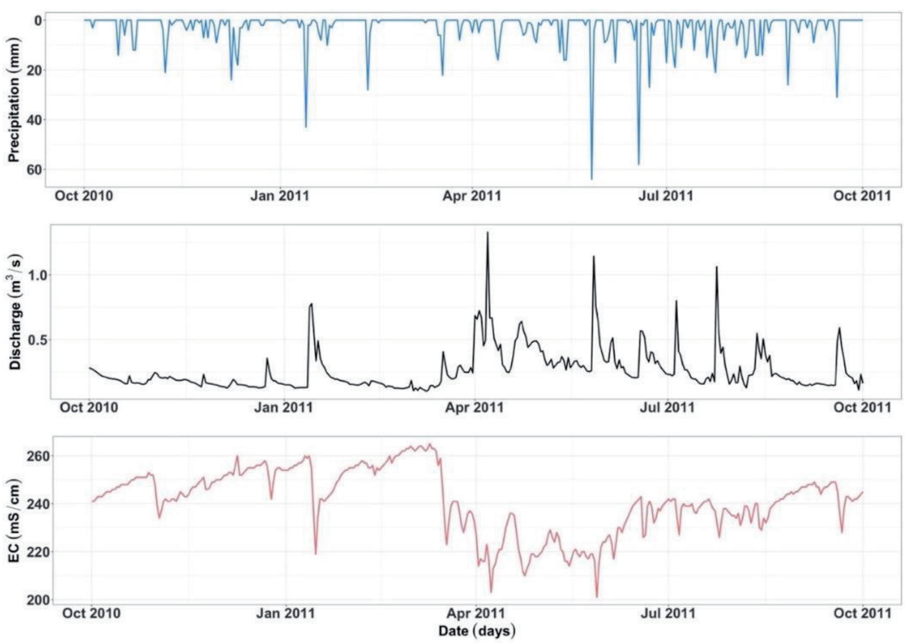
The Range of the Annual Recession Coefficients for the Hammerbach Spring



Note. Here, the Coutagne method was used as a RAM for the model parameterization. The boxplots indicate the 25th and 75th percentile of the annual recession coefficients. The black line in each plot demonstrates the median value of the estimated values.

Figure 7

A Time-Window for the Physicochemical Response of the Sieben Springs Over A One-Hydrological Year (01/10/2010 - 01/10/2011)



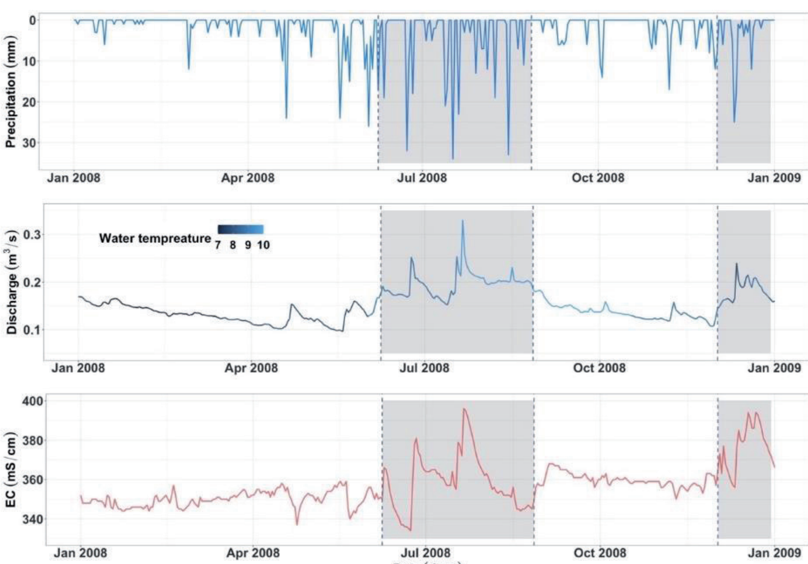
Note. Here, when the young water comes into the aquifer system by the storm (precipitation) event, the old water in storage is quickly mobilized by the propagation of hydraulic pulses, thereby resulting in a corresponding decline in EC.

In Figure 7, the physicochemical response of the hydrological system is mainly characterized by the system hydrological process in such that after the entrance of the new coming water into the karstic system, the stored old water is quickly mobilized by the propagation of hydraulic pulses. This process is primarily known as the 'piston effect' (Ford & Williams, 2013), typically seen in karstic aquifers, thereby resulting in a sudden decline in *EC* in response to the increment of spring discharge. To a lesser extent, this typical response of the karstic system entails the strong cross-correlation between storm events and spring discharge (Fiorillo & Guadagno, 2010; Ford & Williams, 2013).

As oppose to the physicochemical response of Sieben springs in Figure 7, the positive relationship between the Hammerbach spring discharge and *EC* can be observed during the period of late-May and mid-August in Figure 8. Here, the peaky behavior in the spring discharge and *EC* mainly overlapped each other during the shaded periods. Indeed, this is not a typical or common response observed in karstic hydrological system, which can be explained by the piston effect. Instead, the chemical response of the system in the shaded areas could be related to the hydrogeological settings of the karstic aquifer. For that reason, a reasonable explanation is that that the epikarst zone could consist of easily soluble evaporitic rocks such as gypsum, thus leading to a substantial increase in *EC* followed by a snowmelt period around May during which the snowmelt dominates the physicochemical response of Hammerbach spring. Therefore, the shaded time-periods in the Figure 8 are not necessarily informative about the karst spring hydrograph late-time recession characteristics, especially while resembling the late-time recession time and duration.

