Application of high-frequency spring discharge data:
a case study of Mathamali spring rejuvenation in
the Garhwal Himalaya
Vikram Kumar and Santosh Paramanik

ABSTRACT

Water scarcity is becoming the biggest threat to the global population due to unpredictable rainfall,
glaciers melt, and other anthropogenic activities. This study focuses on the analysis of monitored
high-frequency continuous spring discharge and rainfall data in the contact and fracture type
Mathamali spring located in the Garhwal Himalaya. Discharge from the spring and its storage
behavior has been studied by analyzing recession components and flow duration curves. Analyzed
discharge data revealed that the spring can generate maximum volume during monsoon as
compared to winter due to aquifer properties and tendencies to store and transmit water.
Springshed intervention practices were implemented in early April 2017. The measured average flow
was 16.9 lpm but soon after the interventions, the average flow increased by 2.6 times. The
minimum average spring flow was 2.3 lpm which increased by 5 times whereas the average
maximum flow increased by 1.8 times. Post-intervention, storage duration has increased by 16%,
decaying from 143 lpm (peak flow) to 12.7 lpm (baseflow). The preliminary findings from this spring
can be considered as a check for establishing benchmarks for sustainable development of
springsheds, climate change adaptation, and development plans to cope up with growing water
insecurity in the rural Himalayas.

Key words | Garhwal Himalaya, master recession curve, recession coefficients, spring rejuvenation

HIGHLIGHTS

- Study focuses on the analysis of monitored high frequency continuous spring discharge and
  rainfall data for four years in the contact and fracture type Mathamali spring located in Garhwal,
  Lesser Himalaya, which was not previously available.
- Results obtained after indepth analysis can be considered as a check for establishing
  benchmarks for sustainable development of springsheds, climate change adaptation and
development plans to cope up with growing water insecurity in the rural Himalayas.

INTRODUCTION

Rapid population growth, changes in temperature, and rainfall patterns in mountains are leading to high pressure on
domestic water sources. Springs which originate in hills
due to the movement of water from aquifers emerging at
different points of the earth's surface are the principal
source of day to day domestic water needs, animal feeding,
and irrigation purposes for rural communities in the mountains (Vaidya 2015; Sharma et al. 2016). However, the erratic
nature (intensity and distribution) of rainfall patterns (Kumar et al. 2017), deforestation, and steepness of hills
impacts spring flows resulting in an adverse effect on rural
people, agriculture production, and livestock populations

Addressing the multifaceted problems of drying springs or declining volume in a rural mountain system entails an inclusive study of socio-economic and biophysical characteristics and their interlinkages, which is possible by an integrated study involving people’s participation (Timilsina-Parajuli et al. 2014).

The nature of spring discharge relates to changes occurring in the characteristics of a recharge area (the area where rainfall infiltrates into the soil profile) in terms of rainfall pattern changes, land use/land cover changes, and aquifer capacity to store and transmit groundwater. Every spring is different from others in terms of its type, catchment area, nature of discharge, topography, and geological structure present beneath the surface (Kresic 2010). Adapting to global warming and enhancing water availability is one of the biggest challenges in the rural Himalayas (Bharati et al. 2014) which is essential for their food security. Changing rainfall patterns in the Himalayas not only affects water availability and livelihoods but also triggers problems for downstream people (Miller et al. 2012).

Needs and challenges to understand spring discharge and rainfall relationship

Limited research on springs has been done in the Lesser Himalaya related to the discharge behavior of springs with rainfall patterns and recharge area characteristics (Valdiya & Bartarya 1991; Sahin & Hall 1996; Negi & Joshi 2004). The Advanced Center for Water Resources Development and Management (ACWADAM 2011) report suggests that spring outflow is not only a function of rainfall but also depends on the characteristics of the aquifers that feed these springs. Climate change has caused a change in the rainfall pattern and regional studies show that climate impacts are clear in the Himalayas (Cruz et al. 2007; Agrawal et al. 2012). The changed pattern in rainfall and temperature is responsible for less recharging of the springsheds that can be seen by low outflows from the springs during the rainless period. Characteristics of geology and detailed soil behavior and structure still remain largely unknown. Regardless of incremental developments in our understanding to measure rates of forest degradation and impacts of climate changes, there is still no decisive understanding of the impacts of Garhwal forests’ degradation in the hills.

