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Water Supply

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Water Supply Vol 00 No 0, 1 doi: 10.2166/ws.2024.114

Evaluation of spring flows using recession flow analysis techniques

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ABSTRACT

This study delves into the analysis of recession characteristics of spring base flow, focusing on the Hill campus spring (elevation of approximately 2,150 m) and Fakua spring (elevation of approximately 1,850 m) in the Tehri Garhwal district of Uttarakhand, India. Spanning from January 1999 to December 2004, discharge data from G.B. Pant University of Agriculture and Technology's Hill campus are employed. The research employs an automated, objective-based method to generate master recession curves (MRCs) and categorize them into early, intermittent, and late recession segments. Statistical parameters and low-flow indices from flow duration curves (FDCs) are utilized for flow assessment, while base flow indices (BFIs) are analyzed using the Web-based Hydrograph Analysis Tool (WHAT). The findings highlight the importance of water storage strategies during the rainy season for the sustainable utilization of spring water. The study suggests that the techniques applied are equally applicable for analyzing river flow recession characteristics, emphasizing the broader implications for integrated water resources planning and management in mountainous regions.

Key words: spring flow analysis, flow recession modeling, hydrological assessment, recession flow evaluation, spring discharge estimation

HIGHLIGHTS

- This study presents a novel automated and objective-driven method for generating master recession curves (MRCs).
- It categorizes them into early, intermittent, and late recession segments.
- This method employs statistical parameters and low-flow indices derived from flow duration curves (FDCs).

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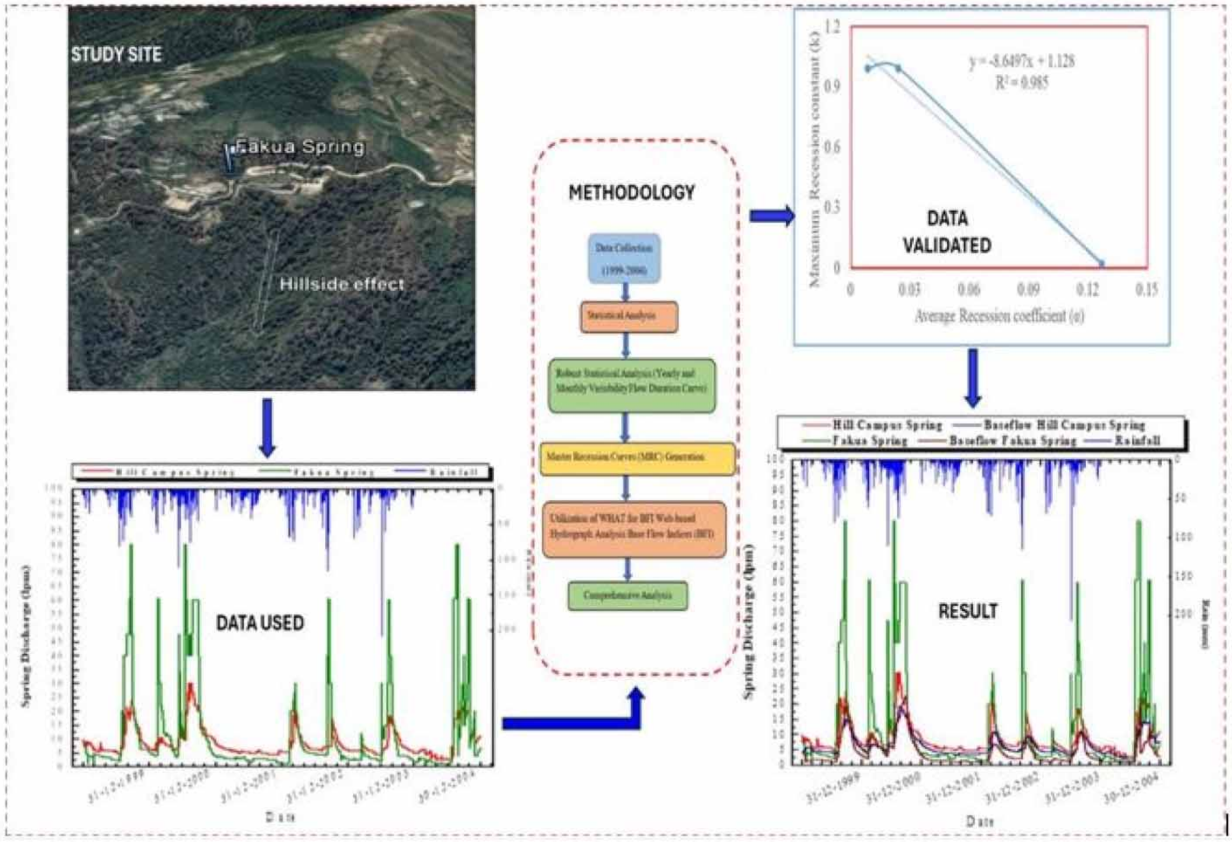
GRAPHICAL ABSTRACT



INTRODUCTION

Aquifers in mountain areas are a strategic resource to ensure water security for the residents of these areas. Particularly, the Himalayan springs provide essential ecosystem services, including water supply for drinking, agriculture, and biodiversity support (Fiorillo 2009; Nautiyal *et al.* 2020). Human activities such as deforestation, urbanization, and land use changes can exacerbate the vulnerability of Himalayan springs to recession flows (Thakur *et al.* 2020). Therefore, the literature assessing the ecological value of these springs often touches upon the vulnerability of their flow to environmental changes, including recessions induced by climate variability or anthropogenic factors. The problem at large is that the discharge from these springs is either drying up or reducing due to deforestation in the hillslopes (Valdiya & Bartarya 1991). Due to data scarcity, not many studies in the Himalayan region were conducted to understand the impact of land use and land cover change or climate variability on spring discharge. Spring discharge varies in nature due to variations in storage and recharge behavior (Valdiya & Bartarya 1989, 1991; Negi & Joshi 1996, 2004; Weiss & Gvirtzman 2007; Peleg & Gvirtzman 2010). However, with the advancement of affordable and efficient experimental techniques, our ability to quantify water resources and monitoring of watersheds becomes easy by using continuous hydrological data. Spring discharge time series are often used for understanding the hydrological processes and for characterization of the aquifer systems (Smart & Hobbs 1986; Kiraly 2002; Amit *et al.* 2002). Research exploring the hydrology of springs in the Himalayas offers foundational knowledge for recession flow analysis (Shrestha *et al.* 2022). Studies have examined factors such as groundwater recharge, aquifer characteristics, and the relationship between precipitation and spring discharge. Understanding these dynamics is essential for predicting how recessions might affect spring flow.

Analyzing the Himalayan spring flows using recession flow analysis techniques is a crucial endeavor for comprehending hydrological systems given their significance for both ecological and human systems in the region. Spring flow characteristics, which can be influenced by factors such as topography, hydrogeology, and surface and subsurface features, play a significant role in watershed management. The sustainable development of springs requires a proper assessment of flow characteristics

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of the springs. Furthermore, it is well-known fact that the optimization of future spring water management basically depends upon the understanding of hydrogeological systems from both geological and hydrogeological perspectives (Bosch *et al.* 2017; Nisa *et al.* 2024). As the springs integrate the signal of geological and hydrological processes over large spatial areas and long periods of time, they are indirect sources of information for water managers in that particular area (Kresic & Stevanovic 2010). Recession flow curves and flow duration curves (FDCs) during dry periods provide distinct signatures of a watershed's spring flow behavior which considerably depends on catchment characteristics (e.g. topography, hydrogeology, surface and subsurface characteristics, etc.) and recharge characteristics in the watershed (Vogel & Fennessey 1995). These signatures serve as valuable indicators for evaluating water availability, sustainability, and ecological health. Analyzing recession flow patterns can help researchers understand the dynamics of groundwater recharge and discharge processes within a watershed. The applications of hydrograph recession analysis have been numerous and include areas such as low-flow frequency analysis, water allocation, hydrograph analysis, base flow augmentation and the assessment of evapotranspiration loss (e.g. Ponce & Lindquist 1990; Gottschalk *et al.* 1997). Furthermore, the application of recession flow analysis techniques allows for the identification of factors that influence spring flow variability, aiding in informed decision-making for water resource management. By combining hydrological modeling and field observations, researchers can refine their understanding of spring flow dynamics and their responses to changing environmental conditions. Such evaluations contribute to the development of effective strategies for water allocation, conservation, and ecosystem preservation in watersheds that rely on spring sources. An advantage of the recession method is that it does not require prior knowledge of the distribution of the potential and the individual parameters of the aquifer, although the recession coefficient directly depends on them.

