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Depleting spring sources in the Himalayas: Environmental drivers or just perception?

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ABSTRACT

Study region: Rangun Khola Watershed, Mahakali River Basin, Far Western Nepal.
Study focus: We mapped and examined the status of 1122 springs in a typical mid-hill watershed in the Sudurpaschim Province of Nepal. Land use/cover trajectory analysis, quantification of climate change indices, analysis of spring flow trends and community perception were used to understand the changing dynamics of the mountain springs.
New hydrological insights: 73% of the springs show a continuous declining trend in flow, with 2% already dried up. Land fragmentation between 1990 and 2018 due to the conversion to agricultural land causes landscape disturbances in the spring vicinities, affecting natural spring flows. Climate data assessment revealed a significant increase in temperature and frequency of localised high-intensity rainfall. Local climate and land use change are concurrent with drying spring sources and consistent with the local community's perceived manifestation of changes. Moreover, the growing population and haphazard rural road expansion are overexploiting and disturbing the spring resources. Drying spring sources are leading to implications on water availability and accessibility for livelihood activities, exacerbating gendered vulnerability to climate change. However, the government and local households are lagging in taking direct actions to mitigate the problem, increasing the likelihood of critical long-term consequences for the ecosystem and the local economy in Rangun Khola and similar watersheds in the Himalayas.

1. Introduction

The snow and glacier-fed rivers flowing from the Himalayas provide water to more than 1.4 billion people in South Asia and are lifelines for the Hindu Kush Himalayan region (ICIMOD, 2009; Immerzeel et al., 2010). Many upstream mountain communities depend on natural springs to meet household and agricultural demands (Chapagain et al., 2019). Therefore, springs are crucial sources of water for drinking and sanitation for mountain communities (Negi and Joshi, 2002). Springwater, serving over 40 million people in the Himalayas (Mahamuni and Kulkarni, 2012), occupies a significant portion of the Himalayan water budget (Bookhagen and Burbank, 2010; Andermann et al., 2012). In Nepalese mountain watersheds, the contribution of groundwater from fissured aquifers is even significantly higher than runoff from high-altitude snowfields and glaciers for community use purposes (Andermann et al., 2012).

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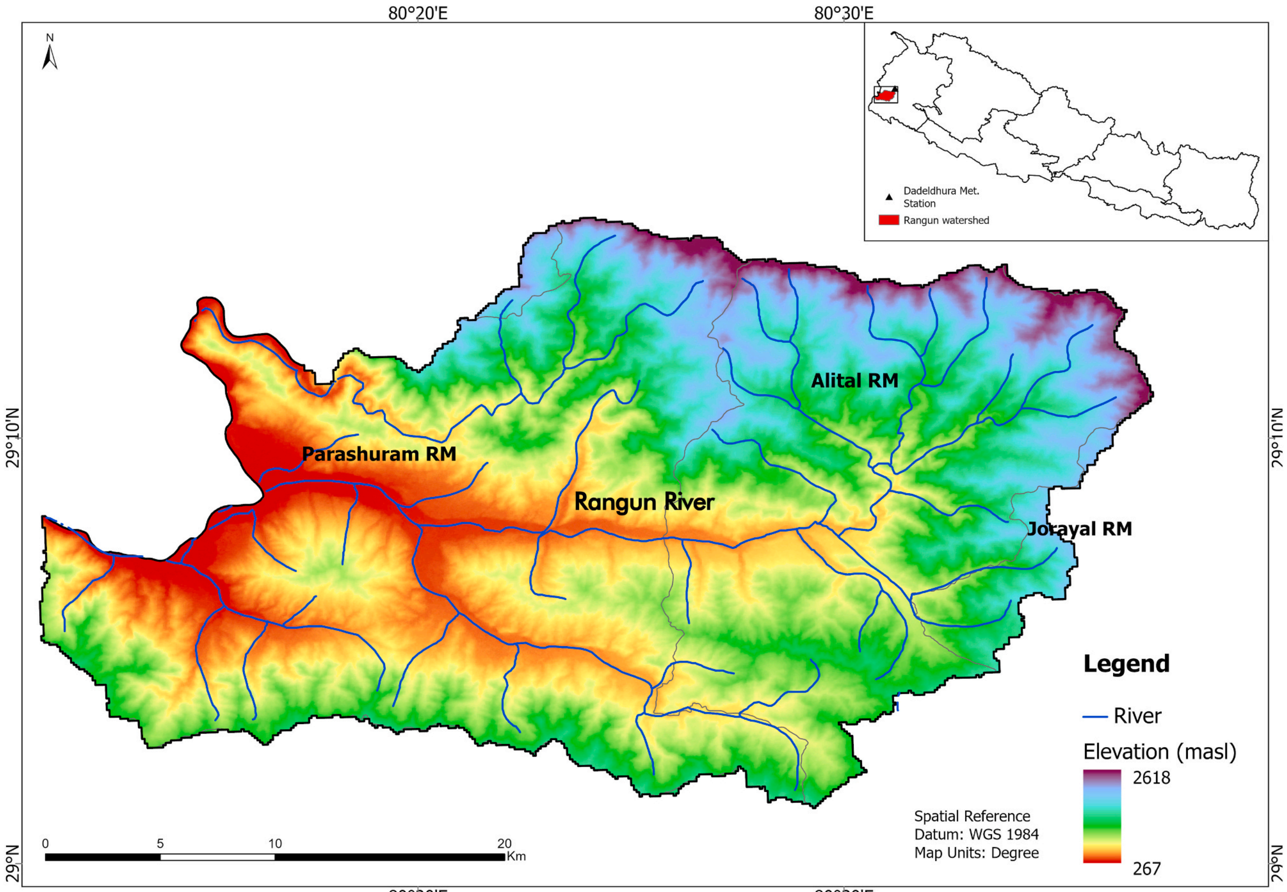

Fig. 1. Location and elevation of the Rangun Khola watershed in the far western part of Nepal, with indicated location of three rural municipalities (RM).

Springs are not only instruments for fulfilling water demands; they are essential for biodiversity and are considered an integral part of cultural and spiritual beliefs in mountain communities (Tambe et al., 2012). Given the tremendous ecological and societal significance of the freshwater springs in the mountainous regions of the Himalayas, they should receive adequate attention for research and conservation actions aiming for sustainability.

Mountain springs flowing under gravity are fed mainly by precipitation (Sharma et al., 2016) and discharge from unconfined aquifers (Tambe et al., 2012). Therefore, springs are strongly influenced by seasonal changes in precipitation (Fiorillo, 2009), land use-land cover (LULC), vegetation cover, soil characteristics, and geomorphology (Valdiya and Bartarya, 1989; Negi and Joshi, 2004). Recent research on the sustainability of springs in the Himalayas has reported that the synergetic effect of multiple anthropogenic activities, together with biophysical and social factors, have caused changes in the flow dynamics of water resources in mountain aquifers (ICIMOD, 2015; Dass et al., 2021). Among the drivers of these changes are haphazard infrastructure development and associated changes in LULC, which are leading components in disturbing the hillslope hydrology and contributing to catchment degradation in the fragile mountain watersheds (Reisman et al., 2017; MoPE, 2017).