The opinion of local communities in the past few years towards changes in rainfall pattern and other climatic variables are that there is hardly any rainfall after mid-September to May-end with just few rainfall events in December/January resulting in drying of springs or reduction in flows. Most people believe that reduction of flow in these springs could be because of less snow in the top mountains (Chaudhary et al. 2011) but it could be because of catchment degradation too. Therefore, there is a requirement for a proper understanding of the spring discharge quantification with influencing factors (Pellikka et al. 2009).

Past research has focused on runoff processes on different terrains in natural conditions and many times using a rainfall simulator; however, less attention has been given to understanding subsurface flow (springs) characteristics on slopes and spring outflows in varying rainfall conditions. Hydrological interpretations from spring hydrographs are based on time series and recession curve analysis of a single event or combined multiple events. Time series of monitored spring discharge and rainfall investigation offers a mathematical study of the hydraulic response of recharge events.

Several functions have been formulated to describe the decay of springs during the lean season (Dewandel et al. 2003; Kumar & Sen 2010a, 2010b). Baedke & Krothe (2001) divided spring recession into three components, an early component is related to conduit flow, the last component is linked to diffusive flow, and the intermediate component is the grouping of conduit and diffusive flows. The shape of the recession curves is generally concave which suggests the hydrodynamic properties of the aquifer such as slope, hydrogeological properties (storage and transmissivity).

Exponential and quadratic equations are the most used approaches for recession analysis which is based on fitting the observed recession curve with calculated discharge (Dewandel et al. 2003). However, the hydrograph shape during recession varied among different seasons due to the variability of hydrogeological settings and climate characteristics (Atkinson 1977). The main advantage of estimating recession coefficients is that it does not require detailed knowledge of the physical characteristics of the springshed as the analysis is mainly based on observed time-series data of spring discharge.
To mitigate the water issues in a hilly area, analysis of the relationship between rainfall and spring discharge has been done using regression (Agrawal et al. 2012), field study (Tambe et al. 2012), aspect-based studies (Negi & Joshi 2004) and springshed development (GoS 2014). One of the major constraints of the above studies in terms of hydrological understanding is that of the resolution of the data collection, i.e., rainfall and spring discharge measurements were taken at monthly, or weekly, or rarely at daily-scale. Since the costs of instrumentation and computation power have reduced significantly, the current study puts forth the advantage and the need for high-frequency data collection for enhancing hydrological understanding (Manuelito 2017; Luna Juncal et al. 2020). The spring was considered for a springshed development program in 2017 by the Indian Institute of Technology Roorkee (IITR) with the help of the People’s Science Institute (PSI), Dehradun. The specific objectives of this study were to (i) understand the spring hydrograph and recession behavior which plays a vital role in quantification of spring volume during the rainless period, (ii) undertake impact analysis studies of springshed interventions (like contour trenches, percolation pits along with broom grass fodder plantation) and (iii) put forth recommendations for sustainable management of springs in hills. The study emphasizes that quantification of spring water (at the micro-level) by utilizing high-frequency data, analyzing the behavior of the spring and formulation of a master recession curve are key factors to be considered for proper springshed development and can help plan better strategies for rejuvenation of springs in Garhwal and other Himalayan mountains.

STUDY AREA

The study area of Mathamali spring is located in the valley of Aglar watershed of the lesser Himalaya in Uttarakhand (Figure 1), a humid subtropical climatic zone of India. Aglar is the major tributary of the River Yamuna, one of the country’s most sacred rivers. Mathamali spring is the only perennial spring available in the vicinity for domestic water usage. The geographical location of the spring is at a latitude of 30° 30’ 0” N and longitude of 78° 9’ 35.99” E. The elevation of Aglar watershed ranges from 450 m to 3,022 m

Figure 1 | Study location with the conceptual diagram of a fracture and contact type spring.
and the relief ratio (which is a relationship between the relief and channel gradient) is 0.001. The northern part of Aglar watershed is recognized for its snow-covered peaks, rivers, and valley.

The main occupations of people in this area are agriculture and livestock rearing. A large part of the land (agricultural/barren) in the study location is hilly with steep slopes and loose soils that lead to frequent soil erosion during high-intensity precipitation, particularly during the monsoon season. The geological structure and steepness of the location are very complex. The entire ridge consists of a sequence of phyllite, slate, and quartzite rocks overlaid by a layer of colluvial sediments formed due to movement of rock mass under the influence of gravity at the base of the ridge (ACWADAM 2011). Forests, agricultural tracts, and grasslands are the major land cover and land use types. The general drainage pattern is parallel and subdendritic type. The study area is an understudied springshed due to the lack of any hydro-meteorological station. Based on the records (1977–1986) available from Mussoorie meteorological station adjacent to Aglar, the average monthly temperature fluctuates between 6°C and 19.8°C and the mean annual precipitation is 2,223 mm. The whole study area is influenced by the southwest (SW) monsoon, which generally begins around mid-June and remains up to mid/end September. Saha & Singh (1991) studied and prepared the map of Aglar watershed, classifying the soil erosion of the area into none to slight (19.13%), moderate (45.61%), severe (26.51%) and very severe (7.92%).

