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Review article

Springs of Uttarakhand Mountains: A State of Knowledge with Focus on Rejuvenation of Drying Springs

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ABSTRACT

This review focuses on the springs of the Uttarakhand mountains, particularly within the Indian Himalayan Region (IHR), synthesizing existing published work. It delves into the empirical evidence supporting the reasons for the drying up of springs and the decline in spring discharge. Furthermore, it explores various methodologies and techniques employed in spring hydrological studies; including spring recharge zone delineation, spring rejuvenation strategies, and springshed management efforts undertaken by diverse stakeholders such as R&D organizations, Government Departments, and Non-Government Organizations, specifically within the Uttarakhand mountains. The key emphasis of this review is to underscore that existing studies on springs in Uttarakhand are inadequate for drawing firm conclusions on sustainable water management. Research varies widely - some focus only on summer discharge, others take single measurements, or report annual averages - often without considering spring types. Many studies also lack methodological rigor and fail to interpret key factors like discharge, climate, geology, and land use, hindering problem assessment and solution development. Efforts to enhance spring discharge through recharge zone treatments are often based on limited understanding, particularly regarding appropriate species for plantation. Additionally, the effectiveness and cost-efficiency of these measures, along with their ecosystem service benefits, remain under-evaluated. There is a clear need for more rigorous research by regional R&D institutions. The review also notes that significant work by NGOs and community stakeholders often remains undocumented and unrecognized in academic literature, limiting its influence and visibility. The overarching conclusion is that augmenting water yield in drying mountain springs necessitates a transdisciplinary and community-centric approach. This involves seamlessly integrating scientific knowledge with local wisdom, effectively translating research findings into actionable practices through a robust Science-Policy-Practice interface, and empowering communities to effectively overcome the prevalent water scarcity challenges in this region. Additionally, there is a strong imperative to build the capacity of implementing agencies and NGOs in springshed management methods and techniques. Regional research institutions, universities, and the newly established Spring and River Rejuvenation Authority (SARRA, Government of Uttarakhand) are expected to take a leading role in fostering better coordination across the region to contribute towards fulfilling SDG 6. Finally, the review highlights specific gap areas in spring hydrology and spring rejuvenation research, outlining avenues for future R&D activities. Uttarakhand has emerged as a significant hotspot for drying springs, evidenced by the highest number of publications among all the IHR States.

Key words: Himalayan springs, Diminishing discharge, Hydrology, Climate change, Land use and land cover change, Sustainable development goals

INTRODUCTION

Springs are groundwater discharge points where an aquifer - a water-bearing soil or rock layer - intersects the ground surface, allowing water to seep continuously through pores, fissures, fractures, or depressions. Groundwater origin, movement, and presence are influenced by rainfall, slope, drainage density, land use, geology, lineament density, and geomorphology (Rajaveni et al. 2017). Aquifers, which store and transmit water, feed springs and regulate stream and river hydrology (Kumar et al. 2024). Each spring is unique in type, catchment, recharge, and discharge (Glazier 2014). Based on the geology that governs their behavior over time and space, springs are categorized into five types: depression, contact, fracture, karst, and fault springs (Kresic 2010).

In the Himalayan region, natural springs from unconfined aquifers are vital freshwater sources for millions. An estimated 3 million springs exist in the Indian Himalayan Region (IHR), and 20% of its 89,712 villages rely heavily on them (Anonymous 2018a). Springs are essential for achieving Sustainable Development Goal 6 but are highly susceptible to tectonic activity, climate change, anthropogenic pressures, and land use/land cover change (LULC) (Kumar et al. 2024). Himalayan aquifers vary widely in extent, geometry, and hydrology due to complex regional geology, resulting in diverse spring types, discharge rates, and water quality (Kumar et al. 2024). The weathered and fractured rocks of the Lesser Himalaya filter water and direct it through conduit (fast) or diffused (slow) flow paths (Agrawal et al. 2012). In the Central Himalaya, Valdiya and Bartarya (1991) identified eight spring types from four aquifer categories based on geology and water-bearing formations, with variable water yields. Kumar and Naithani (2021) reported four spring types - fracture/joint-related, colluvial, karst and seepages, and contact springs - finding colluvial springs to have higher yields than fracture/joint-related ones.

Springs – the lifeline of Uttarakhand

Uttarakhand is rich in water resources, including springs, streams, rivers, glaciers, and lakes, supporting household use, agriculture, energy, tourism, and urban needs. About 260,000 springs provide nearly 90% of drinking water for the state's 10.3 million residents (Anonymous 2018b). In the mountains, springs (locally *Dhara*) and stepwells (*Naula*, 1-2 m deep stone structures with porous floors housing spring orifices) serve as primary sources for drinking and domestic needs (Fig. 1). *Naulas* (revered as Water Temples) reflect ancient Himalayan scientific knowledge and are worshipped as sacred spaces dedicated to Lord Vishnu. Spring-site marriages (*Pani Dhara vivah*) were traditionally recognized by society (Rawat and Sah 2009). Most springs in this region are cold-water types - gravitational, contact, fracture, seepage, fault-bounded, and valley-floor. According to CGWB (Anonymous 2022a, 2025), discharges range from <1 lps in seepages to 30 lps in streams. Hot water springs (geysers) are structurally controlled, mainly along the Main Central Thrust, with temperatures of 32-90°C and discharges from 1-10 lps (Anonymous 2022b).

Drying up of springs imperils the life of people in Uttarakhand

Over the past three decades, numerous studies have reported that many perennial springs and streams are turning seasonal or drying up, affecting water supply, agriculture, livelihoods, and climate resilience (Valdiya and Bartarya 1989, Singh and Rawat 1995, Negi and Joshi 1996, Anonymous 2018a, Pant et al. 2024). Key reasons include deforestation, forest degradation, grazing, fire, infrastructure development, mining (Singh and Rawat 1995), land use/land cover change (Joshi and Tiwari 2014, Sheikh et al. 2024), changes in forest type (Naudiyal and Schmerbeck 2015), rising temperatures, climate change (Pandey et al. 2018), geology (Kumar and Naithani 2021), and earthquakes (Thapa et al. 2023). Recent long-term analyses suggest declining spring flows are linked to deficient monsoons, dry winters, and mid-century droughts (Kumar and Sen 2018, Tarafdar and Dutta 2023).

The drying of springs was first noted in 1985 in Kumaun region of Uttarakhand (Singh and Rawat 1985). Singh and Pande (1989) reported that 17% of springs had disappeared and 53% had reduced discharge in 20 years. Valdiya and Bartarya (1989) showed a 25–75% decline in spring flow in the Gaula River catchment. In Pauri-Garhwal, Negi and Joshi (1996) found summer discharge reductions of 36% in fracture/joint springs and 100% in colluvial types. Tiwari (2000) found 45% of springs in a Central Himalayan catchment had dried or become seasonal. In Almora, spring numbers dropped from 100 to 70 over 150 years due to urbanization and land use change (Pant 1995, Rawat 2009). In Kumaun Hills, 159 springs dried and 50 became seasonal over 30 years due to deforestation (Tiwari 2008). In Kosi basin, Panwar (2020) found the number of perennial springs decreasing @3 springs per year and the non-perennial springs increasing @1 spring per year. In Gagas watershed, 88% of water mills became non-functional due to reduced stream flow (Bisht et al. 2022).