Many researchers have tried to analyze the recession flow characteristics due to the importance of the hydrograph recession in engineering hydrology. Base flow rates and recession mechanisms of streams and springs have been extensively investigated for more than a century (Boussinesq 1877; Maillet 1905; Tallaksen 1995). In hydrology, such a method is needed to determine the possibilities for storage and exploitation of underground water resources for several uses (Thomas & Cervione 1970; Tasker 1972; Parker 1978; Vogel & Kroll 1992). Karst hydrogeology-specific methods for recession analysis were developed in the 1970s (Drogue 1972; Mijatovic 1974; Mangin 1975; Atkinson 1977; Brutsaert & Nieber 1977; Troch *et al.* 1993). These methods have been used to characterize hydraulically contrasting aquifer volumes (e.g. highly permeable conduit networks and low-permeability rock masses with fissure porosity) and karst aquifers (i.e. based on the quantitative values of hydrodynamic parameters, such as the permeability and storage coefficient). Recession constants obtained from the recession curve analysis can be applied for hydrographs separation and modeling surface runoff (Bates & Davies 1988; Berhail *et al.* 2012). The recession constant is also needed for hydrograph separation using the digital filter base flow separation technique (Chapman 1999; Lim *et al.* 2010). The graphical hydrograph separation technique also known as a semi-logarithmic plot of flow recession is originally applied to a single hydrograph recession (Barnes 1939) used for separating a hydrograph into linear components of surface flow, interflow, and base flow. In order to consider the impact of different factors that affect individual recession segments, a master recession curve (MRC) is a commonly used technique in recession flow analysis (Toebes *et al.* 1969). To develop optimal MRC, Posavec *et al.* (2006) developed an analytical method based on the principle of the adaptive matching strip. The method uses five different linear/nonlinear regression models to adjust individual recession segments to their correct positions in the MRC. Lim *et al.* (2010) have incorporated an automated recession curve analysis method in the Web GIS-based Hydrograph Analysis Tool, called WHAT. A comprehensive review of recession analysis techniques has been carried out by various researchers (e.g. Hall 1968; Tallaksen 1995; Szilagyi *et al.* 1998; Fiorotto & Caroni 2013; Stewart 2015; Jachens *et al.* 2020; Kang *et al.* 2022). The base flow recession analysis of the spring flow has been studied in the literature with some of the studies showing that the recession behaviors during the early recession stage and the late recession stage are different. However, research on the transition from early recession stage to late recession stage is limited and the hydrologic control on the transition is not completely understood. Furthermore, one of the useful characteristics of the spring hydrograph is the ratio of peak discharge to base flow which is very important to estimate subsurface regime (conduit or diffuse flow) in the aquifer system contributing to the spring.

Base flow, including the groundwater, the slow soil runoff, and the water resource replenishment from lakes, reservoirs, and glaciers, greatly helps in determining the available water resources and environmental protection during dry periods (Hall 1968). Sufficient spring discharge must be ensured based on the efficient quantification or prediction of the base flow source. However, the spatial variation and generation of base flow remain unclear due to the complex aquifer condition. Thus, the in-depth analysis of the driving factors of the base flow is essential to understanding sustainable water resources management (Araza *et al.* 2021).

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In view of the above insights, the objective of the present study is to investigate the recession patterns of spring base flow, specifically focusing on Hill campus and Fakua springs in Uttarakhand, India. The study aims to analyze discharge data from January 1999 to December 2004 obtained from G. B. Pant University's Hill campus, utilizing MRCs to categorize recession phases. Statistical parameters and low-flow indices from FDCs are examined to understand flow characteristics, while base flow indices (BFIs) are assessed using the WHAT system. The study highlights the importance of implementing water storage strategies during the monsoon season to ensure sustainable spring water utilization. Additionally, the research aims to demonstrate the potential of these techniques in analyzing river flow recession, particularly valuable for integrated water resources planning in mountainous regions. The disparities in peak flow rate (Q_{max}) and minimum flow rate (Q_{min}) between Hill campus and Fakua springs, along with their sustained discharge patterns, are identified and discussed. These statistical findings are intended to inform the development of effective water resource management and conservation strategies tailored to optimize the utilization potential of these natural springs.

STUDY AREA

The study was conducted to analyze the recession flow characteristics of the springs from the Hill campus of G.B. Pant University of Agriculture and Technology, Ranichauri located at latitude 30° 15′ N and longitude of 78° 2′ E and an altitude of 2,100 m above mean sea level, in Tehri Garhwal district of Uttarachal state of India (Figure 1). This area falls under the middle Himalayas and is sometimes called the outer or lesser Himalayas and the area is strongly undulating and hilly.

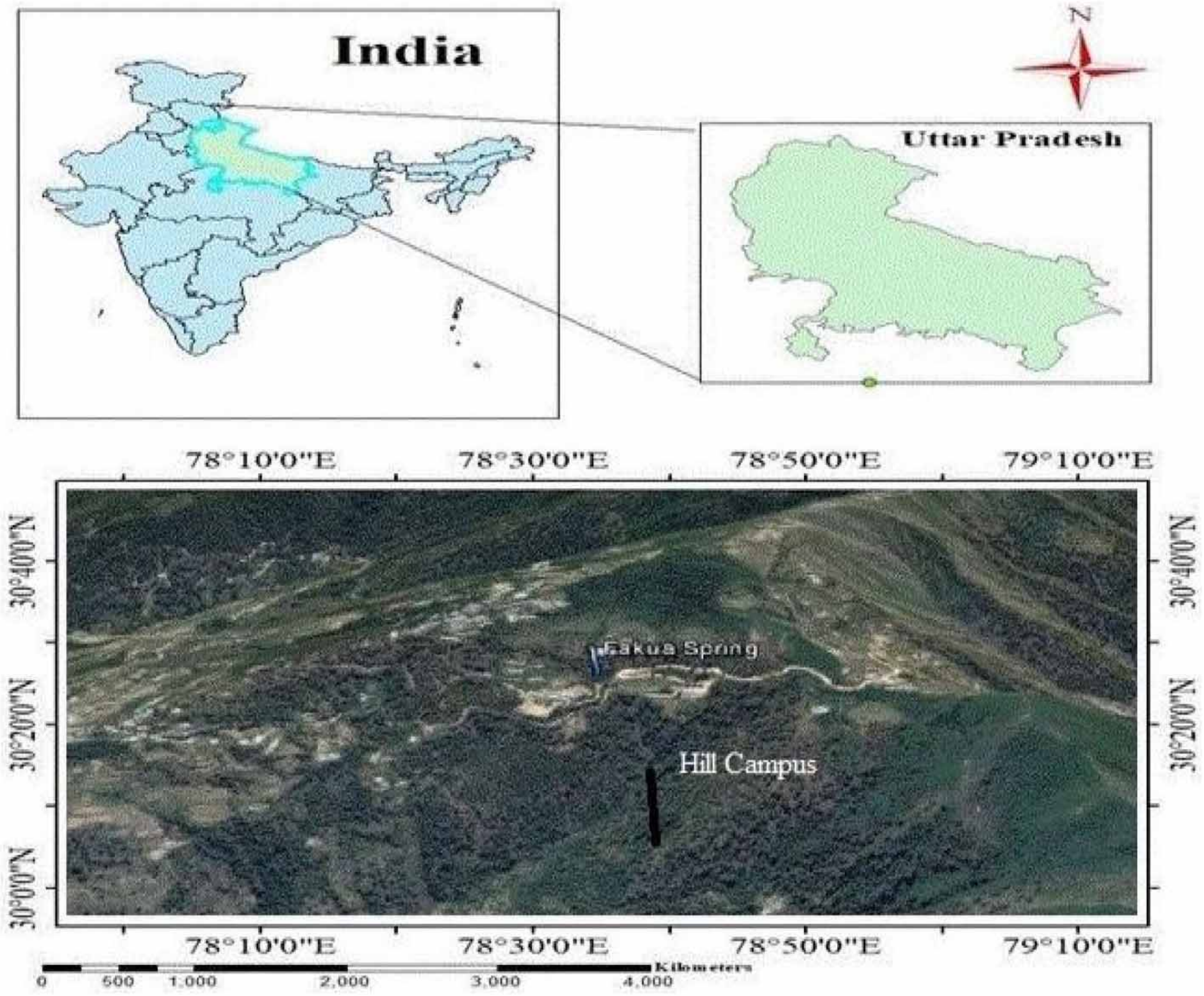

Figure 1 | Location map of the study area.