The rocks dip in NE direction, with numerous vertical and inclined fractures present in them. The water infiltrating at the top of the ridge flows downwards through the fractures and along with the dip of the rocks and emerges out to the surface in the form of a spring at the contact of colluvial sediments. The Lesser Himalayan belt is geologically very intricate, consisting of a vast stretch of an unfossiliferous zone in Garhwal and Kumaon regions bounded by the Main Boundary Fault (MBF) to the south and the Main Crystalline Thrust (MCT) in the north.

**METHODOLOGY AND DATA AVAILABILITY**

This section deals with the methodology and data used for the determination of different parameters of the recession curve, hydrograph analysis, and springshed rejuvenation work to fulfill the study objectives.

**Data used**

Rainfall data used for the present study is taken from a tipping-bucket rain gauge installed at Mathamali village (near the spring location), whereas the spring discharge is monitored from a calibrated 18.29 cm (0.6 feet) HS flume installed at the outlet of the spring for every 15 minutes' time interval (Figure 2). Short time interval monitoring helps to characterize even short duration rainfall-spring flow events. Considering the small size of the Mathamali springshed, rainfall occurring in the region was considered as spatially uniform and therefore only one rain gauge was installed. Daily average spring discharge and cumulative rainfall and its correlation coefficient are illustrated in Figure 2.

Measured 15-minutes data were averaged to daily average, smoothing up time series for noise corrections and allowed working with daily data. The yearly correlation coefficient between rainfall and spring discharge is not strong, which indicates that spring discharge is influenced by other springshed characteristics, such as topography, geology, and soil conditions.

**Methodology**

**Recession analysis**

Recession coefficients for Mathamali spring were computed using individual recession and master recession curve (MRC) analysis methods. The recession storage of a spring system can be expressed in an exponential decay form as

\[ Q_t = Q_0 e^{-\alpha t} \] (1)

where \( Q_t \) = flow at specified time (t), \( Q_0 \) = flow at the beginning of recession (t₀), \( \alpha \) = rate of decay (1/day), \( \alpha = -\ln K_r \). Rate of decay (\( \alpha \)) has broadly two components (for spring flow) such as a recession coefficient for interflow (\( a_i \)) and recession coefficient for baseflow (\( a_b \)). The process of calculating recession coefficients involves the baseflow separation.
method in which baseflow is extracted from total discharge that gives the interflow component.

**Springshed interventions**

To increase spring discharge, springshed development approaches have been adopted to revive the Mathamali spring using rainwater harvesting structures and plantation of native tree species. Before carrying out intervention work certain steps were adopted like hydrogeological mapping of the springshed, delineation of the spring aquifer, and identification of the recharge area. For recharge structures, the stable area had to be identified which does not have to slope more than 50% which might cause landslides and more erosion. After identification of suitable slopes in the recharge area, recharge interventions comprising of 14 staggered contour trenches and 5 percolation pits of different dimensions were undertaken (Figure 3). Out of the 14 contour trenches, 9 trenches were freshly dug and 5 trenches were repaired.

In the upper ridge of the springshed, construction of contour trenches and small recharge structures has been undertaken because of the more stable area and slopes being less steep. This area was also planted with native tree species (Banjh, Garhiwal, etc.) to reduce surface runoff, prevent soil erosion, and increase the rate of infiltration. The middle of the springshed, has relatively steeper slopes and less area was available for treatment, therefore, the construction of percolation pits rather than trenching was undertaken to facilitate spring recharge. The dimensions of contour trenches

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**Figure 2** | Daily observed time series of rainfall and spring discharge and its yearly correlation coefficient.

**Figure 3** | Intervention work in the springshed: (a) Recharge area identification, (b) Mapping for slope, (c) Contour trench, and (d) Percolation pit.
trenches and percolation pits were chosen based upon the slope of the area and soil structure. Most of the contour trenches have a common dimension of $2\,\text{m} \times 0.6\,\text{m} \times 0.45\,\text{m}$ whereas for percolation pits it was $0.9\,\text{m} \times 0.6\,\text{m} \times 0.45\,\text{m}$.

