Ecohydrological and Hydrogeological Investigations in Groundwater Springs of Eastern Himalaya, India

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Research paper

Ecohydrological and hydrogeological dynamics of groundwater springs in Eastern Himalaya, India

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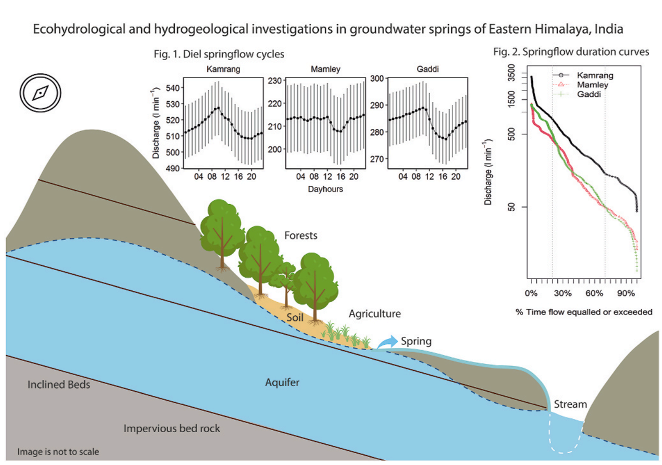
HIGHLIGHTS

- Characterising precipitation-discharge relationships in Eastern Himalayan springs.
- Evidence of more than one aquifer governing a single spring discharge.
- Significant diel springflow cycles induced by evapotranspiration and hydrogeology.
- Future precipitation intensification will reduce net recharge to spring aquifers.
- Karst and Depression springs are vulnerable to climate and land-use change.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater springs are critical to achieving Sustainable Development Goals (SDG 6, access to clean water) in the Himalaya and remain highly vulnerable to climate change and land-use and land cover change. In a first from Eastern Himalaya, we analysed the relative controls of land-use, precipitation, soil properties, and hydrogeology on the diel and seasonal variability in three representative springs using high-frequency discharge monitoring. Kamrang spring is a high-discharge depression spring fed by a homogenous aquifer, whereas Mamley and Gaddi show dual-flow characteristics attributed to primary matrix-based flows and secondary conduit (karst) or

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Ecohydrology
Sustainable development goals (SDGs)

unconsolidated storage-based flows, respectively. The first reports of strong diel fluctuations in springflows show significantly higher amplitude in the depression spring (22 ± 41 l min^{-1}) than the fracture (15 ± 26 l min^{-1}) and karst springs (12 ± 24 l min^{-1}), attributed to evapotranspiration and hydrogeology, respectively. The forest spring (Gaddi, low soil hydraulic conductivity, K_{sat}) showed a faster response at intense precipitation (>30 mm h^{-1}), whereas the agriculture springs (Kamrang and Mamley, high K_{sat}) showed the lowest lags at low-moderate intensities (<20 mm h^{-1}). The depression spring showed high recharge potential, whereas the karst and fracture springs were constrained by their relatively smaller recharge area and low K_{sat}, respectively. The per capita daily water availability was barely sufficient to support the minimum (20 l) and mandated (55 l) requirements for 30–70% and 2–47% of days a year, respectively. Thus, future precipitation intensification and land-use change will disproportionately impact the >5th-order karst and fracture springs. The study provides an integrated analytical framework for understanding Himalayan springs, which are critical for achieving SDG 6 (access to clean water) and a baseline for developing appropriate springshed models for effective management of freshwater ecosystems (SDG 15) against future climate change impacts (SDG 13), as well as informing the water security assessment in the Himalaya.

Abbreviations

ACF	Auto-correlation coefficient
AWS	Automatic weather station
EC	Emerging contaminants
FDC	Flow duration curve
GoI	Government of India
GPU	Gram Panchayat unit
LAI	Leaf area index
LULC	Land-use and land cover
lpcd	Litres per capita per day
masl	Meters above sea level
MODIS	Moderate Resolution Imaging Spectroradiometer
RMDD	Rural Management and Development Department
SDG	Sustainable Development Goals
VDAP	Village Development Action Plans

1. Introduction

Long-term sustainability and management of critical water resources is the cornerstone of the Sustainable Development Goals (SDGs), which aim to provide access to clean water and sanitation (SDG 6) through sustainable management of terrestrial ecosystems and their services (SDG 15) against climate change impacts (SDG 13) (United Nations, 2015). However, groundwater remains markedly underrepresented in the SDG guiding frameworks despite constituting up to 97% of globally available freshwater and the primary water resource in the tropics (Guppy et al., 2018). In high tropical mountains, groundwater springs are the principal water resource for 60–90% of the population (NITI Aayog, 2018a; Salas-Navarro et al., 2019; Verma and Jamwal, 2022). Predominantly occurring at places where surface topology crosses the groundwater table, montane springs are inherently complex groundwater-dependent systems equally governed by groundwater/-aquifer properties, geomorphology and surface land-use and land cover (LULC) properties (Cantonati et al., 2020; Trcek and Zojer, 2009; White, 2019). The ecohydrological interactions between land surface and groundwater springs are further accentuated in geologically diverse mountains such as the Himalaya (Buono et al., 2015; Mahamuni and Kulkarni, 2012; Somers and McKenzie, 2020). However, hydrological research in the Himalaya and other tropical mountains remains disproportionately focused on glacial retreat, snowmelt decline, and its potential impacts on flows in the major rivers (Bajracharya et al., 2015; Maurya et al., 2018), and fewer studies have looked at the groundwater springs and headwater streams, and their contributions to higher-order river flows (Hassenruck-Gudipati et al., 2023; Kumar et al., 2024b (Andermann et al., 2012)).

Kresic (2010) classified groundwater springs based on discharge rate, hydraulic head (artesian or gravity-based), geomorphological, and water quality, while Springer and Stevens (2009) added several other parameters, including habitation, biota present, management, and spring usage. Based on the geomorphological conditions dominating the groundwater outflow, Himalayan springs can be classified into four principal typologies: (a) A depression spring originates at the lower end of unconsolidated sediments with loose debris, soil, and loose rocks; (b) A fracture spring originates from a single or set of fractures, which impede groundwater movement and cause the spring origin; (c) A contact spring originates at the contact point of two different lithologies with an upper porous and lower impervious layers, and (d) A karst spring originates out of karstic features in carbonate-rocks (Daniel et al., 2021; Mahamuni and Kulkarni, 2012; Valdiya and Bartarya, 1991). The typological classification uses hyper-local geological information to assess structural features dominating the spring and provide a qualitative understanding of key aquifer properties, i.e. transmissivity and storativity (Shrestha et al., 2018; Siddique et al., 2019). Storativity is the drainable porosity of an aquifer and indicates its size as well as the temporal longevity of the spring. Transmissivity quantifies the permeability of an unconfined aquifer and governs the magnitude of spring discharge (Kulkarni et al., 2021; Manga, 1999; Tambe et al., 2020). The typological classification can also be *a priori* indicative of spring behaviour and patterns. For example, a karst or depression spring may show a flashier response to precipitation than a fracture or contact spring (Kresic, 2010), whereas a depression spring with a vertically shallower aquifer may be more affected by LULC changes than a fracture spring with a deep-seated aquifer (Mahamuni and Kulkarni, 2013).

Based on the morphology of the outlet and access mechanism, springs can be commonly divided into free-flowing springs known as *Dhara*, shallow seepage-based step-wells known as *Naula*, and at places, even first-order streams are also categorized as springs (known as *Khola or Gaad*) (Pant and Rawat, 2015; Singh and Pant, 2018; Springer and Stevens, 2009). It is important to note here that springs are novel and unique in being completely dependent on groundwater and differ significantly from headwater streams. For example, springs are more influenced by local hydrogeology and precipitation (Kulkarni and Mahamuni, 2013; Tambe et al., 2020), whereas streams are governed by larger-scale controls of vegetation, precipitation regime, and edaphic factors (Asbjornsen et al., 2011; Kumar et al., 2024a, 2024b). Similarly, the temporal response of springflows to precipitation varies significantly from that of streams (Agarwal et al., 2012; Kumar and Sen, 2018a). Under ideal conditions, springflow will not have any surface runoff contributions (Kresic and Bonacci, 2010), whereas streams may receive inputs from both the surface and sub-surface components, including upstream springs (Kumar et al., 2024a; Miranda, 2016) and ground-water systems (Andermann et al., 2012; Beal et al., 2020; Hassenruck-Gudipati et al., 2023). However, despite being groundwater-dependent, springs are heavily influenced by land-use, soil characteristics, and hyperlocal hydrogeological features such as fractures, sink-holes, and soil macropores (Buono et al., 2015; Dass et al., 2021a; Wittenberg et al., 2019). In turn, the physiochemical and discharge characteristics of springs can heavily influence their aquatic biodiversity (Bhat et al., 2021; Chauhan and Sharma, 2015; Kuotsu et al., 2022; van der Kamp, 1995), ability to transport pollutants and the presence or absence of emerging contaminants (ECs) such as microplastics (Yanuar et al., 2024). Despite the recent push for household-level water distribution infrastructure, the *dhara*, *naula,* and headwater streams remain the preferred source of water for drinking for their perceived higher quality and taste and for domestic and agricultural use in more than 90% of Himalayan communities and 20% of communities in entire India (NITI Aayog, 2018a,b; Kumar et al., 2023b). Although quantitative evidence is limited, recent decades have seen a widespread public perception of declining springs and their dry season discharge in the Himalaya (Kumar et al., 2023b; Pandit et al., 2024; Panwar, 2020), which has affected water availability and agricultural productivity in the Himalaya (Rana and Gupta, 2009; Scott et al., 2019; Verma and Jamwal, 2022).

Kumar et al. (2023b) describe three major paradigms in the research on Himalayan springs, including the preliminary work geochemistry of cold and geothermal (hot) springs to understand regional geology (Choubey et al., 2000; Ghosh, 1948; Mishra, 1984), followed by watershed hydrology research (Datta and Virgo, 1998; Joshi, 2004) and the spring-sanctuary model, which linked the decline in spring discharge and numbers to precipitation and land-use changes, declining forests, and increasing urbanization (Negi and Joshi, 2002, 2004), but failed to account for the role of aquifers and sub-surface hydrogeology (Joshi, 2006; Kumar et al., 2023b). Later, research focus shifted from the surface hydrology approach to aquifers as the unit of investigation for understanding springs using multiple methods such as hydrogeological, electrical resistivity and electromagnetic surveys (Gentry and Burbey, 2004; Zhang et al., 2013), water chemistry (Jeelani et al., 2015; Kumar et al., 2020), and isotope techniques (Rawat et al., 2022; Shivanna et al., 2008; Tambe et al., 2020). The hydrogeological approach has led to numerous spring-revival or springshed management efforts across Himalaya, including hydrogeological mapping by trained para-hydrogeologists to delineate 'springsheds', i.e., a combination of the watershed and underlying aquifer systems, identifying their recharge areas, carrying out soil and water conservation activities such as check-dams, trenches, and percolation pits, alongside reforestation, and discharge and quality monitoring, with community ownership at its centre (Kumar et al., 2023b; Shrestha et al., 2018; Siddique et al., 2019). Springshed research has used water chemistry and natural isotope-based methods to quantify the relative contribution of precipitation to discharge, illustrate hydrogeological pathways, identify potential recharge areas, and delineate the aquifer boundaries (Bhat et al., 2022; Tambe et al., 2020). Studies based on the spring hydrology approach, which focuses on quantifying aquifer properties through discharge analysis, are relatively scarce and remain heavily influenced by stream hydrology, especially low-flow hydrology (Agarwal et al., 2012; Kumar and Sen, 2018b). The last decade has seen a surge in spring potential mapping research using deep learning and computing tools to quantify the number of springs in a region through proxy association with geology, land-use and topography, but are limited by the complex Himalayan terrain and lack of ground occurrence data, and are unable to distinguish spring typologies (Ghimire et al., 2019; Pathak et al., 2021).

Despite the increased attention on groundwater springs in the Himalaya, four critical knowledge gaps remain unaddressed:

(1) Lack of high-frequency data on springs- The majority of the discharge-based studies on Himalayan springs are based on seasonal (Parmar et al., 2016; Valdiya and Bartarya, 1991), monthly (Mukherjee et al., 2023), weekly (Bartnik and Moniewski, 2019; Soulsby et al., 1999), daily resolution (Agarwal et al., 2012; Kumar and Sen, 2018b; Negi and Joshi, 2004; Rathi et al., 2020), and very few have analysed spring behaviour using high-frequency (sub-hourly) datasets (Dass et al., 2021a, 2021b). Thus, fewer studies have investigated diurnal or diel variations in springflows (Chicken et al., 2007; Springer et al., 2008), even globally.
(2) Lack of studies comparing spring behaviour and aquifer properties across typologies –Fewer studies have quantified the aquifer properties, i.e. transmissivity and storativity, of springs due to the scarcity of fine-resolution data (Kumar et al., 2023b; Shrestha et al., 2018). In conventional groundwater studies, well-based pump-tests and continuous water-level monitoring are used to estimate aquifer transmissivity and storativity. However, pump-tests are challenging to perform on springs due to the free-flowing nature of the *dhara* and the small sizes of the step-well-like *naula*, and most studies are restricted to manual discharge measurements using the bucket or floatation methods (for *dhara* and *khola*) or level-drop methods (for *naula*) (Pandit et al., 2024). Further, few studies have quantified net recharge to spring aquifer using discharge analysis (Dass et al., 2021b; Kumar and Sen, 2018b), a key impact indicator for the springshed management projects in the Himalaya (Kulkarni et al., 2021; Kumar et al., 2023b; Sen and Kansal, 2019), whereas tracer and isotope methods are constrained by logistical challenges and access to laboratory infrastructure (Jeelani et al., 2021; Matheswaran et al., 2019).
(3) Few studies have assessed the impact of spring discharge variability on water availability for dependent communities (Barua et al., 2014; Bharti et al., 2020; Tambe et al., 2012), agriculture (Bhadwal et al., 2017; Kumar and Sen, 2020), socio-economic and cultural aspects (Bharti et al., 2020; Sen and Kansal, 2019), and overall water security (Daniel et al., 2021; Dumaru et al., 2021; Vijhani et al., 2022).
(4) Lack of multi-disciplinary integrated approach – There is a paucity of research describing the effect of different ecohydrological factors, including woody vegetation, on groundwater and spring behaviour across typologies (Buono et al., 2015), assess their vulnerabilities to climate change and LULC (Biswas et al., 2023) and explore nature-based solutions for their revival (Rathod et al., 2021; Tambe et al., 2020). Further, there is a lack of regional research on the impact of the observed decline in forest cover (Bhutia et al., 2019; Kanade and John, 2018) and changing precipitation patterns (Sharma and Goyal, 2020) on spring discharge and numbers in the Eastern Himalaya (Kumar et al., 2023b; Tambe et al., 2020).