Water scarcity has major socio-environmental impacts. Spring discharge loss reduces rural water

Figure 1. Traditional water sources in Uttarakhand - Naula (a), inner view of Naula (stepwell) with water stored (b), and Dhara (c). Many of these (Naula (d) and Dhara (e)) are now dried and defunct in this region (Photo credits: Deep Bisht, Almora)

supply to 25-30 litre per capita per day (lpcd) - about half the WHO standard (Negi and Joshi 2004). This raises risks of waterborne diseases from poor sanitation (Anonymous 2017a). The Jal Jeevan Mission recommends 55 lpcd as a basic standard. The situation has worsened, with 21 of 95 development blocks declared water-scarce in Uttarakhand (Kumar et al. 2019). In summer, 72% of women and 14% of children carry water, with 60% walking 0.5–5 km; 10% of women walk 4 km (Singh 2019, Babu et al. 2000). Scarcity forces reliance on unsafe water, abandonment of agriculture and livestock, and increased migration (Anonymous 2017a, Dass et al. 2021, Kumar et al. 2023). Water-related conflicts and litigation are rising, despite the region being a Ganga-Yamuna headwater zone, due to poor infrastructure and legal governance (Vani and Asthana 2000).

Spring drying is now widely reported across the Himalaya. In Himachal Pradesh, 40% of 43 monitored springs showed reduced discharge (Thakur and Bhardwaj 2024), and 45% of 276 springs dried over four decades (Choubey 2024). In Kashmir, Jeelani (2008) observed reduced flow in 40 springs over 25 years due to warming and poor precipitation. Seikh et al. (2024) found that 13-29% of springs in different altitude zones in the Sindh basin show high discharge reduction. In Sikkim, spring discharge declined by ~50% in drought-prone and 35% in other areas during the lean season (Tambe et al. 2012). Similar trends are seen in Nepal (Chapagain et al. 2019, Adhikari et al. 2021, Pandit et al. 2024) and Bhutan (Dendup et al. 2024), with smaller springs (<5 lpm) more vulnerable to climate change and human activities (Chapagain et al. 2019). Clearly, drying springs and water scarcity are affecting the entire Himalayan region, particularly during the lean and summer months.

Causes of drying up of springs supported by empirical evidence

In this region, the drying of springs and perennial streams becoming seasonal has been linked to climate change impacts on precipitation patterns - such as erratic rainfall, increased intensity, reduced rainy days and winter rains - as well as earthquakes, LULC changes, and other human-induced factors like expanding infrastructure and activities (Table 1). Singh and Pande (1989) first reported a significant reduction in spring discharge due to the replacement of broadleaf Oak (*Quercus* spp.) forests by Pine (*Pinus* spp.) in Kumaun Himalaya. Pine forests, with higher transpiration rates, reduce spring discharge, while Oak forests aid rain water infiltration and soil moisture retention (Ghimire et al. 2014). However, studies that comprehensively examines the interplay of meteorology, topography/geology, and forests on spring flows in Uttarakhand are lacking. Valdiya and Bartarya (1991) empirically demonstrated that Gaula River (Kumaun hills) flow dropped by 29.2% (1951-1960 to 1961-1970) and 38.5% (1971-1981), due to rainfall decline (9.7-76%) from 1958-1986. Negi and Joshi (1996) reported spring discharge decline from 36 to 100% in a Pauri-Garhwal micro-watershed, with perennial spring catchments supported by good vegetation, terraces, and low grazing. Subsequent studies identified several causes for spring depletion, including rapid LULC changes (Saraf et al. 2000, Rawat and Pant 2016), human activities such as settlements, grazing, and deforestation (Joshi 2006), and erratic rainfall patterns (Vashisht and Sharma 2007, Agarwal et al. 2012, Tambe et al. 2012). Other contributing factors include climate change and low groundwater potential (Kaushik 2017), rising temperatures over the period 1901-2016 and declining rainfall from 1950-2016 (Liniger et al. 2020, Sahu 2023), and effects of LULC, snowmelt, and evapo-transpiration (Panwar 2020). Additionally, grassland conversion to pine forests has played a role in reducing water availability (Pant et al. 2024). Rawat et al. (2016), monitoring the Kosi watershed for 22 years, found it transformed from perennial to ephemeral due to increased rainfall intensity exceeding soil infiltration capacity. This shift led to higher runoff and dry lean periods, which can be explained by Horton-and Dunne-type runoff processes (Horton 1940, Dunne and Black 1970, Negi 2001), although these processes are still poorly understood in mountainous watersheds. Also, seismic activity is among the least understood causes. Earthquakes can alter spring flow by consolidating surface materials or creating new fractures. Some studies show altered flows in Uttarakhand (Sarkar and Chander 2002), dried springs in Nepal (Chapagain et al. 2019), and increased discharge in Sikkim (Barfal et al. 2022). Thus, in tectonically

Table 1. A summary of published literature in chronological order on drying up of springs in Uttarakhand and other parts of the Himalayan mountains

