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Assessment of seasonal variability in spring discharge and implications for drinking water supply in Solan District (Himachal Pradesh), sub-Himalayan India

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Abstract

Spring-fed sources constitute a major component of rural and peri-urban drinking water supply in mountainous regions, yet their seasonal reliability remains poorly quantified. This study evaluates the seasonal and inter-annual variability of spring discharge and its implications for water supply sustainability in a sub-Himalayan region. Spring yield (Lpm) was monitored at 50 representative springs distributed across five blocks during pre-monsoon and post-monsoon periods for two consecutive years (2021 and 2022). Seasonal variability was assessed using box-plot analysis to examine changes in discharge distribution, while statistical significance between pre- and post-monsoon yields was evaluated using paired *t*-tests at a 95% confidence level. Results indicate a consistent and statistically significant increase in spring discharge following the monsoon across all locations in 2021 ($p < 0.01$) and in four out of five locations in 2022, with mean post-monsoon yields increasing by 27–95% in 2021 and 25–105% in 2022. Box plots reveal a pronounced upward shift in median discharge and a reduction in low-flow occurrences during the post-monsoon period, confirming effective monsoon recharge. Despite seasonal recovery, several locations exhibit persistently low pre-monsoon yields, indicating continued vulnerability to water scarcity. The findings demonstrate that spring-fed water supply systems are strongly controlled by monsoon recharge and remain seasonally constrained. These results highlight the need for recharge augmentation, storage provision, and springshed management to ensure a reliable year-round drinking water supply under increasing climatic variability.

Keywords: Monsoon recharge; Box plot; Paired t-test; Himalayan region; Springshed management

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1. Introduction

Spring-fed water supply systems play a vital role in meeting drinking water requirements in mountainous and hilly regions worldwide. In India, especially across the Himalayan and sub-Himalayan belt, springs form the backbone of rural and peri-urban water supply, supporting domestic consumption, livestock needs, and local livelihoods. These systems generally operate under gravity flow and derive water from shallow aquifers, weathered zones, and fractured rock formations, which makes them highly sensitive to variations in rainfall, land-use change, and groundwater recharge processes.[1,2]

Over recent decades, a widespread decline in spring discharge has been reported across many hill regions of India, leading to increased seasonal water stress. National-level assessments indicate that a substantial number of springs have either become seasonal or exhibit sharply reduced discharge during dry months, particularly in the pre-monsoon period when water demand is at its highest.[3,4] Several factors, including changing rainfall patterns, reduced groundwater recharge, deforestation, land-use change, slope instability, increasing water extraction, and climate variability, have been identified as major causes of spring depletion in Himalayan regions.[1,2] Comparable challenges have been documented internationally in mountain environments such as Nepal, Bhutan, the European Alps, and parts of East Asia, where spring-fed systems show strong dependence on precipitation patterns and limited subsurface storage capacity.[5–7]

In the Indian subcontinent, groundwater recharge in hill terrains is predominantly controlled by the South-West Monsoon. Several studies have demonstrated that monsoonal rainfall contributes the majority of annual recharge to shallow aquifers, resulting in a noticeable increase in spring discharge during the post-monsoon season.[2,8] However, this seasonal recharge is often transient, as limited aquifer thickness, steep slopes, and rapid runoff lead to declining discharge during the dry season.[9] As a result, many spring-based drinking water schemes struggle to provide a continuous year-round supply, frequently experiencing shortages during the summer months. Recognizing the growing threat to drinking water security in hill regions, national programs such as the Jal Jeevan Mission and dedicated spring rejuvenation initiatives have underscored the need to scientifically assess spring discharge behavior, recharge potential, and long-term sustainability.[3,10] At the global level, research on decentralized and small water supply systems increasingly highlights the need for integrating hydrological monitoring with statistical and risk-based evaluation methods to improve source reliability.[11]

Despite the acknowledged importance of springs, detailed comparative studies that quantitatively evaluate seasonal and inter-annual variability in spring discharge using robust statistical techniques remain limited, particularly in sub-Himalayan regions. Many existing investigations rely on short-term datasets or qualitative assessments, with relatively few studies applying paired statistical tests to rigorously confirm the significance of monsoon-driven recharge effects.[5,12] Although monsoon-controlled recharge of Himalayan springs is generally recognized, statistically validated comparative assessment of seasonal discharge variability and its implications for drinking water reliability remains relatively limited for sub-Himalayan springsheds. The present study provides field-based quantitative evidence using paired statistical analysis and graphical interpretation to evaluate seasonal recharge responses and spring sustainability across multiple locations.

Against this background, the present study examines pre-monsoon and post-monsoon spring discharge over two consecutive years (2021–2022) across selected locations in the Solan district of Himachal Pradesh. By integrating field-based yield measurements with box-plot visualization and paired *t*-test analysis, the study aims to (i) quantify seasonal changes in spring discharge, (ii) statistically evaluate the influence of monsoon recharge, and (iii) assess the implications of discharge variability for the reliability of spring-fed drinking water supply systems. The outcomes of this work contribute to both national and international understanding of spring hydrology and provide evidence-based insights for planning and managing sustainable and climate-resilient water supply systems in mountainous regions under increasing climatic and anthropogenic pressures.