Thus, a deeper ecohydrological understanding of an individual spring is critical for refining its overall typological behaviour and response to climate and LULC changes (Buono et al., 2015; Pandit et al., 2019).

In this study, we use an integrated ecohydrological approach combining hydrogeological mapping and high-resolution hydrological analyses to assess the relative controls of LULC, precipitation, and hydrogeology on the behaviour of three representative spring typologies, i.e. karst, depression, and fracture springs, in the Eastern Himalaya. We address four specific questions on springs: (a) What are the key drivers of diel and seasonal variability in spring discharge?; (b) How does LULC influence precipitation-springflow relationships across different typologies?; (c) What are the key variables influencing net recharge to spring aquifers?; and (d) How do the seasonal variability springflow and recharge rates affect the water security of the spring-dependent communities? We hypothesize that diel springflow behaviour will be driven by the evapotranspiration losses from the local LULC, and the intensity of diel signals is likely to vary across the typologies. Similarly, the responses of springflow to precipitation will likely be governed by LULC and aquifer properties (typology). For example, a depression spring is likely to be influenced by the local characteristics of deposited soil, gravel, and vegetation-water use. In contrast, a fracture or contact spring is likely to be fed by deeper confined or unconfined aquifers that are relatively impervious to the direct impact of LULC. Thus, we hypothesize that, compared to a fracture or contact spring, a depression spring may show prompt responses to precipitation events and pronounced diel variations in spring discharge. Further, we hypothesize that the dry season discharge will be primarily governed by the local hydrogeology and the aquifer properties, whereas net aquifer recharge will be governed by LULC, soil hydraulic properties and precipitation characteristics (intensity, volume and duration). Lastly, we predict that the dry season water availability will be lowest for springs with lower recharge and high discharge variability. We tested the hypotheses using high-frequency discharge data from the instrumentation of three typical springs in Sikkim, one of the first in the Himalaya.

2. Material and methods

2.1. Study area description

Sikkim is a representative of the Eastern Himalayan sub-tropical climatology characterised by high altitudinal gradients (300–8534 m above sea level, masl) and almost year-round precipitation, which supports high ecosystem diversity (Kumar et al., 2021) (Fig. 1a). Approximately 80% of the total state area is covered under forests, which provide sanctuary to the principal water resources, the springs and streams (Kumar et al., 2024a; Tambe et al., 2020). Southern Sikkim is densely populated and highly vulnerable to climate change (Tambe et al., 2011, 2020). In late 2000s, the Rural Management and Development Department (RMDD) of the Government of Sikkim initiated a state-level spring-rejuvenation effort (named “*Dhara Vikas*”) (Dhakal and Karki, 2023; Seidler et al., 2016; Tambe et al., 2012), which included a regional spring survey and hydrogeological assessment of the Tendong region near Namchi, South Sikkim (Kulkarni and Mahamuni, 2013; Mahamuni and Kulkarni, 2013). The three selected springs, *Mukter dhara* (Kamrang), *Mamley dhara* (Mamley), and *Gaddi khola* (Gaddi), fall under the Mamley watershed (of the Rangit River basin) in the Tendong region (Fig. 1b–Table 1). The region has seen a decline in perennial streams and springs, attributed to long-term climate change

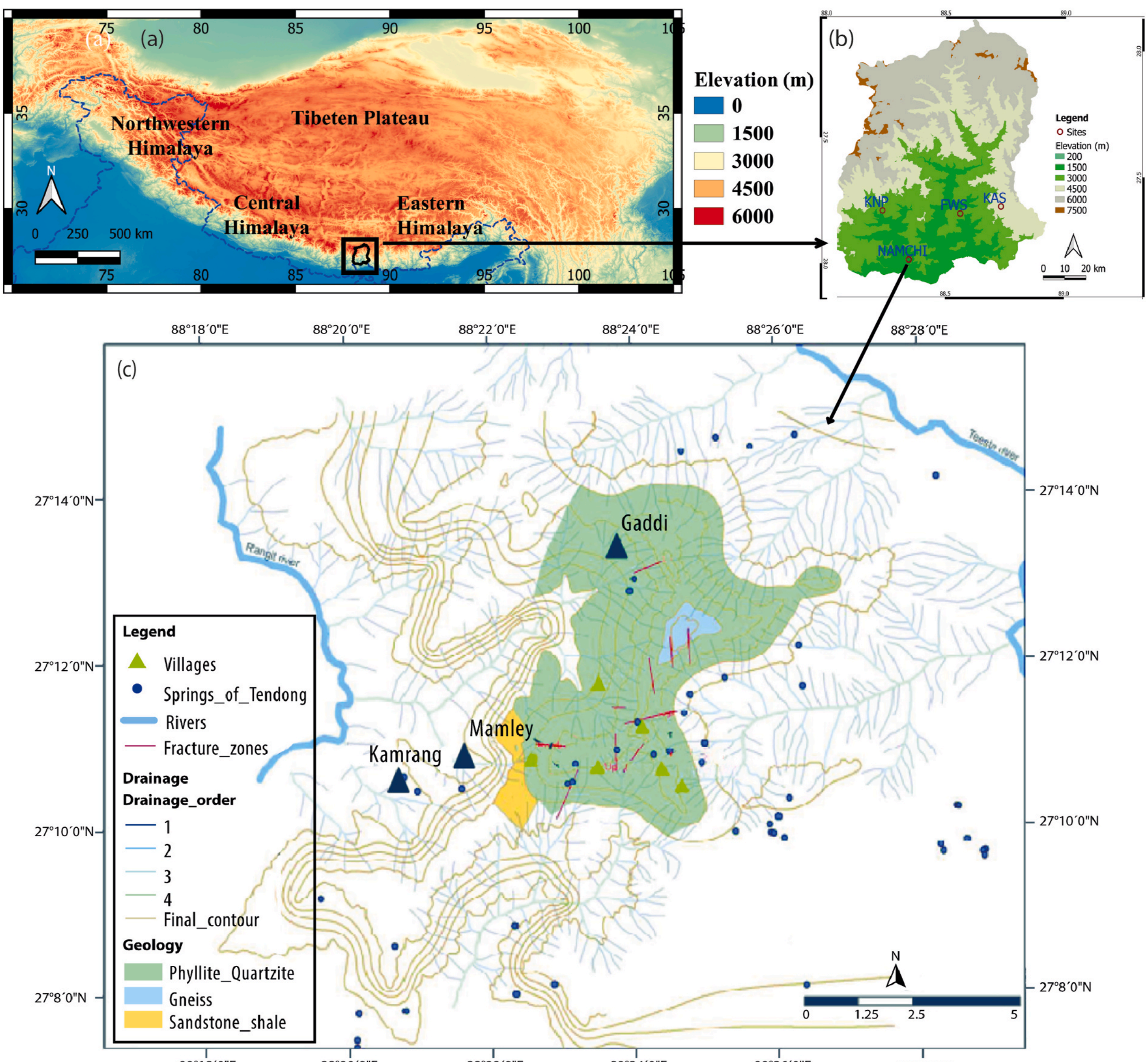

Fig. 1. Study area map showing (a) the digital elevation model (DEM) map of the Himalaya with (b) the location of Sikkim in the Eastern Himalaya, and (c) the hydrogeological map of the Tendong hill region in Sikkim highlighting the location of the three springs, Kamrang, Mamley, and Gaddi. The hydrogeological map shows gneiss (blue) overlying alternating beds of phyllite-quartzite (green) sitting above sandstone-shale (brown) layers (reproduced with permission from Kulkarni and Mahamuni (2013). The maps are prepared in QGIS (QGIS Team, 2024) using the ASTERGDEM 003 (elevation in meters). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Location and characteristics of the instrumented springs in Sikkim.

Springs	Typology	Land-use	Springshed Area (ha)	Elevation (masl)	Annual Precipitation (mm)	Dependent population
Mukter Dhara, Kamrang (Kamrang)	Depression	Agriculture	1.56	1040–1120	2600	170
Mamley Dhara, Mamley (Mamley)	Karst & Contact	Agriculture	4.96	1140–1500	2600	320
Gaddi Khola, Gaddi (Gaddi)	Fracture & depression	Mixed-oak forests	7.68	2000–2308	3960	60

impacts (e.g. precipitation decline) and episodic disruptions (e.g. 2011 Sikkim earthquake) (Barfal et al., 2022), and significantly higher overland flow and sediment and carbon losses (Sharma and Rai, 2004).

2.2. Springs characteristics

The *Mukter dhara* (referred to as Kamrang) in the Kamrang village and the *Mamely dhara* (referred to as Mamley) in the Mamley village falls under the Mamley-Kamrang village administrative unit (*Gram Panchayat* unit, GPU) and support populations of 170 individuals and 320 individuals, respectively (RMDD, 2011a). The *Gaddi Khola* (referred to as Gaddi) in the Gaddi village falls under the Damthang-Jaubari GPU and supports a population of 60 individuals (RMDD, 2011b). The Kamrang and Mamley springs lie at similar elevations (~1100 masl) on the south-eastern aspect in adjacent valleys and receive similar precipitation. The Gaddi spring lies on the eastern aspect near the ridge of the Tendong hills at an elevation of 2000 masl. Kamrang and Mamley receive ~2600 mm of annual precipitation, most of which falls in the monsoon months. In contrast, Gaddi receives much higher annual precipitation (3960 mm), with significant summer and monsoon precipitation (Table 1, Supplementary Figure A1a).

The regional lithology can be summarised into metamorphic rocks dominating the elevations above 1700 masl and sedimentary rocks below dipping in north-east directions at 30°–40° with two dominant fracture sets along NNE-SSW and ENE-WSW directions (Barfal et al., 2022; Mahamuni and Kulkarni, 2013). The metamorphic segment is further divided into a small gneiss segment at around 2500 masl, sitting over alternative bands of folded phyllites and weathered quartzites, and sedimentary formations of weathered shale-sandstone constitute the region below 1700 masl. The fractured and weathered sedimentary rocks and metamorphic rocks are the principal aquifers, whereas the fracture systems heavily influence the location of the springs and the stream-drainage network. Most of the springs in the region fall under agriculture (49%) or forest (36%) land-use, and along the escarpment slopes on the ESW aspects (35%) (Dhakal and Karki, 2023). The Tendong Ridge area is covered by dense mid-elevation wet temperate mixed oak forests (Bhutia et al., 2019). The selected springs lie on the escarpment slope facing the SSW aspect and cover both the lithologies and dominant land-use types in the region (Kulkarni et al., 2021; Kulkarni and Mahamuni, 2013; Mahamuni and Kulkarni, 2011).

2.3. Data collection

The Kamrang spring was instrumented with a 3-inch Parshall flume, whereas the Mamley and Gaddi springs were instrumented with 2-inch Montana flumes. Each flume was fitted with a capacitance water level recorder (Dataflows Systems LTD, New Zealand) installed in the outer chamber, and the height of the water column (H in m) was recorded at 10 min resolution. The height of the water column was converted to volumetric discharge (Q in $m^3 s^{-1}$) using their respective standardized equations (equations (1) and (2)).