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Two perennial natural water springs were selected for the study, namely Hill campus spring located at an altitude of about 2,150 m and Fakua spring located at about 1,850 m above mean sea level and at an aerial distance of about 500 m from Hill campus spring. The climate of the study area is monsoonal. The mean maximum temperature recorded at Hill campus, Ranichauri varied from 10.6 °C (January) to 25.5 °C (May). The mean minimum temperature varied from 1.9 °C (January) to 14.9 °C (May). The average humidity recorded at 2 p.m. is minimum (30.4%) during April and maximum (83%) during August. Mean annual rainfall is about 1,176 mm and ranges between 4 mm (November) and 246.75 mm (August). Based on temperature, rainfall and humidity characteristics, an average year could be divided into three distinct seasons, i.e. summer, rainy and winter. During the summer season (i.e. March, April, and May months), the mean maximum temperature varied between 16.6 to 21.1 °C and the mean minimum temperature ranged from 7.8 to 14.2 °C. Humidity ranges from 36.4 to 57.1%. The total average rainfall for this season is 62.6 mm. The rainy season (June to September) is the wettest period of the year with the rainfall ranging from 702 to 857 mm. About 75% of the annual rainfall is received during this period. The fluctuation in the temperature is minimum during this period and it varies from a minimum temperature of 17.8 °C to maximum temperature of 22.8 °C. Humidity is maximum in this season and ranges from 66% minimum to 84% maximum. Winter season (October to February) has low temperature. The minimum temperature of 2.1 °C is found in the month of January and the maximum temperature is 14.6 °C in the month of October. Humidity fluctuates between 25.2 and 34.5%. The average rainfall among different months of the season varies from 10 to 157 mm. Frequent snowfall is observed over the catchment from December to February. The clay fraction is dominant in the Hill campus spring shed in comparison to the Fakua spring shed.

METHODOLOGY

The methodology employed in this study comprises three integral components, each contributing to a comprehensive understanding of the spring flow dynamics. In the first part, a robust statistical analysis was conducted to evaluate the yearly and monthly variability in spring flow for both selected springs. This involved an in-depth examination of the data to discern patterns and trends, shedding light on the temporal nuances of the springs' hydrological behavior. Additionally, low-flow indices, derived from FDCs, were employed to systematically assess the flow characteristics, providing insights into the frequency and duration of low-flow events.

The second part of the methodology involved the implementation of a fully automatic, objective-based method proposed by Posavec in 2006. This method was utilized to generate MRCs for the springs, and subsequently, to optimally partition the curves into three distinct segments representing early, intermittent, and late recession phases. This approach facilitated the extraction of recession constants, enabling a nuanced analysis of the springs' recession characteristics over time.

In the final segment of the methodology, the WHAT, as introduced by Lim *et al.* in 2010, was employed. This system played a pivotal role in analyzing the BFIs for the selected springs. BFI is a crucial parameter for understanding the proportion of spring flow derived from base flow, providing valuable insights into the sustained contribution of groundwater to the overall spring flow. The utilization of WHAT (Figure 2) ensured a comprehensive assessment of the base flow dynamics, further enriching the understanding of the selected springs' hydrological behavior. Together, these three methodological components form a robust framework for analyzing and interpreting the complex dynamics of spring flow in the study area.

Hydro-metrological data used

In this study, hydro-metrological data collected during a 6-year period (1999–2004) from the observatory of Hill campus, Ranichauri of G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand were used. The discharge time series records for Hill campus spring and Fakua spring during the period from January 1999 to December 2004 are used for recession flow analysis. These hydro-meteorological data are shown in Figure 3.

RESULTS AND DISCUSSION

The statistical analysis of flow characteristics of the Hill campus and Fakua springs is carried out using various statically parameters such as maximum discharge ($Q_{\max}$), minimum discharge ($Q_{\min}$), average discharge (Q_{avg}), spring flow variability (%) and variance. The year-wise flow characteristics of these two springs along with annual rainfall values are presented in Table 1. Similarly, the monthly average flow characteristics over a 6-year period and monthly average rainfall over a 5-year period are presented in Table 2.

Referring to Table 1, it can be revealed that the flow characteristics of the Hill campus and Fakua springs were $Q_{\max} = 30.3$ and 80.0 Lpm; $Q_{\min} = 2.69$ and 0.86 Lpm; and $Q_{\text{avg}} = 8.71$ and 10.84 Lpm, respectively. The Fakua spring shows high

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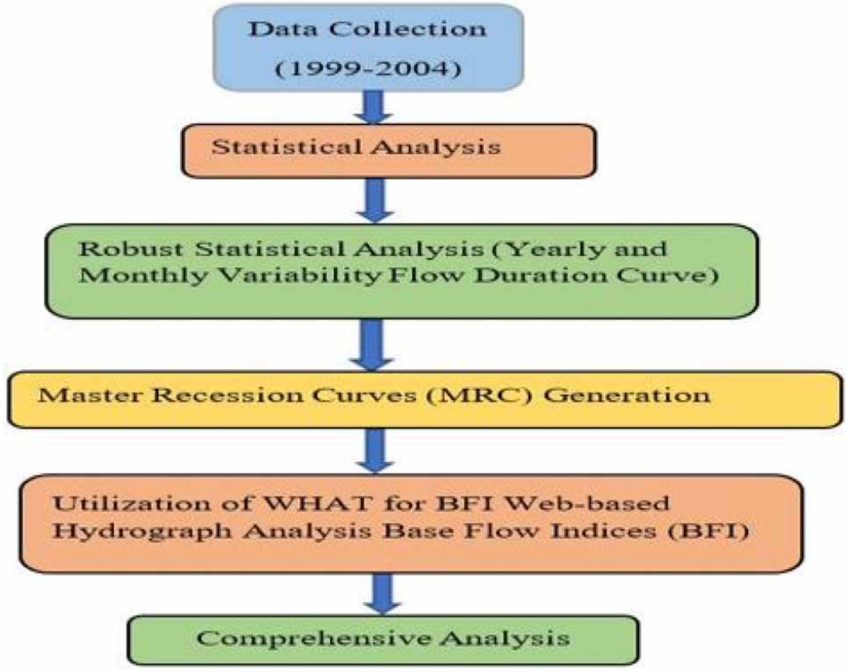

Figure 2 | Flow diagram.