**RESULTS AND DISCUSSION**

**Rainfall and spring discharge characteristics**

Rainfall and spring discharge in Aglar watershed appears to have an annual and inter-seasonal variability (Figure 2). There is evidence revealing a decreasing rainfall trend in the region over the past 100 years (Mishra 2017). However, there seems to be a gentle increase in the rainfall received in the Aglar region in the years 2015–2017. Average annual rainfall in Aglar during the observed period (2014–2017) was measured to be 44% less than that received in Mussoorie (average annual rainfall 2,000 mm), clearly an orographic effect. This significant difference in rainfall magnitude is also commonly conveyed by the local community of the region.

The average spring flow rate from the springshed varied before and after the 2017 intervention work: before it was $16.9 \pm 11.7\,\text{lpm}$ ($\pm$ Standard Deviation) and after the intervention, it changed to $41.6 \pm 31.6\,\text{lpm}$ from the observed record (Figure 2). During the monsoon months (15th June–15th September), minimum spring discharge was $3.3\,\text{lpm}$ before the intervention but the minimum flow is around $25.5\,\text{lpm}$ after the intervention. After the intervention work, the maximum flow rate is noticed during the monsoon season with a discharge rate of $146\,\text{lpm}$ which was previously $80.1\,\text{lpm}$ in the monsoon month.

Spring data analysis shows that the springshed can generate maximum volume during monsoon (48.5% of the total volume) as compared to the winter season (11.8%) in December and January. Rainfall and soil moisture alone explained this discharge variation in this typical mountainous watershed of Lesser Himalaya with different land use and land cover (Nanda et al. 2018). Nanda et al. studied the discharge behavior of two springsheds having different land cover (agroforestry and degraded). Their study highlighted the importance of the water holding capacity of the soil as higher rainfall intensity is expected to generate more peak discharge but the exception was found in the study due to variations in soil moisture.

**Spring discharge hydrological response**

**Rainfall pattern during 2014–2017**

Hydrologically, spring discharge is influenced by rainfall (amount and intensity), geology, along with soil and vegetative factors but in this study, the emphasis is on the influence of rainfall on spring discharge characteristics (as other characteristics are more or less constant). In general, the larger the rainfall amount, the more recharge will take place eventually having more spring outflow. However, the antecedent moisture present in soils also plays a significant role in spring recharge and thus discharge. To understand Mathamali’s spring behavior with rainfall, eight major rainfall events were selected. Here a rainfall event is denoted by a rainstorm with continuous rainfall above $50\,\text{mm}$ in a day (last 24 hours). A total of eight events have been selected to understand the behavior of spring outflow with rainfall, event numbers 1–5 are the events before the 2017 intervention in the springshed whereas events 6–8 are after the intervention work as discussed earlier. From Figure 4, it was validated that there was not any significant change in the rainfall pattern in terms of the distribution of low to high-intensity rainfall events during the study period, i.e., 2014–2017.

![Figure 4](http://iwaponline.com/ws/article-pdf/20/8/3380/812409/ws020083380.pdf)
Influence of rainfall characteristics on spring discharge

Based on the rainfall characteristics observed during the study period 2014–2017, it was found that the rainfall amount, duration, and the time of the year (wet/dry season) shows a significant influence on spring discharge. Table 1 provides the detail information of 8 such rainfall events. It can be seen from the data, that events 4 and 8, having similar rainfall amounts (55.8–57.8 mm), with effective rainfall duration of the order 24 hrs and 30 hrs in 5 and 11 days, occurring within July and December (months) time frame generated cumulative spring volume of the order 37,457 litres and 77,004 litres – as compared to rainfall events 1 and 6 having similar rainfall intensity characteristics (7–7.5 mm/hr), which generated spring discharge in the range of 1,15,940 litres and 2,07,187 litres. In both the scenarios, there is a significant variation of lag time between the peak rainfall and spring discharge, i.e., for wet condition events, it ranges from 4 to 19 hrs and for dry condition events, ranged between 17 and 72 hrs. Further, the comparison of spring discharge between the pre- and post-intervention events clearly shows an increase in terms of total volume.

During event 1, the total spring flow measured was 1,15,940 litres with the peak spring flow at the rate of 6.76 lpm. The time lag between the peak of the rainfall and the spring flow for this event was 72 hours. Before this event, there was no rainfall and the soil was in a dry state, thus the long-time gap for peak response is because of the dry antecedent moisture level of the soil. Event 6 that took place in 2017 just after the intervention work in the springshed has similar soil antecedent moisture conditions but a different response. The total outflow measured for event 6 was 2,07,186.5 litres which was 1.8 times more (showing the impact of spring recharge interventions) than that of event 1.