Locality / study details	**Magnitude and cause of drying up of springs**	**Reference**
Kumaun Himalaya*	Loss in the broadleaf oak (*Quercus* spp.) forests and its partial replacement by pine (*Pinus* spp., a conifer) forests	Singh and Pande (1989)
Gaula river basin, Kumaun Himalaya	Flow of the Gaula river reduced by 29.2% between 1951-1960 and 1961-1970, and by about 38.5% between 1971 and 1981, owing partly to the decline in rainfall from 9.7% to 76% between 1958 and 1986 in the river basin.	Valdiya and Bartarya (1991)
A micro-watershed in Pauri-Garhwal	Spring flow has mainly geological control, however the spring recharge zone with good vegetation cover, agricultural terraces and low grazing influence supports high water yield in springs.	Negi and Joshi (1996)
Chandrabhaga watershed, Garhwal Himalaya*	Locations of various springs have changed leading to diminished flows, perhaps due to rapid changes in the landuse patterns between 1981 and 1997.	Saraf et al. (2000)
Eight springs in Kosi watershed, Kumaun region	Spring discharge is highly influenced by the settlements, open grazing, mismanaged agriculture and deforestation activities.	Joshi (2006)
Dabka river, Siwalik ranges of Kumaun Himalaya	Land use changes during the last 2 decades (1991–2011) has led decline in the flow of Dabka river and its streams by 35%.	Pant and Rawat (2015)
Long-term monitoring (22 years period since 1991) in rain-fed Kosi watershed	The watershed has transformed from a perennial to an ephemeral system, despite an increasing trend of rainfall owing primarily to the increasing rainfall intensities exceeding the infiltration capacity of soil, which triggers high-intensity run-off with dry spells in lean periods.	Rawat et al. (2016)
Devprayag, Garhwal Himalaya	Recent changes in climate, coupled with the low groundwater potential of the region could be reasons for the current situation of water scarcity	Kaushik (2017)
Kosi watershed, Kumaun Himalaya	The conversion of barren land to Pine forests (between 1990 and 2023) has turned a perennial stream (until 2005) into an ephemeral stream.	Pant et al. (2024)
Garhwal Himalaya	Annual springflow pattern is strongly dependent on snowmelt, rainfall, and evapo-transpiration, and Karst aquifers to be highly vulnerable among other types of springs.	Kumar and Paramanik (2020)
Pithoragarh, Kumaun Himalaya	Long-term climate data (1901-2016) indicated that increased temperatures (average increase of 0.35^{o}C, half of the global average of 0.7^{o}C over the past century) and reduced rainfall (decline in annual average rainfall of 1692 mm by 120 mm between 1950 and 2016) are contributing to decreased spring flows.	Liniger et al. (2020)
Uttarakhand (1975 to 2019)	The spring discharge has reduced by 50-60% in 28.7% of the total geographical area. Only 2% of the area is under normal discharge conditions, whereas 98% of the area is under the threat of decreasing spring discharge.	Vijhani et al. (2022)
Himachal Pradesh (1981 to 2021)	Using topographic index assumptions it was found that climate parameter was most closely correlated with spring discharge volumes.	Sahu (2023)
Chamoli earthquake (March 29, 1999)	Moderate magnitude earthquake led to changes in flow of ten springs located in regions of higher intensity that show a strong spatial correlation with perturbing pore pressure field induced in the water saturated shallow rocks by the earthquake.	Sarkar and Chander (2002)
Nepal earthquake (2015)	An immediate drying effect in about 18% of the springs in Kathmandu.	Chapagain et al. (2019)
Seismically active zone, Sikkim Himalaya	Few springs dried up following the Mw 6.9 earthquake in 2011 while some springs discharged at a higher rate than before.	Barfal et al. (2022)

*Kumaun Himalaya and Garhwal Himalaya are two sub-divisions of Uttarakhand.

active Himalaya, earthquakes influence hydrology regionally and should be factored into spring rejuvenation strategies.

Spring hydrology and spring water yield

Researchers have investigated spring discharge and groundwater recharge across Uttarakhand and the Himalayas to support better water management. Reported discharge rates range from 0.001 lpm (summer) to 300 lpm (peak flow), with fluvial springs generally yielding more than fracture/joint (Fr/Jt)-related ones (Table 2). Bartarya (1993) reported higher discharge from fluvial springs (mean = 281 lpm) and lowest from colluvial (Coll) ones (5 lpm), due to poor water retention. In Pauri-Garhwal's Dugar-Gad micro-watershed, Negi and Joshi (1996, 2001) found spring discharge (7.8-119.3 lpm peak) accounted for just 0.53-2.94% of annual rainfall. Seasonal springs declined faster than perennial ones. Negi and Joshi (2004) compared two catchments and found Fr/Jt/Coll springs (mean = 6.47 lpm) in Pine-dominated areas discharged twice as much as Fr/Jt springs (3.94 lpm) in Oak-dominated zones, highlighting geology over forest type. Rainfall-discharge correlation was stronger in Fr/Jt/Coll springs (r = 0.595) than in Fr/Jt springs (r = 0.174). Studies on rock types and spring discharge are limited. Agrawal et al. (2012, 2016) reported 0.1-300 lpm flows in phyllite and schist of the Chandpur formation. Bagchi and Singh (2011) and Bagchi et al. (2021) found phyllite springs had consistent flows across seasons, whereas limestone and dolomite springs showed minimal pre-monsoon flow (<0.001-1.39 lpm) and high post-monsoon output (4.92–60 lpm). Quartzite springs had moderate pre-monsoon flow (0.19-54.5 lpm) (Table 2). Other studies in the region have shown spring discharge variations tied to rainfall patterns, such as in Ranichauri (Vashisht and Sharma 2007). Stepwells (Naula) were found to outperform springs (Dhara) in parts of Kumaun (Mehra and Kulkarni 2018), and streams were observed to yield more during lean periods (Kumar et al. 2019). In Sikkim, spring flow variability was linked to rainfall (Rai et al. 1998, Rathi et al. 2020), and predictions suggest up to 50% discharge reduction by 2030 (Vijhani et al. 2022).

A number of other hydrological studies on springs have dwelt into more details on their behaviour. Agrawal et al. (2012, 2016) noted a 1-30 day time lag between precipitation and spring response in Garhwal's Chandrabhaga and Danda watersheds. Kumar and Paramanik (2020) examined recession patterns and storage in Mathamali spring using flow duration curves. Rawat et al. (2019) used ANN models for spring flow prediction in Tehri Garhwal, showing good fit even with limited data. Chauhan and Negi (2023) categorized three Rudraprayag springs as endangered or vulnerable. Kale et al. (2024) emphasized the importance of storing rainwater for sustainable spring use, based on base flow analysis of Fakua spring. Tambe et al. (2012) observed a 50% lean-season discharge decline in drought-prone areas of Sikkim. Kumar et al. (2024) compared three spring types in the Eastern Himalaya and found that depression springs (22 ± 41 lpm) showed higher recharge and evapo-transpiration (ET) sensitivity than fracture or karst types. Unlike Uttarakhand's strong monsoon seasonality, rainfall in Sikkim and Northeast India is more evenly distributed across the year, possibly buffering spring flows. However, such comparisons remain preliminary due to limited data from the Northeast. Spring water yield data remain insufficient for sustainable management conclusions due to varied methods (some summer discharge only, some single measurements). Reported discharge ranges from 0.001 to 300 lpm (Table 2). Many studies lack methodological rigor and ignore spring types, though fluvial and colluvial springs generally discharge more than Fr/Jt springs. Bagchi and Singh (2011) and Bagchi et al. (2021) linked rock types with discharge rates but found no significant variation. Seasonality varies by rock type, but spring structural controls (Coll, Fr/Jt) seem more influential. More research is needed on rock types and structural impacts on discharge.