2. Materials and methods

2.1. Study area

The study was conducted in the Solan district of Himachal Pradesh, located in the sub-Himalayan region of north-western India (Figure 1), where spring-fed sources constitute the primary means of domestic water supply for rural and peri-urban settlements. The district is characterized by undulating to steep terrain, fractured and weathered geological formations, and a monsoon-dominated climate. Annual rainfall is primarily received during the South-West Monsoon season (June–September), which governs groundwater recharge and seasonal spring discharge behavior. The region mainly consists of shallow aquifer systems developed within weathered and fractured rock formations, making spring discharge highly sensitive to variations in rainfall, infiltration, runoff, and recharge conditions.[2,4]

2.2. Selection of springs and discharge measurement

A total of 50 springs were selected for discharge monitoring across five blocks of the Solan district (Figure 2). Springs were identified through field reconnaissance, interaction with local communities, and consultation with available records from line departments. Selection

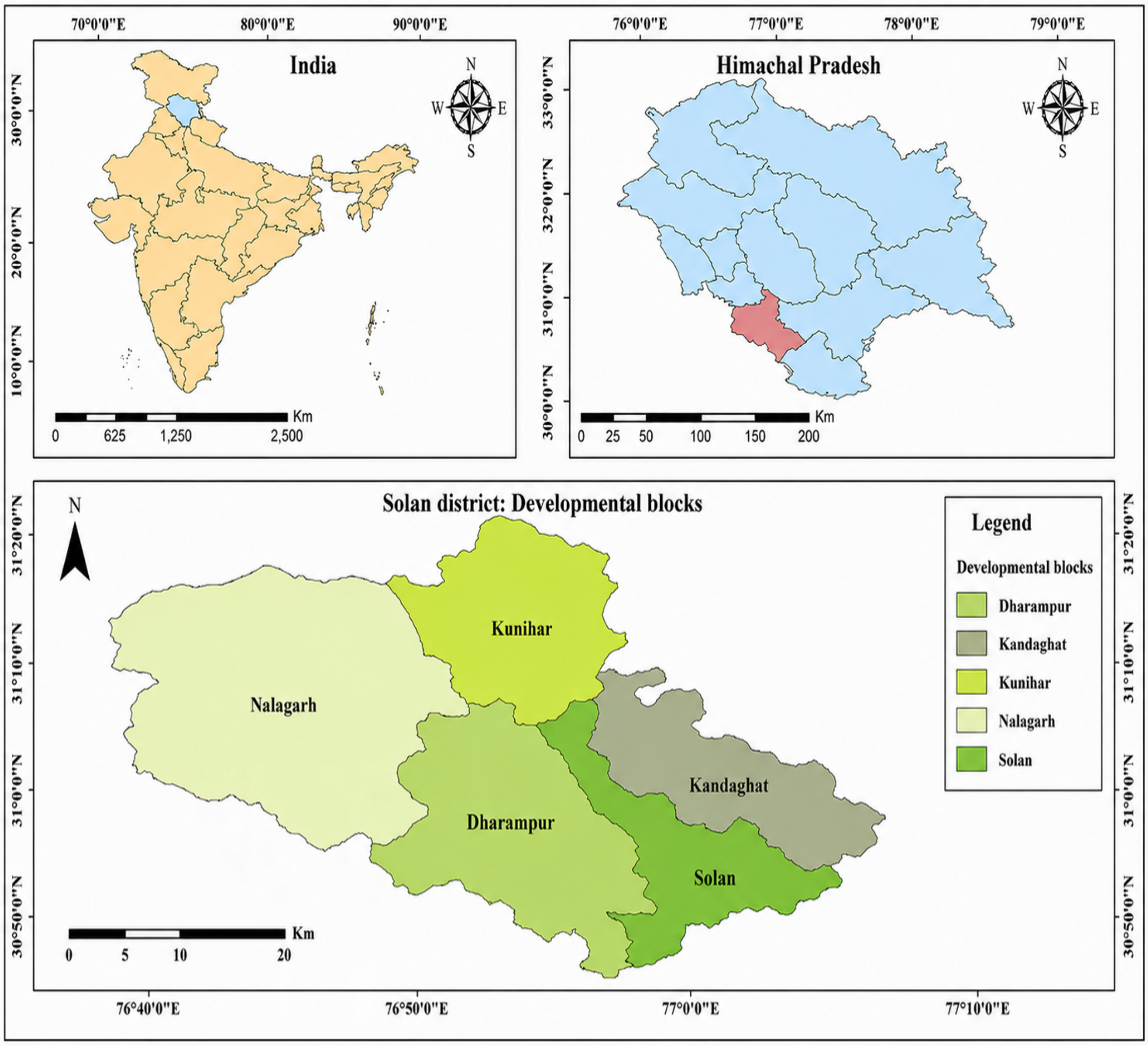

Figure 1. Map of the study area

criteria included (i) dependence of local communities on the spring for domestic water use, (ii) accessibility for repeated measurements, (iii) representation of both perennial and seasonal springs, and (iv) spatial distribution across varying elevations and hydrogeological settings. Geographic coordinates and elevation of each spring were recorded using a handheld Global Positioning System.