The discharge-height equation for Kamrang spring (3-inch Parshall flume)

$$Q = 0.1765 * H^{1.55} \tag{1}$$

The discharge-height for Gaddi and Mamley springs (2-inch Montana flumes)

$$Q = 0.1207 * H^{1.55} \tag{2}$$

Precipitation (P in mm h^{-1}) was recorded using an automated tipping-bucket rain gauge at each spring along with air temperature (T_r in °C) and relative humidity (R_h in%) (iButton Hygrochrons, Maxim Int., USA). Hydrogeological mapping was conducted using Brunton's compass, a geological hammer, and a GPS device (Garmin Int., USA). The springflow and precipitation datasets were subjected to stringent quality control, including tests for abnormally large or physically improbable hourly and daily springflow/precipitation values, unusually long sets of consecutive values, physically improbably long dry spells, and improbable zero values (Blenkinsop et al., 2017; Einfalt and Michaelides, 2008; Kumar et al., 2021). Additionally, each site's precipitation and springflow time-series were visually compared using event hydrographs. Any suspect or missing data or height values outside the minimum and maximum detection limits of the flumes were marked "Not available (NA)" during the quality check. The final analysis was done for the three-year period between 24th September 2014 to 11th November 2017. Unfortunately, the discharge monitoring of the Mamley spring was discontinued after October 2015 due to multiple instances of instrument theft. The average data availability was 70% (Q = 66%, P = 74%), including Kamrang (Q = 81%, P = 90%), Mamley (Q = 23%, P = 61%) and Gaddi (Q = 95%, P = 70%) (Supplementary Table A1 provides the seasonal breakup of data availability). Reference evapotranspiration (ET_0) was estimated from climatic data for nearby automatic weather stations (AWS) accessed through the Indian Space Research Organisation (ISRO) using FAO's Penman-Monteith method (Allen et al., 1998) and the Turc method (for periods with limited climate data; Krishnaswamy et al., 2013; Turc, 1961). Leaf area index (LAI) was extracted for the site from MCD15A3Hv006 level-4 product (4-day temporal and 500 m spatial pixels) from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Myneni et al., 2015). We collected eight soil cores till the bedrock in catchments of Kamrang (N = 3, 50–80 cm depth), Mamley (N = 3, 30–50 cm depth), and Gaddi (N = 2, 70 cm depth). Bouyouco's hydrometer method was used to determine the depth-wise (10 cm blocks) distribution of particle sizes (Bouyoucos, 1928). The available water holding capacity was estimated based on soil texture and bulk density (Aina and Periaswamy, 1985). Soil infiltration rates were measured on a flat ground surface after removing any leaf litter using a Mini-disc Infiltrometer (Decagon Devices, Inc., USA) in the catchments of Kamrang (N = 3), Mamley (N = 3) and Gaddi (N = 6), to estimate the unsaturated soil hydraulic conductivity (Kumar et al., 2024a; Nanda et al., 2019). Traverse mapping surveys and existing hydrogeological information were used to assess the geomorphological features dominating the spring typologies (Kulkarni et al., 2018; Mahamuni and Kulkarni, 2011).

2.4. Data analysis

The data quality check, analysis, and visualization were done in R version 4.3.3 (R Core Team, 2024) under RStudio environment (RStudio Team, 2024).

2.4.1. Discharge variability analysis

Four different measures of seasonal discharge variability were computed, including the Flow duration curve (FDC), Coefficient of variation (C_v), Meinzer's variability index (M_V), and Flow duration curves (Bartnik and Moniewski, 2019; Kritz, 1973). Flow duration curves map the frequency distribution of discharges across different exceedance thresholds using the Weibull function. It depicts the ability of a catchment to generate various flows and provides insights into springshed and aquifer characteristics (Dass et al., 2021a; Kumar and Sen, 2018b; Vogel and Fennessey, 1996). The coefficient of variation (C_v in%) is a measure of dispersion around the mean and was estimated as the ratio of standard deviation to average hourly discharge. In the absence of data on a large number of Himalayan springs, it is difficult to estimate the empirical thresholds of behaviour in springs. Thus, the C_v values derived by (Kritz, 1973) and later used by (Bartnik and Moniewski, 2019) were used as indicative thresholds to understand the relative behaviour in Himalayan springs. Here, C_v values (<20%) indicate stable flows, medium C_v (20–40%) for moderately variable flows, high C_v (40–100%) for high variability, and very high C_v (>100%) for unstable flows. Meinzer's variability index (M_V) is usually estimated using annual maxima and minima and is prone to measurement errors at both ends. Thus, instead of using the absolute maxima and minima, we used the average of the Q falling above 90% quantile ($Q_{90\%}$) as maxima and below 10% quantile ($Q_{10\%}$) as minima to avoid measurement errors (Equation (3)) (Kumar et al., 2024a). Springflows with M_V ranging from 0 to 25 were categorized as stable or permanent, with 25–100 having low variability and greater than 100 highly variable, indicating flash responses or steep recessions.

$$M_V = \left(\frac{Q_{90\%} - Q_{10\%}}{Q_{mean}}\right) * 100 \tag{3}$$

We used three measures to understand the diel springflow variability, including visualization of diel cycles, the ratio of diel amplitude to daily Q, and the variance ratio between diel and daily Q. The diel analyses were conducted for precipitation-free days only and the day of precipitation and 24 h after the last precipitation were excluded. The diel cycles were averaged for each hour, and the daily occurrence of maxima (peak) and minima (trough) was compared across seasons. The drawdown and recovery times provide useful information on catchment properties and were computed as the hourly difference between a peak and the following trough and between the trough and following peak, respectively. In evapotranspiration-induced diel cycles, a rapid drawdown may suggest strong diel uptake by vegetation or land-use from shallow groundwater (McMillan, 2020), whereas a longer recovery time may indicate low aquifer transmissivity (Gribovszki, 2018; Gribovszki et al., 2010). The amplitude of diel discharge ($Q_{daily.amp}$) was computed as the difference between daily maxima and minima, and its ratio to average daily Q was used to measure the strength of the diel signal (Kumar et al., 2024a; Lundquist and Cayan, 2002). A $Q_{daily.amp}$/Q ratio >30% is considered significant in stream hydrology (Wondzell et al., 2007). However, the significance threshold could be lower (>20%) for groundwater-dependent systems such as springs and headwater streams (Kumar et al., 2024a). The capacitance-based water-level recorders used in the study are sensitive to diel fluctuations in the ambient temperature (Larson and Runyan, 2009), which induces a diel measurement error of (0.8 mm) empirically estimated by placing the recorder in a column of standing water for a few days (Kumar et al., 2024a). The estimated error was treated as noise in the diel signature of streamflow and removed while estimating $Q_{daily.amp}$.

The variance ratio between the diel component of springflow ($Q_{dielvar}$) and the variance of springflow (Q_{var}) was computed for contiguous rainless periods longer than 5 day as a measure of seasonal variability in the significance of the diel cycle of Q to overall Q (Kumar et al., 2024a). The seasonal time decomposition based on the lowess method (STL) decomposes a springflow time series into three components: diel cycle (Q_{diel}), long-term trend (Q_{trend}), and remaining perturbations ($Q_{remainder}$) (Lu et al., 2022; Wenrui Zhang et al., 2024). Thus, the $Q_{dielvar}$ is also part of the denominator Q_{var} and a high $Q_{dielvar}/Q_{var}$ ratio denotes an increase in diel cycles during stable springflow periods (low Q_{var} and $Q_{remainder}$), whereas a low ratio suggests that the variability in springflow (high Q_{var} and $Q_{remainder}$) overpowers the diel signal (low Q_{diel}) (Kumar et al., 2024a).

2.4.2. Precipitation-discharge lag-correlation analysis

Time-series or hydrograph analyses have been central to understanding the response of a spring or stream to precipitation and its aquifer properties (Kresic and Bonacci, 2010). A typical spring hydrograph consists of two components: the rising and the falling limbs. The rising limb constitutes the discharge from the base of the previous rise to the peak in discharge, usually in response to a precipitation input. The falling limb comprises the decline from peak discharge to the base discharge until the subsequent precipitation-induced rise. The rising limb characterizes the aquifer's response to the net recharge by the antecedent precipitation pulse, whereas the falling limb corresponds to the subsequent draining of the aquifer. Analysing rising and falling limbs can provide clues to aquifer properties like recharge, storage, and transmission and their interactions with LULC (Kumar and Sen, 2018a, 2018b). Individual precipitation events were identified for each spring, with a minimum starting threshold precipitation of 1 mm h^{-1}, a minimum precipitation event volume of 2.5 mm, and a minimum inter-event of at least 24 h. The lag between antecedent precipitation and springflow was estimated for each rain event using cross-correlation analysis (*ccf* function in R) (Fiorillo and Doglioni, 2010; Krishnaswamy et al., 2012; Kumar et al., 2024a). Events with an auto-correlation coefficient (ACF) value higher than 0.2 were selected, and lag time (in hours) was extracted at the highest ACF value. High lag indicates the longer transit time for a recharge pulse in an aquifer, whereas low lag suggests the flashy nature of spring or shorter flow pathways (Florea and Vacher, 2006; Kumar et al., 2024a; Nayak et al., 2023). The variability in lagged responses across the springs was compared with their respective LULC, soil properties, and typologies (Agarwal et al., 2012; Fiorillo and Doglioni, 2010; Zhang et al., 2013).

2.4.3. Estimating net recharge from spring hydrographs

Individual recession events were identified by averaging the hourly data to daily time steps and using a 3-day moving average to identify the start and end dates. Events smaller than six days were excluded from further analysis. The recession events were used to estimate net recharge (R in m^3) to the spring after each precipitation event using the hydrograph method (Korkmaz, 1990; Kumar and Sen, 2018b). Based on the conservation of mass approach, we assume the springflow hydrograph to be an exponential form of its antecedent condition (equation (4)):

$$Q_t = Q_0 e^{-kt} \tag{4}$$

where Q_0 and Q_t are the springflow at the start of the recession event and after t hours at the end of the recession event, respectively. Assuming springflow to be directly proportional to storage (S) (equation (5)) (Korkmaz, 1990; Kumar and Sen, 2018b):

$$S = k * Q_{bf} \tag{5}$$

Combining equations (4) and (5):

$$S = k * Q_0 e^{-kt} \tag{6}$$

We estimate the change in storage (ΔS) at the start and end of a recession as the difference in dynamic storage computed from springflow at the start (Q_0) and end (Q_t) of a recession event (equation (6)). Net recharge (R in mm) was computed as the sum of the change in storage (ΔS) and cumulative baseflow during the recession event period per unit time (equation (7)).

$$R = \frac{\left(\Delta S + \sum_{0}^{t} Q\right)}{t} \quad (7)$$

The estimated net recharge was compared with antecedent precipitation event characteristics, i.e. total volume and maximum precipitation intensity (estimated as the 95th quantile of the non-zero hourly precipitation).

2.4.4. *Estimating water availability and future demand*

The minimum global requirement threshold for drinking and cooking purposes is 20 L per capita per day (lpcd) (WHO, 2022), whereas the Indian national water supply guidelines specify the desired daily drinking and domestic water requirements at 55 lpcd (NJJM, 2020) and 135 lpcd (CPHEEO, 1999), respectively. The daily spring discharge available for consumption was estimated at 90% after accounting for potential capturing and transmission losses (Swajal, 2011), and the per capita water availability was estimated by dividing the user group population as per the 2011 Census reported in the Village Development Action Plans (VDAP) of the Mamley-Kamrang (RMDD, 2011a) and Damthang-Jaubari GPUs (RMDD, 2011b). The VDAPs were developed by RMDD, Government of Sikkim, in 2011 after extensive consultations with the user communities and documentation of their scarcities and requirements. The pre-feasibility guidelines for government-sponsored drinking water schemes in mountain states of India (Swajal, 2011) specify that the dry season discharge should not be less than 9 l min^{-1}, and it should be sufficient to support a future increase in demand as well, which is arbitrarily estimated as an assumed 1.5-time increase in the user group population over 20 years. The available water at the household level was compared against 20 lpcd (minimum requirement) and 55 lpcd (desired requirement) thresholds for drinking and domestic usage for different seasons. The future demand and availability were estimated for an assumed 1.5-time increase in the user group population for the same thresholds as per the (Swajal, 2011) guidelines.

3. Results

3.1. *Hydrogeological and environmental characteristics of the springs*

Kamrang Spring lies close to a NE-SW trending fracture set in heavily weathered and fractured shale-sandstone with high secondary porosity. It is overlain by gently sloped (10°–30°) terraced agricultural fields with a thick soil horizon (50–80 cm), the slope terminating abruptly at the point of the spring outlet. The Kamrang spring is classified as a high discharge fracture-depression spring with the aquifer formation due to the unconsolidated debris and the densely fractured lithology (Supplementary Figure A2a and A2b). The Mamley springshed is overlain by moderately sloped (20°–50°) overlain by small agricultural terraces and fallow land with a thin soil horizon (30–50 cm). The local hydrogeology comprises alternate phyllite-quartzite bands with an intervening layer of limestone. The limestone layer is heavily fractured, weathered, and karstic, forming the principal aquifer, and the spring is classified as a low-discharge contact and karst spring (Supplementary Figure A2c and A2d). The uppermost Gaddi spring is situated within the metamorphic belt dominated by phyllite-quartzite bands dipping at 30–40° and is close to a set of NNE-SSW trending fractures and overlain by unconsolidated debris above the spring outlet. The highly fractured and weathered phyllite-quartzites constitute the principal aquifer, while the unconsolidated debris houses the secondary aquifer, and the spring is classified as a moderate-discharge fracture-depression spring. The springshed has moderate slopes (30°–50°) and is covered with dense mixed-oak forests with thick clay-rich soil horizon (60–70 cm) (Fig. 2f). A detailed hydrogeological assessment of Mamley and Gaddi springs is provided by Mahamuni and Kulkarni (2011). We updated their assessment for Gaddi (referred to as Gati spring in their document) to fracture-depression spring based on further hydrogeological assessments (Supplementary Figure A2e and A2f).