Methods used for spring hydrological studies

In recent years, isotope techniques have emerged as promising tools for studying spring hydrology and recharge. In the Jhelum River basin (NW Himalaya), Jeelani et al. (2010) analyzed 14 streams and six springs across eight sites, noting substantial spatio-temporal variation in 18O composition. They found dominant snowmelt contribution in May, which shifted to rainfall after snow depletion. Tarafdar et

Table 2. Spring water yield under various geological, LULC and landscape characteristics reported from Uttarakhand and other parts of the Indian Himalayan Region

Description of spring (locality, geology, etc.)	**Mean spring discharge (lpm)**	**Reference**
Gaula river catchment, Central Himalaya. Spring arising from fluvial and colluvial deposits	5-281	Bartarya (1993)
Hill springs of Silkkim. Colluvium-originating springs	5-39	Rai et al. (1998)
5 springs in Dugar-Gad micro-watershed (3 ha area), Pauri-Garhwal. Fr/Jt/Coll and Fr/Jt springs. Only about 10% area under Pine forest	3.4-13.5	Negi and Joshi (1996)
6 springs in two drainage catchments of Pauri-Garhwal. Fr/Jt and Fr/Jt/Coll springs	3.94-6.47	Negi and Joshi (2004)
12 springs in Uttarakhand. Recharge zone having a range of edaphic, topographic and geological characteristics	9.8-105	Negi and Joshi (2004)
103 springs (69 Dhara, 28 Naula and 6 streams) in Almora and Pauri districts	Lean period discharge for Springs: 3-86 Naula: 3.4-57	Kumar et al. (2019)
One spring monitored for eight years in Ranichauri (Tehri Garhwal)	5.5 – 13.1	Vashisht and Sharma (2007)
48 springs in different rock types in Tehri Garhwal		Bagchi and Singh (2011)
(i) Phyllite rock type (22 springs)	Pre-monsoon (0.71-56) Post-monsoon (1.3-57.4)	
(ii) Limestone and Dolomite rock type (9 springs)	Pre-monsoon (0.001-1.39) Post-monsoon (4.92-60)	
(iii) Quartzite rock type (29 springs/streams)	Pre-monsoon (0.19-54.5)	
21 springs in Chandrabhaga and Danda watersheds, Tehri Garhwal. Phyllite and schist rocks of Chandpur formation	Danda springs max = 15-300 min = 0.12-7.5 Chandrabhaga springs max = 10-162 min = 0-1.3	Agrawal et al. (2012)
Chandrabhaga watershed, Tehri Garhwal	0.57-219	Agrawal et al. (2016)
33 springs in Chandrabhaga and Danda watersheds of Uttarakhand	4.5-45.5	Rathi et al. (2020)
Sikkim Himalaya	Lean season and peak discharge: 8 and 51	Tambe et al. (2012)
Eastern Himalaya (three springs)	Depression spring: 22±41 Fracture spring: 15±26 Karst spring: 12±24	Kumar et al. (2024)

al. (2019) used stable isotopes in a Pauri-Garhwal micro-watershed and reported that phreatic groundwater aligned with the local meteoric water line, showing minimal evaporative alteration, indicating rapid recharge and limited shallow aquifer storage. Maurya et al. (2021) observed $\delta^{18}O$ variation over 700 m elevation in the Semalta watershed, Dehradun, with -0.21‰ per 100 m for streams and 0.5‰ for rainwater. Narrow subsurface pathways were observed at higher altitudes, suggesting small recharge structures for low-altitude springs. Using tritium (^3H), Chatterjee et al. (2023) monitored three Pauri-Garhwal springs and found a gradual decline in ^3H, indicating reduced recent rainwater and short residence times (5 months to 1.46 years), suggesting active recharge and high rejuvenation potential. Modelling efforts include Pingale et al. (2013), who used a fuzzy rule-based algorithm to predict weekly spring flow in Tehri Garhwal using climatic variables, showing strong correlation with observed flow at a four-week lag. Mukherjee et al. (2023) analyzed six Jt/Fr and depression springs in the Kosi watershed (Kumaun Himalaya), predicting high-flows via machine learning. A discriminant analysis model using rainfall and electrical conductivity was most effective for spring flow prediction.

Spring recharge zone delineation methods used

Recharge zone delineation, crucial for spring protection and groundwater management, identifies areas contributing water to springs. A springshed - land where rain falls and emerges at a spring - is the appropriate unit. Springsheds integrate watersheds and aquifers in three possible configurations (Shrestha et al. 2018): (i) one watershed-one aquifer, (ii) one watershed–multiple aquifers, or (iii) multiple watersheds–one/more aquifers. Due to Himalayan folding and faulting, springsheds often span multiple watersheds, making their identification essential for integrated surface-groundwater recharge (Valdiya 1997, Shrestha et al. 2018). Various techniques are used for delineation, including geological methods (Shivanna et al. 2008, Bagchi and Singh 2011), LULC change via RS and GIS (Saraf et al. 2000, Rani et al. 2019, Bagchi et al. 2021, Dass et al. 2021, Thakur et al. 2022, Chand et al. 2023, Singh et al. 2024), rainfall vs. spring flow patterns (Jeelani et al. 2010, 2015, 2017), isotope tracing (Bartarya et al. 1995, Jeelani et al. 2010, Kumar et al. 2010, Rawat et al. 2022, Shah et al. 2023), and multi-criteria decision-making (AHP/Fuzzy AHP) using meteorological/topographical indices (Joshi et al. 2024, Nijesh et al. 2024). Chinnasamy et al. (2016) emphasized isotope and chemical analyses to map complex spring pathways and aquifer links. Shivanna et al. (2008) used isotopes, geology, geomorphology, and hydrochemistry in Chamoli's Gaucher area to identify recharge zones for artificial recharge structures. Jeelani et al. (2010) traced spring origins using δ^{18}O in the Liddar watershed. Srivastava et al. (2015) noted isotopic composition in Dehradun's Shahstradhara spring varied by monsoon influence. Jeelani et al. (2010, 2015, 2017) used hydrographs and tracers to reveal that springs in three snow/glacier-dominated basins are recharged mainly via point sources, not diffuse infiltration. Rawat et al. (2022) found higher δ^{18}O variation and spring density in tectonically active zones of the Alaknanda valley, indicating increased permeability and recharge.

RS, GIS, and AHP-based delineation has been key to assessing groundwater potential in the Himalayas. In a micro-catchment of the Kosi watershed, Rani et al. (2019) found 24.1% area had good-to-moderate recharge potential for artificial recharge. Saraf et al. (2000) showed that lineament coincidence with drainage density correlated with spring sites in the Chandrabhaga watershed. Bagchi et al. (2021) used LISS-IV and Cartosat-I data to delineate springsheds in Mussoorie, linking spring potential to high lineament density, gentle slope, and positive NDVI. Singh et al. (2021) used 2D resistivity imaging to locate low-resistivity zones feeding the Gaurikund (Kedarnath) spring. Chand et al. (2023), using AHP and satellite data, identified recharge zones and proposed check dams, trenches, and tanks for NW Himalaya. Singh et al. (2024) used RS and GIS to classify Uttarakhand's groundwater zones into six categories, with 89.9% accuracy. Low-cost hydrogeological methods are also prevalent. Tarafdar (2013) emphasized medium-storage structures to conserve base flow in hard rock aquifers during winter. In the Aglar watershed (Yamuna basin), Kumar and Sen (2018) found 90% of spring discharge data under 23 lpm, indicating characteristic minimum flow for recharge planning. Dass et al. (2021) monitored springs in two Kumaun micro-watersheds, concluding one had better revival potential, validating this approach for the IHR. Joshi et al. (2024), in the Saryu watershed, used AHP/Fuzzy AHP to identify recharge zones and recommend springshed treatment structures. In the Kosi River micro-watershed, Nijesh et al. (2024) used AHP with seven thematic layers to classify groundwater potential into five zones. The best zones, tied to perennial springs, rainfall, porous soils, and forest cover, showed 4.3–30.9 lpm discharge. Poorer zones were linked to barren land, low rainfall, and seasonal springs. These insights help prioritize sustainable development strategies for spring revival at the watershed level.