2.3. Discharge and volume measurement procedures

Spring discharge was monitored during both pre-monsoon and post-monsoon periods over two consecutive years (2021 and 2022). Discharge was measured using the volumetric method, which is widely applied for low-discharge springs and rural water supply assessments in mountainous regions.[1,2] Measurements were carried out at the spring outlet or at a hydraulically stable section immediately downstream of the emergence point to ensure complete capture of flow and minimize losses due to seepage or diversion. For each spring, a calibrated container of known volume (V) was placed directly under the flowing water, and the time (T) required to fill the container was recorded using a digital stopwatch (Figure 3). Spring discharge (Q) was calculated using **Equation 1**:

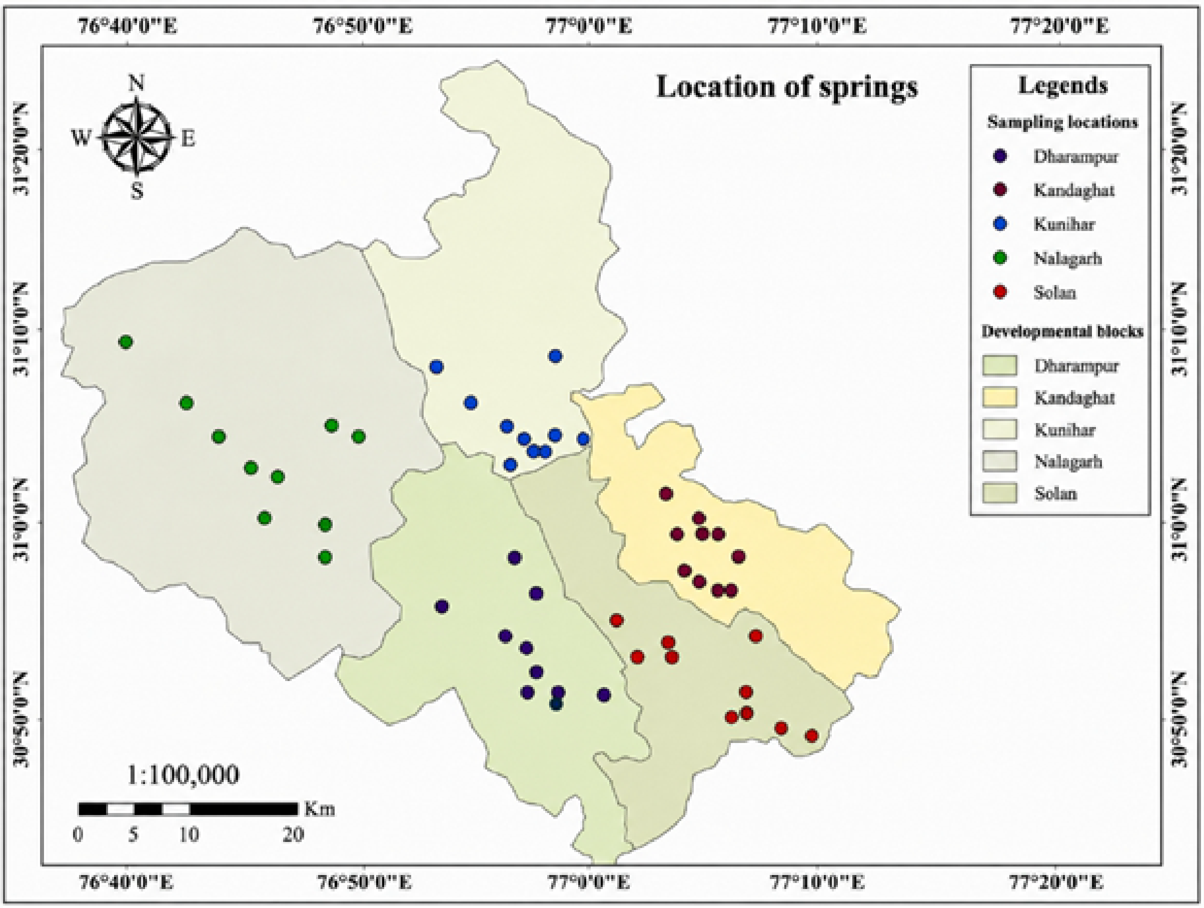

Figure 2. Location map showing the distribution of monitored springs across selected blocks of the Solan district, Himachal Pradesh

$$Q = \frac{V}{T} \quad (1)$$

where Q is the discharge in L per second (Lps), V is the volume of the container in L, and T is the time taken to fill the container in seconds. The discharge values were subsequently converted to L per minute (Lpm) by multiplying them by 60.