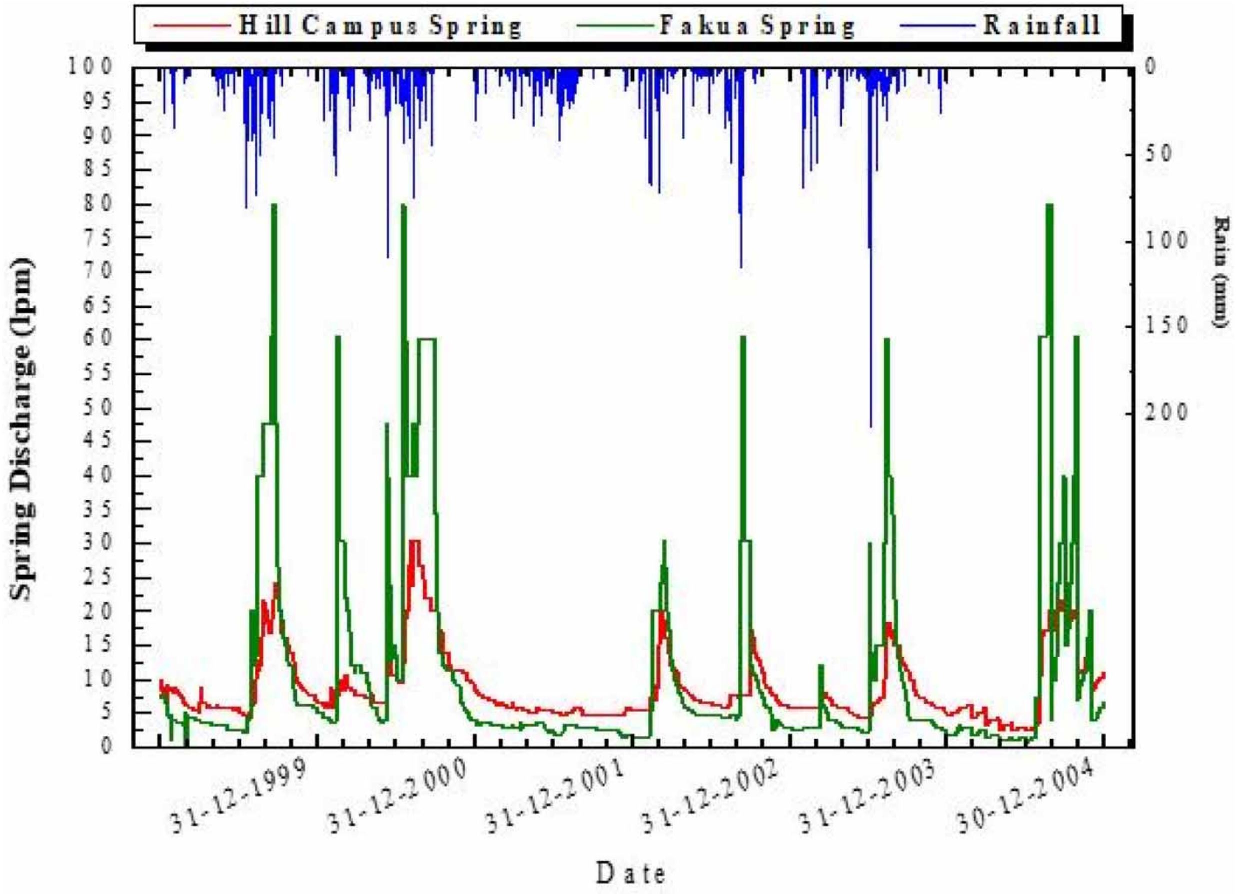

Figure 3 | Rainfall and spring discharge data for the Hill campus and Fakua springs.

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variability as can be seen from parameters such as variability (%) and variance as compared to the Hill campus spring. Both springs show low variability during the comparatively dry year (i.e. 2001) as compared to the wet year (i.e. 2000). Furthermore, it can be seen from annual rainfall and flow characteristics for years 2000–2002 that there is no significant impact of previous high rainfall year on the flow characteristics of both the springs if the successive year has low annual rainfall and vice-versa. Referring to Table 2, it can be seen that the $Q_{\max}$ and $Q_{\min}$ values generally occur in the month of August and June (Hill campus spring), and August and July (Fakua spring), respectively. Hill campus spring shows high flow variability during July–October and March whereas the Fakua spring shows high flow variability during July to October and February to March.

The significance of spring flow variability extends to its profound implications for drinking water supply, warranting meticulous examination and discussion. Springs represent vital sources of freshwater, serving as the essence for countless communities worldwide. Variability in spring flow directly impacts the quantity and quality of water available for drinking purposes, thus necessitating a comprehensive understanding of its dynamics. Fluctuations in flow rates can result in periods

Table 1 | Year-wise flow characteristics of the Hill campus and Fakua springs along with annual rainfall records during the period 1999–2004

	Hill campus spring					**Fakua spring**					
Year	**$Q_{\max}$ (lpm)**	**$Q_{\min}$ (lpm)**	**Q_{avg} (lpm)**	**Variability (%)**	**Variance**	**$Q_{\max}$ (lpm)**	**$Q_{\min}$ (lpm)**	**Q_{avg} (lpm)**	**Variability (%)**	**Variance**	**Annual rainfall (mm)**
1999	24.19	4.8	9.38	206.68	25.05	80	1.19	12.06	654.17	263.26	939.70
2000	30.3	5.84	12.42	196.89	44.86	80	3.58	21.18	360.80	414.60	1,334.40
2001	8.58	4.7	5.58	69.54	0.80	4	1.33	2.86	93.27	0.37	719.10
2002	20	5.46	8.59	169.19	11.87	60.6	1.33	9.00	658.36	95.13	1,255.40
2003	18.46	4.28	7.49	189.18	10.62	60	2	7.62	761.42	98.18	1,160.20
2004	21.73	2.69	8.75	217.43	39.39	80	0.86	12.33	641.92	398.14	
Whole series	30.3	2.69	8.71	317.17	26.31	80	0.86	10.84	737.97	242.59	

Table 2 | Monthly average flow characteristics of the Hill campus and Fakua springs along with monthly average rainfall records during the period 1999–2004

	Hill campus spring					**Fakua spring**					
Month	**$Q_{\max}$ (lpm)**	**$Q_{\min}$ (lpm)**	**Q_{avg} (lpm)**	**Variability (%)**	**Variance**	**$Q_{\max}$ (lpm)**	**$Q_{\min}$ (lpm)**	**Q_{avg} (lpm)**	**Variability (%)**	**Variance**	**Monthly average rainfall (mm)**
Jan	9.83	4.80	6.45	77.93	1.52	7.81	1.19	3.33	199.10	2.93	64.34
Feb	10.05	5.46	6.86	66.90	1.58	60.60	1.33	8.48	699.16	186.34	129.5
Mar	20.00	4.28	8.15	192.83	15.99	30.30	1.71	8.93	320.12	66.61	81.28
Apr	12.00	3.20	6.74	130.49	4.31	13.33	1.50	5.44	217.50	12.71	38.1
May	8.58	2.73	5.71	102.50	2.26	8.58	1.02	3.63	208.36	2.50	65.3
Jun	12.65	2.69	5.80	171.81	5.70	47.60	1.02	5.35	870.35	60.41	108.36
Jul	21.97	2.73	6.44	298.82	14.59	80.00	0.86	10.31	767.28	274.32	218.56
Aug	30.30	3.81	13.70	193.32	67.77	80.00	3.00	30.78	250.13	598.79	220.34
Sep	25.64	4.80	14.69	141.85	44.09	80.00	2.92	29.69	259.61	544.90	127.72
Oct	21.97	4.70	13.23	130.56	26.35	60.60	2.45	13.38	434.75	151.73	5.92
Nov	15.04	4.70	9.11	113.53	8.63	20.00	2.35	6.69	263.87	13.62	4.36
Dec	11.30	4.70	7.46	88.50	3.94	6.67	1.33	3.99	133.92	2.59	17.98
Whole series	30.30	2.69	8.71	317.17	26.31	80.00	0.86	10.84	737.97	242.56	

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of scarcity or abundance, directly affecting the reliability and accessibility of drinking water sources. Furthermore, changes in spring flow patterns can influence water treatment processes, as alterations in flow rate may impact water quality parameters such as turbidity and dissolved oxygen levels. Moreover, groundwater recharge, facilitated by spring flow, plays a pivotal role in replenishing aquifers and sustaining drinking water supplies in many regions. As such, discussions surrounding spring flow variability must delve into its implications for drinking water availability, quality, and management, emphasizing the urgency of adopting adaptive strategies to safeguard this essential resource for human health and well-being.

Furthermore, the low-flow indices based on FDCs for these two selected springs are computed to analyze the sustainability of these springs. The FDCs of the Hill campus and Fakua springs are shown in Figure 4. Furthermore, computed low-flow indices are given in Table 3.