Changing geomorphology triggered by earthquake events imposes negative pressure on the spring sources in the mountain areas (Ghimire et al., 2019). Moreover, climate change is adding further uncertainty to the changing flow regime of these lifelines of the mountains (MoPE, 2017; Nepal et al., 2021; Sharma et al., 2019). The accumulated impacts of these dynamic factors in a mountain environment may result in a temporary alteration in the flow regime, which may change the quantity of flow as well as the timing, duration, and seasonal pattern of ecologically important flow events (Tambe et al., 2012; Mahamuni and Kulkarni, 2012; Agarwal et al., 2012) or may even cause a natural spring to dry up permanently (Agarwal et al., 2014).

Research in the eastern and western Himalayas has helped to clarify the present status and implication of changing natural spring dynamics (Negi and Joshi, 1996, 2002; Negi et al., 2007; Poudel and Duex, 2017; Gurung et al., 2019; Adhikari et al., 2021). Studies in the Indian Himalayas and the central and eastern Nepal Himalayas have reported declining spring flow in the mountain areas, which they attributed to the cumulative effects of changing climate (e.g., significantly increasing temperature, altered precipitation patterns) with associated physical and social factors of environmental change (ICIMOD, 2009, 2015). Overall, research has increasingly focussed on determining the causes and consequences of declining water flows and drying spring sources in mountain pockets, which is indicative of the importance and urgency of gaining a better understanding of this issue (Negi and Joshi, 2002; Tambe et al., 2012; Agarwal et al., 2014).

Documenting the status of natural springs is the basis of future research and development of water management strategies in the region (WECS, 2011). Earlier studies have raised concerns about drying springs and highlighted the increasing water crisis in western Nepal (Gurung et al., 2019; Adhikari et al., 2021). Nevertheless, occurrence, distribution, and change dynamics are poorly understood, leading to a gap in the current understanding of spring dynamics in some pockets of the Himalayas, particularly in western Nepal (Negi and Joshi, 2002; Chinnasamy and Prathapar, 2016).

Consequently, knowledge is inadequate to support a holistic picture of sustainable water resource management in these regions (Alford, 1992; Bruijnzeel and Bremmer, 1998; Sharma et al., 2016; Chapagain et al., 2019). Scientific evidence-based policy responses are crucial for sustainable spring watershed management (Mahamuni and Kulkarni, 2012). However, questions on spring dynamics

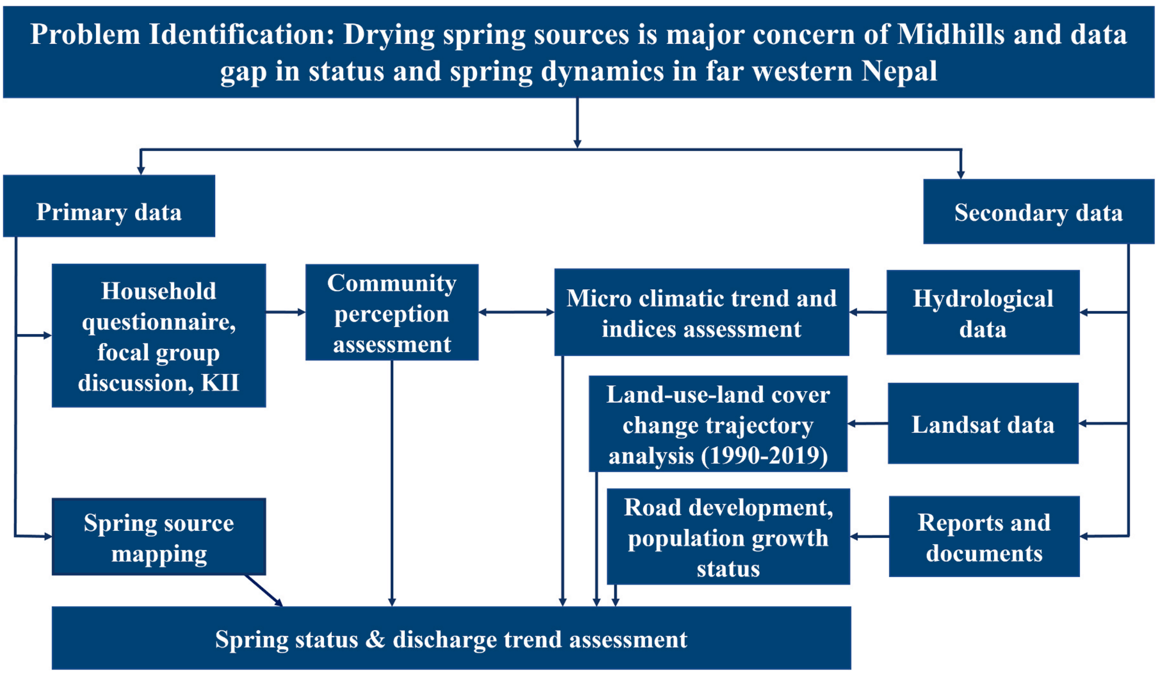

Fig. 2. Methodology framework (KII: Key Informant Interview).