2.4. Data preparation

Spring discharge data were collected from 50 representative springs at five locations during the pre-monsoon and post-monsoon periods. The same springs were measured in both seasons and years to ensure paired observations. All discharge values were recorded in Lpm and checked for completeness and consistency prior to analysis.

2.5. Box plot analysis

Box plot analysis was employed to examine the distribution, central tendency, variability, and seasonal behavior of spring discharge variability among study locations and monitoring periods. Separate box plots were generated for pre-monsoon and post-monsoon discharge data from 2021 and 2022 to facilitate visual comparison of seasonal and interannual variability. Each box plot displays the median, the interquartile range (25th–75th percentile), the minimum and maximum values, and the overall spread of discharge observations. The graphical representation enables the identification of variability in discharge magnitude, low-flow conditions, skewness, and the consistency of recharge response across different springsheds. Box plots were selected because they provide a simple, effective nonparametric method for summarizing hydrological datasets that may not follow a normal

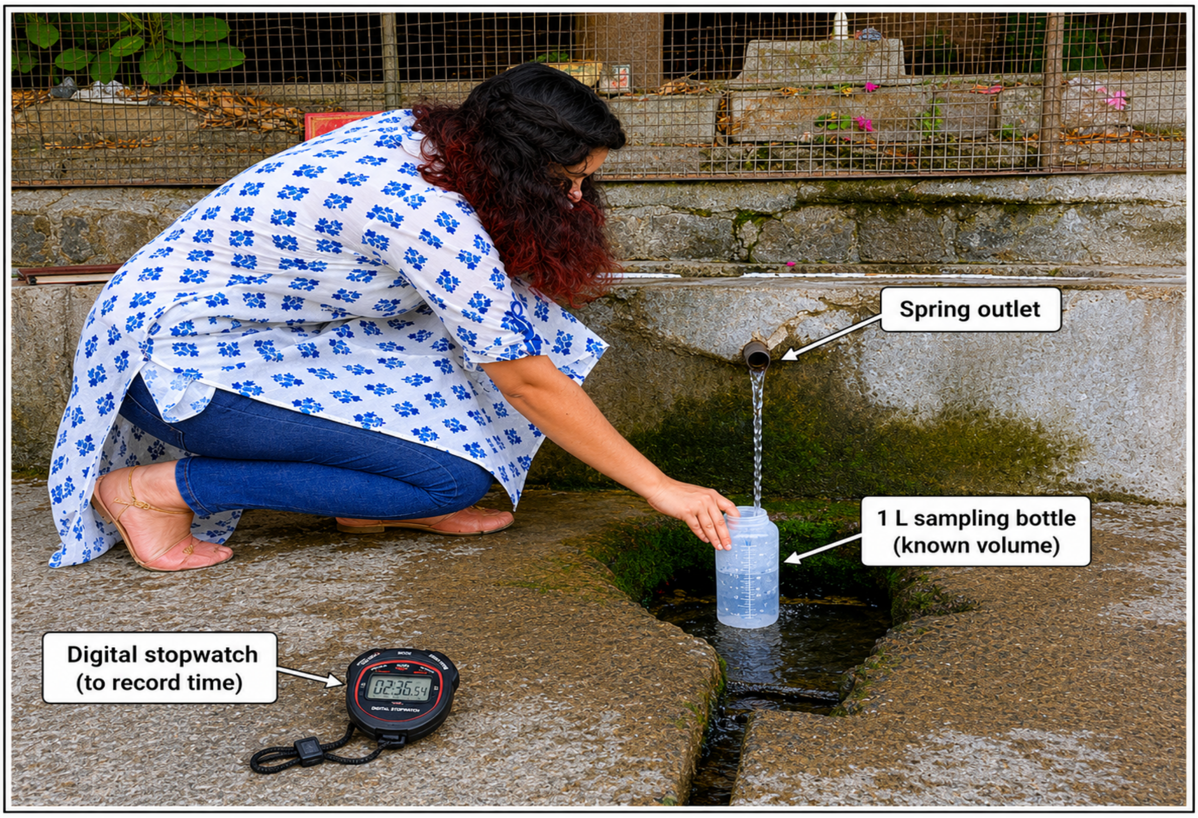

Figure 3. The volumetric method for spring discharge measurement using a calibrated sampling bottle and a digital stopwatch at the spring outlet

distribution. The method allows rapid visualization of seasonal shifts in discharge patterns and helps identify differences in recharge response between locations. Comparison of box-plot distributions between pre-monsoon and post-monsoon periods was used to evaluate changes in median discharge, variability, and occurrence of low-flow conditions associated with monsoon recharge processes.