Spring rejuvenation efforts by R&D organizations

Research pilots across the region have highlighted the importance of harvesting rainwater runoff and promoting soil infiltration to recharge springs. Effective water conservation - using engineering, vegetative, agronomic, or management techniques - must be tailored to geology, land use, topography, and ownership patterns in recharge areas. Several notable pilot-scale rejuvenation efforts have been undertaken by researchers in Uttarakhand (Table 3). As early as 1995, Negi and Joshi (2002), inspired by Valdiya's (1997) "Spring Sanctuary Concept", used bio-engineering and social measures - contour trenches, bunds, mud ponds, plantation of *Alnus, Prunus*, and *Quercus* spp., and restrictions on grazing and quarrying - over 18.5 ha in the Dugar Gad MWs (Pauri-Garhwal). The spring discharge rose from 1055 to 2153 L/d (1995-2000), attributed partly to high rainfall in 2000. Yet, rain water retention in the treated MWs improved from 7.0% to 12.3%, and annual yield rose from 12403 L/day (1994-95) to 30409 L/day (1998-99). In Gauchar (Chamoli), Shivanna et al. (2008) reported increased spring discharge via sub-surface dykes, check bunds, and trenches in recharge zones. Kumar and Paramanik (2020) found flow in Mathamali spring (Garhwal Himalaya) increased 2.6 times post-intervention, with storage duration extended by 16%. In Almora, Panday et al. (2021) enhanced lean-season discharge by 152.4% using rooftop rainwater harvesting, trenching, and *Alnus nepalensis* plantations; rainfall-to-discharge ratios rose from 1.8% (2000) to 7.7% (2018). In two Uttarakhand springsheds, spring discharge rose from 4.2 to 8.5 lpm (Sonarkot) and 96.7 to 133.4 lpm (Than) post-intervention (Sinha 2022). In Kangra (H.P.), Rawal et al. (2024) reported groundwater level increases of 32 cm and 23 cm in the recharge zones of two bowries. In the Sikkim Himalaya, Tambe et al. (2012) revived five springs using springshed development techniques, raising lean season discharge from 4.4 to 14.4 lpm.

Given the region's complex hydrogeology and groundwater decline, replenishing aquifers is critical for long-term water security. Spring rejuvenation offers a climate-resilient solution aligned with multiple SDGs (Anonymous 2018a). Bagchi and Singh (2011) recommended gully plugs, contour/nala bunds, check dams, and contour trenches to recharge shallow aquifers. Shrestha et al. (2018) proposed a Six Step Methodology integrating hydrogeology, socio-economics, and governance for broad stakeholder adoption. Engineering techniques include: (i) small dug-out ponds in depressions (Anonymous 2017b, 2021); (ii) inward terraces guiding runoff uphill; (iii) contour trenches with vegetated berms; (iv) semi-circular bunds/eyebrow pits with mulch; (v) triangular snow pits; and (vi) check dams with vegetative reinforcements to curb erosion. Vegetative methods include: (i) afforestation using water-efficient, undergrowth-supporting species; (ii) contour hedgerows and Sloping Agriculture Land Technology, SALT (Panwar et al. 2017) to create terraced croplands; (iii) palisades using live cuttings planted across slopes; and (iv) brush layering with soil between woody cuttings to enhance infiltration (Agrawal and Rikhari 1998). However, a plant species list specific to Uttarakhand's agro-climatic zones is still needed, as current suggestions are too generic.

Notable efforts on spring rejuvenation by Government Departments and NGOs

In recent decades, NGOs, government agencies, and local communities have actively addressed drying springs and springshed management across Uttarakhand and Himalaya, which has been summarized as follows:

(i) Since 2002, Tata Trusts' Himmotthan Pariyojana (tatatrusts.org) has restored recharge zones of 800+ springs and trained para-hydrogeologists, benefiting 400 villages. Spring discharge increased by 15–130% (avg. 2.44±0.33 lpm) during lean seasons. In Chureddhar (Tehri Garhwal), discharge rose 17% after periodic de-siltation of trenches and ponds (himmotthan.org).

(ii) WAPCOS (Anonymous 2022c) implemented interventions across eight hilly districts, yielding reduced surface flow (7.1%), improved lateral flow (0.9%), aquifer recharge (9%), and stream baseflow (8.4%) from 2014 to 2021.

(iii) CHIRAG (Nainital) created a "Spring Atlas of Uttarakhand" (Mehra and Kulkarni 2018) with an inventory of 948 springs and recharge plans for 10 Naulas. Treatment from 2013–2017 boosted discharge in 6 Naulas (avg. 5.4 lpm) and 4 springs (avg. 3.5 lpm).

(iv) PSI, Dehradun, has revived 400+ springs region-

Table 3. Spring rejuvenation work carried out by R&D organizations in Uttarakhand and the IHR