Resultant outflow for event 2 from 125.7 mm rainfall was 2,67,685.8 litres. For event 5 which also has huge cumulative rainfall of 108.6 mm, the total outflow observed was 1,20,579.2 litres which was low compared to the net rainfall received. During this event, the antecedent soil moisture was wet because of past small rainstorm events, and the cumulative infiltration was slower as compared to events 1 and 6 resulting in less net recharge as most rainfall generates surface runoff. It was observed that when soil moisture was low, it initially absorbs most of the rainfall which results in the delayed generation of flow. A similar phenomenon has been reported by Tian & Liu (2011).

Table 1 summarises the rainfall event and spring discharge outflow characteristics with start and end times for different events. Analysis of spring flow from event 7 shows a major change as the total outflow was 4,58,172.8 litres with a peak of 157.6 lpm and the lag between maximum rainfall and peak flow was 41 hrs. During this event, the topsoil layer didn’t show any runoff as all the rainfall gets infiltrated and recharges the aquifer which eventually comes as a result of spring flow. As the slope of the springshed is the same for all the events, therefore, the amount of rainfall and intensity is a major factor responsible for the recharge of springshed.

Table 1  | Rainfall-spring discharge event characteristics

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Duration (days)</th>
<th>Rainfall</th>
<th>Spring discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cumulative (mm)</td>
<td>Max intensity (mm/h)</td>
</tr>
<tr>
<td>1</td>
<td>14–26, Feb - 2014 (13)</td>
<td>97.4</td>
<td>7.45</td>
</tr>
<tr>
<td>2</td>
<td>15–27, Aug - 2014 (13)</td>
<td>125.67</td>
<td>31.6</td>
</tr>
<tr>
<td>3</td>
<td>15–19, Apr - 2015 (5)</td>
<td>62.19</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>26–30, Jul - 2015 (5)</td>
<td>55.8</td>
<td>18.54</td>
</tr>
<tr>
<td>5</td>
<td>2–11, Jul - 2016 (10)</td>
<td>108.6</td>
<td>23.4</td>
</tr>
<tr>
<td>6</td>
<td>5–26, Apr- 2017 (22)</td>
<td>66.9</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>23 Sep-8 Oct - 2017 (16)</td>
<td>75.6</td>
<td>15.4</td>
</tr>
<tr>
<td>8</td>
<td>12–22, Dec - 2017 (11)</td>
<td>57.3</td>
<td>8.6</td>
</tr>
</tbody>
</table>
Intervention work as proved by events 8 and 6 leads to an increase in total volume as compared to other events with similar rainfall characteristics. The response of the springshed in terms of discharge to the rainfall events was not the same and it varies according to soil moisture and rainfall intensity and cumulative rainfall. The average flow of Mathamali spring which is the only domestic water resource is 16.9 lpm but soon after the spring intervention works in the springshed, the average flow increased by 2.6 times. The presence of top forest cover in the recharge area allows the land below to gradually store and then release. Alteration of the land cover in the future may have unforeseen impacts on the water cycle which can in turn alter spring discharge.

**Recession curve analysis**

The recession behavior of the daily monitored spring discharge was studied for 12 different small recession events which include events before and after the intervention work. Recession events were identified based on the portion of a hydrograph which extends from peak discharge to the low flow of the next rise continuously for at least 5 days. The summary of analyzed recession behavior for different rainfall conditions is illustrated in Table 2.

The value of the recession slope varies from 0.02 to 0.16 before the intervention to 0.06–0.11 after the intervention. During the summer, the slope of the recession curve (events 2, 7, 9, and 11) is more as compared to others because of increased evaporation. The total volume of spring from each recession event is calculated by the relation $V_t = \frac{Q_t}{\alpha}$, where $\alpha$ is the slope of the recession curve. The shape of a recession curve is governed by the rainfall amount and intensity along with the antecedent moisture condition. When cumulative rainfall was higher and occurred for a longer period with less intensity, the base of the hydrograph observed is more and vice versa (event 3 and event 12). When rainfall occurs during wet conditions (events 2, 4, 7, 10, and 11), infiltrated water will raise the hydraulic head and build pressure and the movement of subsurface flow becomes easier through fracture and cracks leading to high peak discharge.