Figure 8

A Time-Window for the Physicochemical Responses of the Hammerbach Spring During the Period of 01/01/2008 - 01/01/2009



Note. The spring discharge hydrograph is classified considering the variations in the temperature. The hydrograph is also accompanied by the temporal variations in the *EC*.

As for the temporal relationship between Q and *T* for Hammerbach spring in Figure 8, the lowest values of *T* primarily characterize the matrix-dominated flow regimes whereas an increase in the spring discharge leads to a decline in *T* due to the dilution effect. More importantly, the time-period during which the discharge flow component (either conduit or matrix, or a combination of both) dominating the spring flow can be identified by the analysis of the temporal variation of *T* in karst spring. For instance, at the beginning of the time-period – indicated by the shaded areas – the spring flow still reflects the matrix-dominated discharge characteristics with the values of *T* varying between 7°C and 8°C. However, the substantial increase in the water temperature, *T* after mid-July could be explained by the domination of the conduit/fracture flow component on the spring hydrograph. Therefore, as compared to *EC*, the temporal variation in *T* is particularly important as it is more likely to bring the process-based system knowledge into the pure late-time recession curve/segment analysis.

Conclusions

Our research attempted to explore the applicability of the REMs procedures to the late-time recession analysis in the karst spring hydrograph. To do so, we comparatively evaluated the REMs by combining with four RAMs, while obtaining late-time recession parameters.

Our results confirmed that although the procedures of the REMs for the streamflow recession curve analysis is a convincingly systematic approach to objectively extract the candidate curves (– or segments), it is not necessarily possible to capture the late-time recession characteristics of karst spring hydrograph by the REMs during in our research. In fact, the primary problem encountered over five spring hydrograph analysis was that the candidate recession curves/segments did not necessarily reflect a certain type of flow characteristic in each hydrograph. Instead, the automated REMs extracted the different recession segments – mainly considering the decreasing discharge rate (- dQ/dt) – while reflecting the different sub-regimes in the karstic hydrological system. Therefore, since each REM procedure mainly ignores the early-time recession behavior to analyze the catchment baseflow characteristics from the streamflow hydrograph under the assumption that the early-time recession segment is more frequently influenced by the storm events – considering its intensity and duration –, it might not be possible to define the recession characteristics of the conduit-dominated flow mechanism, either. At this point, when an automated recession procedure is applied to the spring hydrograph analysis it would be wise to first decide upon which type of hydrograph (e.g., flashy, or steady) is under the examination, then to estimate the recession parameters by those recession segments.

To define the recession time and the duration for the spring recession curve analysis, it is also reasonable to couple spring hydrograph analysis with the hydro-chemograph analysis to reliably extract the candidate recession curve/segments based on the hydro(geo)logical process over the karstic system. This, therefore, leads to capturing the hydrological process knowledge of which distinctive flow mechanism could be more dominant on the recession curve.

Due to the hydrological and climatological characteristics of the karstic hydrological system, the automated recession curve selection approach is of great importance to reduce the potential uncertainties conveyed throughout the manually selected curve procedure – which is typically applied in the spring hydrograph analysis –. In this context, our research highlighted the fact that a framework of collectively and automatedly extracted recession curve analysis for karst spring hydrograph is essential to capture the recession variability while eliminating the subjectivity of the manually selected recession curve analysis. Therefore, there is an apparent need to develop an automated recession curve extraction procedure(s) to collectively analyze the recession behaviors of karst spring hydrographs, either characterizing the matrix-dominated flow or quantifying the conduit/fractured-dominated flow characteristics.

Our study provided a research direction to improve the automated recession curve extraction procedures, while drawing a conclusion that the hydro-chemograph analysis is a reasonable complementary technique when this knowledge is coupled by the automated recession curve analysis algorithm. Doing that, the recession time (initial discharge) and its duration (length) of a recession curve/segment could be captured by the physicochemical response of a karst spring, thereby constraining the parameter uncertainty in the recession analysis based on the system process-based knowledge.

Acknowledgment

This research was carried out in the Chair of Hydrological Modelling and Water Resources in Albert-Ludwigs-Universität Freiburg (Freiburg, Germany) during my four-month MSc internship under the supervision of Prof. Dr. Andreas Hartmann in 2019. The research was also a small part of my MSc study in hydrological modeling area in Wageningen University & Research (Wageningen, the Netherlands). Some part of this research was presented in European Geoscience Union (EGU) EGU General Assembly 2019. https://meetingorganizer.copernicus.org/EGU2019/EGU2019-8722-2.pdf

References

Aksoy, H., & Wittenberg, H. (2011). Nonlinear baseflow recession analysis in watersheds with intermittent streamflow. *Hydrological Sciences Journal–Journal Des Sciences Hydrologiques 56*(2), 226-237. **https://doi.org/10.1080/02626667.2011.553614**