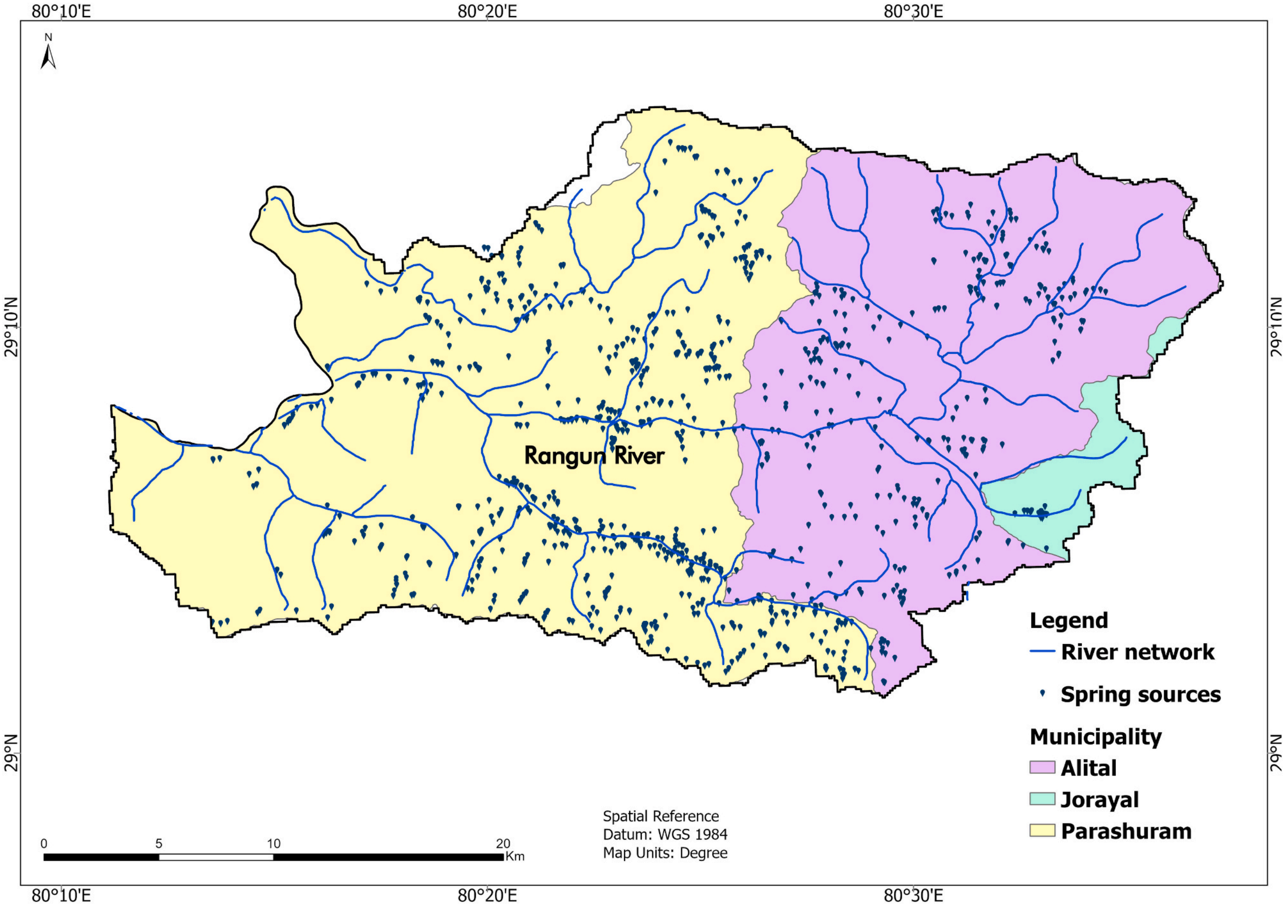

Fig. 3. Location of municipalities and spring sources mapped in the Rangun Khola watershed.

relating to microclimatic variation, LULC change perspectives, and sociohydrology, remained unanswered (Adhikari et al., 2021). Since the hydrological system is an example of interconnected biophysical and social processes, including climate variability, water use, infrastructure, and LULC, the study of springs demands an interdisciplinary approach (Vogel et al., 2015).

The overall objectives of this study are to understand changing spring water dynamics and the implications for the population of the Rangun Khola watershed located in western Nepal (Fig. 1). The specific objectives are i) to assess the spring water availability and trends, ii) to understand the watershed's environmental aspects (LULC change, climatic pattern), and iii) to study the implication of changing spring water dynamics on the local community in the Rangun Khola watershed.

2. Study area

The Rangun Khola watershed in the Mahakali River Basin is located in the Sudur Paschim Province (Fig. 1) and feeds into the Ganges Basin in South Asia. It occupies an area of 687 km^2 and ranges in elevation from 253 m to 2605 m (Fig. 1). The Rangun Khola is the major river in the watershed, which is fed by 135 tributaries along its course. The watershed falls mostly in the Dadeldhura district (Parashuram municipality and Alital rural municipality) and occupies a small portion of the Jorayal rural municipality in the Doti district (Fig. 1).

The climate of the study area ranges from a tropical climate in the south to a warm temperate climate in the north (Paani, 2019). The 30-year average annual rainfall of the Dadeldhura station (station index: 104) between 1989 and 2018 is 1330 mm, with July as the wettest month and November as the driest month in a year. The average temperature varies strongly with the altitudinal gradient, between 10°C to 25°C. The steeply sloping topography of the watershed and high rainfall make it susceptible to floods, landslides, and river cuttings. The population of 53,514 people represents a rich ethno-linguistically diverse community with 75.9% Brahmin Chhetri Thakuri Sanyasi, 8.8% Indigenous Janajaati and 15.3% Dalit minority groups (CBS, 2011).

3. Methodology and data

The framework for the methodology is presented in Fig. 2. Both primary and secondary data were analysed to assess the status of springs, trends in spring discharge, analysis of peoples' perceptions, changes in climate and LULC.

3.1. Spring source mapping

Mapping spring sources is one of the first stages of a scientific and participatory strategy and methodology based on a tailored step protocol for spring revival (Shrestha et al., 2018). The latitude, longitude, and altitude of 1122 springs were mapped with a Global Positioning System (GPS) by a team of on-the-ground experts and trained citizen scientists and imported into a Geographical Information System (GIS) (Fig. 3). The details of each spring, including location, aspects, type, surrounding environment, use, dependency, flow rate, and trend, were collected using a mobile application, with a structured questionnaire designed with the Kobo Toolbox (https://www.kobotoolbox.org/). In 2018, the spring discharge was estimated using the bucket method (761 springs), surface floatation method (33 springs), and level drop method (328 springs).

The bucket method is a simple way of measuring flow in very small streams or springs using a fixed-volume (20 L) bucket. The entire flow is diverted into a bucket, and the time for the container to fill is recorded. The flow rate is obtained simply by dividing the volume of the bucket by the time taken to fill it. The process was conducted three times, and the average value was used (Adhikari et al., 2021).

The level drop method is used to measure the discharge of stagnant springs (ponds, wells, etc.) by taking the dimensions of the springs (length, width and depth) and water level marking. The discharge is measured by removing a certain known volume of water and noting the time to refill the volume of water from the spring (Adhikari et al., 2021).

The surface flotation method, used for calculating the flow rate of the open channel stream/springs, multiplies the cross-sectional area of the channel by the average velocity of the water. The cross-sectional area can be calculated by the direct measurement of the channel dimension, whereas the water velocity can be approximated by the time required for an object floating on the water to traverse a measured section of the channel (Adhikari et al., 2021).

To analyse the historical discharge of springs the recall method was applied for different time slices over the last 20 years. The recall method investigates cognitive processes by engaging participants in recalling their concurrent memory of past practices. It is a well-established methodology used in other research in diverse contexts and locations where there is a shortage of long-term observational data (Allahyari et al., 2016; Osgood et al., 2018). In this study, the historical experience of the time taken to fill a 20 L vessel of particular springs was documented. The spring estimated discharge in three intervals, i.e., 20 years, 10 years, 5 years ago, were documented and compared with the base year (2018) spring discharge (Adhikari et al., 2021).

The data obtained from all the methods (bucket, surface float or level drop) were applied to determine the spring flow rates. These assessed flow rates (2018) were used to determine the changing spring flow dynamic in the Rangun Khola watershed and cross-validate the community perception.

The springs were classified based on flow rate following Meinzer (1923), which consist of eight different classes: 1st >10 m^3/s, 2nd 1 –10 m^3/s, 3rd 0.1–1 m^3/s, 4th 10–100 l/s, 5th 1–10 l/s, 6th 0.1–1 l/s, 7th 0.01–0.1 l/s, 8th <0.01 l/s.

3.2. Household perception assessment

A questionnaire survey of 232 households distributed over the three municipalities of the Rangun Khola watershed (Fig. 4) was conducted by the USAID Paani program in 2018. It was used to gain the perception of the Rangun Khola watershed communities concerning water source management and issues (Paani, 2019). The questionnaire had three sub-sections of questions on livelihood, drying water sources, and community perception of climate change. Each sub-section included 10–20 multiple-choice questions. Questionnaires were applied to collect household-level information. First, the identification of the places experiencing problems with drying up water resources was aided by a multi-stakeholder consultation conducted at the watershed and municipality levels. Next, using a basic random sample technique, a home questionnaire survey was conducted in designated sites along the Rangun River stretch. Data from household surveys documented information on household dependency and accessibility to water sources, the perceived implications of changing water availability, and climate change variability. Simple statistics such as mean, standard deviation, frequency, and range were calculated using MS Excel for community perception assessment.