Overall, the soil depth was highest in Kamrang (80 cm), followed by Gaddi (70 cm) and Mamley (40 cm) (Fig. 2a). The texture analysis shows

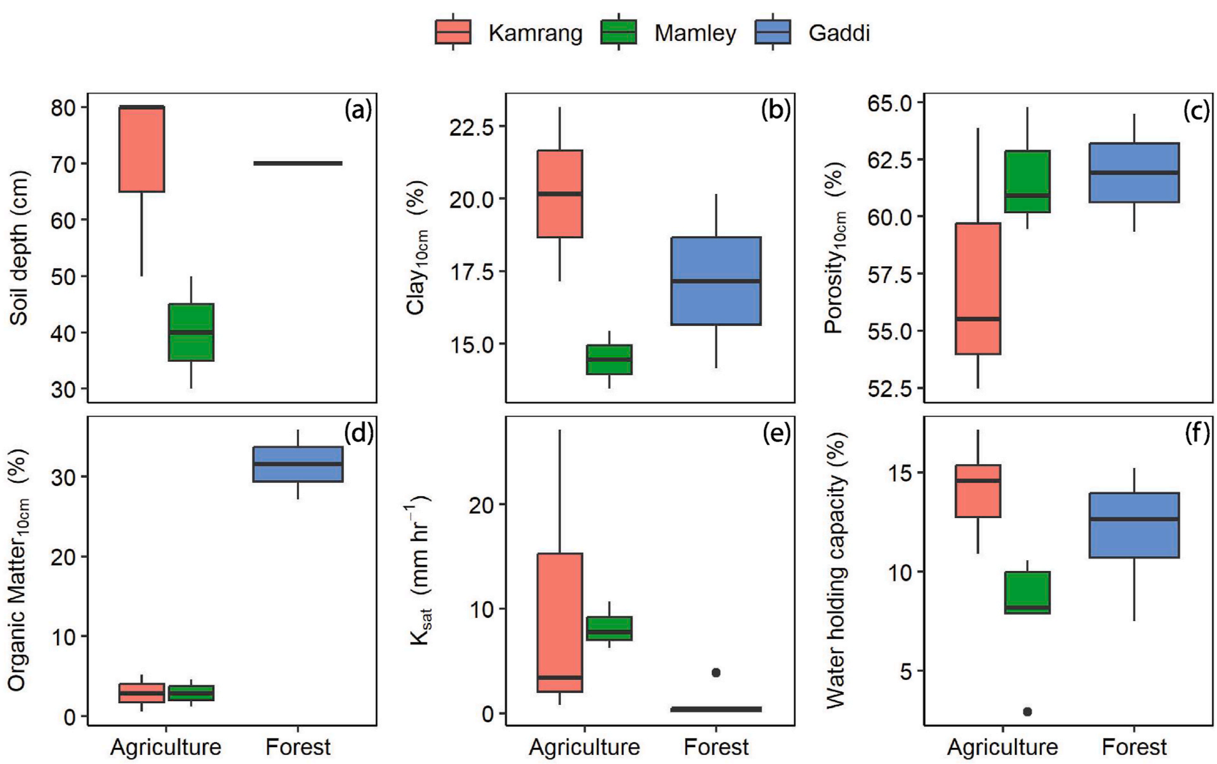

Fig. 2. Box and Whisker's plots compare soil physical and hydraulic properties in contrasting land-use classes in the three springs, including (a) maximum soil depth (cm), (b) percentage clay in topsoil (10 cm depth), (c) porosity in topsoil (% in 10 cm depth), (d) percentage organic matter in topsoil (10 cm depth), (e) unsaturated soil hydraulic conductivity (K_{sat}, mm h^{-1}), and (f) available water holding capacity (%).

that the soil in Mamley and Gaddi is sandy loam, whereas Kamrang is sandy clay loam (Supplementary Figure A3). Despite agricultural land use, the soil depth and clay percentage were much lower in Mamley than in Kamrang, whereas the clay content was intermediate in Gaddi (Fig. 2b). On a closer look, the clay percentage in the soil increased with depth from 14% (top 10 cm) to 19% (40 cm depth). Correspondingly, the available water holding capacity in Gaddi increased with depth (15.2% at 50 cm depth), whereas the opposite was seen in Mamley (10.6% at 10 cm depth), while Kamrang remained consistent (17.1% at 10 cm depth) (Supplementary Figure A4). The mean water holding capacity was highest in Kamrang (14.2 ± 4.4%), followed by Mamley (12.1 ± 3%) and Gaddi (8.7 ± 4.1%) (Fig. 2f). Incidentally, the soil porosity and organic carbon content were significantly lower in the compacted agricultural soil of Kamrang and Mamley than in the forest soil of Gaddi (Fig. 2c and d). High unsaturated soil hydraulic conductivity (K_{sat}) in Kamrang (N = 3, range: 0.8–27.1, mean ± SD: 10.4 ± 14.5 mm h^{-1}) and Mamley (N = 3, range: 6.3–10.7, mean ± SD: 8.2 ± 2.2 mm h^{-1}) was observed in the tilled agricultural soil (Fig. 2e). Despite high soil organic content and porosity in the topsoil, the forest-dominated catchment of Gaddi had extremely low K_{sat} (N = 6, range: 0.15–3.9, mean ± SD: 0.91 ± 1.45 mm h^{-1}), which could be influenced by the highly compacted surface soil layer as observed during the sampling. The precipitation intensity was below the mean unsaturated hydraulic conductivity till the 95th quantile in Kamrang and 90th quantile in Mamley, with a maximum of 46 mm h^{-1}, whereas the intensities were consistently higher than the mean K_{sat} in Gaddi (Supplementary Figure A5).

Gaddi saw significantly higher summer precipitation in April–May than Kamrang and Mamley, which received precipitation from June onwards (Supplementary Figure A1a). The annual pattern in Reference evapotranspiration (ET_0) and Leaf area index (LAI) showed a bimodal pattern (Supplementary Figure A1b and A1c). The Reference evapotranspiration (ET_0) was significantly higher at lower elevation springs at Kamrang (and Mamley) (3.82 ± 1.82 mm d^{-1}) than at higher elevation spring Gaddi (2.83 ± 1.24 mm d^{-1}). The ET_0 at Gaddi showed bimodal peaks in April and September, whereas Kamrang and Mamley showed an unimodal peak around summer (Supplementary Figure A1b). LAI showed bimodal peaks in vegetation productivity in April–May and October in Gaddi, which has mixed-evergreen forests in the catchment. (Supplementary Figure A1c). Kamrang and Mamley were part of the same MODIS-LAI pixel and exhibited a bimodal pattern but with half the values of Gaddi, except in October, when the values were equal.

3.2. Discharge variability in springflows

3.2.1. Flow duration curves

The inferences from the discharge variability analysis agreed with the hydrogeological assessment of the aquifer properties of the three springs. In Fig. 3a, the steeper slope in the very high flows in Kamrang is typical of depression spring behaviour, where the aquifer (located mainly in the unconsolidated debris) has high transmissivity and discharges rapidly after saturation. Kamrang and Mamley show broken-stick-type curves with slightly different patterns, whereas Gaddi shows a more or less linear slope with tapering at the end (Fig. 3a). The broken-stick type slope curves typically have three segments with breakpoints at very high flows (<10% exceedance) and at low-flows (80–90 % exceedance). Under high-flow conditions (<10% exceedance), both Kamrang and Mamley show almost vertical slopes, in contrast to the observed gentler slope in Gaddi. In the mid-flows (10–90% exceedance), both Mamley and Gaddi show a steeper decline than Kamrang, which has the lowest slope. Mamley and Gaddi show wave-like patterns in mid-flows, whereas Kamrang had a uniform slope. Under low-flow conditions (>90%), Mamley and Gaddi show an almost vertical drop, indicating a steep recession, whereas Kamrang retained a much more stable low-flow regime.

3.2.2. Seasonal variability in springflows

The annual hydrograph of the three springs showed a rapid response

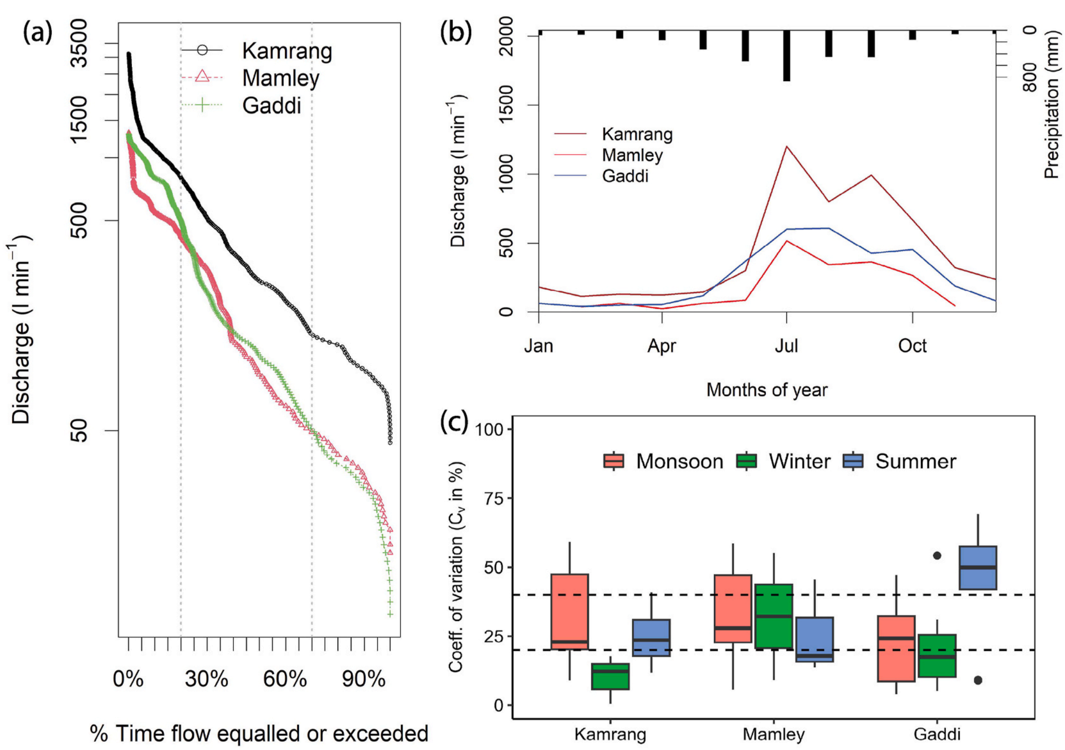

Fig. 3. Seasonal variability in discharge is shown using (a) flow duration curves (the vertical dotted lines represent discharge within 30–70% exceedance), (b) the average monthly discharge of the three springs, and (c) the coefficient of variation in discharge (C_v in %). The horizontal dotted lines mark the C_v thresholds for stable and variable flows at 20% and 40%, respectively.

of discharge to precipitation events but with variability across seasons (Fig. 3b). A lag of a few weeks in peak discharge was seen in all springs in the early part of the monsoon, which could be attributed to the time taken to fill up the depleted aquifers. Both Kamrang and Gaddi show a consistent rise in discharge with the onset of monsoon. Interestingly, the post-June precipitation had little impact on Mamley discharge, whereas Kamrang and Gaddi continued responding throughout the monsoon. The lean season flows were considerably higher in Kamrang than in the other springs.

Based on average discharge, all three springs fall under the 5th-order (60–600 l min^{-1}) as per Meinzer's classification index, although the average discharge of Kamrang was almost twice that of Gaddi and Mamley (Table 2). The seasonal differences in average springflow are stark as the discharge dropped 6–8 times between monsoon and summer. Similarly, within a season, the difference in discharge minima and maxima was 100 times in monsoon and around 8–10 times in summer and winter. All three springs were classified as highly variable based on the coefficient of variability assessments (C_v>40%). Annually, Kamrang (95 ± 22%) showed the highest variability, followed by Gaddi (88 ± 7%) and Mamley (72 ± 41%) (Fig. 3c). In Monsoon, Kamrang (32 ± 17%) and Mamley (33 ± 19%) showed higher fluctuations than Gaddi (23 ± 15%), which had more stable flows. However, in winter, Kamrang (11 ± 6%) and Gaddi (20 ± 14%) showed very stable flows, whereas Mamley had higher variability (32 ± 33%). In summers, Gaddi showed much higher fluctuations (45 ± 22%) than Kamrang (25 ± 10%) and Mamley (26 ± 17%). Meinzer's variability index (M_V) showed similar patterns to C_v with highly variable flows in Mamley (101 ± 58%) and low variability flows in Gaddi (91 ± 61%) and Kamrang (81 ± 51%) (Supplementary Figure A6). Contrary to C_v estimates for Mamley, M_V was lower in winter (75 ± 62%) than in summer (97 ± 57%). C_v and M_V highlight monsoon flows in Kamrang and Mamley, and summer flows in Gaddi are highly variable, whereas the flow remained low-moderately variable the rest of the year. Only the winter flow in Kamrang was recognized as stable.

3.2.3. Diel variability in springflows

Strong yet contrasting diel fluctuations in discharge were observed in all three springs (Fig. 4). The diel fluctuations were significantly higher in Kamrang (22 ± 41 l min^{-1}) and Gaddi (15 ± 26 l min^{-1}) than in Mamley (12 ± 24 l min^{-1}). Seasonally, the diel amplitude was lowest in winter in Kamrang and Gaddi, followed by summer and monsoon, whereas, in Mamley, the diel amplitude was lowest in the summer, followed by winter and monsoon (Supplementary Table A2). However, the patterns varied seasonally within and between the springs with varying timings of lowest (troughs) and highest discharge (peaks). In Kamrang, the lowest discharge (trough) shifted from night (2000 h) in monsoon to evening (1800 h) in winter, whereas in summer, two troughs were in the afternoon (1400 h, major) and at midnight (minor). Contrastingly, Mamley did not exhibit significant diel fluctuation in the monsoon and summer, whereas winters showed bimodal patterns with twin troughs in the afternoon (1500 h) and morning (0600 h). In Gaddi, a weak bimodal pattern was visible in monsoon with troughs in the evening (1700 h) and midnight, which got pronounced in the winter before shifting to deep early morning (0500 h) troughs in summer.