Amit, H., Lyakhovsky, V., Katz, A., Starinsky, A., & Burg, A. (2002). Interpretation of spring recession curves. *Groundwater*, *40*(5), 543-551. **https://doi.org/10.1111/j.1745-6584.2002.tb02539.x**

Arciniega-Esparza, S., Breña-Naranjo, J. A., Pedrozo-Acuña, A., & Appendini, C. M. (2017). HYDRORECESSION: A Matlab toolbox for streamflow recession analysis. *Computers & Geosciences*, *98*, 87-92. **http://doi.org/10.1016/j.cageo.2016.10.005**

Atkinson, T. (1977). Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology 35*(1-2): 93-110. **http://doi.org/10.1016/0022-1694(77)90079-8**

Birk, S., & Hergarten, S. (2010). Early recession behaviour of spring hydrographs. *Journal of Hydrology, 387,* 1-2, 24-32. **http://doi.org/10.1016/j.jhydrol.2010.03.026**

Biswal, B., & Marani, M. (2010). Geomorphological origin of recession curves. *Geophysical Research Letters, 37*(24), 1-5. **http://doi.org/10.1029/2010GL045415**

Bonacci, O. (1993). Karst springs hydrographs as indicators of karst aquifers. *Hydrological Sciences Journal, 38*(1)*,* 51-62. **http://doi.org/10.1080/02626669309492639**

Boussinesq, J. (1904). Recherches théoriques sur l'écoulement des nappes d'eau infiltrées dans le sol et sur le débit des sources. *Journal de Mathématiques Pures et Appliquées,* 10, 5-78.

Brutsaert, W., & Nieber, J. L. (1977). Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research, 13*(3), 637-643. **http://doi.org/10.1029/WR013i003p00637**

Brutsaert, W. (2008). Long- term groundwater storage trends estimated from streamflow records: Climatic perspective. *Water Resources Research, 44*(2), 1-7. **https://doi.org/10.1029/2007WR006518**

Calli, K. O., & Hartmann, A. (2019). Applicability of recession extraction approaches and recession analysis methods procedures to karstic springs. In *Geophysical Research Abstracts* (Vol. 21). **https://doi.org/10.13140/RG.2.2.10597.76001**

Çelik, M., & Çallı, S. S. (2021). Conduit and fracture flow characteristics of Pinarbaşi estavelle, Central Taurus Region, Seydişehir, Turkey. *Acta Carsologica, 50*(1), 97-118. **https://doi.org/10.3986/ac.vi.6997**

Chapman, T. (1999). A comparison of algorithms for stream flow recession and baseflow separation. *Hydrological Processes*, *13*(5), 701-714. **https://doi.org/10.1002/(SICI)1099-1085(19990415)13:5<701::AID-HYP774>3.0.CO;2-2**

Chen, B., & Krajewski, W. F. (2015). Recession analysis across scales: The impact of both random and nonrandom spatial variability on aggregated hydrologic response. *Journal of Hydrology*, *523*, 97-106. **https://doi.org/10.1016/j.jhydrol.2015.01.049**

Chen, B., & Krajewski, W. (2016). Analysing individual recession events: sensitivity of parameter determination to the calculation procedure. *Hydrological Sciences Journal 61*(16), 2887-2901. **http://doi.org/10.1080/02626667.2016.1170940**

Clark, M. P., Rupp, D. E., Woods, R. A., Tromp-van Meerveld, H. J., Peters, N. E., & Freer, J. E. (2009). Consistency between hydrological models and field observations: linking processes at the hillslope scale to hydrological responses at the watershed scale. *Hydrological Processes: An International Journal, 23*(2), 311-319. **http://doi.org/10.1002/hyp.7154**

Coutagne, A. (1948). Météorologie Et Hydrologie-Etude générale des débits et des facteurs qui les conditionnent. *La Houille Blanche, 34*(3), 228-245. **https://doi.org/10.1051/lhb/1948035**

Dewandel, B., Lachassagne, P., Bakalowicz, M., Weng, Ph., & Al-Malki, A. (2003). Evaluation of aquifer thickness by analysing recession hydrographs. Application to the Oman ophiolite hard-rock aquifer. *Journal of Hydrology, 274*(1-4), 248-269. **http://doi.org/10.1016/S0022-1694(02)00418-3**

Estrela, T., & Sahuquillo, A. (1997). Modeling the response of a karstic spring at Arteta aquifer in Spain. *Groundwater, 35*(1), 18-24. **http://doi.org/10.1111/j.1745-6584.1997.tb00055.x**

Fiorillo, F., & Guadagno, F. M. (2010). Karst spring discharges analysis in relation to drought periods, using the SPI. *Water Resources Management, 24*(9), 1867-1884. **https://doi.org/10.1007/s11269-009-9528-9**

Fiorillo, F. (2014). The recession of spring hydrographs, focused on karst aquifers. *Water Resources Management, 28*(7), 1781-1805. **https://doi.org/10.1007/s11269-014-0597-z**

Fiorotto, V., & Caroni, E. (2013). A new approach to master recession curve analysis. *Hydrological Sciences Journal, 58*(5), 966-975. **http://doi.org/10.1080/02626667.2013.788248**

Ford, D., & Williams, P. (2013). *Karst hydrogeology and geomorphology*. John Wiley & Sons, Ltd.