3.3. Hydrometeorological trend analysis

Due to the absence of a meteorological station within the watershed, daily precipitation and temperature data from 1980 to 2018 were obtained from the nearest meteorological station (25 km distance) located in Dadeldhura district (Station index 104). The Hargreaves method was used for potential evapotranspiration calculation (ETo) (mm) (Eq. (1)) (Hargreaves and Samani, 1982).

$$ETo = KET*RA*(T+17.8)*TD^{0.5} \tag{1}$$

Where

KET = the Hargreaves method's empirical coefficient equal to 0.0023
RA = mean extra-terrestrial radiation (MJ/(m^2 day))
TD = difference between the maximum and minimum temperature (°C).
T = mean average temperature (°C).

Monthly precipitation, temperature, evapotranspiration, and net rainfall data (P-ETo) were used for annual and seasonal time-

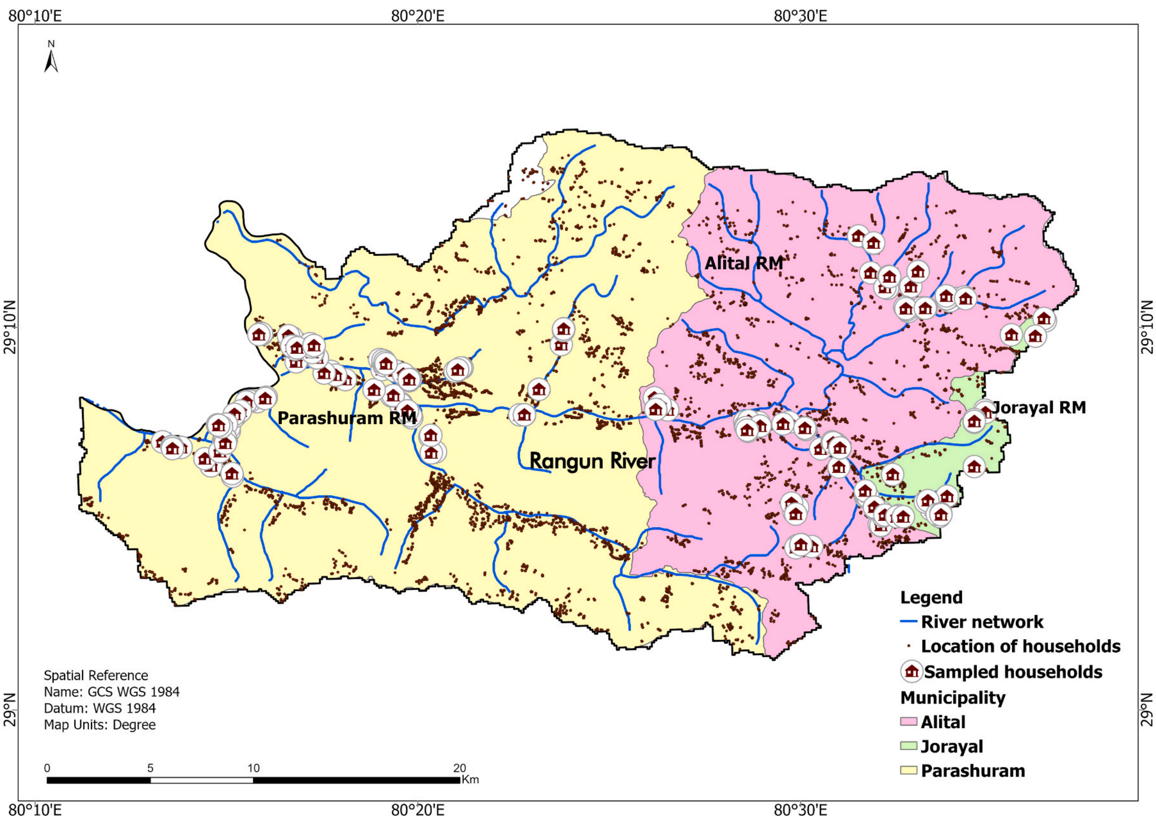

Fig. 4. Location of households and households surveyed with a questionnaire on water source management and issues.

series non-parametric Mann-Kendall trend analyses with the R WQL package (Mann, 1945; Khatiwada et al., 2016; Nema et al., 2018; Silwal et al., 2020). Climate indices (Table 1), derived from precipitation and temperature data, were analysed with the RclimDex program as analytical tools for understanding climate variability (Zhang and Yang, 2004; Deniz and Gönençgil, 2015). The first nine indices (Table 1) are temperature-based, while the remaining seven are precipitation-based.

3.4. Land use-land cover trajectory analysis

Change in LULC plays an important role in groundwater recharge (Negi and Joshi, 1996). LULC trajectories were used to identify linkages with spring source change trends. A trajectory of LULC refers to the sequential transformation of land cover in the sampling unit over a period of time (Liu and Zhou, 2004). Time series (1990, 2000, 2010, and 2018) LULC maps from object-based classified Landsat-TM 30 m spatial resolution images, prepared by ICIMOD as a National land cover database (Uddin et al., 2021), were applied to assess LULC change in the Rangun Khola watershed. The LULC types were reclassified into seven uniform LULC classes (with subsequent trajectory code), as Forest (1), Shrub (2), Grass (3), Agriculture (4), Riverbed, Bare land (5), Water (6), and Built-up (7) in the temporal slices (1990, 2000, 2010 and 2018) for each pixel (Fig. 6a).

Creating an overlay with ArcGIS Pro version 2.7 (ESRI, 2020) of the different LULC time slices results in a trajectory code (Fig. 5). This method produces a LULC transformation map for a four-decade period (1990–2018) in the form of codes, such as 1111, 1112…. and so on until 6666, whose logic can be evaluated.

Initial trajectory analysis resulted in 457 combinations, of which 168 were logical, 58 were considered non-logical, and 231 were unclear trajectories. Based on the rationality rule, the non-logical and unclear trajectories were reviewed and corrected (Table 2) (Liu and Zhou, 2004). After the correction of each map and redoing the trajectory analysis, the 457 combinations were reduced to 168 logical trajectories. The area percentages of the corrected LULC maps for each of the different time slices are presented in Fig. 6b.

The accuracy of the corrected 2018 LULC map was assessed with the Kappa index using the accuracy point and confusion matrix (Müller and Guido, 2016) computation method to measure the difference between the independent reference map and the corrected LULC map. The overall Kappa value of the corrected 2018 map was 0.727 as compared to 0.548 for the original 2018 LULC map (Table S1).

LULC change analysis was done after trajectory correction improved the accuracy of the LULC maps. Forest was assigned code 1 and other LULC classes were assigned code 2. Vegetation change trajectories were determined as '1111' for intact forest throughout the period, '1112' for forest turned to other land use types in 2018, '1122' for forest degraded to other land use types in 2010, and '1222' for forest degradation initiated in 2000.