Study area / Salient methodology	Results / Impacts	Reference
An experiment to increase spring discharge with simple ecotechnology employing bio-engineering measures (spring sanctuary development) in the recharge zone of a nearly extinct spring in Pauri-Garhwal during 1995-2000.	In the years following the interventions, water discharge increased from 1055 to 2153 L/day. Though much of this increase was probably because of above-average rainfall in the dry season of 2000, but the water retention (as % of the rainfall) increased from 7.0-12.5% thereby increasing the annual water yield of the spring from 12.4-34.4 x 10^3 m^3/yr.	Negi and Joshi (2002)
In Gaucher (Chamoli) environmental isotope technique was employed to identify the recharge areas of springs in order to construct artificial recharge structures for rainwater harvesting and groundwater augmentation for their rejuvenation.	Based on local geology, geomorphology, hydrochemistry and isotope information, the possible recharge areas were located. Water recharge structures such as subsurface dykes, check bunds and contour trenches were constructed at the identified recharge areas. The spring discharge not only increased significantly, but springs also did not dry up during the dry period.	Shivanna et al. (2008)
Study taken up in Sikkim Himalaya	The springshed development approach to revive 5 springs using rainwater harvesting and geohydrology techniques resulted into increase in the lean period discharge from 4.4 to 14.4 L/min in 2010-2011.	Tambe et al. (2012)
In a contact and fracture type Mathamali spring, Aglar watershed (Garhwal Himalaya) springshed interventions (like contour trenches, percolation pits along with plantation of broom grass and native fodder species) were carried out by the Indian IIT, Roorkee with PSI, Dehradun.	The average flow of 16.9 lpm before interventions in early April 2017 was increased by 2.6 times. The minimum average spring flow (2.3 lpm) increased by 5 times whereas the average maximum flow increased by 1.8 times. Post-intervention, storage duration has increased by 16%, decreasing from 143 lpm (peak flow) to 12.7 lpm (baseflow).	Kumar and Paramanik (2020)
Six gravity springs and spring sheds selected at Mussoorie Hills, Garhwal Himalaya spring rejuvenation. LISS-IV and Cartosat-I data used to study topography, delineate springshed boundary, analyzing structural setting, surface water flow pattern.	The high lineament density, gentle slope and positive NDVI determined the springsheds potential for groundwater resources augmentation and development. This technology can be adopted elsewhere in the steep mountainous terrains of the Himalayan region.	Bagchi et al. (2021)
A spring of which discharge was reduced heavily selected for revival and to enhance discharge by harvesting rooftop and runoff water in trenches and planting of broad leaf species *Alnus nepalensis* on trench risers in Almora.	The average annual discharge increased by 118.9% and in 2019 (147.8%) compared to discharge (794.0 m^3/yr) recorded in 2000 before the treatment. Similarly, lean period (October–June) average discharge enhanced by 117.8% and for 2018–19 it enhanced by 152.4% compared to discharge (500.7 m^3/yr) recorded in 2000 before the treatment. The discharge to percent rainfall was lowest (1.8%) in year 2000 however, after treatment it increased from 3.6% in 2006 to 7.7% in 2018. Hence, it can be recommended that rooftop water and runoff harvested in trenches with broad leaves plantation can enhance discharge of water in springs.	Panday et al. (2021)
Two springs were selected for discharge revival during 2021-2022 in Kangra (H.P.).	In the Bhatlahru region, the water level in the *boweris* rose from 127 to 159 cm, whereas in the Salol region, a rise from 119 to 142 cm was observed during the dry seasons as a result of recharge structures constructed.	Rawal et al. (2024)

wide. In Sirmour (H.P.), discharge in Luhali spring rose 2.5 times from 2012-2015, despite 2.8x lower rainfall. Between 2018 and 2021, PSI rejuvenated 13 springs via desiltation and replantation, increasing discharge by 40%. Their regeneration of 100 critical springs (2017-21) saw consistent gains (Anonymous 2021-22).

(v) Himalayan Gram Vikas Samiti has focused on drinking water in 75 border villages of Pithoragarh district (Dainik Jagran, 31 March 2022).

(vi) Himalaya Sewa Sangh and Himalaya Consortia, with 45 women SHGs in 24 Garhwal villages, rejuvenated 14 springs serving 500 households (Sahay et al. 2019).

(vii) The Uttarakhand Forest Department reforested 697 ha of the Heval River catchment (25466 ha) Tehri, covering 66 springs and 17 streams, boosting groundwater by 86.6 million litres and raising discharge in 23 springs (Upadhyay 2021).

(viii) Sikkim's Dhara Vikas program revived 50 springs, raising discharge by 1.5-5 times in six springs (2010-11) (Anonymous 2018a).

(ix) ICIMOD (Kathmandu) took up springshed work in Uttarakhand in 2021 to improve water security.

(x) IUCN also launched a pilot with CHIRAG (Nainital) support.

(xi) Uttarakhand Forest Department partnered with UNDP on springshed management. Many other groups and individuals contribute to spring rejuvenation, though their work often lacks documentation and academic recognition (Pant et al. 2024). Field-based insights from such efforts remain under-represented in scientific literature.

DISCUSSION

This review summarizes over four decades of R&D on spring hydrology and rejuvenation in Uttarakhand and the broader IHR, highlighting key gaps for R&D organizations. The literature shows limited studies on spring typology based on geology (Valdiya and Bartarya 1989) and classification by discharge (Meinzer 1923), which provide a foundation for future work. For instance, Rathi et al. (2020) found most springs in two Uttarakhand watersheds fall in Meinzer's 6th and 7th class orders, with flow rates of 6.5-65.5 and 0.5-6.5 m^3/day. The interaction of precipitation, geology/topography, and forest cover influencing spring origin, discharge, and hydrological cycles needs thorough investigation. Early reports on spring drying relied mainly on anecdotal evidence, with only a few long-term studies empirically linking drying to natural and human factors (see Table 1). Causes like rising temperature-induced ET, loss of watershed sponge function, Hortonian runoff, saturation overland flow (Dunne type), and drivers shifting perennial springs to seasonal ones remain understudied. Further, ET may vary from one method to the other (Bhat et al. 2017). There is limited understanding of LULC effects on infiltration and recharge. For example, runoff studies comparing agroforestry (AF) and degraded land (DE) in Garhwal hills at similar rainfall intensities showed higher infiltration and lower runoff in AF plots (Nanda et al. 2018). Hortonian flow dominated since only topsoil layers saturated, indicating the need for detailed eco-hydrological studies, supported by modelling and remote sensing (RS), to optimize headwater treatments and groundwater augmentation under climate change. The effects of earthquakes on spring flows are poorly understood, with reports of both drying (Chapagain et al. 2019) and discharge increase (Barfal et al. 2022).

The Himalaya, especially Uttarakhand, experience moderate to severe forest fires each pre-monsoon summer. Almost no studies examine how forest fires affect mountain watersheds' rainwater storage capacity, especially under high-intensity rainfall, which risks storm runoff and soil loss (Negi 2018). Fires alter soil water repellence and macropore structure, creating hydrophobic layers or soil sealing that increase peak and storm flows but reduces baseflows (Scott and Schulze 1992, Bart and Tague 2017). Pine trees, which demand high amounts of water, hinder native plant regeneration and contribute to more fires (Dobriyal and Bijalwan 2017). Given the dramatic increase in forest fires (from 922 in 2002 to 41,600 in 2019) correlated with rising atmospheric temperatures (Mina et al. 2023), research on forest fire impacts on spring drying and water crises is urgently needed. The role of springs in supporting forest biodiversity and ecosystem services such as water quality regulation is critical yet poorly understood (Paudyal et al. 2015). Rising water demand from population growth and non-consumptive uses (tourism, urbanization, industries) has led to over extraction of springs and groundwater (Madan and Rawat 2000), necessitating research on water resource carrying capacity.