Referring to Table 3, it can be seen that the variation of range of the low-flow indices for the Hill campus and Fakua springs are Q10/Q90 = 3.65 and 16.57%, Q90/Q50 = 0.72 and 0.44% and Q50/Q90 = 1.39 and 2.25, respectively. From these results, it can be concluded that the Fakua spring has a high value of Q10/Q90 ratio as compared to the Hill campus spring. The

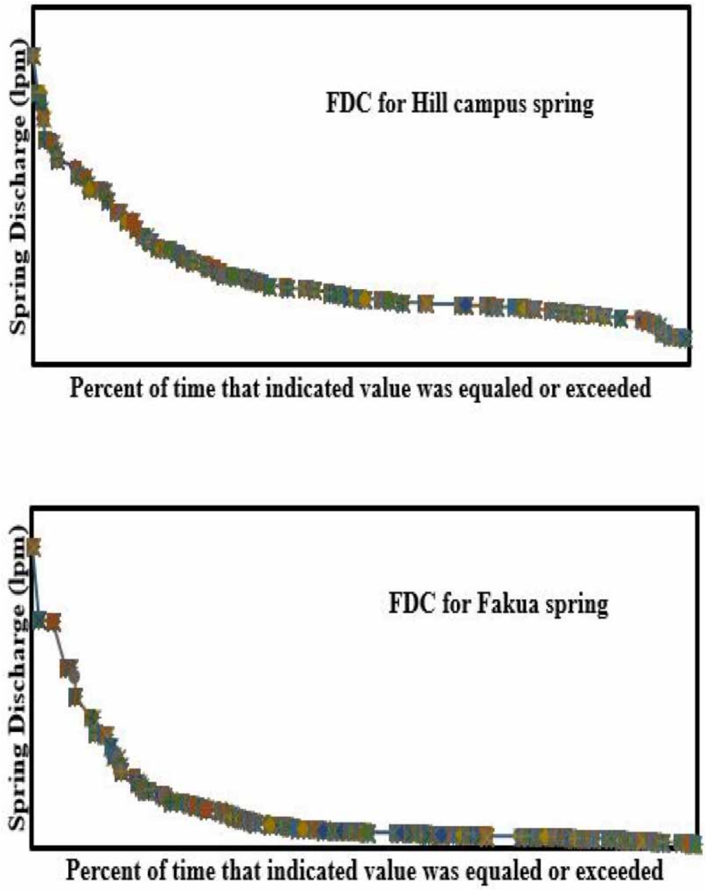

Figure 4 | FDCs of the Hill campus and Fakua springs for the period 1999–2004.

Table 3 | Low-flow indices based on obtained FDCs for the Hill campus and Fakua springs

Spring name	Q10	Q30	Q50	Q90	Q10/Q90	Q90/Q50	Q50/Q90
Hill campus	17.14	8.85	6.54	4.70	3.65	0.72	1.39
Fakua	30.00	8.57	4.08	1.81	16.57	0.44	2.25

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higher value of the Q10/Q90 ratio suggests that the spring flows are highly variable and there is the possibility of very small spring flow discharge during summer months. The ratio Q90/Q50 shown in Table 3 gives information about the contribution of groundwater flow. The results show that the Hill campus spring has a large contribution to the base flow into the total spring flow as compared to the Fakua spring. These results clearly suggest that Hill campus springs have very high potential to be used as a potential drinking water resource to manage the water need especially in summer months as compared to the Fakua spring.

As mentioned earlier, to account for the different factors that affect individual recession segments a fully automatic objective-based method (Posavec *et al.* 2006) is applied for the generation of MRCs for the Hill campus and Fakua springs and its separation into three segments namely early, intermittent and late recession segments. The optimally separated MRCs for both of the springs are shown in Figure 5. Furthermore, the obtained recession coefficients and recession constants from the separated three segments of the optimal MRCs of both springs are given in Table 4. It can be observed from Figure 5 that the MRC of the Hill campus spring shows a distinct early recession segment (i.e. runoff) but intermittent and late recession segments are not that distinct. However, there is quite a difference in the obtained intermittent and late MRC segments as seen from the recession parameters presented in Table 4. The Fakua spring shows three distinct recession segments as compared to the Hill campus spring as can be seen from Figure 5 and Table 5. Furthermore,

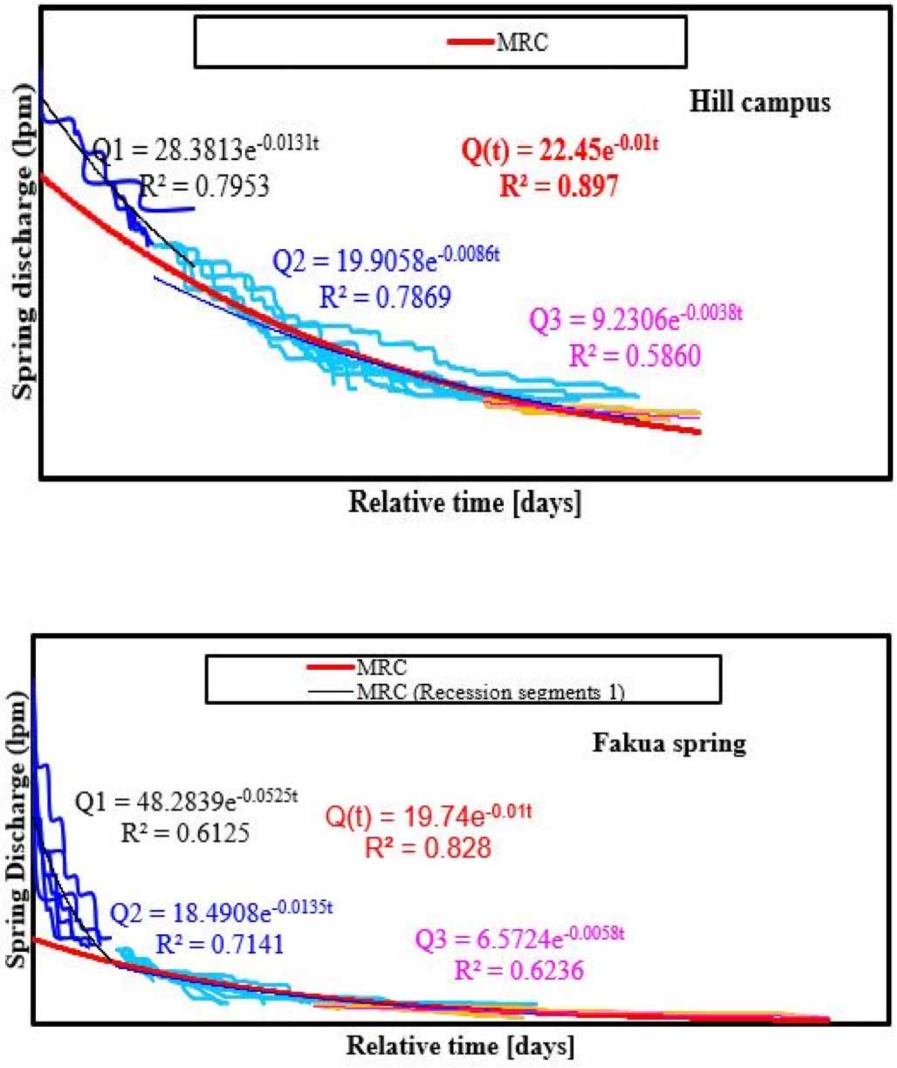

Figure 5 | Optimally separated MRCs into three segments of the Hill campus and Fakua springs for the period 1999–2004.