3.5. Analysis of impacting factors on spring sources

Spring source data was compared with LULC in the springs' immediate (50 by 50 m) surroundings. A Chi-square test was performed to test the association between LULC and spring flow trend. A graphical comparison assessed a logical association between changing climate parameters (temperature, precipitation, evapotranspiration) and spring flow trends. Socio-economic data (e.g., road development, yearly budget allocation in different sectors, demographic status) of two municipalities within the study area were used to assess the association between the anthropogenic drivers and their implication on spring flow change.

Table 1
Climate indices considered for trend analysis.

#	ID	Indicator name	Definition	Units	Parameter
1	FD0	Frost days	Annual count of days when TN (daily minimum temp) < 0 °C	days	Temperature
2	Su25	Summer days	Annual count of days when TX (daily max temp) > 25 °C	days	Temperature
3	TR20	Tropical nights	Annual count of days when TN (daily minimum temp) > 20 °C	days	Temperature
4	TN10p	Cool nights	Percentage of days when TN < 10th percentile	days	Temperature
5	TX10p	Cool days	Percentage of days when TX < 10th percentile	days	Temperature
6	TN90p	Warm nights	Percentage of days when TN > 90th percentile	days	Temperature
7	TX90p	Warm days	Percentage of days when TX > 90th percentile	days	Temperature
8	TXx		Monthly maximum daily maximum temperature	Degree C	Temperature
9	TNx		Monthly maximum of daily minimum temperature	Degree C	Temperature
10	R10	Number of high RR days	Annual count of days with RR > 10 mm	days	Precipitation
11	R20	Number of very high RR days	Annual count of days with RR > 20 mm	days	Precipitation
12	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	days	Precipitation
13	CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	days	Precipitation
14	R95p	Very wet days	Annual total precipitation when RR > 95th percentile	mm	Precipitation
15	R99p	Extremely wet days	Annual total precipitation when RR > 99th percentile	mm	Precipitation
16	PRCPTOT	Annual total wet-day precipitation	Annual total precipitation in wet days when RR ≥ 1 mm/d	mm	Precipitation

Source: Adapted from Zhang and Yang (2004); RR is daily precipitation total (mm/d)

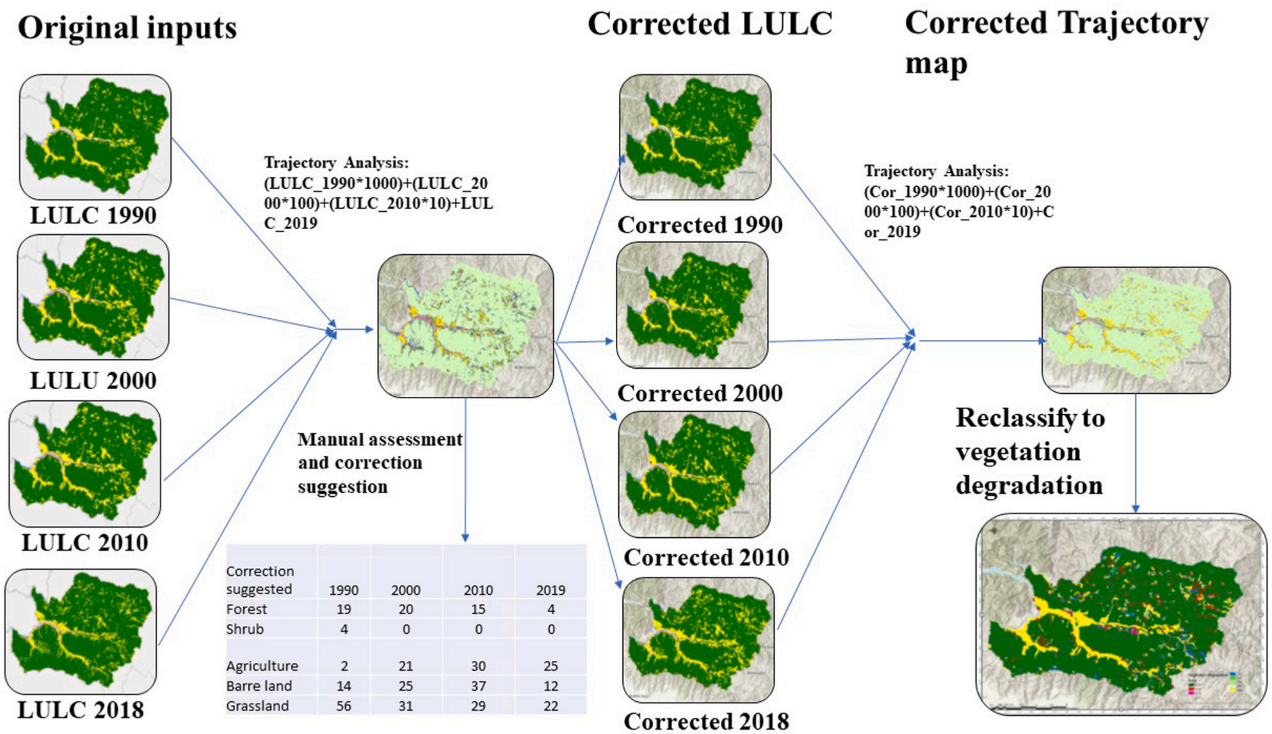

Fig. 5. Trajectory analysis flow chart.

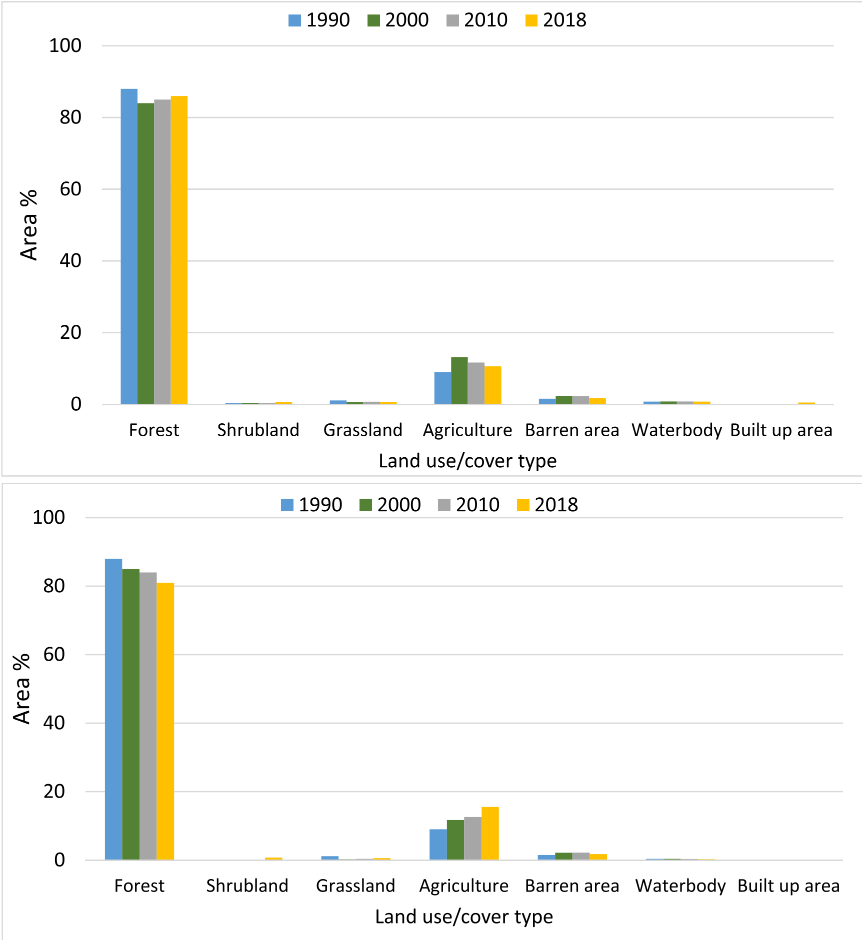

Fig. 6. (a): Area (in %) for each LULC in the Rangun Khola watershed for 1990, 2000, 2010, and 2018 before trajectory correction; (b): Area (in %) for each LULC in the Rangun Khola watershed for 1990, 2000, 2010, and 2018 after trajectory correction.