The choice of vegetation in springshed treatment is yet unclear

Vegetation affects the hydrological cycle by intercepting rainfall, reducing raindrop velocity, and enhancing infiltration, which recharges springs (Dunne et al. 1991). In Uttarakhand, the debate over plantations (broadleaf vs. conifers) for springshed management remains unresolved. Preliminary studies show higher infiltration and forest floor interception in broadleaf forests (Sal, Oak, Horse Chestnut) compared to conifers (Chir Pine, Silver fir) (Negi et al. 1998). Liniger et al. (2020) reported a 30% dry season spring discharge increase by protecting broadleaf and mixed Oak/Pine forests, whereas degraded Pine forests yielded much less. Whether forests consume more water than grasslands is a key unresolved question (Madani et al. 2018). Research from Nepal (Gilmour et al. 1987) suggests forestation of grazed grasslands improves soil water absorption. Vegetation cover must increase to enhance infiltration and groundwater recharge. Deforestation accelerates erosion, land degradation, and reduces dry season flows (Bruijnzeel and Bremmer 1989). Climate change impacts, with Himalaya warming faster than the global average (Shrestha et al. 2012) and fewer wet days at 1000-2500 m asl (Ballav et al. 2021, Verma and Jamwal 2022), plus increased extreme rainfall events (Mishra 2017, Alam et al. 2018), may increase runoff and reduce recharge (Shrestha et al. 2012). Lag time between rainfall and spring peak flow indicates water transit speed, influenced by aquifer geology, porosity, permeability, and fractures. Modelling in Uttarakhand shows daily lag times of 1-30 days and monthly lag up to 60 days, indicating rapid spring response and proximity to watersheds. Positive storage and homogenous aquifers suggest good potential for management and revival (Dass et al. 2021). More spring typology-based studies are needed to determine lag periods and treatment impacts on lean season flow. Models using ANN, fuzzy algorithms, discriminant classifiers, and predictors like rainfall and conductivity show promise in predicting flows in data-scarce areas (Pingale et al. 2013, Rawat et al. 2019, Mukherjee et al. 2023), saving time and effort in rugged terrain, and merit promotion in R&D.

Methods/techniques used for recharge zone delineation

RS / GIS, and environmental isotopes (Oxygen-18, Hydrogen) are more commonly used than intensive geological fieldwork or rainfall vs. flow pattern analysis. Satellite hydrological and meteorological data combined with springshed monitoring have improved spring condition understanding and management (Shukla and Sen 2021). Stable isotopes are vital for recharge zone delineation and water origin tracing. Studies using Oxygen-18 and Tritium indicate shallow aquifers have rapid recharge and limited storage, synchronized with seasonal rainfall, and short residence times (5 months to 1.46 years) indicating active recharge and good renewal potential (Jeelani et al. 2010, Tarafdar et al. 2019, Chatterjee et al. 2023). More isotope studies are needed to support recharge interventions enhancing spring resilience (Matheswaran et al. 2019). Techniques like tracers, vertical electrical sounding, and audio magnetotelluric remain underutilized here (Shah et al. 2017, Simpen et al. 2025). Thus, field geology supplemented by stable isotopes can better define recharge pathways and aquifer capacity. Although isotope analysis is available in many R&D labs, its cost and time remain challenges (Dhakal et al. 2014). Therefore, combined geo-hydrological, RS and GIS studies remain the primary scalable methods due to local geological heterogeneity.

Treatment measures in the spring recharge zone are based on inadequate knowledge

Applying geo-hydrological knowledge to recharge aquifers and augment spring water through bio-engineering in springshed treatments is a key R&D outcome addressing drying springs and lean season water availability. In the recent years two popular Himalayan protocols are (i) ICIMOD's "Six Step Methodology" integrating hydrogeology and socio-economic governance (Shrestha et al. 2018), and (ii)

Sikkim's "Dhara Vikas Handbook" based on extensive spring recharge work (Tambe et al. 2011). Kulkarni et al. (2021) advocate an aquifer-based springshed approach blending science and community participation. Earlier, Valdiya (1997) proposed the "Spring Sanctuary" concept emphasizing reforestation, suitable land use, and community engagement, piloted successfully in Pauri-Garhwal, doubling water yield in drying springs (Negi and Joshi 2002). Despite these protocols, no concrete recommendations exist on suitable tree/plant species for recharge zones. In Uttarakhand, Oak (*Quercus* spp.), Alder (*Alnus nepalensis*) and a few other broadleaf species are commonly promoted for water conservation based on traditional knowledge linked to their natural proximity to water sources and moist soils (Upadhyay 2020). Deep-rooted species with high leaf area indices may consume more water, but limited data on their ET demand exist. Evapo-transpiration (ET), a key hydrological component linking soil, vegetation, and atmosphere, accounts for over half of terrestrial water loss (Novak 2012). Studies report Potential ET (PET) ranging 0.84-3.74 mm/day depending on species and season in Tehri Garhwal (Semalty et al. 2011). Pine's (3.74 mm/day) marginally higher PET than Oak (3.31 mm/day) in June may increase fire vulnerability. Other studies report similar ET ranges for Sal forests (Jana et al. 2016, Purohit et al. 2021). Oak, often recommended for recharge zones, has high water demand due to deep roots (Upadhyay 2020). For example, Ozcelik and Sengonul (2021) found Oak transpiration thrice that of Anatolian Black Pine. Nepal's central Himalaya study (Ghimire et al. 2014) reports lower annual transpiration from Alder than Pine. However, recent studies in Uttarakhand show that Pine has higher ET than Oak (Mohanty et al. 2025, Unpublished work of authors). Thus, promoting vegetation for recharge zone management requires careful water balance studies and ET quantification. Planting exotic species like *Eucalyptus* in springsheds can deplete water resources and should be avoided (Tambe et al. 2011).

The uncertainty around ET losses from Oak and Pine forests in Uttarakhand remains unresolved, highlighting the need for focused research. Additionally, large-scale afforestation on barren lands, if not guided by geo-scientific principles, can disrupt the hydrological balance and trigger landslides (van Dijk et al. 2012). While grasses are often recommended along trenches in spring recharge zones, no definitive list exists. Mandal et al. (2017) identified hybrid Napier (*Pennisetum purpureum*), sambuta (*Saccharum munja*), and broom grass (*Thysanolaena maxima*) as effective for water retention and soil conservation in the Himalayas. Sudhishri et al. (2008) showed sambuta and vetiver (*Vetiveria zizanioides*) grasses reduced runoff and soil loss by over 60%, with sambuta scoring highest on performance metrics. Sundriyal (2003) recommended *Flemingia macrophylla*, *Desmodium rensonii* and *Indigofera anil* as hedgerows for terrace risers in the Northeastern Himalaya. More research on native grasses and shrubs is essential to enhance rainwater retention, reduce erosion, and improve groundwater infiltration in recharge zones. Similarly, the actual impact and cost-effectiveness of springshed treatment measures like trenches, recharge pits and plantations on spring water yield must be evaluated to support policy decisions. Madhusoodanan (2023) proposed recharging aquifers by directing rooftop runoff through graded filters (sand, charcoal, gravel) into defunct hand pumps. In Uttarakhand, around 2,000 non-functional Mark-II hand pumps, originally installed to access deep aquifers, could be repurposed. As rooftop runoff can capture 80–90% of rainfall, this method shows potential, though its effects on water quality and long-term viability need further study.