2.6. Paired *t*-test analysis

To statistically evaluate seasonal changes in spring discharge, a paired *t*-test was performed for each location and monitoring year. Pre-monsoon and post-monsoon discharge values recorded from the same springs were treated as paired observations because measurements were repeatedly collected from identical sampling locations across seasons. The paired *t*-test was selected as an appropriate inferential statistical method for assessing whether the mean difference between seasonal discharge observations was statistically significant. The null hypothesis (H_0) assumed that there was no significant difference between mean pre-monsoon and post-monsoon spring discharge, whereas the alternative hypothesis (H_1) assumed that post-monsoon discharge was significantly higher due to monsoon-driven groundwater recharge. Statistical analysis was conducted at the 95% confidence level ($\alpha = 0.05$), and p-values < 0.05 were considered statistically significant. In addition to significance testing, mean discharge values and relative percentage increases from pre-monsoon to post-monsoon conditions were computed to quantify seasonal recharge dynamics and assess the influence of monsoon rainfall on spring flow variability.

3. Results

3.1. Seasonal variation in spring discharge

Spring discharge data for the years 2021 and 2022 exhibited a clear and consistent seasonal variation between pre-monsoon and post-monsoon periods across all five study locations. Box-plot distributions show that pre-monsoon spring yields are generally low, with lower median values and compressed interquartile ranges, particularly at Nalagarh, followed by Kunihar and Dharampur. In contrast, Solan and Kandaghat display higher medians and greater variability, indicating stronger aquifer storage and recharge connectivity (Figures 4–6). During the post-monsoon period, box plots show a pronounced upward shift in median discharge values, along with expansion of the upper quartile and reduction in low-flow occurrences across all locations (Figures 5–7). This seasonal pattern is consistently observed in both study years, confirming the strong response of spring discharge to monsoon recharge.

3.2. Statistical significance of seasonal change

The seasonal increase observed in the box plots was supported by a paired *t*-test analysis (Table 1), which quantitatively evaluated differences in pre- and post-monsoon discharge for each location and year. In 2021, post-monsoon spring discharge was statistically significantly higher ($p < 0.01$) than pre-monsoon discharge at all locations, with mean discharge increases ranging from 27% to 95%. In 2022, statistically significant seasonal increases ($p < 0.01$) were observed for Solan, Dharampur, Kunihar, and Nalagarh, while Kandaghat showed a positive but not statistically significant increase ($p = 0.099$), indicating reduced seasonal contrast during that year. Overall, post-monsoon yields increase by 25–105%, highlighting the dominant role of monsoon recharge in enhancing spring discharge.

3.3. Spatial and inter-annual variability

Box-plot analysis revealed distinct spatial variability in spring discharge. Solan consistently recorded the highest median and maximum yields in both years (Figures 4–7), indicating comparatively reliable water supply conditions. Kandaghat exhibited moderate to high yields with some inter-annual variability, while Dharampur and Kunihar showed moderate seasonal improvement but remained constrained during pre-monsoon months. Nalagarh consistently recorded the lowest median discharge and narrowest interquartile range, reflecting limited aquifer storage and high sensitivity to seasonal recharge. Despite large relative post-monsoon increases, absolute discharge levels remained low, indicating continued vulnerability to seasonal water scarcity.

3.4. Implications for seasonal water supply reliability

The combined graphical (Figures 4–7) and statistical (Table 1) evidence demonstrates that spring discharge is strongly controlled by monsoon recharge, resulting in significant seasonal enhancement of water availability. However, persistent low pre-monsoon yields in several locations indicate that spring-fed water supply systems remain seasonally constrained, emphasizing the need for storage, recharge augmentation, and springshed management to ensure a reliable year-round drinking water supply.

4. Discussion

The present study provides statistically validated evidence of seasonal and inter-annual variability in spring discharge and its implications for drinking water reliability in the sub-Himalayan region of Solan District, Himachal Pradesh, India. Although monsoon-controlled recharge of Himalayan springs is widely recognized, the novelty of this study lies in integrating field-based discharge monitoring, box-plot visualization, and paired *t*-test analysis to quantitatively assess seasonal discharge variability across multiple springsheds. Unlike many previous studies that have qualitatively described seasonal spring behavior, the present investigation statistically validates seasonal and inter-annual discharge differences and provides empirical evidence of monsoon-controlled recharge dynamics in spring-fed water supply systems.

The results demonstrated that post-monsoon spring discharge was significantly higher than pre-monsoon discharge across most study locations during both 2021 and 2022. The paired *t*-test analysis confirmed that these differences were systematic rather than random, highlighting the dominant influence of monsoon rainfall on groundwater recharge and spring flow behavior. Similar seasonal recharge responses have been widely documented in Himalayan springs, where shallow aquifers and fractured geological formations rapidly respond to precipitation inputs.[1,2,9] The box-plot analysis further supported these findings by showing a consistent increase in median discharge and a reduction in low-flow occurrences during post-monsoon periods, reflecting improved aquifer recharge conditions and temporary recovery of spring-fed water supply systems following the monsoon season. Comparable seasonal discharge behavior has been reported in mountain regions of Nepal, Bhutan, and other parts of the Himalaya, where spring systems exhibit strong hydrological dependence on rainfall and limited groundwater storage capacity.[5,13] Similar relationships between precipitation variability and spring discharge have also been observed in fractured aquifer systems of Europe and other mountainous regions.[6,7] Therefore, the findings of the present study contribute to the growing body of evidence demonstrating the critical role of monsoon rainfall in sustaining spring-fed drinking water systems in mountain environments.