Table 2
Number of pixels corrected in the different time slice LULC maps.

Correction suggested	1990	2000	2010	2018
Forest	19	20	15	4
Shrub	4	0	0	0
Agriculture	2	21	30	25
Bare land	14	25	37	12
Grassland	56	31	29	21

Table 3
Classification of the Rangun Khola watershed springs based on discharge.

Discharge (l/s)	**Class**	**Total**	**%**
1–10	5th	17	2
0.1–1	6th	277	25
0.01–0.1	7th	585	52
<0.01	8th	217	19
0		26	2
Grand Total		**1122**	**100**

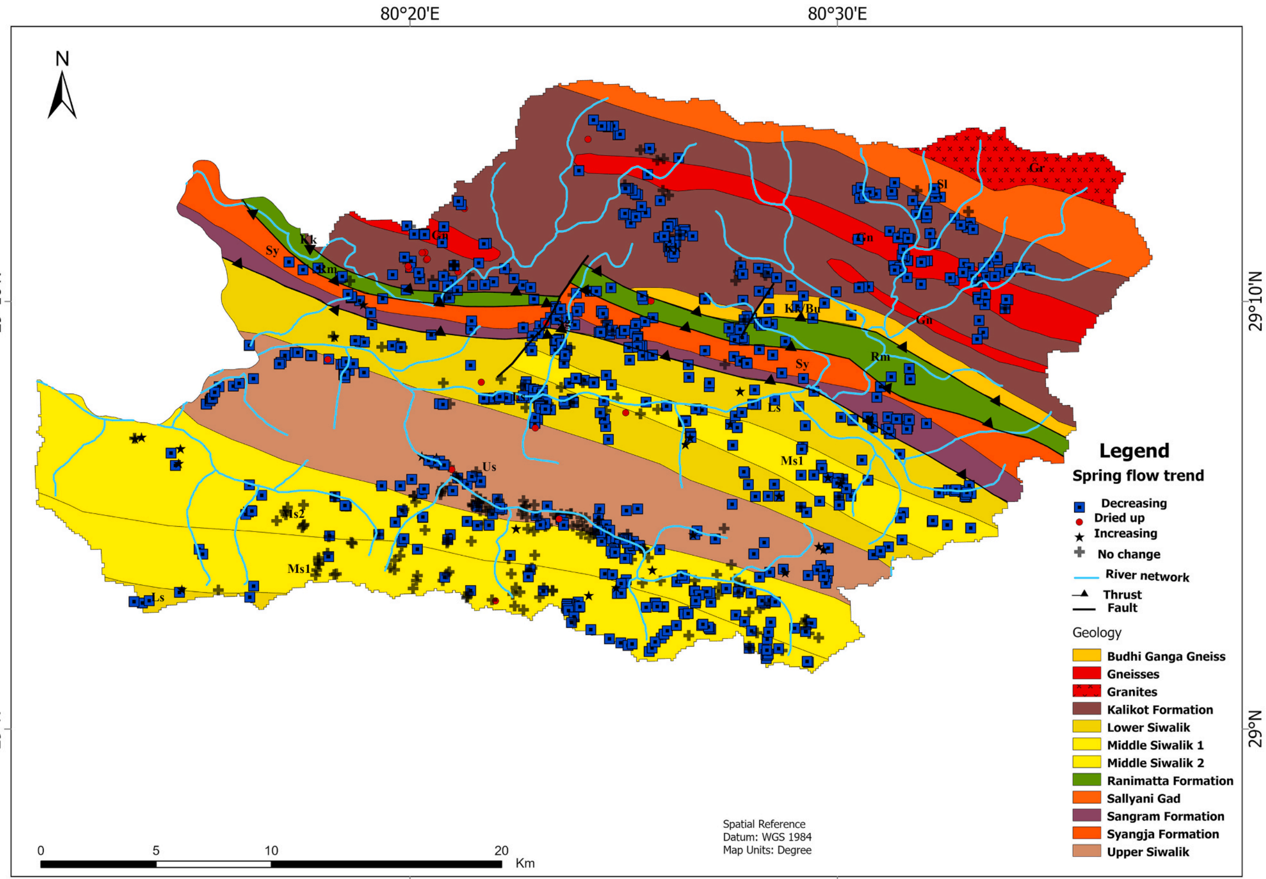

Fig. 7. Geological (DMG, 1994) control on the occurrence and discharge of springs.

4. Results and discussion

4.1. Status of springs in Rangun Khola watershed: an inventory

Spring resource assessment revealed that springs are the primary source of water in the study area, similar to many mountain watersheds. A total of 1122 documented springs gave an overview of the status of spring water sources in the Rangun Khola watershed. With a density of 1.63 springs/km^2, almost 43% of springs are located in mild (0–30°) northern sloping forests within an elevation range of 500–1000 masl.

Categorisation of the springs based on the flow rate (Meinzer, 1923) (Table 3) showed that springs ranged from the 5th class (<10 l/s) to the 8th class (<0.01 l/s). Larger springs of class 1–4 did not appear in the study area. The maximum discharge recorded is 3.33 l/s. 73% of the springs have a discharge below the 7th class (<0.01 l/s), including 2.5% that dried up, whereas 27% were in the 6th and 5th class. The distribution of the springs over the discharge classes is similar to the results of the study in the Khar village, Darchula district in Far western Nepal (Kc and Rijal, 2017), although, in this area, the majority of the springs were in the 6th class.

Geological control on springs and their discharge is evident in many study areas. Different types of springs overlain on the geological formations are shown in Fig. 7. It shows that the mountain ridges comprised of Precambrian high-grade metamorphic rocks, comprising gneisses, and various mixtures of mica-schist and phyllite, characterise the geology of the Rangun Khola watershed. An active fault passes in proximity to the main boundary thrust and runs through Budar, Alital, and Kalena (Dhital, 2015). Following the lower and upper Siwalik types of formation, the majority of the dried springs were found in the Kalikot formation, which was observed to be one of the diminishing and dried spring sources within the Rangun Khola watershed. This result closely aligns with the findings reported in the USAID country profile (USAID, 2021). However, a detailed investigation with regularly monitored data would allow a better interpretation of the springs with declining flow trends with geology.