Forkasiewicz, J., & Paloc, H. (1967). *Le regime de tarissement de la Foux de la Vis. Chronique d'hydrogeologie, 10,* 59-73.

Fu, T., Chen, H., & Wang, K. (2016). Structure and water storage capacity of a small karst aquifer based on stream discharge in southwest China. *Journal of Hydrology, 534*, 50-62. **http://doi.org/10.1016/j.jhydrol.2015.12.042**

Harman, C. J., Sivapalan, M., & Kumar, P. (2009). Power law catchment-scale recessions arising from heterogeneous linear small-scale dynamics. *Water Resources Research, 45*, 1-13. **https://doi.org/doi:10.1029/2008WR007392**

Jachens, E. R., Rupp, D. E., Roques, C., & Selker, J. S. (2019). Recession analysis 42 years later–work yet to be done. *Hydrology and Earth System Sciences Discussions,* 1-16. **http://doi.org/10.5194/hess-2019-205**

Kirchner, J. W. (2009). Catchments as simple dynamical systems: Catchment characterization, rainfall- runoff modeling, and doing hydrology backward. *Water Resources Research*, *45*(2). **https://doi.org/10.1029/2008WR006912**

Kovács, A., Perrochet, P., Király, L., & Jeannin, P. Y. (2005). A quantitative method for the characterisation of karst aquifers based on spring hydrograph analysis. *Journal of Hydrology, 303(1-4),* 152-164. **http://doi:10.1016/j.jhydrol.2004.08.023**

Kovács, A., & Perrochet, P. (2008). A quantitative approach to spring hydrograph decomposition. *Journal of Hydrology, 352*(1-2), 16-29. **http://dx.doi.org/10.1016/j.jhydrol.2007.12.009**

Maillet, E. T. (1905). *Essais d'hydraulique souterraine & fluviale.* A. Hermann Press.

Nathan, R. J., & McMahon, T. A. (1990). Evaluation of automated techniques for base flow and recession analyses. *Water Resources Research, 26*(7), 1465-1473. **https://doi.org/10.1029/WR026i007p01465**

Padilla, A., & Pulido-Bosch, A. (1995). Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *Journal of Hydrology, 168*(1-4), 73-89. **http://doi.org/10.1016/0022-1694(94)02648-U**

Rimmer, A., & Hartmann, A. (2012). Simplified conceptual structures and analytical solutions for groundwater discharge using reservoir equations. *Water Resources Management and Modeling 2:* 217-238. **https://doi.org/10.5772/34803**

Rupp, D. E., & Selker, J. S. (2005). Drainage of a horizontal Boussinesq aquifer with a power law hydraulic conductivity profile. *Water Resources Research, 41*(11), 1-8. **https://doi.org/10.1029/2005WR004241**

Sánchez-Murillo, R., Brooks, E. S., Elliot, W. J., Gazel, E., & Boll, J. (2015). Baseflow recession analysis in the inland Pacific Northwest of the United States. *Hydrogeology Journal, 23*(2), 287-303. **http://doi.org/10.1007/s10040-014-1191-4**

Shaw, S. B., & Riha, S. J. (2012). Examining individual recession events instead of a data cloud: Using a modified interpretation of dQ/dt–Q streamflow recession in glaciated watersheds to better inform models of low flow. *Journal of Hydrology, 434*, 46-54. **http://doi.org/10.1016/j.jhydrol.2012.02.034**

Stevanović, Z. (Ed.). (2015). *Karst aquifers-characterization and engineering*. Springer.

Stewart, M. (2015). Promising new baseflow separation and recession analysis methods applied to streamflow at Glendhu Catchment, New Zealand. *Hydrology and Earth System Sciences, 19*(6), 2587. **http://doi.org/10.5194/hess-19-2587-2015**

Stoelzle, M., Stahl, K., & Weiler, M. (2013). Are streamflow recession characteristics really characteristic? *Hydrology and Earth System Sciences, 17*(2), 817-828. **http://doi:10.5194/hess-17-817-2013**

Tallaksen, L.M., (1995). A review of Baseflow Recession Analysis. *Journal of Hydrology, 165*(1-4), 349-370. **http://doi.org/10.1016/0022-1694(94)02540-R**

Tague, C., & Grant, G. E. (2004). A geological framework for interpreting the low- flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research*, *40*(4). **https://doi.org/10.1029/2003WR002629**

Vogel, R. M., & Kroll, C. N. (1992). Regional geohydrologic- geomorphic relationships for the estimation of low- flow statistics. *Water Resources Research, 28*(9), 2451-2458. **http://doi.org/10.1029/92WR01007**

Yuce, G. (2007). Yenişehir ve Cüdeyde (Reyhanlı–Hatay) Karst Kaynaklarının Boşalım Hidrodinamiği ve Hidrojeokimyasal Özellikleri. *Eskişehir Osmangazi Üniversitesi Mühendislik ve Mimarlık Fakültesi Dergisi*, *20*(2), 159-188.