Despite substantial post-monsoon increases in discharge, several springsheds continued to exhibit low absolute discharge during pre-monsoon periods,

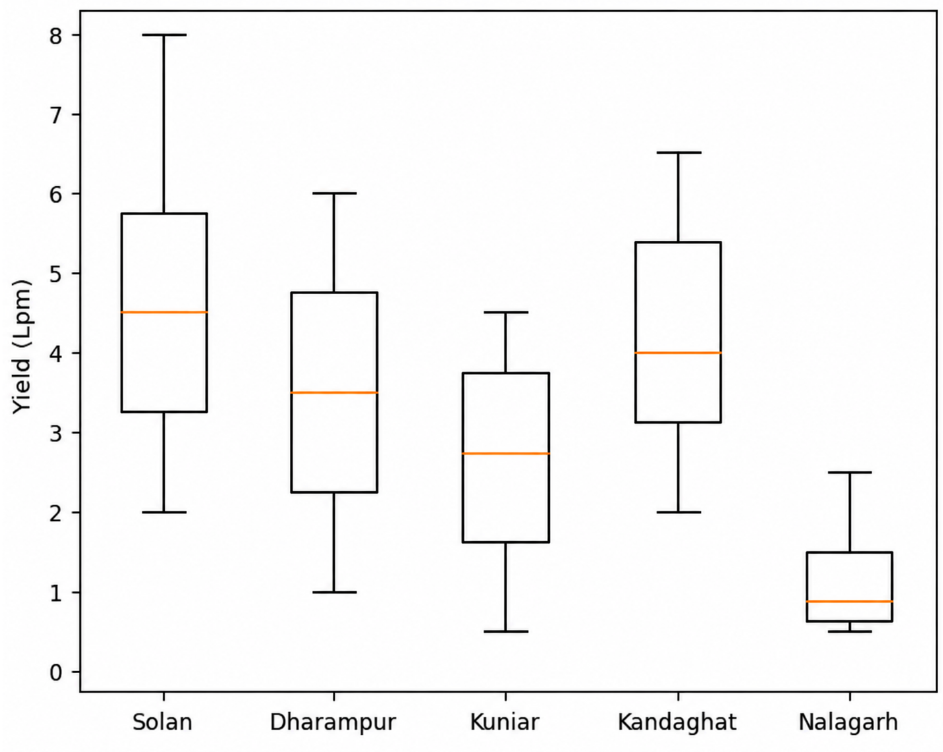

Figure 4. Pre-monsoon spring yield distribution across study locations (2021)

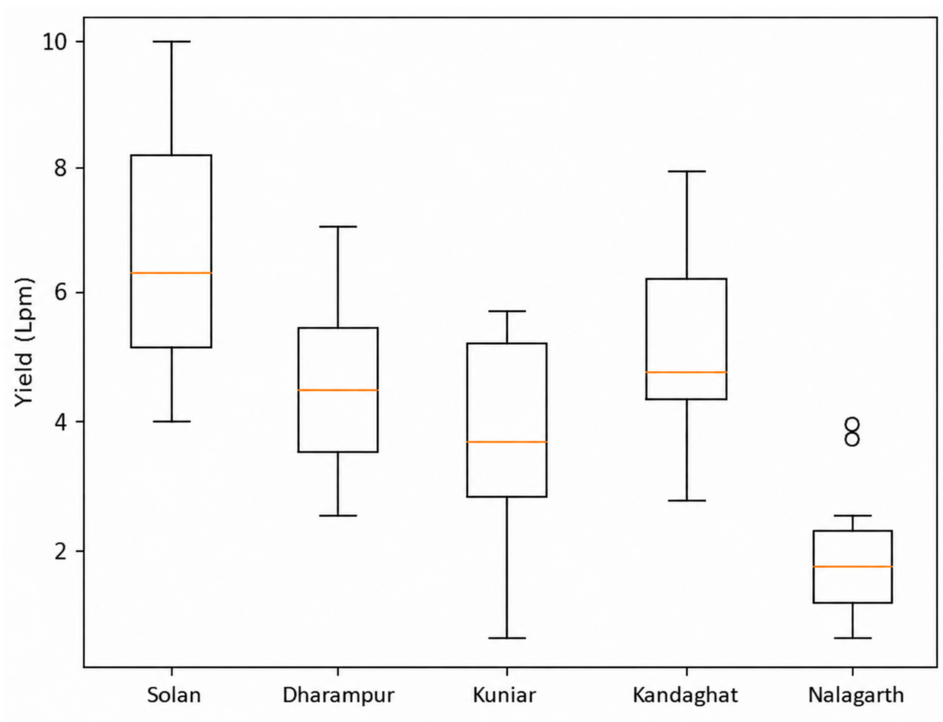

Figure 5. Post-monsoon spring yield distribution across study locations (2021)