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Table 4 | Recession parameters based on separated MRCs of the Hill campus spring and Fakua springs

	Hill campus spring				**Fakua spring**			
Recession parameters	**First Seg.**	**Second Seg.**	**Third Seg.**	**Cinkus *et al.* (2021)**	**First Seg.**	**Second Seg.**	**Third Seg.**	**Cinkus *et al.* (2021)**
Recession coefficient (α)	0.0131	0.0086	0.0038	0.127	0.0525	0.0135	0.0058	0.127
Average recession coefficient (α)		0.0085				0.023933		
Recession constant (k)	0.987	0.991	0.996	0.02	0.949	0.986	0.994	0.02
Maximum recession constant (k)		0.991				0.994		

Table 5 | Classification of different equations having different parameters

Model	**Equation**	**Unit**	**Limiting value**	**Classification**
Boussinesq (1903)	$Q = \frac{Q_0}{(1+\propto t)^2}$	m^3/s	As $t \to \infty, Q \to 0$	Non-influenced stage, surface water
Maillet (1905)	$Q = Q_0 \times e^{-\propto t}$	m^3/s	As $t \to \infty, Q \to 0$	Non-influenced stage, surface water
Horton (1933)	$Q = Q_0 \times e^{-\propto t^n}$	m^3/s	As $t \to \infty, Q \to 0$	More suitable to surface water
Barnes (1939)	$Q = \sum_{i=1}^{k} Q_0^{e^{\propto_i t}}$	m^3/s	As $t \to \infty, Q \to 0$	More suitable to surface water
Coutagne (1949)	$Q = Q_0 \times [1+(n-1) \propto t]\frac{n}{1-n}$	m^3/s	As $t \to \infty, Q \to 0$	Suitable for karst systems
Padilla *et al.* (1994)	$Q = (Q_0 - Q_c)[1+(n-1) \propto t]\frac{n}{1-n} + Q_c$	m^3/s	As $t \to \infty, Q \to 0$	Suitable for karst systems – Qc strengthens Coutagne model
Drogue (1972)	$Q = \frac{Q_0}{(1+\propto t)^n}$	m^3/s	As $t \to \infty, Q \to 0$	Suitable for karst systems
Mangin (1975)	$Q_t = Q_{R0} e^{-\propto t} + q_0 \frac{1-\eta t}{1+\varepsilon t}$	m^3/s	As $t \to \infty, Q \to 0$	Suitable for karst systems – Associated classification
Kullman (2000)	$Q_t = \sum_{i=1}^{k} Q_0^{e^{\propto_i t}} + \sum_{j=1}^{k} (\frac{1}{2} + \frac{\lvert 1-\beta_j t \rvert}{2(1-\beta_t)} Q_{0j}(1-\beta_j t)$	m^3/s	As $t \to \infty, Q \to 0$	Suitable for karst systems – Associated classification

Fakua spring shows the fast-receding early recession component as compared to the Hill campus spring. Although, the Hill campus and Fakua spring show a difference in the intermittent recession component, the late recession components of both springs are relatively close to each other (Table 6). As the early and intermittent components are closely related to rainfall characteristics, topographical characteristics of landforms as both the springs face slope in opposite directions. However, it may be envisaged that the slow-draining aquifer characteristics are likely to be the same and therefore the late recession segments of both the springs are close to each other irrespective of their topographical settings.

We chose to not include the indicator RT in the classification methodology, as it seems that the global inertia of a karst system is relatively independent of its main characteristics of functioning, especially for systems in C3, C4, and C5.

The shape of the recession can be used to diagnose the spring type (Kresic & Stevanovic 2010). For full-flow springs, α is constant which is relatively rare. Overflow springs are characterized by convex log-normal base flow recession (α is increasing with time), with strongly seasonal or intermittent springs having discharge of zero and α tending to ∞. More classifications are shown in Table 5.

Underflow springs may be of two types. Losing or high-stage underflow springs are controlled by constrictions or aggradations close to the output, so at a high stage, the water backs up in the conduit until an overflow outlet is activated. This provides a constant head and a slightly decreasing or constant α depending on the magnitude of the recharge from the

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Table 6 | Characterization of karst hydrology in six classes, examining storage, drainage, and response variability using precise indicators

Class	Capacity of dynamic storage	Draining dynamic of the capacitive function	Variability of the hydrological response	k_{max}	α_{mean}	IR
C1	Very low to medium	Fast	Medium to high	≤ 0.4	≥ 0.03	≥ 0.25
C2	Very low to medium	Fast	Low to medium	≤ 0.4	≥ 0.03	<0.25
C3	Very low to medium	Moderate	Medium to high	≤ 0.4	<0.03	≥ 0.25
C4	Very low to medium	Moderate	Low to medium	≤ 0.4	<0.03	<0.25
C5	Medium to high	Moderate to slow	Medium to high	>0.4	<0.03	≥ 0.25
C6	Medium to high	Moderate to slow	Low to medium	>0.4	<0.03	<0.25

catchment relative to the output. Gaining or low-stage underflow springs have a concave recession, with α decreasing as a full-flow recession is supplemented by underflow from surface stream beds or other cave streams.

Figure 6 presents a graphical comparison of recession parameters between our study and the findings of Cinkus *et al.* 2021. The parameters analyzed include recession rates, durations, and shapes, providing insights into the similarities and differences in hydrological behavior observed in the two studies. This comparative analysis enhances our understanding of the dynamics of recession flows and contributes to the broader understanding of groundwater systems in diverse hydrological contexts.

Springs of the type under study would likely be classified as karst springs. These springs are distinguished by their distinct hydrological behavior, frequently displaying intermittent overflow and underflow patterns. The examination of recession parameters, including rates, durations, and shapes, aligns with the typical characteristics of karst hydrology, in which spring discharge can fluctuate significantly over time due to the intricate interactions within karst aquifer systems. Furthermore, the comparison of recession parameters with another study enhances our comprehension of the dynamics of recession flows, which is particularly pertinent in karst environments where flow patterns can be intricate and variable. Consequently, based on the information provided, the springs studied in this research are likely karst springs exhibiting underflow-overflow behavior.

Finally, the WHAT with BFImax analyzer (Lim *et al.* 2010) has been used to analyze the BFIs of the selected two springs. The Base Flow Index (BFI) is used as a measure of the base flow characteristics of a spring shed. It provides a systematic way of assessing the proportion of base flow in the total outflow of a spring shed. It indicates the influence of soil and geology on spring flow and is important for low-flow studies. The separated base flow hydrographs of the selected two springs are shown in Figure 7. The obtained BFIs of the Hill campus and Fakua springs are 0.72 and 0.38, respectively. This analysis also shows that the Hill campus spring has maximum base flow contribution from the slow-draining aquifer as compared to the Fakua spring.

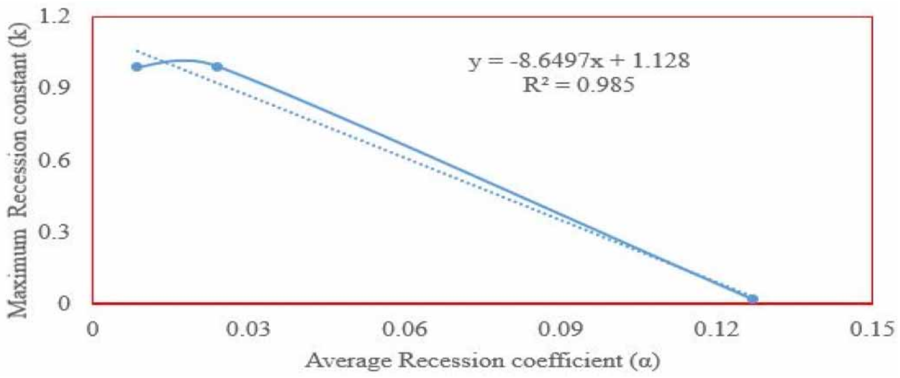

Figure 6 | Between average recession coefficient (α) and maximum recession constant (k) for the Hill campus spring, Fakua spring, and (Cinkus *et al.* 2021) karst springs fall into the last category of underflow–overflow, where the spring is intermediate in a hierarchy and functions as an underflow spring for part of the time and then reverts to the intermittent overflow type.