Wittenberg, H. (1999). Baseflow recession and recharge as nonlinear storage processes. *Hydrological Processes, 13*(5), 715-726. **http://doi.org/10.1080/02626667.2011.553614**

Xu, B., Ye, M., Dong, S., Dai, Z., & Pei, Y. (2018). A new model for simulating spring discharge recession and estimating effective porosity of karst aquifers. *Journal of Hydrology*, *562*, 609-622. **https://doi.org/10.1016/j.jhydrol.2018.05.039**

Appendix

Figure A1

Automated Recession Curve Analysis by HYDRORECESSION for the Gollinger Wasserfall Spring over the Period of 01/01/2002 - 31/12/2012

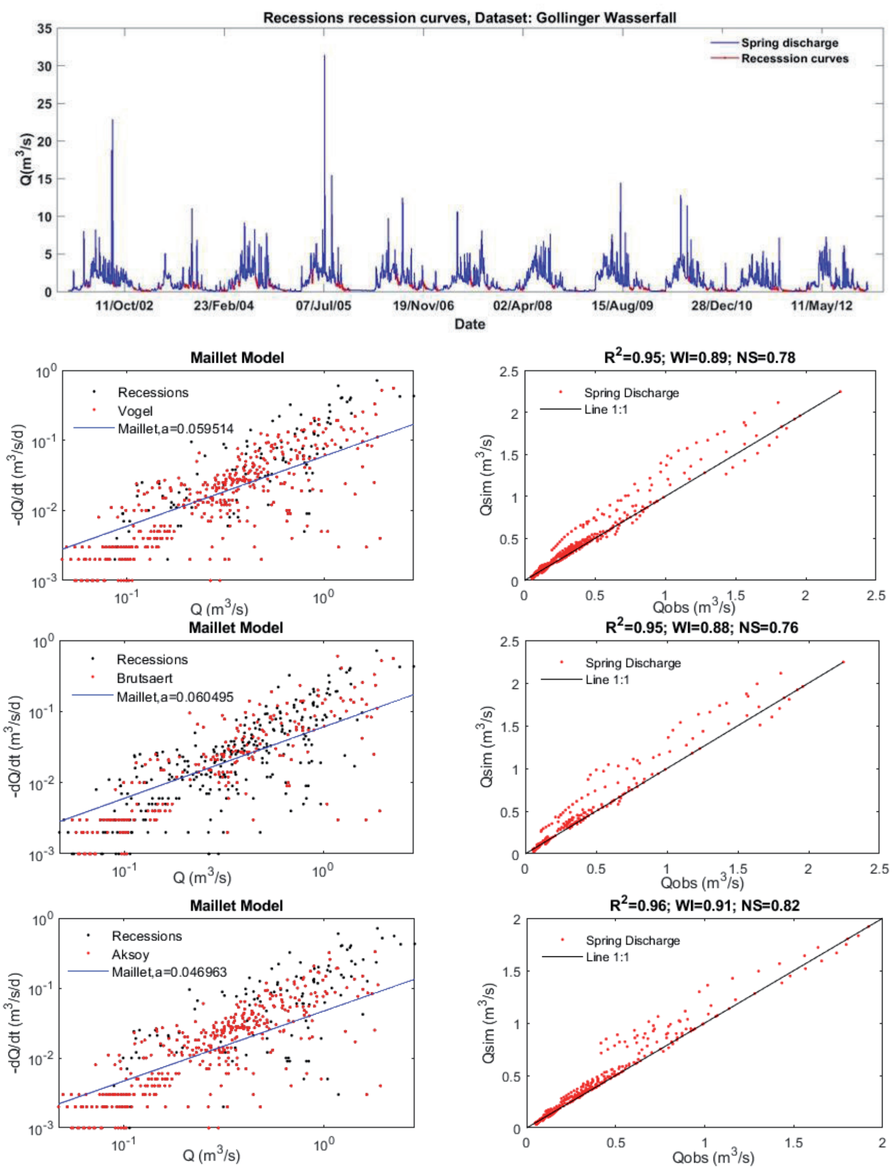
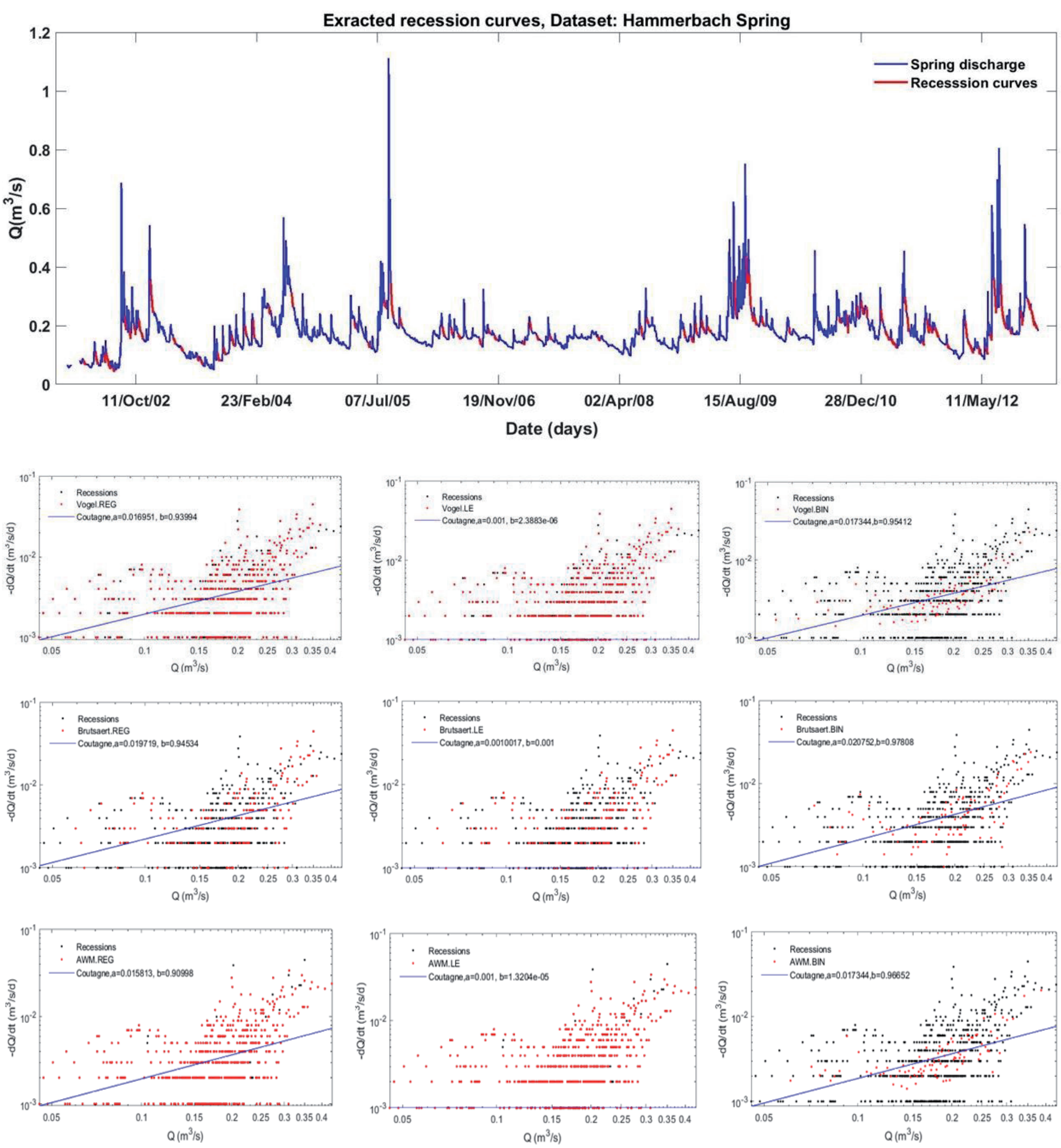