Among the mapped springs, 71% were used for drinking and direct household purposes, 9% were supporting the community in fulfilling an agricultural need, while 20% of the mapped springs were not in direct use by the community but were indirectly serving the ecological needs. Of the unused springs, almost 90% were located far from households or in the middle of the forest and, therefore, inaccessible under normal circumstances.

Subsistence agriculture-based communities in the watershed are predominantly relying on public spring sources (95%) for their domestic and agricultural needs. Inaccessibility to supplementary irrigation support compels the communities to rely on rainfall or natural spring sources for agricultural needs, as with many mid-hills and mountain watersheds in the Himalayas (Tambe et al., 2012; Sharma et al., 2019). With an average spring dependency of 17 households per spring with a range of 1–300, a large variation in household dependency was recorded in the Rangun Khola watershed. It illustrates the importance of adequate flows from springs in the watershed to communities.

4.2. Trend in spring flows

The comparative assessment of flow rates over a period of 20 years revealed that nearly 73% of the springs had shown a declining trend in flow rate, concurrent with the rise in drying up of spring sources (Table 4). Drying up of springs has been a noticeable trend in recent years. In terms of spring orifice type, open sources show more abrupt changes than closed sources (Table 4). In the case of seasonality, even though perennial springs have declined in spring flow, seasonal spring sources have declined sharply, as indicated by 10% of seasonal springs already having dried up within the last two decades (Table 4).

Detailed spring flow rate assessment revealed that the number of springs with a flow rate of more than 0.1 l/s has reduced by 63%.

Table 4
Perception on spring flow trend and its distribution across different categories of spring.

Spring category		Total	Decreasing	Dried up	Increasing	No change
Type of spring	Concrete tank	136	90	1	9	36
	Open spring	625	488	12	14	111
	Ponds	217	137	8	9	63
	Stone spout	144	85	5	4	50
Nature of spring	Perennial	1012	705	15	33	259
	Seasonal	110	95	11	3	1
Slope	<30	481	362	17	10	92
	30–45	304	238	4	4	58
	45–60	75	51	1	6	17
	>60	262	149	4	16	93
Dependent HHs	0–10	499	358	13	18	110
	10–50	349	245	5	11	88
	50–100	27	15	0	1	11
	>100	18	11	0	1	6
	Not known	229	171	8	5	45
Surrounding environment	Disturbed	1071	771	23	29	248
	Partially Disturbed	33	16	2	5	10
	Undisturbed	18	13	1	2	2
Grand Total		1122	800	26	36	260

In comparison, springs with discharge below 0.1 l/s have increased almost 1.5 times compared to 20 years earlier (Fig. 8). Along with the shift in spring categories, the number of drying springs and sources indicates a significant increasing trend in the recent ten years.

The comparative maps based on the spring flow rate (Fig. 9) shed light on the variability in discharge over time. They verified the findings of declining spring densities with high flow rates with concurrent increasing density of the group of springs with lower flow rates. This change in the spring flow trend was further supported by the household questionnaire survey, where nearly 82% of households perceived reductions in water resource availability over the past 10 years. These trends are indicative of impending acute water scarcity in the Rangun Khola watershed.

4.3. Natural drivers of change

4.3.1. LULC change

The LULC analysis showed that almost 70 km^2 or 10% of the Rangun Khola watershed had undergone land cover changes, while almost 90% of the area was unchanged in the past 20 years (Table S2). In 1990, the area was 88% forested, which reduced to 81% in 2018 with subsequent augmentation of agricultural land from 9% to 15%, which were the prominent shifts in land cover.

The LULC trajectory analysis for the period 1990 till 2018 verified the subsequent increment in agricultural land with a corresponding decline in forest cover and associated alteration in other land covers (Fig. 10).

Trajectory analysis with LULC maps of 1990, 2000, 2010, and 2018, and reclassification of total change due to forest degradation and reforestation revealed that within 29 years, total forest cover reduction was 7.2% (49.5 km^2) compared to a negligible upsurge by 0.62% (6.5 km^2) with a resulting 6.6% (45.3 km^2) of forest degradation in the Rangun Khola watershed (Table S2). The conversion of forest land to agricultural land by 6.23% (42.79 km^2) was the prominent transformation, followed by 0.97% (7.43 km^2) to other land covers (Table S2). Of the total forest degradation during the 20 years, almost 87% was credited to the agricultural expansion of more than 6%. The other five land covers change in total less than 2% from 1990 till 2018 (Fig. 10).

Among the transformations, the 1990–2000 decade experienced prominent forest clearance of 23.3 km^2, with 8.7 km^2 of deforestation during 2000–2010, and 17.5 km^2 during the recent decade (2010–2018) (Table 5).

Gradual fragmentation of landholding is one of the emerging problems in Nepal (Paudel and Waglé, 2019), and Rangun Khola is no exception, with almost 50 km^2 of the area undergoing land-use change. A study done for the whole of Nepal on forest conversion to cropland (Li and Deng, 2017) showed comparable results to the Rangun Khola watershed, where forest reduction and agricultural land expansion complemented each other.

Nepal experienced extensive deforestation as a by-product of population growth, urban expansion, and agricultural growth before 2000 (DFRS, 1999). This coincides with almost 50% of the recorded forest clearance in the Rangun Khola watershed from 1990 to 2000. The introduction of community forestry interventions has been instrumental in stabilising deforestation to a certain extent (Birch et al., 2014; Li and Deng, 2017), reducing the forest clearance rate during 2000–2010.

The Chi-square test conducted for negative consequences of changes in LULC, specifically in terms of forest loss, alongside the evolving spring flow trend, showed a significant association between the shifting LULC patterns and changing dynamics of spring flow. The analysis establishes a notable association between LULC trajectory and spring flows, demonstrating that increased disturbance in the LULC is strongly connected to the decline in spring flow. This underscores the crucial role of undisturbed vegetation, as Negi and Joshi (2004) recommended, in preserving and supporting spring protection.

Forests have a higher water retention capacity than other landforms (Joshi, 2006) and, therefore, sustain spring sources. The

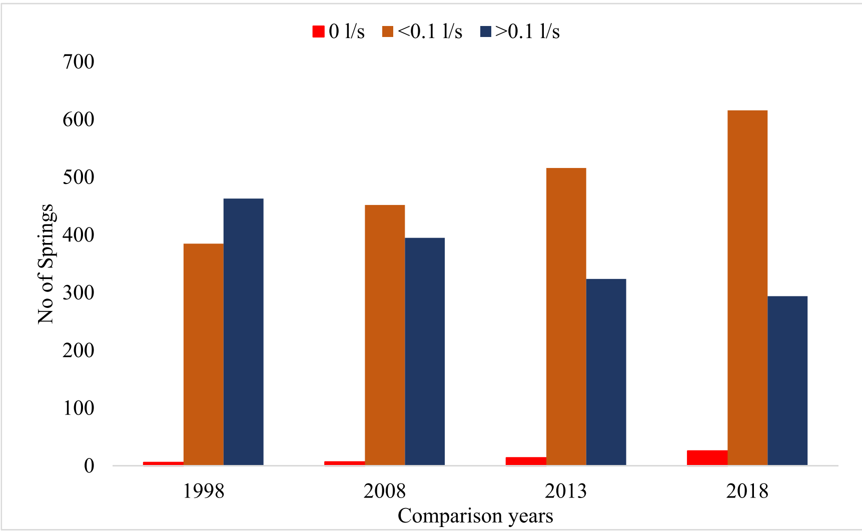

Fig. 8. Number of springs with flow rates of 0, <0.1 and >0.1 l/s at different years in the past, indicating the decreasing number of high flow rate springs with concurrent increment in low flow rate springs.