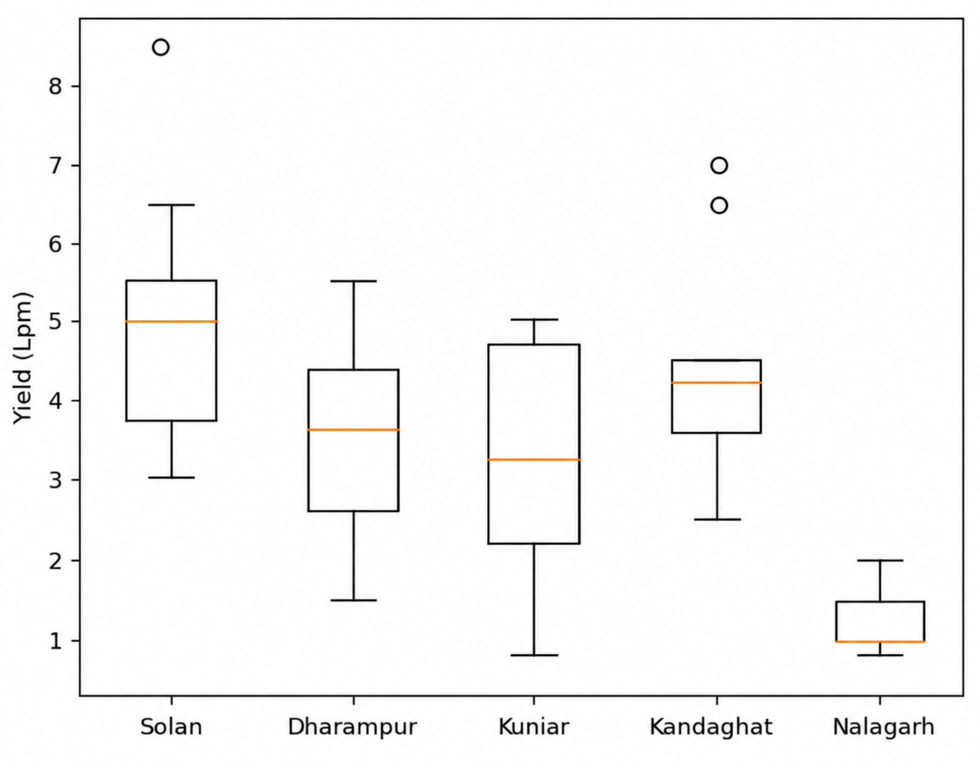

Figure 6. Pre-monsoon spring yield distribution across study locations (2022)

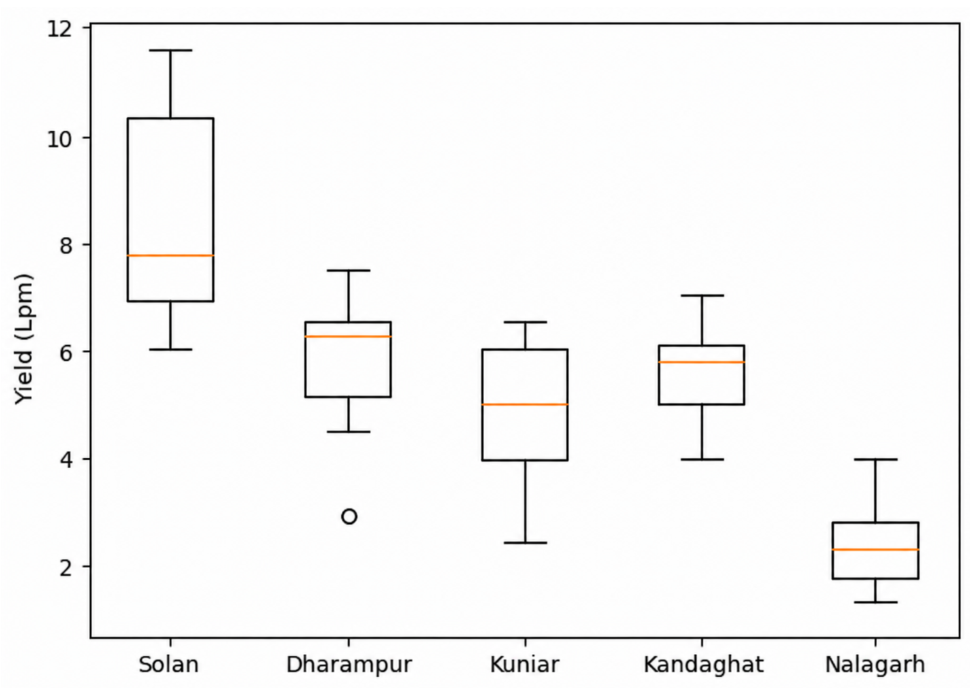

Figure 7. Post-monsoon spring yield distribution across study locations (2022)