Figure A2

The Model Results Obtained by the Automated REMs for the Hammerbachquelle Spring



Note. REMs and PFTs were compared based on the Coutagne Method.

Figure A3

The Time-Series of the Precipitation, Discharge, and EC for the Sieben Springs Over the Period of 01/01/2002 – 31/12/2012

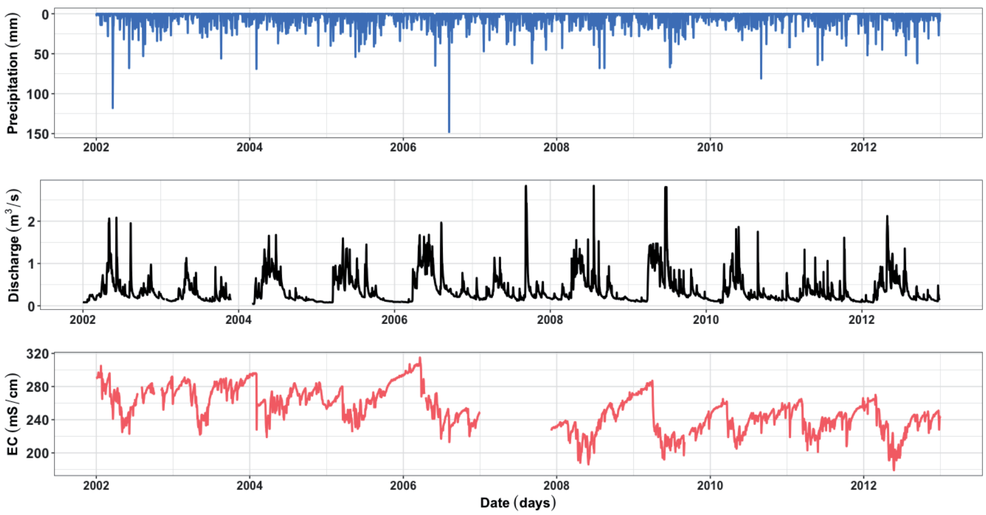
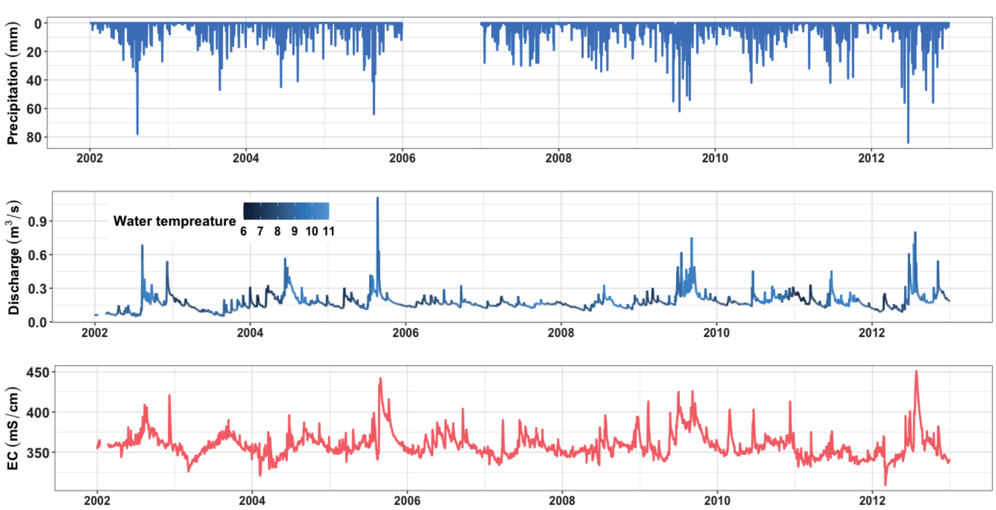