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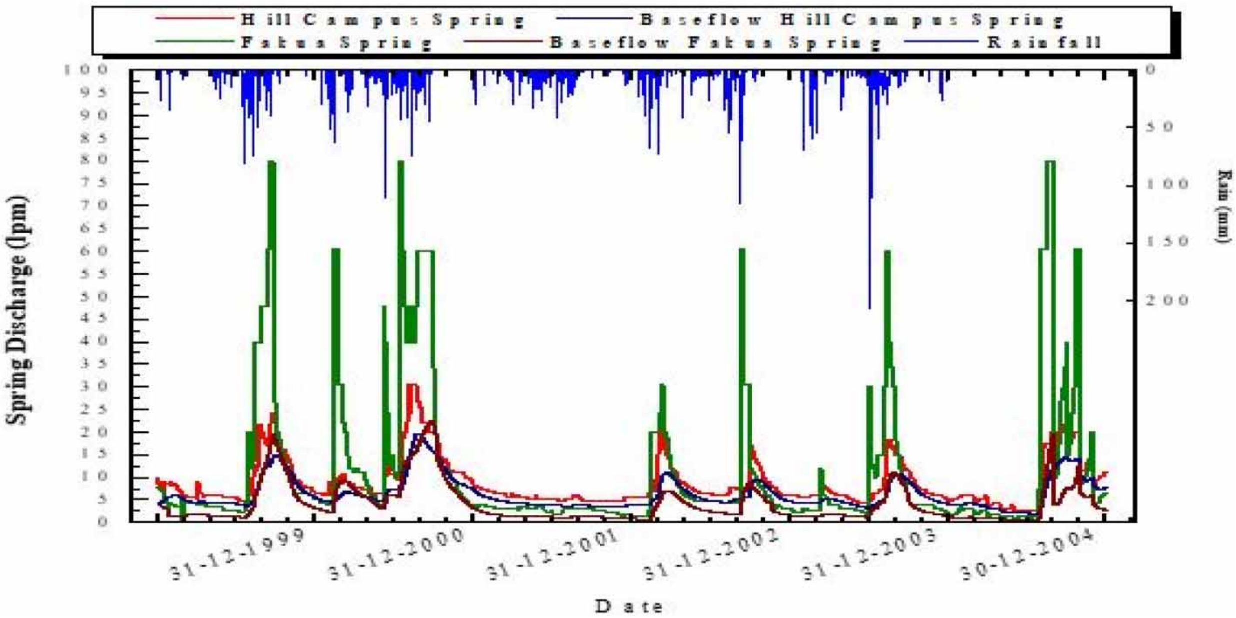

Figure 7 | Separated base flow hydrographs of the Hill campus and Fakua springs for the period 1999–2004.

The WHAT with the BFImax analyzer is a valuable tool for examining the hydrological functioning of springs. By isolating the base flow component, researchers can gain insights into the gradual release of water from the aquifer systems, which is important for maintaining streamflow during dry periods and preserving ecological integrity. The stark differences in BFIs between the Hill campus and Fakua springs highlight the heterogeneity of hydrogeological settings within the study area. This heterogeneity may result from variations in geological formations, land use practices, or hydrological connectivity with adjacent water bodies. Understanding these variations is crucial for effective water resources management and can guide targeted interventions to mitigate the impacts of human activities on spring ecosystems. Furthermore, the use of WHAT with the BFImax analyzer demonstrates the integration of technological advancements in hydrological research, enabling more accurate assessments of base flow dynamics and enhancing our ability to address emerging water resource challenges in a rapidly changing environment.

CONCLUSIONS

This study offers a detailed exploration of the recession patterns of spring base flow, specifically focusing on the Hill campus and Fakua springs in Uttarakhand, India. Over the period from January 1999 to December 2004, discharge data was meticulously analyzed to construct MRCs, facilitating the categorization of recession phases into early, intermittent, and late stages. Through this approach, announced understanding of the temporal variations in flow characteristics, including peak flow rates ($Q_{\max}$), minimum flow rates ($Q_{\min}$), and average flow rates (Q_{avg}), was achieved. Moreover, statistical parameters and low-flow indices extracted from FDCs provided essential insights into flow behavior, complemented by the examination of BFIs using the WHAT. The findings of this analysis highlight the necessity of implementing tailored water management strategies, particularly emphasizing the importance of water storage initiatives during the monsoon season to ensure the sustainable utilization of springwater resources in the region. Furthermore, the methodologies employed in this study hold significant promise for broader applications, such as the analysis of river flow recession, which is essential for integrated water resource planning in mountainous terrains. The observed disparities in flow rates between Hill campus and Fakua springs underscore the unique hydrological characteristics of each, emphasizing the need for customized conservation and management approaches. These findings serve as a foundational framework for the development of effective measures aimed at optimizing the utilization potential of these natural springs, thus ensuring their long-term sustainability amidst evolving environmental conditions. This comprehensive analysis not only deepens our understanding of spring hydrology but also underscores

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the importance of adopting tailored approaches to water resource management to maximize the benefits of these invaluable natural assets.

The results of this study have significant implications for water resource management and conservation efforts in Uttarakhand, India, and similar mountainous regions globally. The identification of distinct recession patterns and flow characteristics of the Hill campus and Fakua springs underscores the necessity for tailored approaches to water storage and utilization. Specifically, the observed disparities in peak flow rates ($Q_{\max}$) and minimum flow rates ($Q_{\min}$) between the two springs highlight the variability in their hydrological regimes, necessitating site-specific management strategies. For instance, the significantly higher $Q_{\max}$ of Fakua spring suggests the potential for greater water yield during peak demand periods, warranting infrastructure investments for storage and distribution. Conversely, the lower $Q_{\min}$ of Hill campus indicates the need for measures to ensure sustained flow during dry seasons to meet ecological and societal needs. Moreover, the utilization of BFIs through the WHAT offers a systematic approach to understanding base flow dynamics, crucial for designing efficient water management practices. By emphasizing the implementation of water storage strategies, particularly during the monsoon season, this study advocates for sustainable utilization of spring water resources while minimizing the risk of water scarcity during dry periods. Furthermore, the applicability of the analytical techniques employed in this study extends beyond spring hydrology to river flow recession analysis, essential for informed decision-making in integrated water resources planning. Overall, the insights derived from this research serve as a foundation for developing comprehensive and context-specific strategies aimed at optimizing the utilization potential of natural springs, thus contributing to the long-term resilience and sustainability of water resources in mountainous regions.

ACKNOWLEDGEMENTS

The study's researchers express their sincere appreciation to the All India Coordinated Research Project on Groundwater Utilization (AICRP-GWU), which is situated within the Department of Irrigation and Drainage Engineering at G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Amit, H., Lyakhovsky, V., Katz, A., Starinsky, A. & Burg, A. 2002 Interpretation of spring recession curves. *Ground Water* **40** (5), 543.

Araza, A., Perez, M., Cruz, R. V., Aggabao, L. F. & Soyosa, E. 2021 Probable streamflow changes and its associated risk to the water resources of Abuan watershed, Philippines caused by climate change and land use changes. *Stochastic Environmental Research and Risk Assessment* **35**, 389–404.

Atkinson, T. C. 1977 Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology* **35** (1–2), 93–110.

Barnes, B. S. 1939 The structure of discharge-recession curves. *Eos, Transactions American Geophysical Union* **20** (4), 721–725.

Bates, B. C. & Davies, P. K. 1988 Effect of base flow separation procedures on surface runoff models. *Journal of Hydrology* **103**, 309–322.

Berhail, S., Ouerdachi, L. & Boutaghane, H. 2012 The use of the recession index as indicator for components of flow. *Energy Procedia* **18**, 741–750.

Bosch, D. D., Arnold, J. G., Allen, P. G., Lim, K. J. & Park, Y. S. 2017 Temporal variations in baseflow for the Little River experimental watershed in South Georgia, USA. *Journal of Hydrology: Regional Studies* **10**, 110–121.

Boussinesq, J. 1877 Essay on the theory of running waters. Print national.

Boussinesq, J. 1903 Sur un mode simple d'écoulement des nappes d'eau d'infiltration à lit horizontal, avec rebord vertical tout autour lorsqu'une partie de ce rebord est enlevée depuis la surface jusqu'au fond. *Comptes rendus de l'Académie des Sciences* **137** (5), 11.

Brutsaert, W. & Nieber, J. L. 1977 Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research* **13** (3), 637–643.