Rapid decay of the spring from its peak discharge indicates limited storage capacity and the presence of more fractures with additional permeability (Stevanovic et al. 2010). Findings from recession curve analysis are consistent with the result of Wittenberg (1999) for the storage discharge relationship. The average recession slope before the intervention was 0.08 which increased to 0.09 after the intervention work indicating almost no effect on the decay rate.

**Table 2 | Summary of recession events of Mathamali spring**

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Date</th>
<th>Total duration</th>
<th>Discharge (lpm)</th>
<th>Rainfall (mm)</th>
<th>Recession value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Beginning</td>
<td>End</td>
<td>Total</td>
</tr>
<tr>
<td>1</td>
<td>12–19 March-2014</td>
<td>8</td>
<td>7.27</td>
<td>5.31</td>
<td>43.9</td>
</tr>
<tr>
<td>2</td>
<td>14–20 May-2014</td>
<td>7</td>
<td>7.61</td>
<td>2.9</td>
<td>14.03</td>
</tr>
<tr>
<td>3</td>
<td>07–12 March-2015</td>
<td>6</td>
<td>7.54</td>
<td>6.69</td>
<td>163.71</td>
</tr>
<tr>
<td>4</td>
<td>23–28 September-2015</td>
<td>6</td>
<td>31.73</td>
<td>22.07</td>
<td>32.8</td>
</tr>
<tr>
<td>5</td>
<td>27 Nov-02 December-2015</td>
<td>6</td>
<td>21.8</td>
<td>14.74</td>
<td>5.4</td>
</tr>
<tr>
<td>6</td>
<td>23–28 April-2016</td>
<td>6</td>
<td>13.69</td>
<td>10.83</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>31 August-5 September-2016</td>
<td>6</td>
<td>69.85</td>
<td>41.2</td>
<td>21.4</td>
</tr>
<tr>
<td>8</td>
<td>8–13 March-2017</td>
<td>6</td>
<td>29.83</td>
<td>20</td>
<td>44.25</td>
</tr>
<tr>
<td>9</td>
<td>31 May-5 June-2017</td>
<td>6</td>
<td>33.41</td>
<td>20.85</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>09–14 September-2017</td>
<td>6</td>
<td>80.72</td>
<td>58.63</td>
<td>11.8</td>
</tr>
<tr>
<td>11</td>
<td>26-September-2 October-2017</td>
<td>7</td>
<td>97.59</td>
<td>51.77</td>
<td>75.2</td>
</tr>
<tr>
<td>12</td>
<td>24–30 January-2018</td>
<td>7</td>
<td>21.13</td>
<td>12.92</td>
<td>22.6</td>
</tr>
</tbody>
</table>
Seasonal recession coefficient analysis

The recession coefficient (decay) of Mathamali spring discharge is a combined response of different hydrological processes (i.e. rainfall) and influenced by soil conditions. The spring decay ($\alpha$) shows the decrease of spring volume without rainfall. The rate of decay of spring discharge from peak usually displays a non-exponential behavior, which is probably due to abnormally frequent rainfall that results in faster decay during the summer as compared to winter where we have very little rainfall.

Seasonal spring decay analysis (Table 3) reveals that the decays of the spring from peak discharge during monsoon season (Kharif) appear to be diverse and more (0.036 day$^{-1}$) compared to the winter (Rabi) season (0.026 day$^{-1}$). The total water availability during the Rabi season for required irrigation is less compared to the Kharif when about 70% of annual rainfall is received. Farmers of the region having marginal lands because of non-availability of water during the Rabi season are not growing wheat crop, which is the major crop of India.

Results of the spring decay indicated that during the Rabi season the aquifer of Mathamali spring has more storage capacity (40 days) as compared to the Kharif season. The water requirement of wheat is 5.4 mm/day and it has to be in the field for around 120–140 days. Thus total water requirement for wheat is 648–756 mm of which average rainfall of 250 mm fulfills 35% of the requirement and the rest has to be met by the spring volume. Since rainfed agriculture practices are more predominant in Mathamali with less efficiency, irrigation efficiency can be enhanced by the use of the enhanced spring discharge. Spring discharge increases after intervention and is expected to further increase by more recharge activities. Further to this, water conservation measures can considerably improve the farming systems, withstand fragile systems, and enable farmers to attain self-resilience. The advantage of the decay finding suggests the benefits of seasonal water allocation and the application of water conservation measures.