The drawdown and recovery time also varied significantly between the springs and across the season. In Kamrang, the drawdown time declined with increasing dryness from monsoon (11 h) to winter (9 h) and the bimodal summer pattern (5 h and 3 h), whereas the corresponding recovery period lengthened from monsoon (13 h) to winter (15 h) and summer (6 h and 10 h). Mamley showed a significant bimodal diel pattern in winter only with rapid drawdowns (5 h and 11 h) and faster recoveries (5 h and 4 h). In Gaddi, the drawdown was similar (6–7 h) across the season, but the recovery time significantly increased from monsoon (3 h) to winter (5 h) and summer (8 h).

The significance of diel cycles to daily mean discharge was computed for contiguous rainless periods (longer than two days) for Kamrang (N = 42), Mamley (N = 18), and Gaddi (N = 36). The variance ratio, i.e. the ratio of variance in Q_{diel} to variance in daily Q, was highest in Gaddi (mean ± SD of 29 ± 30%) followed by Kamrang (21 ± 22%) and Mamley (18 ± 21%). In Gaddi, the variance ratio was marginally higher in winter (24 ± 22%) than in monsoon (23 ± 27%) but almost doubled in summer (51 ± 39%), with the two peaks coming in April–June and August–September (Fig. 5a). Similarly, in Kamrang, the variance ratio was higher in winter (20 ± 35%) to summer (25 ± 21%) than in monsoon (19 ± 20%). Conversely, the variance ratio was significantly higher in the driest part of the year (May–June, 53 ± 18%), followed by September (18 ± 19%). Interestingly, the ratio of the diel amplitude of Q ($Q_{daily.amp}$) to daily Q (Q_{daily}) was highest in Mamley (9 ± 10%), followed by Gaddi (7.2 ± 6.8%) and Kamrang (5.2 ± 5.7%) (Fig. 5b). Seasonally, Kamrang and Mamley showed a modal pattern in diel amplitude ratio with the peak in June (Kamrang = 12 ± 7%, Mamley = 24 ± 13%), whereas Gaddi showed a bimodal pattern with peaks in spring-summer (Feb–May, 11 ± 10%) and autumn (November, 8.4 ± 6.4%) periods. Overall, the fraction of days on which the diel amplitude ratio exceeded the 30% threshold was highest in Kamrang (20%), followed by Gaddi (16%) and Mamley (13%). Similarly, the diel amplitude ratio exceeded the 15% threshold in Kamrang (35%), followed by Gaddi (32%) and Mamley (20%) of the total days.

3.3. Precipitation-springflow lag-correlation analysis

The cross-correlation analysis explored the shifting lags and strength of the cross-correlation coefficient (CCF) between precipitation and discharge across months. Positive (negative) autocorrelation coefficient (ACF) values signified that a high (low) value of the driver variable was followed by a high (low) value of the response variable after the corresponding lag hours (Kumar et al., 2023a, 2024a).

The overall lag between precipitation and discharge was significantly higher in Kamrang (16 ± 16 h) and Gaddi (15 ± 18 h) than in Mamley (7 ± 8 h). Seasonally, the lag hours showed a bimodal pattern in Kamrang and Mamley, with the highest lags in summer and autumn, whereas Gaddi showed the highest lag throughout the dry season (November–February) (Fig. 6a). The lag time showed contrasting patterns across the three springs when plotted against the precipitation intensity and event volume. Both Kamrang and Mamley showed a modal pattern between lag hours and precipitation intensity, with the smallest lags at low (<10 mm h^{-1}) and high-intensities (>30 mm h^{-1}) and the highest lag at moderate intensities (10–30 mm h^{-1}) (Fig. 6b). Contrastingly, Gaddi showed a consistent lag at low-moderate intensities and declined significantly at high precipitation intensity (>30 mm h^{-1}). The size of the precipitation event had little impact on lag time in Gaddi, whereas the lag increased with volume in Kamrang (Fig. 6c). However, Mamely showed a relatively faster response to small (<10 mm) and moderate (10–100 mm) precipitation events, but the lag increased significantly at high volumes (100–200 mm).

Table 2
Annual and seasonal variability average (Q_{mean}), minimum (Q_{min}), and maximum (Q_{max}) springflows.

Springs	Q_{mean}±SD (l min^{-1})				Q_{max}, Q_{min} (l min^{-1})		
	Annual	Monsoon	Summer	Winter	Monsoon	Summer	Winter
Kamrang	514 ± 512	858 ± 541	134 ± 56	223 ± 109	3082, 44	492, 46	583, 61
Mamley	212 ± 236	310 ± 250	48 ± 27	39 ± 16	1311, 13	153, 17	278, 22
Gaddi	284 ± 320	511 ± 340	77 ± 95	106 ± 120	1299, 55	278, 22	850, 10

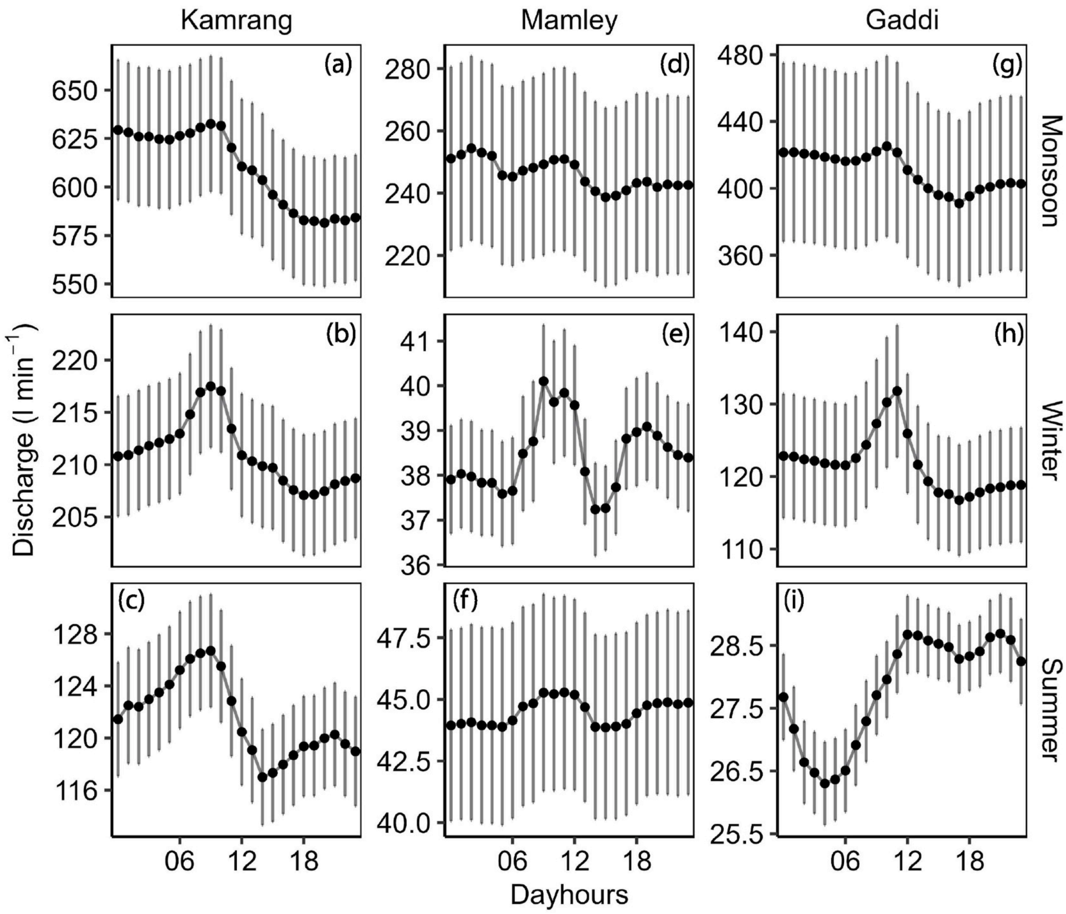

Fig. 4. Diel variability in discharge in the three springs across different seasons (vertical bars represent standard errors).

3.4. Net recharge from spring hydrographs

The mean net recharge (R) was highest in Kamrang (N = 26, 605 ± 599 m^3), followed by Gaddi (N = 31, 148 ± 208 m^3) and Mamley (N = 7, 33 ± 40 m^3). Kamrang showed significantly higher net recharge throughout the monsoon (972 ± 541 m^3) and low recharge in winter (109 ± 50 m^3) and summer (73 ± 65 m^3), peaking early in July (1283 ± 169 m^3) and diminishing until March (26 ± 37 m^3) (Fig. 7a). Similarly, Gaddi showed a significantly higher recharge monsoon (272 ± 251 m^3) than winter (57 ± 65 m^3) and summer (15 ± 15 m^3), with dual peaks in June (215 ± 38 m^3) and October (477 ± 362 m^3). Conversely, the sporadic recharge events in Mamley were consistent across monsoon (36 ± 47 m^3) and summer (40 m^3), peaking in July (94 m^3). In Kamrang, net recharge was better explained by maximum precipitation intensity (r^2 = 0.37, slope = 310) during the event than its total volume (r^2 = 0.14, slope = 518) (Supplementary Figure A7), with twin clusters showing high recharge volumes at low precipitation intensities (<0.5 mm h^{-1}) and moderate recharge at higher intensities (Fig. 7b). Conversely, the net recharge in Gaddi was equally well explained by maximum precipitation intensity (r^2 = 0.36, slope = 36) and event volume (r^2 = 0.48, slope = 45), although one of the highest recharges occurred at a mid-intensity (0.65 mm h^{-1})-long duration (11 days)-high volume (155 mm) event (Fig. 7b). The linear regression models for net recharge in Mamley were equally weak for maximum precipitation intensity (r^2 = 0.01, slope = 33) and event volume (r^2 = 0.11, slope = 48). In Mamley, the highest recharge occurred at two contrasting events, a 94 m^3 recharge episode during a low-intensity (0.02 mm h^{-1}), long duration (10 days), low volume (5 mm) event, and a second with 81 m^3 recharge during a mid-intensity (0.34 mm h^{-1}), mid-duration (6 days) and mid-volume (40 mm) event. It is important to note that the precipitation gauges were close to the spring outlets, and the precipitation in the upper catchments could vary in these steeply sloped mountains.

3.5. Spring water availability and future demand

The mean per capita water availability from the springs was above the desired water requirement (55 lpcd) for Gaddi and Kamrang, but Mamley could not cater to even the minimum requirement (20 lpcd) of their user group (Table 3). However, when split seasonally, the availability was significantly lower in summer than winter for Kamrang and Gaddi, whereas Mamley was equally low in both seasons. Among the three springs, only Gaddi and Kamrang could support the 135 lpcd threshold, mostly restricted to the moisture-surplus monsoon months (Table 3).

Fig. 8 adapts the flow duration curve to depict the per capita availability of water from the three springs across different exceedance thresholds. The Mamley spring was able to support the minimum basic (20 lpcd) and the desired (55 lpcd) requirements of the user group on 30% and 2% of days, respectively (Fig. 8b). In Kamrang (Fig. 8a) and Gaddi (Fig. 8c), the available water was sufficient to cater to the user groups on more than two-thirds of the days of the year for the minimum 20 lpcd and less than half a year for the desired 55 lpcd requirements, and most of these days were spread across the monsoon and first half of the winter. At 1.5 times the present population, the future water demand was unmet by Mamley spring at 55 lpcd threshold and dropped to only 20% of total days at 20 lpcd threshold (present availability is at 30%). Overall, the shortfall in future per capita availability from the springs after the assumed population increase was the sharpest in Gaddi (31 ± 38 lpcd) followed by Kamrang (19 ± 19 lpcd) and Mamley (4.8 ± 5.2 lpcd).

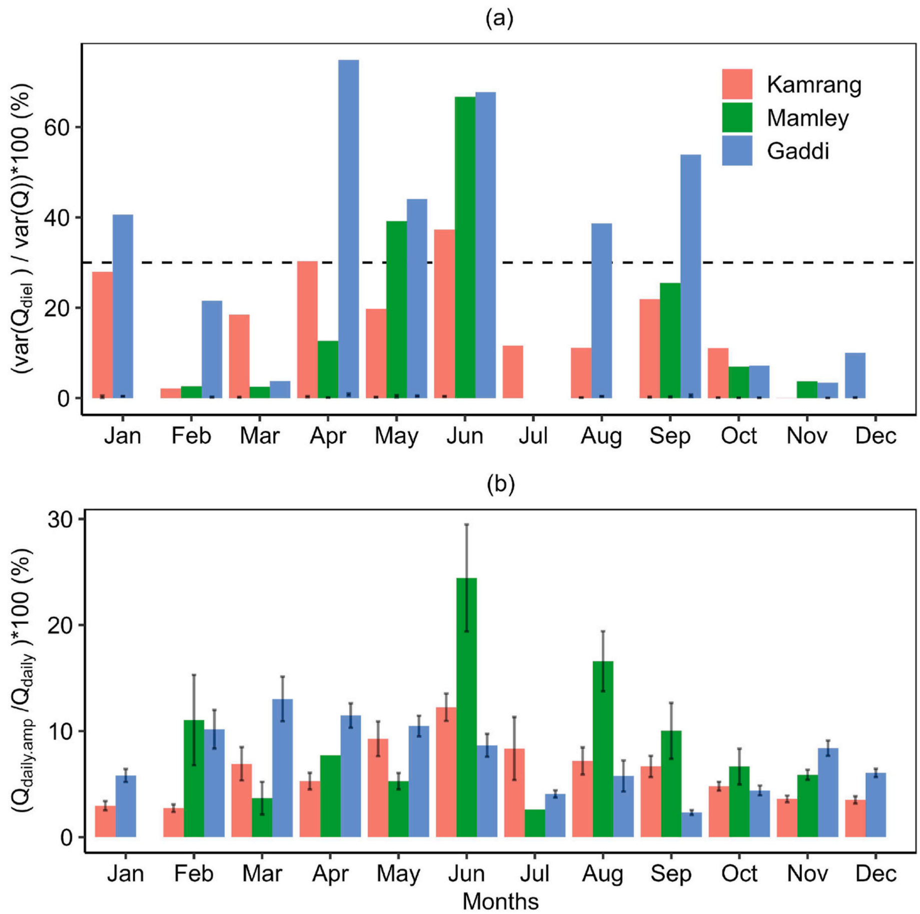

Fig. 5. Barplots show seasonal variability in (a) the variance ratio of the diel component (var (Q_{diel})) to mean discharge (var(Q), and (b) the ratio of the diel amplitude of ($Q_{daily.amp}$) to daily discharge (Q_{daily}) in the three springs. Figure takes double column width.