Figure A4

The Time-Series of the Precipitation, Discharge, Water Temperature, and Electrical Conductivity for the Hammerbach Spring Over the Period of 01/01/2002 – 31/12/2012



Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Otomatik Çekilme Eğrisi Seçim Prosedürlerinin Karstik Kaynak Hidrograflarında Karşılaştırılmalı Değerlendirilmesi

Çekilme eğrisi analizleri, hidrolojik sistemlerin hidrodinamik özelliklerini tanımlamak amacıyla kullanılan temel ve yaygın analiz yöntemlerinden birisidir. Akım hidrografı çekilme eğrisi analizlerinden farklı olarak, karstik kaynak çekilme eğrisi analizlerinde bir çekilme eğrisi üzerinde birden fazla çekilme segmenti tanımlanmaktadır. Bu segmentler farklı boşalım rejimleri ile karakterize edilmekte olup birden fazla çekilme katsayısı belirlenmektedir. Örneğin, bir karstik kaynak hidrografi üzerinde geç-zaman çekilme eğrisi karstik sistemde taban akışını temsil eden taneli ortam akım özelliklerini yansıtmaktadır. Öte yandan, aynı çekilme eğrisi üzerindeki erken-zaman çekilme segmenti kırıklı-çatlaklı ortamları ve/veya karstik kanal boşalım koşullarını karakterize etmektedir.

Geleneksel bir yaklaşım olarak, karstik kaynak boşalım parametrelerinin belirlenmesinde temel adım, çekilme eğrilerinin başlangıç ve bitiş zamanlarının manuel olarak belirlenerek, ilgili çekilme segmentine bir matematiksel model eğrisinin uydurulması esasına dayanmaktadır. Bu yöntemin uygulanabilirliğinin önündeki en temel kısıtlayıcı unsur, aday bir çekilme eğrisinin araştırmacı tarafından sübjektif olarak seçimidir. Bununla birlikte, karstik sistemdeki boşalım özelliklerinin öznel olarak belirlenmiş tek bir çekilme eğrisine dayanarak türetilmesi de temsil edicilik açısından yeterli olmamaktadır. Bunun başlıca nedeni, çekilme eğrisinin yapısının bir hidrolojik olaydan diğerine önemli ölçüde değişmesidir. Bu temelde, bir karstik kaynak hidrografında çekilme eğrilerinin manuel olarak seçimi, ne tüm aday çekilme eğrilerini kapsayacak şekilde pratik bir tekniktir, ne de uzun dönemli bir kaynak hidrografı çekilme davranışındaki tüm hidrolojik/hidrodinamik çeşitliliğinin tanımlanmasına izin vermektedir. Buradan esasla, karstik kaynaklarda çekilme eğrisi analizleri, uzun bir veri kaydı dikkate alınarak akım dinamiklerinin hidrolojik değişkenliğini ve hidrolik özelliklerini yakalamak amacıyla toplu olarak yapılmalıdır.

Akarsu hidrograf analizi için otomatikleştirilmiş çekilme eğrisi belirleme prosedürlerinin çerçevesi, havza baz (temel) akış koşullarını (– veya geç dönem çekilme karakteristiklerini) betimlerken, çekilme eğrilerinin nesnel olarak tanımlanabilmesi için alternatif bir yaklaşım olarak dikkat çekmektedir. Buradan hareketle, otomatik çekilme eğrisi analiz teknikleri, manuel olarak seçilen çekilme eğrisi secim prosedürünün öznelliğinden kaynaklanan olası belirsizlikleri ve önyargıları ortadan kaldırmak için önemli bir fırsat sağlamaktadır.