Master recession curve analysis

Analysis of the master recession curve (MRC) characterizes an elongated period of individual recession events. In the present case, average daily spring flow was used to investigate the applicability of the number of recession coefficients to formulate a model which can be later used to predict the spring discharge during a lean period or rainless time. Commonly the Maillet equation is used to model spring flow, i.e. $Q_t = e^{-\alpha(t-t_0)}$, which is an exponential function. The Maillet equation, which has only a single recession coefficient ($\alpha$), is modified for two and three recession components and given by equation

$$Q_t = \left[ \sum_{t=1}^{N} Q_0 e^{-\alpha_1(t-t_0)} \right] + \left[ \sum_{t=N+1}^{N+M} Q_1 e^{-\alpha_2(t-t_0)} \right]$$

(2)

$$Q_t = \left[ \sum_{t=1}^{N} Q_0 e^{-\alpha_1(t-t_0)} \right] + \left[ \sum_{t=N+1}^{N+M} Q_1 e^{-\alpha_2(t-t_0)} \right] + \left[ \sum_{t=N+M+1}^{T} Q_2 e^{-\alpha_3(t-t_0-M)} \right]$$

(3)

where, $Q_0$, $Q_1$, and $Q_2$ are initial discharge values before decaying from one component to another and $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the slope of three recession components; time varies from $t = 1$ to $T$ (Figure 5).

The decay of flow from the Mathamali perennial contact and fracture type spring is well modelled by three exponent components rather than a single ($\alpha$) coefficient. However, the recession curve coefficients ($\alpha_1$, $\alpha_2$, and $\alpha_3$) differed for each year which depends on its peak flow and shape. The initial recession coefficients ($\alpha_1$) characterizes the turbulent

<table>
<thead>
<tr>
<th>Season</th>
<th>Avg. rate of decay (day$^{-1}$)</th>
<th>Storage capacity (days)</th>
<th>Spring water yield (m$^3$)</th>
<th>Major crop</th>
<th>Crop water requirement (mm/d) (based on 2-year data)</th>
<th>Duration (days)</th>
<th>Total water requirement (mm)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kharif</td>
<td>0.036</td>
<td>28</td>
<td>6,665</td>
<td>Rice</td>
<td>7.2</td>
<td>100–110</td>
<td>720–792</td>
<td>694</td>
</tr>
<tr>
<td>Rabi</td>
<td>0.026</td>
<td>40</td>
<td>3,012</td>
<td>Wheat</td>
<td>5.4</td>
<td>120–140</td>
<td>648–756</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 3 | Summary of seasonal crop requirement and average recession coefficient decay
drainage from fractures followed by an intermediate portion where the discharge is less turbulent and redirects the impact of the rock matrix, and the last component ends with the gradual diminishing curve.

It was observed that after the intervention in the springshed, the recession coefficients had increased to 0.041 ($\alpha_1$) and 0.025 ($\alpha_2$) from an average of 0.03 ($\alpha_1$) and 0.017 ($\alpha_2$), whereas the last coefficient ($\alpha_3$) that is responsible for maintaining the flow for a longer time changed from an average of 0.007 to 0.005 after the intervention. The lower value of $\alpha_3$ suggests low hydraulic conductivity which represents slow depletion (Kumar & Sen, 2018a). One year post-intervention, results showed an increase in net recharge and in volume (58%) caused by the storing of rainwater in pits and trenches. There were more coefficients in that spring than reported by Padilla et al. (1994) which might be because of different geological settings.

Post-intervention work (2017) in the springshed has increased storage durations by around 16% (116 days) from decaying 142.98 lpm (peak flow) to 12.69 lpm (baseflow). Before the intervention, it was 100 days to recess from peak to base in the year 2014 and 98 days in the year 2016. The ratio of recession coefficient ($\alpha_2$/$\alpha_3$) for pre-intervention was 2.3 which increased to 5.0 after the intervention. This major change is because of the decrease in $\alpha_3$ value from 0.007 to 0.005 which is related to change in the effective porosity (Fiorillo 2011). More discharge received during post-intervention work indicates the storage of water in the pits and trenches in the recharge zone, which later drains to the aquifer enhancing the holding capacity of the aquifer after the rainfall during the wet period rather than becoming surface flow. In the changing rainfall pattern (shrinking of monsoon time) across the region and Himalayas, promoting this kind of springshed development intervention in hills will increase water availability.