4. Discussion

Groundwater springs are the principal water resources in the Himalaya and are perceived as highly vulnerable to climate change (Jaunat et al., 2016), land-use modification (Duan et al., 2019; Pandit et al., 2024), road and hydropower construction activities (Droppers et al., 2014; Huber, 2019; Rai and Khawas, 2023), natural disasters such as earthquakes and landslides (Dhakal et al., 2016; Kulkarni, 2017), and exponentially increasing mountain tourism and seasonal fluctuations in hill population (Joshi and Dhyani, 2009). However, few studies have attempted to derive a mechanistic understanding of drivers and processes affecting spring behaviour in the Himalaya. In a first-of-its-kind study from the Himalaya, we use hyperlocal hydrogeological information to contextualise the high-resolution discharge analysis on three springs in a mid-elevation region of Sikkim, provide detailed evidence of aquifer properties governing seasonal discharge with considerable variability across typologies and discuss the variable impact of land-use on diel patterns in springflows across typologies. The studied springs are relatively large (5th-order) and likely supported by the high secondary porosity and the wetter climatology in Eastern Himalaya. Together, they provide water security to over 600 households in South District, Sikkim, India, and are managed by local communities.

4.1. Spring classification and typologies in the Himalaya

Most studies on groundwater springs in the Himalaya have focused on discharge-based classification (e.g. Meinzer's classification) to report 6th and 7th-order springs in relatively drier Central Himalaya (Rathi et al., 2020; Sapkota et al., 2021). The studied springs are relatively larger (5th-order), similar to reports from neighbouring Nepal (K.C. and Rijal, 2017; Niraula et al., 2021; Pandit et al., 2024) and Western Himalaya (Taloor et al., 2020), and are likely supported by the high secondary porosity and the wetter climatology in Eastern Himalaya (Kumar et al., 2021). They are also larger than most springs reported by Bartnik and Moniewski (2019) in Poland (over 50% were 7th-order) but were smaller than commonly studied karst springs in Europe (Moniewski, 2015) and the rest of the world (Bonacci, 2001; Li et al., 2017; Qian et al., 2006). Of the three springs, Kamrang (depression) showed the highest variability (C_v), followed by Gaddi (Fracture) and Mamley (Karst), which is contrary to Moniewski (2015), who reported the highest variability in fissure (fracture) and Karst springs and the lowest variability in porous (depression) springs in the Eastern Alps and Western Carpathian Mountains in Europe. However, Gaddi and Mamley showed the highest variability in lean season flow, which is concurrent with observations by Moniewski (2015). The frequency of data collection could be a factor here, as studies with monthly discharge measurements are likely to miss extreme flow events, thereby underestimating the variability across typologies (Rathi et al., 2020). Although we enumerated only three springs, the observation of relatively stable lean season flows in larger springs concurs with other reports (Bartnik and Moniewski, 2019; Moniewski, 2015). The three springs are discussed in detailed for their representativeness, typological behaviour and role of the surrounding geomorphology and LULC.

Recent springshed research has focused on answering the question, "*How many springs are present in the Himalaya?*", to establish representative patterns. Civil society organisations and government departments have partnered with local communities, at times using financial incentives, to map and document springs in Uttarakhand (~2000 springs

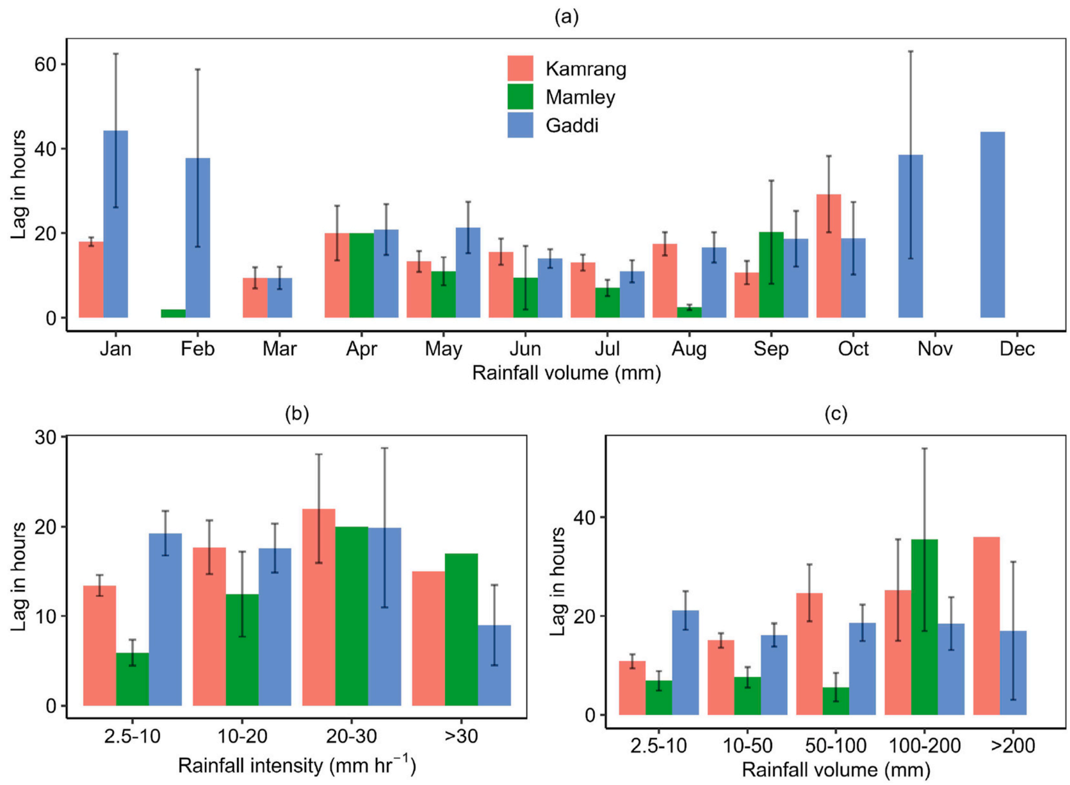

Fig. 6. Barplots showing (a) lag (in hours) between discharge and antecedent precipitation and change in lag (in hours) with (b) precipitation intensity (in mm h^{-1}) and (c) precipitation volume (in mm) across the three springs (error bars represent standard errors).

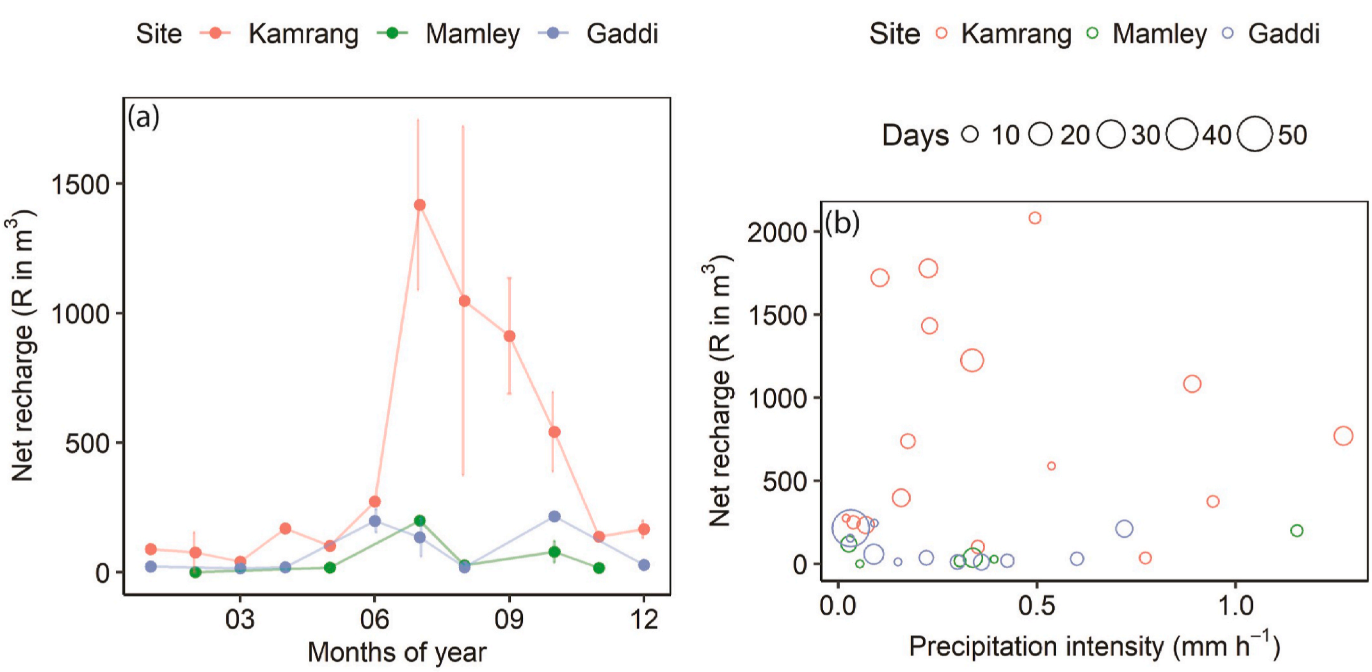

Fig. 7. (a) Seasonal patterns in net recharge (R in m^3) and (b) Scatterplot of net recharge with the antecedent precipitation intensity (in mm h^{-1}) for the three springs.

by Central Himalayan Rural Action Group, People's Science Institute, and the Himmotthan Foundation), Sikkim (~1600 springs by RMDD), West Bengal (667 springs by Prasari and the Govt. of West Bengal), Nagaland (~2400 springs by the Land Resources Department), Meghalaya (~1500 springs by the Directorate of Soil and Water Conservation, Government of Meghalaya), Nepal (1122 springs by the International Centre for Integrated Mountain Development-ICIMOD, Pandit et al. (2024)) and an overlapping pan-Indian dataset of ~600 spring by ACWADAM (Rathod et al., 2021; Siddique et al., 2019). Regional studies report considerable variability in spring densities ranging from 1.63 to

Table 3
Annual and seasonal water availability and annual water supply days (in %) at different requirement thresholds in the three springs.

Springs	Water availability (lpcd)				Annual water supply days at thresholds (%)		
	Annual	Monsoon	Summer	Winter	20 lpcd	55 lpcd	135 lpcd
Kamrang (N = 927 days)	65 ± 65	117 ± 76	18 ± 8	31 ± 15	71 ± 46	47 ± 49	13 ± 34
Mamley (N = 263 days)	14 ± 16	22 ± 18	4 ± 2	3 ± 1	30 ± 46	2 ± 14	0
Gaddi (N = 1088 days)	102 ± 115	198 ± 136	30 ± 37	41 ± 47	69 ± 46	43 ± 50	29 ± 46