The spring rejuvenation efforts in the region have mostly focused on springshed treatment and bioengineering measures but lack technical precision due to poor baseline hydrological data and site-specific recharge zone knowledge (Negi and Joshi 2002). Many employ geo-hydrological principles without isotope or hydrometric data. Other artificial recharge methods in this region are yet to be tried and popularized (Anonymous 2022b). However, spring rejuvenation efforts in Uttarakhand have shown that combining soil and water conservation, vegetation management, and community participation can improve lean season flows (see Table 3). Technical innovations include subsurface recharge through trenches, percolation pits, and check dams (Paudyal et al. 2015), although their effectiveness depends on local geology and rainfall patterns. Lack of detailed monitoring and impact assessment hampers scaling up (Pandey et al. 2021). A key challenge is promoting multidisciplinary approaches combining hydrogeology, forestry, social science, and participatory governance for sustainable spring water management.

Springshed interventions mostly lack clear evidence of impacts

Considering the above issues and knowledge gaps, Rai (2018), citing Sandeep Tambe's springshed rejuvenation work in Sikkim (Tambe et al. 2012), pointed out that "An upcoming study by Azhoni and Goyal (2018) raises concern over the lack of data supporting claims that spring rejuvenation improved water availability in Sikkim". Nowreen et al. (2023) acknowledge that the Six-Step Protocol of springshed management (Shrestha et al. 2018) and related approaches show more promising results. However, Sikkim communities questioned their efficacy due to improper execution. Also, detailed scientific evaluations of these interventions' effects on spring discharge are lacking (Azhoni and Goyal 2018). Often, NGOs' efforts remain unpublished and absent from academic discourse. Therefore, there is a strong need to build capacity in extension agencies involved in springshed management on geo-hydrological mapping, recharge zone delineation, locating suitable bio-engineering measures, monitoring spring water yield, water quality, and other management co-benefits and sustainability issues (Gosavi et al. 2021). NGOs like CHIRAG, Himmotthan, PSI, etc. in Uttarakhand have developed "Para-Hydrologists" to fill this gap in their areas. Frequently, bio-engineering measures applied are inappropriate for unskilled field workers. Documentation, data recording, and synthesis are also critical for replicating spring rejuvenation efforts elsewhere. Strong partnerships among government departments, R&D organizations, and NGOs working on this vital issue in Uttarakhand and the Himalayan region are urgently needed to build synergy and ensure success. Additionally, incentive-based mechanisms must be devised to translate research into action. Recently, to rejuvenate springs and rivers through bio-engineering, the Government of Uttarakhand formed the "Spring and River Rejuvenation Authority (SARRA)" in November 2023, expected to coordinate all stakeholder efforts and lead these initiatives (www.wmduk.gov.in).

WAY FORWARD

Globally, springs have been data deficient and overlooked compared to rivers, streams, lakes, wetlands, and groundwater. In the Himalayas, the hydrogeology governing mountain aquifers is poorly understood, causing misconceptions about springs and misaligned policies that worsen problems (Shrestha et al. 2018). An integrated empirical and analytical approach is needed to strengthen spring hydrology knowledge (Nisa and Umar 2024). Lack of discharge, climate, geological, and land use data makes problem assessment and solution development difficult (Panwar 2020). Gyawali and Wahid (2015) emphasized using advanced scientific methods - tracer studies, geological drilling, and modelling at the micro-watershed level - to link local hydrogeology, recharge structures, water augmentation, and social science aspects like water use and policy. However, the vast heterogeneity in topography, land use, geology, etc., makes such methods often unfeasible. Tambe et al. (2012) identified major springshed challenges: accurate recharge area identification, local capacity building, incentivizing rainwater harvesting, and recommended integrating springshed management into watershed development, rural water supply, and climate adaptation programs in the Himalayas. A critical lack of comprehensive data exists, as most studies are small-scale and focus primarily on hydrology with little on ecological, socio-economic, and developmental aspects (Verma and Jamwal 2022). It has been pointed out that climate change and anthropogenic impacts will increase, urging regional scientific studies on hydro-geochemical evolution, vulnerability, and recharge dynamics for springshed management development (Panwar 2020). Pant et al. (2024) stressed capacity building and knowledge transfer, including training hydro geologists, mapping recharge areas, and sustainable land use to combat declining spring discharge through transdisciplinary, community-centric approaches that support policymakers, researchers, and practitioners, fostering public-private partnerships (PPP) for large-scale spring rejuvenation, a rising water management strategy (Lima et al. 2021). Documenting spring revival initiatives' origins in India, Kumar et al. (2023) noted insufficient rigorous documentation of their effectiveness. They recommended integrating scientific and social governance analyses to improve spring recharge. Springshed management encompasses water management from hydrology to natural resource governance. Hamilton (1985) warned hydrological research suffers from "The 4 Ms: myth, misunderstanding, misinterpretation, and misinformation." Spring water results from "complex ecosystem functions" needing a multi-dimensional approach integrating Science-Policy-Practice (Negi et al. 1998). Better demand-supply management, institutional convergence, capacity building, and empowered communities are keys to a new springshed management paradigm in India (Dhawan 2015). Traditional knowledge and beliefs conserving water sources through generations in the Himalayas should also be respected (Juliet 2018).

In a recent Uttarakhand state-level conference on spring's knowledge, pertinent questions raised were (Negi et al. 2025): (i) What is known about broadleaf vs. conifer forests (particularly Oak vs. Pine) in water conservation and the belief that Oak aids recharge while Pine dries sources? (ii) Does neo-tectonic activity destabilize groundwater, causing drying or sometimes increased spring flow? (iii) What key geo-hydrological factors govern groundwater potential for spring augmentation in Uttarakhand? (iv) Which land use, geology, topography, and soil structures best enhance rainwater percolation, recharge, and spring yield? (v) Does climate change–induced intense rainfall exceed soil absorption capacity, causing runoff (Horton vs. Dunne types), erosion, and floods? (vi) Does global warming increase ET from forests, depleting soil moisture and perched water tables? (vii) What proportion of rainwater is lost to evaporation or deep percolation, not captured in spring/stream flow? (viii) Is there adequate meteorological data collection and access for water resource planning? (ix) What is the impact of artificial recharge structures (contour trenches, gully plugs, field bunds, recharge wells) on micro-watershed water retention and downstream spring flow? (x) What challenges hinder rural participation in water conservation, and how can they be overcome?

To sum up (i) Strong linkages must be established among State Government Line Departments, R&D organizations, universities, NGOs, and agencies working on mountain springs to strengthen the Science-Policy-Practice interface; (ii) Scientific documentation of "Best Practices" for drying spring rejuvenation and traditional water management knowledge should be scaled through state bodies like SARRA, Watershed Management Directorate, and water supply agencies; (iii) A multi-disciplinary, multi-location, multi-institutional R&D consortium project should be developed with leading experts, organizations, and extension agencies to address Uttarakhand springs' knowledge gaps and submitted for funding support to agencies such as SARRA, Govt. of Uttarakhand, National Mission on Himalayan Studies, MoEF&CC, Government of India, etc.

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