Table 1. Comparison of pre- and post-monsoon spring discharge using paired *t*-test (2021–2022)

Year	Location	Mean pre-monsoon (Lpm)	Mean post-monsoon (Lpm)	% increase	*p*-value
2021	Solan	4.60	6.70	45.7	<0.001
2021	Dharampur	3.50	4.60	31.4	<0.001
2021	Kunihar	2.60	3.89	49.6	<0.001
2021	Kandaghat	4.20	5.34	27.1	0.001
2021	Nalagarh	1.17	2.28	94.9	<0.001
2022	Solan	5.05	8.50	68.3	<0.001
2022	Dharampur	3.58	5.80	62.0	<0.001
2022	Kunihar	3.24	4.80	48.1	<0.001
2022	Kandaghat	4.39	5.50	25.3	0.099
2022	Nalagarh	1.22	2.50	104.9	<0.001

particularly in Nalagarh and parts of Kunihar and Dharampur. This suggests that although monsoon recharge improves seasonal water availability, the recharge effect is often temporary and insufficient to sustain reliable year-round spring flow. Such conditions are commonly associated with shallow aquifer thickness, steep slopes, rapid runoff, reduced infiltration, and limited groundwater retention capacity in Himalayan terrains.[4,12] The persistence of low-flow conditions during summer months highlights the increasing vulnerability of spring-fed drinking water systems under growing climatic variability and anthropogenic pressures. Inter-annual comparison between 2021 and 2022 further revealed differences in recharge response and discharge magnitude. Several locations recorded higher post-monsoon discharge in 2022, suggesting that recharge efficiency may vary with rainfall intensity, antecedent soil moisture conditions, and local hydrogeological characteristics. Similar inter-annual variability in Himalayan spring discharge has been linked to fluctuations in monsoon patterns, land-use changes, and climate variability.[2,14] These observations indicate that the long-term sustainability of spring-fed water supply systems cannot rely solely on natural monsoon recharge and requires proactive source management interventions.

From a water resource management perspective, the findings emphasize the importance of integrated springshed management and recharge enhancement measures. Recharge augmentation strategies such as contour trenching, recharge pits, rooftop rainwater harvesting, vegetative stabilization of recharge zones, afforestation, and small check-dam construction can improve groundwater infiltration and prolong spring discharge during dry periods.[3,15,16] In addition, development of localized storage systems, spring protection measures, and community-based water management practices may help reduce seasonal water stress and improve long-term drinking water reliability under changing climatic conditions.[11,13] Similar springshed-based interventions implemented in the Himalayan regions of India and Nepal have demonstrated positive impacts on lean-season spring flow and rural water security.[17]

Certain limitations of the study should be acknowledged. The analysis is based on two consecutive years of monitoring (2021–2022) and therefore does not fully capture long-term hydro-climatic variability associated with climate change and changing monsoon patterns. In addition, detailed hydrogeological investigations, including aquifer characterization, groundwater recharge estimation, soil properties, and long-term rainfall analysis, were beyond the scope of the present study. Socio-economic factors, land-use changes, and water quality aspects influencing spring sustainability were also not explicitly evaluated. Nevertheless, the study provides a practical, field-based framework that integrates discharge monitoring with graphical and statistical analyses to evaluate spring sustainability in data-scarce Himalayan environments.

Future research should focus on long-term hydro-meteorological monitoring to better understand climate-driven changes in spring discharge behavior and recharge processes. Integration of discharge records with rainfall, groundwater level observations, hydrogeological characterization, and climate projections would improve understanding of spring dynamics and support predictive modeling under future climate scenarios.

Further investigations should evaluate the effectiveness of springshed management interventions, assess water quality and socio-economic dimensions of spring dependence, and explore the application of isotopic tracing and groundwater recharge modeling to identify recharge pathways and improve evidence-based spring restoration strategies.

5. Conclusion

Overall, the study demonstrates that spring discharge in the sub-Himalayan region is strongly controlled by monsoon-driven recharge and exhibits significant seasonal and inter-annual variability. By combining field measurements with graphical and statistical validation, the study contributes robust evidence on recharge-controlled spring dynamics and provides a practical framework for identifying vulnerable spring-fed water supply systems. The findings highlight the importance of integrating recharge augmentation, springshed protection, and climate-resilient water management strategies to strengthen long-term drinking water security in Himalayan mountain regions.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization: Upasana Kandpal, Satish Kumar Bhardwaj
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Investigation: Upasana Kandpal
Methodology: Upasana Kandpal, Satish Kumar Bhardwaj
Writing–original draft: Upasana Kandpal
Writing–review & editing: Satish Kumar Bhardwaj

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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