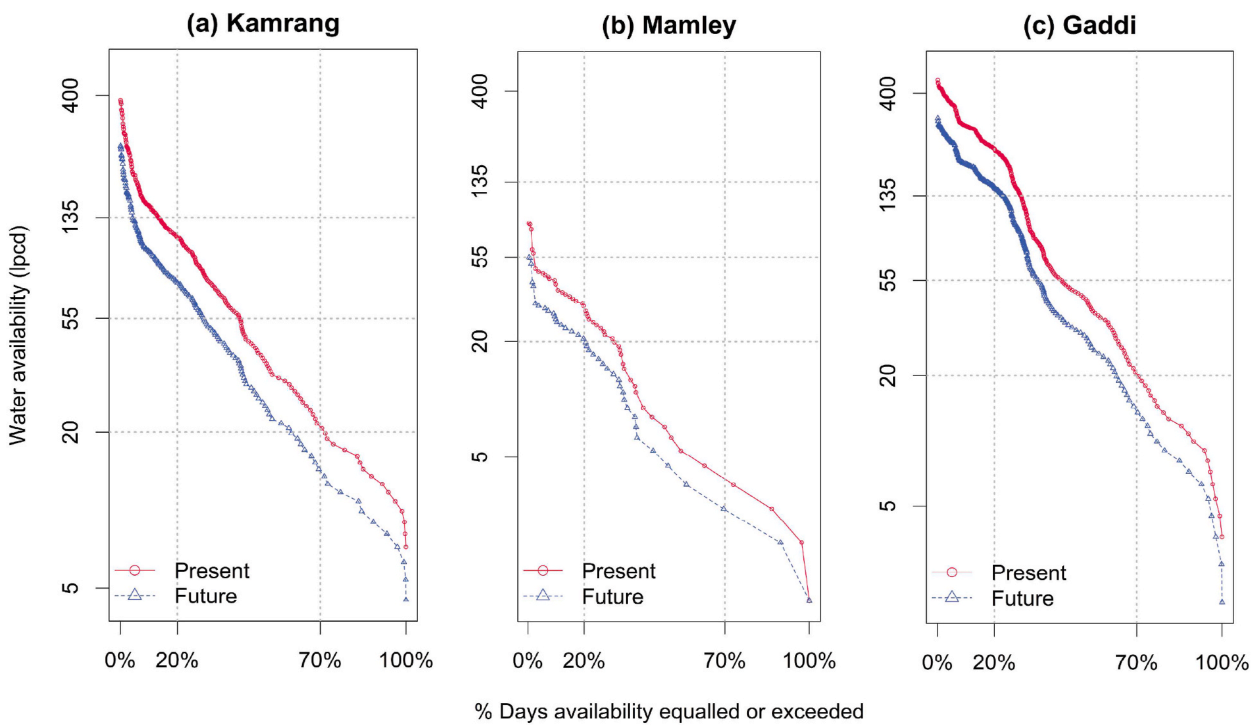

Fig. 8. Exceedance threshold curves of the three springs showing changes in per capita water availability at present (red colour) and future (blue colour) population levels at different requirement thresholds (horizontal black dotted lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.06 springs km^{-2} in the Western Himalaya (K.C. and Rijal, 2017; Pandit et al., 2024; Tiwari and Joshi, 2005) to 5–7 springs km^{-2} in Nepal (Sharma et al., 2016) and 2.5 springs km^{-2} in the Eastern Himalaya (Tambe et al., 2020), which can be crudely extrapolated to ~1–4 million springs in the Himalaya (~600000 km^2 geographical area) (NITI Aayog, 2018a). Recent advances in deep learning techniques have seen a proliferation of spring or groundwater potential mapping studies, which utilize geological and LULC maps to predict spring occurrences with varying degrees of success (Niraula et al., 2021; Pathak et al., 2021; Pradhan et al., 2021; Sapkota et al., 2021; Sheikh et al., 2022). Several studies have reported associations between spring occurrence and lithology (granite/pegmatitic rocks, Sapkota et al. (2021)), lineament density and hydro-geomorphology (Pathak et al., 2021; Pradhan et al., 2021), lithology, soil and lineament density (Sheikh et al., 2022), stream density, slope and aspect (Pandit et al., 2019), internal relief, soil and aspect (Niraula et al., 2021), and vegetation cover, lineament and drainage density, high topographic wetness (Biswas et al., 2023). However, such studies are constrained by the limited number of training and testing spring locations (30–700 points) and the lack of fine-scale hydrogeological/groundwater maps in the Himalaya.

Similarly, few studies illustrate the distribution of springs across different LULC and typologies, addressing the question, "*Where do springs occur in the Himalaya?*". Kulkarni et al. (2019) described the seasonal discharge and water availability, and hydrogeology and LULC aspects of ten representative springs in Uttarakhand, which included fracture springs with either agriculture (3 springs) or mixed forest-agriculture LULC (3 springs), a karst spring with agriculture and mixed forest-agriculture LULC each, and a fracture-depression spring under agriculture LULC. Similarly, studies report a dominance of depression springs (72%) covered by forests (50%) (Khadka and Rijal, 2020) and falling on the dip slope of the mountains (Pokhrel and Rijal, 2020) in Nepal. In the Himalaya, the rock-beds are predominantly dipping towards the NE direction, a reference to the Himalayan hogback geology (Thakur et al., 2021), and under such scenarios, the NE aspects tend to be relatively gentler in slope and more densely forested than the southern aspects. Interestingly, few spring potential mapping studies have highlighted a predominance of springs in northern aspects along the dip slope (Pokhrel and Rijal, 2020) covered with forests (Pandit et al., 2024), whereas some have reported a dominant presence in southern aspects (Dhakal and Karki, 2023; Niraula et al., 2021; Pandit et al., 2019). Some have also observed a dominance of depression and fracture springs in the northern and southern aspects, respectively, in the Central Himalaya (K.C. and Rijal, 2017). Similar to reports from Nepal (Pandit et al., 2019), in the studied region, Dhakal and Karki (2023) highlight that most springs occur in southern aspects (40%) and fall under agriculture (49%) or forest (36%), and on private (68%) and community (20%) land. The studied springs are representative of three combinations of hydrogeological typologies and LULC in Himalaya, i.e. Gaddi represents fracture (typology) and forest (LULC), Kamrang represents fracture-depression (typology) and agriculture (LULC), karst-contact (typology) and agriculture (LULC).

4.2. Springflow variability and aquifer properties in the Himalaya

Studies have used springflow analytics to identify aquifer characteristics, i.e. size, heterogeneity, longevity, and yield (storativity and transmissivity), across diverse lithologies and typologies (Bartnik and Moniewski, 2019; Mocior et al., 2014; Moniewski, 2015), dominated by karst (Amiel et al., 2010; Bagheri et al., 2016; Bonacci, 2001; Hatipoglu-Bagci and Sazan, 2014; Karami et al., 2016; Mossa et al., 2017; Qian et al., 2006), fracture springs (Cervi et al., 2014; Dass et al., 2021a; Manga, 1999; Negi and Joshi, 2004; Neuman, 2005), and depression and contact springs (Kumar and Sen, 2018a). In the karst spring at Mamley, the high C_v in the dry season and the steeper decline at the tail-end of the FDC indicate a smaller and rapidly emptying aquifer and could be attributed to the time taken to recharge the depleted aquifer. The smaller aquifer size is further affirmed by the shorter lag (a few weeks) to peak discharge after the onset of monsoon, suggesting rapid replenishment, while the flashy response indicates that the high transmissivity influences peak flows. This dual behaviour is typically associated with permeable karst aquifer systems and, in our case, is further augmented by vertical fractures. Karst springs studies have highlighted these dual or triple flow characteristics and attributed them to contributions from conduit and matrix (fracture)-based flows in heterogeneous lithologies (Amiel et al., 2010; Rehrl and Birk, 2010; Saller et al., 2013). The flashy high flows, decrease in the slope of the flow-duration curve in mid-flows, and tapering off in the low flows suggest that Mamley is being influenced by two different aquifers or a single heterogeneous aquifer with contrasting transmissivities. The two transmissivities or aquifers could be located in the upper karstic region (conduit flows) and lower fractured phyllite-quartzite beds (secondary porosity and matrix-based flow).

Modelling springs from fractured heterogeneous lithologies is challenging, especially when considering dual-porosity aquifers with linear or non-linear behaviour (Neuman, 2005; Sedghi and Zhan, 2021). Gaddi had the highest C_v in summers, indicating a combined effect of declining discharge and flash response to summer precipitation. The broken-stick-type slope curves in Gaddi typically have two segments. The relatively gentler slope in high flows suggests an absence of interference from monsoonal surface runoff and/or low transmissivity. The decrease in slope in the mid-flows, which further tapers off in the low flows, suggests that the spring is being sourced by at least two aquifers or a large heterogenous aquifer with different transmissivities (Neuman, 2005). Fracture-depression springs are known to show dual-porosity behaviour, where the high flows are influenced by the proximate secondary aquifer situated in the unconsolidated debris with low storage and high transmissivity, while the distal primary aquifer is governed by matrix-based flow-based aquifer with high storage and lower transmissivity, thus maintaining the mid-to-low flows (Kumar and Sen, 2018b; Sedghi and Zhan, 2021). The steeper slope in the very high flows in Kamrang is typical of depression spring behaviour, where the aquifer (located mainly in the unconsolidated debris) has high transmissivity and discharges rapidly after saturation (Dass et al., 2021a; Ghosh et al., 2016). The uniformly linear slope of the flow-duration curve in mid and low flows, coupled with relatively high discharge and low variability (C_v) in the dry season (winter and summer), suggest that a large homogenous aquifer feeds Kamrang, akin to porous springs observed in Eastern Europe (Bartnik and Moniewski, 2019; Moniewski, 2015).

4.3. Impact of land-use and land-cover properties on springflows

The observations of strong diel fluctuations in two out of the three springs are the first report from Himalaya. Even on a global scale, diel observations in spring flows have been rarely observed due to a lack of high-resolution monitoring of springs. Previous studies report diurnal or diel variations in springflows under tidal activity in the USA (Chicken et al., 2007; Springer et al., 2008), while few address diel variation in the physiochemical properties of spring water (Liu et al., 2007). Thus, we draw inferences on understanding diel variation in springflows from similar literature on diel variations in groundwater (Gribovszki, 2018; Gribovszki et al., 2010; Nimmo et al., 2015) and headwater streams (Kumar et al., 2024a, 2024b; McMillan, 2020; Wilcox et al., 2005). Previous literature identifies evapotranspiration as the primary driver of diel variability in stream discharge or groundwater table, along with hydrogeological controls (la Cecilia and Camporese, 2022; McMillan, 2020). Evapotranspiration-induced diel peaks are usually observed in the mornings, as in Kamrang and Gaddi (Gribovszki et al., 2010; McMillan, 2020). The shift from unimodal to bimodal peaks in summer signifies increasing hydrogeological controls, which are known to induce more than one peak in discharge (Kumar et al., 2024a, 2024b; McMillan, 2020).

Since groundwater springs are relatively less influenced by surface evapotranspiration demands (Gannon et al., 2020; Wondzell et al., 2007), a lower significance threshold for diel amplitude ratio (>20%) is recommended to understand the influence of evapotranspiration and aquifer conditions. In the studied context, the diel amplitude ratio exceeded the 30% and 20% thresholds on 16% and 29% of total days, primarily distributed in the dry season when increasing evapotranspiration demand and reducing discharge (Lundquist and Cayan, 2002; McMillan, 2020). The higher diel fluctuations in Kamrang seem to be due to the shallow-unconfined nature of the depression-based aquifer, which closely interacts with the overlaying agricultural land-use. The riparian zone of the Kamrang spring outlet has several trees, which could further induce diel patterns in discharge (Wilcox et al., 2005). The diel amplitude is higher in the monsoon season when the water table is high and much closer to the surface, allowing for upward movement of groundwater through capillary action. Conversely, Mamley shows low diel fluctuations owing to the higher transmissivity and low storage, which remains relatively unaffected by ET. Interestingly, Gaddi shows higher diel amplitudes in pre- and post-monsoons. Gaddi has a densely forested catchment dominated by secondary broad-leaved tropical montane forests (Bhutia et al., 2019; Kanade and John, 2018). Thus, it is highly likely that the observed diel cycles in Gaddi are induced by forest-transpiration cycles, especially in the lean season. Kumar et al. (2023a) observed significant nocturnal and pre-dawn uptake of water by oak trees in Sikkim, and Kumar et al. (2024a) provide evidence of transpiration inducing diel cycles in headwater streamflow, which together could explain the observed early-morning troughs Gaddi springflow in the summer. The seasonal peaks in diel amplitudes of spring also matched with periods of high forest productivity in Eastern Himalaya, suggesting vegetation-driven evapotranspiration tapping into groundwater (Mishra and Mainali, 2017; Sebastian et al., 2019). Similarly, the bimodal pattern in Mamley and Kamrang seems to be driven by the presence of rainfed agriculture, which peaks with the rabi crop in spring (March–May), followed by a dip in the fallow period in Summer (May–July) and again peaks with the Kharif crop at the end of monsoon and autumn (September–October) period (Singha et al., 2016). Thus, it is very likely that, despite being groundwater-sourced, springs are still significantly influenced by vegetation-based water uptake and/or evaporative demand, and the LULC influence is not restricted to infiltration and recharge rates, as previously imagined but extends to aquifer-vadose zone-surface interactions. Here, it is important to note that the presence of dense and potentially groundwater-accessing vegetation in the recharge zone (more likely to be in the upper part of the catchment) of spring will have a different impact (longer drawdown and slower recovery of diel peaks) than the presence of vegetation in the discharge zone near the spring outlet (faster drawdown and recovery). In the discharge zone, dense vegetation is likely to induce diurnal cycles in spring discharge, as seen in Kamrang and Gaddi, whereas the vegetation in the recharge zone will influence the groundwater recharge through interception and regulating soil hydraulic conductivity, and precipitation-discharge response times (Doležal and Kvítek, 2004; Ghosh et al., 2016; Hosseini et al., 2017).

This is further illustrated by the observed lag in spring discharge after precipitation, which depends upon land-use properties like saturated hydraulic conductivity (K_{sat}) (Fiorillo et al., 2007), aquifer properties like transmissivity (Bonacci, 1993; Jeelani et al., 2021; Zhang et al., 2013) and antecedent storage conditions (Memon, 1995; Winston and Criss, 2004) and precipitation characteristics such as intensity and volume (Krishnaswamy et al., 2012, 2013). The overall lag time in the karst spring (Mamley) was half of the fracture (Gaddi) and depression (Kamrang) spring, suggesting a bigger role of typology than land-use, although the role of soil hydraulic conductivity (K_{sat}) remains critical. Although both Kamrang and Mamley had agricultural land-use with high K_{sat}, the soil horizon and clay percentage in Mamley was much lower than in Kamrang. Despite high soil organic content and porosity, the forest-dominated catchment of Gaddi had extremely low K_{sat} due to a higher proportion of clay in the topsoil (personal observation). The short lag time in Mamley in response to precipitation is typical of karst springs (Zhang et al., 2013) and is explained by the moderate K_{sat}, low soil depth, and high transmissivity of the karstic head, whereas Kamrang exhibited a longer lag at marginally higher K_{sat}. Apart from very low K_{sat} and net recharge volume, the longer lags in Gaddi could also be attributable to lower transmissivity. Bonacci (1993) reported higher lag time in schists than in karst aquifers). Interestingly, the lagged response of springs to precipitation intensities and event volume contrasted between different land-use. The forest-catchment spring Gaddi showed a faster response at higher precipitation intensities (>30 mm h^{-1}) but was not affected by the change in event volumes. Conversely, the agriculture-based springs (Kamrang and Mamley) showed the lowest lags at low-moderate intensities (<20 mm h^{-1}) and event volumes (>50 mm). Studies have reported a positive impact of long-duration and low-intensity events on springflow (Huang et al., 2006; Li et al., 2017) than intense events (Fiorillo and Doglioni, 2010), most of these being restricted to karst springs. This study is one of the first explorations of precipitation-springflow lags in relatively slower fractured or porous groundwater media with contrasting LULC.