The percentage duration in which discharge is equaled or exceeded from the Mathamali spring after and before the intervention has been calculated using the Weibull equation (Figure 6). The average minimum spring flow before the intervention was 2.3 lpm which increased to 11.5 lpm (5 times) after intervention whereas the average maximum flow increased from 80.1 lpm to 146.4 lpm (1.8 times). The total volume of water available from the spring
after intervention is 19,901 m³, whereas the local community’s requirement is 3,818 m³ (Kumar & Sen 2018a, 2018b). The flow duration curve reveals that the characteristic value for the study spring was 30.6 lpm before intervention which has also increased to 95 lpm after the intervention.

Findings from the flow duration curve revealed that on average the Mathamali spring will be able to meet the domestic water requirements under minimum flow conditions by constructing storage tanks having a total capacity of 1,000 m³. Considering decreasing rainfall trends in the area, this major outcome of interventions in terms of increased spring volume can change the economy and livelihoods of mountain rural people. John (2012) emphasized that for sustainable resource management, the participation of the community and their attentiveness necessitates more understanding of other untouched evidence. In just a year (of post-intervention), it is hard to show the rate of increment of spring volume with hydro-meteorological parameters, therefore a further measurement of rainfall and discharge along with measuring other hydro-geological parameters is necessary to develop this relationship.

CONCLUSIONS AND RECOMMENDATIONS

Springs are the backbone of mountain communities. Their drying up and the reduction of base flow is a threat to mountain communities. Rainfall is the only source of recharging springsheds and lack of conservation practices and degradation of springsheds are the main causes of reducing recharge and thus spring outflow. Thus this study was undertaken to collect and analyze high-frequency data of rainfall and spring discharge to understand the behavior of springs’ discharge and availability of spring water during dry periods. This helps to gain insights into the hydrological behavior of the aquifer and concerned storage-discharge relationships. In the present case, Mathamali spring, which is a contact-and-fracture type spring system, base flow decays at a constant rate of 0.01 day⁻¹ which signifies that the permeability of Mathamali’s aquifer system is likely to remain constant throughout the year.

The average spring flow rate from Mathamali’s springshed has increased to 41.63 lpm from 16.9 lpm with recharge interventions, suggesting that integration of farmers’ participation and springshed intervention practices is needed to revive drying springs. One year post-intervention, results show an increase in net recharge and in volume. Flow duration analysis of daily flow suggests that the characteristic value for Mathamali spring was 30.6 lpm before intervention which increased to 95 lpm (3.1 times) after the intervention. Even in the minimum flow conditions, the spring will be able to meet domestic as well as water requirements for irrigating a 2-hectare area if we construct 5 storage tanks, each of capacity of 200 m³. It is concluded that the fitting of the recession curves by the three-exponential recession coefficients helps forecast the spring discharge in the recession period with an accuracy of about 90% as compared to one recession coefficient (70%) and two recession coefficients (16%). The ratio of recession coefficients ($a_2/a_3$) was earlier 2.3 which increased to 5.0 after the interventions because of a decrease in the value of $a_3$ from 0.007 to 0.005 which is related to change in the effective porosity and is responsible for maintaining the spring flow for a longer time.

The present study after just a year of intervention shows only immediate hydrological changes that took place and needs to be supplemented through long term monitoring (which is being continued). Finally, the study suggests the following recommendations for securing the life of rural mountain communities on a sustainable basis:

1. Establishment of appropriate instrumentation and monitoring systems by research institutions and universities that can generate high-frequency data to understand spring hydrologic response which can help design and implement technologically sound community based springshed development practices.
2. Execution of awareness campaigns focusing on the role of communities for sustaining increased spring volume and base flows post springshed interventions otherwise springs are likely to get back into the previous state. Mountain communities need to be mobilized against practices like cultivating on steep slopes and adopting efficient water management practices.
3. Promotion of watershed management programs, especially in mountainous regions integrating springshed development along with continuous monitoring systems.
maintained by local NGOs and/or government departments with help of research institutions.

(4) Creation of a cadre of para-hydrogeologists through capacity building of community-level persons focusing on basic hydro-geology and spring recharge and conservation practices.

(5) Designing policies and guidelines by concerned government authorities that adhere to the Forest Act, Water Act, and other recommendations suggested by the World Environment Organization (WEO) that would strengthen springshed development activities.

The paper also recommends the need for collaborative efforts among different active stakeholders such as NGOs, Government Departments (like Rural Department, Forest Department, Public Health Engineering Department, Irrigation Department, etc.), Research Institutions and Universities, along with Panchayati Raj Institutions to identify and understand drying springs in the Indian Himalayan region for the upliftment of the socio-economic status of mountain communities.

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DATA AVAILABILITY STATEMENT

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

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