Bu çalışma kapsamında, karstik kaynaklarda geç-dönem çekilme eğrisi analizlerinde otomatik çekilme eğrisi belirleme prosedürlerinin uygulanıp uygulanmayacağı araştırılmıştır. Bu kapsamda, üç adet otomatik çekilme eğrisi belirleme yöntemi (Vogel Metodu, Brutsaert Metodu, Aksoy ve Wittenberg Metodu) ile dört adet çekilme eğrisi analiz metodu (Maillet, 1905; Boussinesq, 1904; Coutagne, 1948; Wittenberg, 1999) birleştirilerek karstik kaynak hidrograflarında geç-dönem çekilme eğrisi parametreleri belirlenmiş ve ilgili yöntemler karşılaştırmalı olarak değerlendirilmiştir. Avusturya'da bulunan beş karstik kaynakta (Wasseralm spring, Sieben springs, Hammerbach spring, Gollingen Wasserfall, Schreniende Brunnen) kaynak çekilme eğrisi analizi uygulanarak otomatik çekilme eğrisi belirleme prosedürlerinin olası zayıf yönleri değerlendirilmiştir. Buna ilaveten, karstik kaynak suyu fizikokimyasal verileri (elektriksel iletkenlik ve yeraltı suyu sıcaklığı) kaynak çekilme eğrisinin çekilme başlangıcı ve çekilme süresinin belirlenebilmesi kapsamında değerlendirilmiş ve

karstik sistemdeki hidrodinamik süreçler ile ilişkilendirilerek çekilme eğrisinin tanımladığı boşalım koşulları karakterize edilmeye çalışılmıştır.

Çalışma metodolojisi sırasıyla dört temel adımı içermektedir: (1) otomatik çekilme eğrisi belirleme yönteminin seçimi (REM), (2) çekilme eğrisi analiz metodunun seçimi (RAM), (3) çekilme parametrenin belirlenmesinde eğri uydurma tekniklerinin seçimi ve (4) karstik kaynak hidro-kemografları ile çekilme eğrisi zamanı ve süresinin tahmini.

Çalışma sonucunda, akarsu akışı çekilme eğrisi analizi için geliştirilen REM prosedürlerinin, aday çekilme eğrilerini nesnel olarak çıkarmak/belirlemek için ikna edici sistematik yaklaşım olduğu desteklenmiştir. Ancak, ilgili metotların karstik kaynak boşalım hidrografının geç zaman çekilme özelliklerini yakalamada yeterli olmayabileceği görülmüştür. Bu temelde, çalışmada otomatik REM'ler ile gerçekleştirilen kaynak çekilme eğrisi analizlerinde beş adet karstik kaynakta karşılaşılan temel ve ortak sorun, aday çekilme eğrilerinin farklı kaynak hidrograflarında belirli bir boşalım karakteristiğini yansıtmaması olmuştur. Bunun yerine, otomatikleştirilmiş REM'ler, karstik akifer sistemdeki farklı alt boşalım rejimlerini yansıtmıştır. Burada ilgili yöntemler, kaynak boşalımının zamanla değişimini (- dQ/dt) dikkate alarak farklı çekilme eğrilerini çıkarmayı başarmıştır.

Bir karstik kaynak hidrografi üzerinde erken dönem çekilme segmentinin yağış girdilerinden doğrudan etkilendiği bir gerçektir. Bu durum özellikle kanal baskın boşalımın hâkim olduğu karstik akifer sistemlerinde önemli ölçüde sistem hidrodinamiğini etkilemektedir. Dolayısı ile bu kaynaklarda geç-dönem çekilme özelliklerini otomatik REM'ler ile tanımlamak mümkün olmayabilir. Bu nedenle, boşalım hidrograf analizine otomatik bir çekilme prosedürü uygulanmak istenildiğinde, önce hangi tip akım hidrografının (örneğin kanal ya da gözenek baskın akım) inceleme altında olduğuna karar verilmeli, ardından çekilme parametreleri bu esasa göre otomatik çekilme eğrisi secim metotları ile tahmin edilmelidir.

Karstik bir hidrolojik sistemin otomatik çekilme eğrisi seçimi yaklaşımı, geleneksel olarak uygulanan çekilme eğrisinin manuel olarak seçiminde karşılaşılan potansiyel belirsizlikleri azaltmak için büyük önem taşımaktadır. Bu bağlamda, araştırmamız, manuel olarak seçilen çekilme eğrileri için hesaplanan çekilme katsayıları sonuçları üzerindeki öznelliği ortadan kaldırmıştır. Çalışma ayrıca, karstik kaynak hidrograflarında çekilme değişkenliğini yakalamak amacıyla kaynak boşalım analizi için toplu ve otomatik olarak çıkarılan bir çekilme eğrisi analizi prosedürünün gerekliliğini vurgulamıştır. Çalışma sonucunda, karstik kaynak hidrograf-kemograf analizlerinin otomatik çekilme eğrisi analizleri ile birleştirildiğinde, makul bir tamamlayıcı teknik olduğu sonucuna varılmıştır. Buna ilaveten, bir çekilme eğrisinin çekilme süresinin bir karstik kaynağın fizikokimyasal tepkisi ile yakalanabildiği, böylece sistem sürecine dayalı çekilme analizindeki parametre belirsizliğinin sınırlandırılabileceği sonucuna ulaşılmıştır.