As stated earlier, the lag time also depends upon the net recharge to the aquifer. In turn, the recharge potential of a spring, i.e. the ability to recharge after a precipitation event, is governed by soil properties (e.g. K_{sat}, epi-karstic vertical openings) and precipitation characteristics (Fiorillo et al., 2019; Ghosh et al., 2016; Trcek and Zojer, 2009). Studies have estimated net recharge to spring aquifers using tracer and natural isotopes (Busenberg and Plummer, 2014; Jeelani et al., 2010; Tambe et al., 2020), mass balance (Schindel et al., 1995), and discharge recession analysis (Korkmaz, 1990; Kumar and Sen, 2018b). The recharge estimates tend to have a degree of uncertainty introduced by leaking aquifers which may straddle two watersheds or basins with significant inter-basin transfers (Frisbee et al., 2016; Tambe et al., 2020; Verma and Jamwal, 2022), and indirect estimations of storage and transmissivity in the absence of direct pump-tests. In the absence of isotopic data, we relied on discharge analysis to estimate net recharge to the aquifer and linked it to precipitation characteristics (intensity and volume), LULC (K_{sat}), and aquifer properties. The depression spring (Kamrang) showed consistently higher recharge volumes for similar precipitation events than the karst (Mamley) and the fracture-depression (Gaddi) springs. Kamrang showed high recharge potential across the range of precipitation intensities and volumes facilitated by the high secondary porosity and thus would be more vulnerable to changes in LULC affecting K_{sat} than to climate variability (e.g. precipitation intensification). Conversely, net recharge in the karst spring (Mamley) was constrained by its relatively smaller size and high transmissivity, making it the most vulnerable to increasing climate variability and precipitation intensification (Zhang et al., 2024a,b), as Ghosh et al. (2016) observed in the USA. In Gaddi, net recharge was highest at mid-intensity-long-duration events, beyond which it plateaued. The threshold effect could be due to the low K_{sat} observed in the Gaddi catchment, which does not facilitate an extra increase in infiltration at high intensities and volumes. Although the net recharge volume was a magnitude higher than a much smaller fracture-depression spring, the seasonality of recharge was similar to the observation by (Kumar and Sen, 2018b) in Central Himalaya. In South Sikkim, Tambe et al. (2020) used isotope data and household surveys to observe a strong dependence between precipitation and spring recharge. Thus, any extreme intensification of precipitation in the Eastern Himalaya is likely to disproportionately impact smaller (>5th-order) karst and fracture springs.

4.4. Water availability, demand, and springshed management in the Himalaya

The recent focus on spring recharge or rejuvenation, be it academic, civil society, or government efforts, is closely tied to the public perception of diminishing discharge and spring numbers in the Himalaya (Kumar et al., 2023b; NITI Aayog, 2018a). As discussed earlier, there is limited information on the actual number of springs in the Himalaya, and any information on historical water availability remains primarily localized to communities (Kumar et al., 2023b; Pandit et al., 2024). Based on community surveys and seasonal discharge measurements, studies have reported 45–75% of perennial springs going seasonal or drying up in the last 50 years in Uttarakhand (Kumar, 2009; Pant and Rawat, 2015; Valdiya and Bartarya, 1991), a 73% and 30% decline in spring discharge in Western and Central Nepal, respectively (Chapagain et al., 2019; Pandit et al., 2024) and linked the long-term decline in spring discharge with rural poverty in Sikkim (Barua et al., 2014). The decline in Himalayan springs has been attributed to changes in precipitation patterns (Chakraborty et al., 2019; Macchi et al., 2015) and land-use (forest to agriculture, Joshi et al. (2013); Kumar (2009); Pant and Rawat (2015)), forest transitions (mixed-oak forests to pine forests, Ghimire et al. (2014); Naudiyal and Schmerbeck (2017)) and infrastructure development (roads and hydropower, Huber (2019); Mukherji et al. (2018)). However, In the absence of high-frequency long-term monitoring data on springflow, the existing knowledge on the decline in Himalayan springs heavily relies on public perceptions and the living memory of the user communities (Barua et al., 2014; Sen et al., 2021; Tambe et al., 2020), and few studies have documented long-term springflows, e.g. (Kumar and Sen, 2018b) use hourly spring discharge data to report a decline in discharge from Uttarakhand. The Central Ground Water Board, the designated groundwater monitoring institution in India, reports only 6% groundwater extraction in Sikkim based on recharge estimates from groundwater wells, and spring monitoring is restricted to water chemistry only despite acknowledging that springs are a primary source of water in the state (Central Ground Water Board, 2022).

Per capita water availability and household-level water supply coverage are useful proxy metrics for understanding spring decline from the end user's perspective (REAL-Water, 2023; Tambe et al., 2013). Two decades ago, People's Science Institute (2003) reported that less than 22% of the sampled villages and 15% of the hill towns in the Western Himalaya (Himachal Pradesh and Uttarakhand) could access the minimum 20 lpcd target. Reeling under tourism pressures, the neighbouring Darjeeling town is able to supply only 29 lpcd, out of which 50–60% is supported by various springs (Shah and Badiger, 2020), whereas Bharti et al. (2020) report 27–80 lpcd supply from springs and streams in two hill towns of Uttarakhand. In the studied region, Tambe et al. (2013) reported a decline of >50% in the lean season discharge of 42% of sampled springs and streams (N = 151), resulting in a 30% decline in per capita water availability for 109 households based on community surveys, with higher impacts on springs and people living near the ridgeline than the valley. Later, Tambe et al. (2020) reported a three-fold increase in dependent households and a 25–111% increase in discharge of three springs against baseline after a springshed management effort in South Sikkim. The Government of India also reports a 66% increase in the rural households in Sikkim with home-supply of water under the Jal Jeevan Mission, a pan-India rural water security programme by the Ministry of Jal Shakti, which is designed to provide a minimum 55 lpcd water availability (Ministry of Jal Shakti, 2023). While, the study shows that the existing springs are unable to provide sufficient water supply to the dependent communities, in regions with low population density, the competition for water resources is lesser, and communities augment the water supply by tapping multiple primary and secondary springs and streams (RMDD, 2011a, 2011b). The overall narrative of decline in spring discharge and numbers remains consistent across the Himalaya (Khadka et al., 2019; Kumar et al., 2023b; Pandit et al., 2024; Rani et al., 2022).

Springs are an integral part of Himalayan communities, and the societal implications of the decline in spring water availability are being observed across key SDG goals, i.e. human health (SDG 3 and 6), socioeconomic growth (SDG 1 and 11), and local culture (SDG 5 and 10) (Guppy et al., 2018; Kumar et al., 2023b). While springshed management has focused on improving discharge and access, the issue of deteriorating water quality has been relegated to source protection efforts. Future research should carefully look at the sources of spring pollution (chemical, biological and ECs) under springshed management efforts to fulfil SDG (3 and 6) targets (Matta et al., 2022; Singh et al., 2019; Tiwari, 2012). The decline in springs and headwater streams has resulted in a loss of agricultural productivity, livelihoods, and net migration from the villages to urban hill towns (Adhikari et al., 2021; Dhakal et al., 2016). Simultaneously, the seasonal influx of tourists and associated urbanization pressures have stretched the water supply to its limit (Joshi and Dhyani, 2009; Kovács et al., 2019). Himalayan urban and rural hillscapes are staring at an acute water crisis and require an integrated springshed management approach combining supply and demand management, sustainable ecotourism practices and sewage management to achieve SDG (1 and 11) targets (Bharti et al., 2020; Shah and Badiger, 2020). The cultural aspects of springshed management manifest in terms of gender and caste in Himalaya and remain poorly studied (Kumar et al., 2023b). In most mixed-caste villages, access to nearby springs is controlled by the *upper* or dominant caste and the *lower* castes (Dalit) communities have to rely on distant springs (Khadka et al., 2019; Sen and Kansal, 2019). Thus, lower castes are disproportionately affected by the decline in spring discharge and venture out far to supplement their water requirements (Guram, 2020; Tsering, 2014). Women bear this burden disproportionately compared to men and have to travel farther to fetch water on their heads (Khadka et al., 2019; Risko, 2018). Despite springs being revered as a manifestation of the divine goddess (Risko, 2018), spring decline is often attributed to impurification by women (during menstrual periods) and Dalits (Joshi, 2011; Joshi and Fawcett, 2001). Although springshed management efforts have focused on engaging with women groups, the caste dynamic still influence the selection of springs for revival, thereby perpetuating the embedded inequalities (Kumar et al., 2023b; Sen and Kansal, 2019).

The Government of India (GoI) has recognized spring revival as central to sustainable resource management in the Himalaya, explicitly aiming at SDGs 6, 13 and 15 for water and SDGs 4 and 8 for skill development of the para-hydrogeologists (NITI Aayog, 2018b). The recently released annual SDG index 2023-24 by the GoI reports significant progress on SDG 6 by the Himalayan states (80–97% score), with Sikkim reporting improved water sources (100%) and adequate water availability (89%) in the rural areas (NITI Aayog, 2023). Springshed management programmes, such as the *Dhara Vikas* in Sikkim, are at the core of the reported improvements with positive impacts across different geographic and socio-cultural settings (NITI Aayog, 2018a,b; Kumar et al., 2023b). The impacts are documented through changes in discharge, preferentially of the lean season, improvement in water quality, and improved year-round access to the user group. In the absence of long-term data on spring discharge, water quality, and microclimate, most impact assessment studies rely on monthly or seasonal discharge data (Kumar et al., 2023b; Tambe et al., 2020), whereas a few have used daily soil moisture and discharge measurements to report a reduction in recession slope of a treated spring in comparison to a nearby untreated one in Nepal (Rani et al., 2022). An impact assessment study in Nagaland used fortnightly discharge and precipitation data collected by para-hydrogeologists to report an increase in discharge of 77% of treated springs (N = 26) against 43 control springs (untreated, 65% showed no change) (Sen et al., 2021). However, in the absence of a periodic baseline, it is difficult to assess the true impact of springshed activities. It is recommended that future discharge-based impact assessments of springshed programmes should be backed by at least bi-monthly or monthly data (baseline and post-implementation) on discharge and precipitation to account for changes due to climate variability (Kulkarni et al., 2010; Sen et al., 2021; Siddique et al., 2019). Automated or high-frequency monitoring should be coupled with community-led citizen science initiatives for large-scale and long-term spring monitoring. We also need to reevaluate the efficiency of and adapt the existing soil and water conservation measures for targeted recharging of shallow groundwater (NITI Aayog, 2018a,b; Kumar et al., 2023b; Rani et al., 2022; Rathod et al., 2021).

5. Conclusions

In a first-of-its-kind study from the Himalaya using high-resolution discharge data, we analysed springs using ecohydrological and aquifer-based approaches to understand their characteristic behaviours in reference to the spring typologies. We summarise that Kamrang is a high-discharge depression spring with stable low flows fed by a homogenous aquifer with high transmissivity. Mamely and Gaddi showed dual-flow characteristics attributed to conduit and matrix (fracture)-based flows, and unconsolidated secondary aquifer and matrix-based primary aquifer, respectively. Land use has a significant impact on diel fluctuations in springflows as well as the infiltration rates, which further affects net recharge to the aquifers. We provide the first reports of strong diel fluctuations (>20% diel amplitude ratio) in springflows controlled by catchment and riparian evapotranspiration in Kamrang and Gaddi. Shorter lags between precipitation and springflow in the karst spring than fracture and depression suggest typology predicts water transit time better than land-use, which controlled soil infiltration rates alongside precipitation characteristics. The depression spring (Kamrang) showed relatively higher net recharge potential than karst and fracture springs. Thus, any extreme intensification of precipitation is likely to impact the >5th-order karst and fracture springs disproportionately, whereas depression springs are more vulnerable to LULC changes in Eastern Himalaya. Lastly, the three springs could barely support the minimum (20 lpcd) and mandated (55 lpcd) water supply requirements for 30–70% and 2–47% of days a year, respectively.

While in no way complete and conclusive, this study is a step forward in improving our understanding of groundwater springs in the Himalaya and other tropical mountains. We address the existing knowledge gaps on Himalayan springs by providing detailed evidence of aquifer properties governing seasonal discharge with considerable variability across typologies. It also illustrates the benefits of high-frequency spring monitoring using automated flumes (for *dhara*-type springs) or stilling wells (*naula* and *khola*-type springs), which, along with microclimate and precipitation datasets, can provide valuable insights into the aquifer properties, its responses to land-use and precipitation across typologies. We use an integrated analytical framework for understanding Himalayan springs, which are critical for achieving SDG 6 (access to clean water) through springshed management actions suited to the governing ecosystems (SDG 15) and adaptive to future climate change impacts (SDG 13). The study will also act as a baseline for understanding the impacts of springshed management programmes and developing appropriate springshed and regional-level ecosystem services models for predicting future water security challenges in the Eastern Himalaya.

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Data sharing

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions. A sample subset of the data that support the findings of this study is available on Dryad at https://datadryad.org/stash/share/NzJX2CsGaTfukml1hVGcfu_i2fHXimLQJ3hFYhtcV-I.

CRediT authorship contribution statement

Manish Kumar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sumit Sen:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Himanshu Kulkarni:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Shrinivas Badiger:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Girish R. Varma:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Jagdish Krishnaswamy:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix ASupplementary data

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