Chapman, T. 1999 A comparison of algorithms for stream flow recession and base flow separation. *Hydrological Processes* **13** (701), 714.

Cinkus, G., Mazzilli, N. & Jourde, H. 2021 Identification of relevant indicators for the assessment of karst systems hydrological functioning: Proposal of a new classification. *Journal of Hydrology* **603**, 127006.

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Coutagne, A. 1949 Etude generale des variations de debit en fonction des facteurs qui les conditionnent. *La Houille Blanche* **2**, 134–146.

Drogue, C. 1972 Analyse statistique des hydrogrammes de decrues des sources karstiques statistical analysis of hydrographs of karstic springs. *Journal of Hydrology* **15** (1), 49–68.

Fiorillo, F. 2009 Spring hydrographs as indicators of droughts in a karst environment. *Journal of Hydrology* **373** (3–4), 290–301.

Fiorotto, V. & Caroni, E. 2013 A new approach to master recession curve analysis. *Hydrological Sciences Journal* **58** (5), 966–975.

Gottschalk, L., Tallaksen, L. M. & Perzyna, G. 1997 Derivation of low flow distribution functions using recession curves. *Journal of Hydrology* **194**, 239–262.

Hall, F. R. 1968 Base-flow recessions – A review. *Water Resources Research* **4** (5), 973–983.

Horton, R. E. 1933 The role of infiltration in the hydrologic cycle. *Eos, Transactions American Geophysical Union* **14** (1), 446–460.

Jachens, E. R., Rupp, D. E., Roques, C. & Selker, J. S. 2020 Recession analysis revisited: Impacts of climate on parameter estimation. *Hydrology and Earth System Sciences* **24** (3), 1159–1170.

Kang, T., Lee, S., Lee, N. & Jin, Y. 2022 Baseflow separation using the digital filter method: Review and sensitivity analysis. *Water* **14** (3), 485.

Kiraly, L. 2002 Karstification and groundwater flow. In: *Proceedings of the Conference on Evolution of Karst: From Prekarst to Cessation. Postojna-Ljubljana*, pp. 155–190.

Kresic, N. & Stevanovic, Z. 2010 *Groundwater Hydrology of Springs: Engineering, Theory, Management and Sustainability*. Butterworth-Heinemann, Elsevier, Oxford, UK, pp. 1–573.

Kullman, E. 2000 Nové metodické prístupy k riešeniu ochrany a ochranných pásiem zdrojov podzemných vôd v horninových prostrediach s krasovo–puklinovou priepustnosťou. *Podzemná Voda* **6** (2), 31–41.

Lim, K. J., Park, Y. S., Kim, J., Shin, Y.-C., Kim, N. W., Kim, S. J., Ji-H, J. & Engel, B. A. 2010 Development of genetic algorithm-based optimization module in WHAT system for hydrograph analysis and model application. *Computers & Geosciences* **36**, 936–944.

Maillet, E. T. 1905 *Essais d'hydraulique Souterraine & Fluviale*. A. Hermann, LGCgE Villeneuve d'Ascq, France.

Mangin, A. 1975 *Contribution à l'étude hydrodynamique des aquifers karstiques*. *Doctoral dissertation*, Université de Dijon.

Mijatovic, B. 1974 Determination de la transmissivity et du coefficient d'emmagasinement per la course de tarissement dams les aquifers karstiques. *International Association of Hydrogeologists* **10** (1), 225–230.

Nautiyal, R., Kala, C. P. & Singh, J. 2020 Community perceptions of spring dynamics in the Indian Himalaya: Implications for water governance. *Mountain Research and Development* **40** (2), R1–R11.

Negi, G. C. S. & Joshi, V. 1996 Geohydrology of springs in a mountain watershed: The need for problem solving research. *Current Science* **71** (10), 772–776.

Negi, G. C. & Joshi, V. 2004 Rainfall and spring discharge patterns in two small drainage catchments in the Western Himalayan Mountains, India. *Environmentalist* **24**, 19–28.

Nisa, F. U. & Umar, R. 2024 Spring water system classifications and their methods of study: An overview of the current status and future perspectives. *Journal of Earth System Science* **133** (1), 10.

Padilla, A., Pulido-Bosch, A. & Mangin, A. 1994 Relative importance of baseflow and quickflow from hydrographs of karst spring. *Groundwater* **32** (2), 267–277.

Parker, G. W. 1978 *Methods for Determining Selected Flow Characteristics for Streams in Maine* (No. 78-871). US Geological Survey, Reston, VA, USA.

Peleg, N. & Gvirtzman, H. 2010 Groundwater flow modeling of two-levels perched karstic leaking aquifers as a tool for estimating recharge and hydraulic parameters. *Journal of Hydrology* **388** (1–2), 13–27.

Ponce, V. M. & Lindquist, D. S. 1990 Management of base flow augmentation: A review. *Water Resources Bulletin* **26** (2), 259–268.

Posavec, K., Bacani, A. & Nakić, Z. 2006 A visual basic spreadsheet macro for recession curve analysis. *Ground Water* **44** (764), 767.

Shrestha, S., Babel, M. S. & Pandey, V. P. 2022 Hydrological response of Himalayan springs to climate change: A case study from Langtang Valley, Nepal. *Hydrological Sciences Journal* **67** (1), 109–122.

Smart, P. L. & Hobbs, S. L. 1986 Characterization of carbonate aquifers: A conceptual base. In: *Proceedings of the Environmental Problems in Karst Terranes and Their Solutions Conference*. National Water Well Association, Dublin, OH. 1986. pp. 1–14, 7 figs, 25 ref (Vol. 1986).

Stewart, M. K. 2015 Promising new baseflow separation and recession analysis methods applied to streamflow at Glendhu Catchment, New Zealand. *Hydrology and Earth System Sciences* **19** (6), 2587–2603.

Szilagyi, J., Parlange, M. B. & Albertson, J. D. 1998 Recession flow analysis for aquifer parameter determination. *Water Resources Research* **34** (7), 1851–1857.

Tallaksen, L. M. 1995 A review of base flow recession analysis. *Journal of Hydrology* **165** (1–4), 349–370.

Tasker, G. D. 1972 Estimating low-flow characteristics of streams in southeastern Massachusetts from maps of ground water availability. Geological Survey Research, D217-D220.

Thakur, R. K., Singh, P. & Bhardwaj, A. K. 2020 Impacts of land use/land cover changes on spring discharge in the Beas basin, Western Himalaya. *Environmental Monitoring and Assessment* **192** (1), 1–17.

Thomas, M. P. & Cervione, M. A. 1970 A proposed streamflow data program for Connecticut. Connecticut Water Resources Commission.

Toebes, C., Morrissey, W. B., Shorter, R. & Hendy, M. 1969 Base-flow-recession curves. In: Handbook of Hydrological Procedures. In: *Proceeding 8. Wellington, New Zealand: Ministry of Works. (Cited by Tallaksen 1995)*.

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Troch, P. A., De Troch, F. P. & Brutsaert, W. 1993 Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. *Water Resources Research* **29** (2), 427–434.

Valdiya, K. S. & Bartarya, S. K. 1989 Diminishing discharges of mountain springs in a part of kumaun himalaya. *Current Science* **58** (8), 417–426.

Valdiya, K. S. & Bartarya, S. K. 1991 Hydrogeological studies of springs in the catchment of the Gaula river, Kumaun Lesser Himalaya, India. *Mountain Research and Development* **11** (**3**), 239–258.

Vogel, R. M. & Fennessey, N. M. 1995 Flow duration curves II: A review of applications in water resources planning 1. *JAWRA Journal of the American Water Resources Association* **31** (6), 1029–1039.

Vogel, R. M. & Kroll, C. N. 1992 Regional geohydrology-geomorphic relationships for the estimation of low-flow statistics. *Water Resources Research* **28** (9), 2451–2458.

Weiss, M. & Gvirtzman, H. 2007 Estimating ground water recharge using flow models of perched karstic aquifers. *Groundwater* **45** (6), 761–773.

First received 24 November 2023; accepted in revised form 7 May 2024. Available online 27 May 2024

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