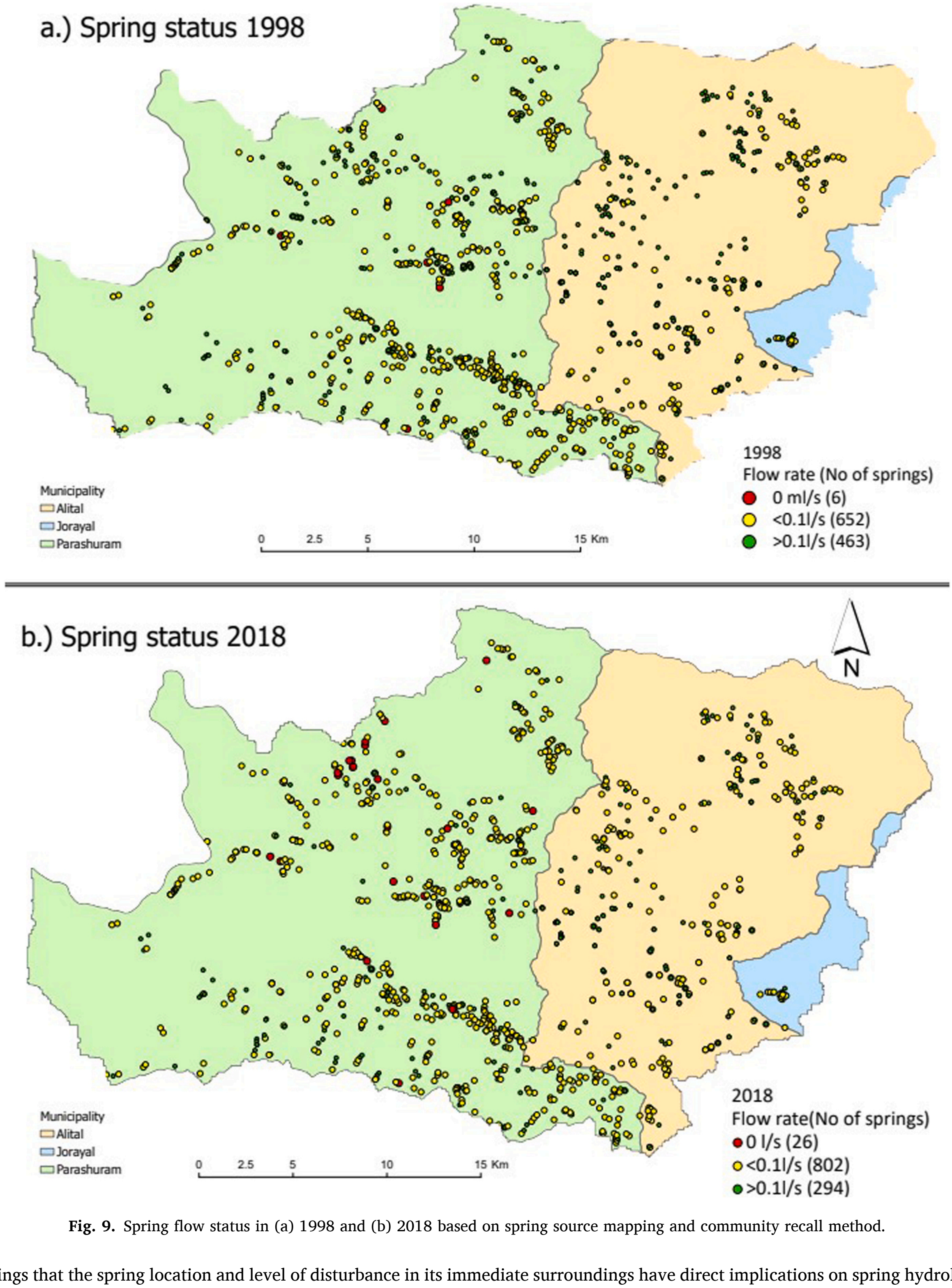

Fig. 9. Spring flow status in (a) 1998 and (b) 2018 based on spring source mapping and community recall method.

findings that the spring location and level of disturbance in its immediate surroundings have direct implications on spring hydrology, flow dynamics, and water quality were consistent with the study by Valdia and Bartarya (1989) and Joshi (2006). However, LULC assessment with a high spatial resolution map would be required for better understanding.

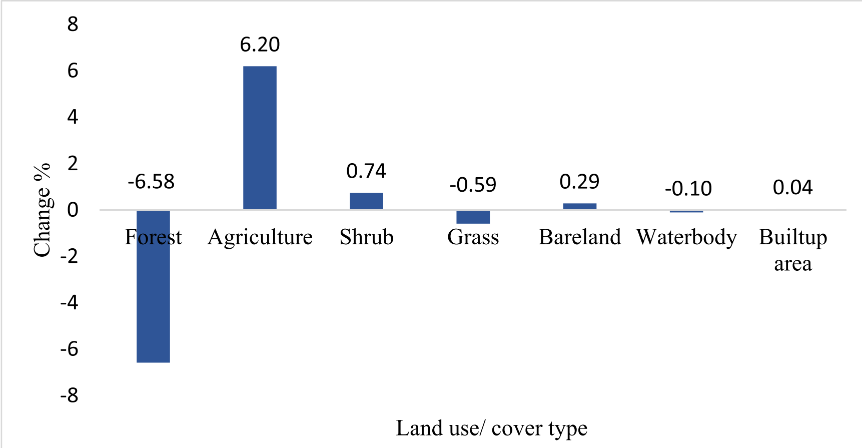

Fig. 10. Total change LULC per class (in %) in the Rangun Khola watershed between 1990 and 2018.

Table 5
LULC trajectory changes in the Rangun Khola watershed between 1990, 2000, 2010 and 2018.

#	Change trajectory	Area km^2	%
1	Unchanged forest	554.3	80.68
2	Forest Degradation 2000	23.3	3.39
3	Forest Degradation 2010	8.7	1.27
4	Forest Degradation 2018	17.5	2.54
5	Reforestation 1990	0.7	0.10
6	Reforestation 2000	1.4	0.21
7	Reforestation 2018	2.1	0.31
8	Unchanged other land use	79	11.50
	Total	687	

4.3.2. *Local climatic variability*

An analysis of rainfall, temperature, evapotranspiration, and net precipitation data from the Department of Hydro-Meteorology (DHM) revealed variations in climate patterns in the Rangun Khola watershed between 1980 and 2018. The summary of trends in major climate parameters is shown in Table 6. The results indicate that precipitation showed a decreasing trend, whereas temperature and consequent evapotranspiration showed an increasing trend. Among the trends, the change was significant at a 95% confidence level for temperature (Tmax and Tan), evapotranspiration, and net precipitation (precipitation minus evapotranspiration), while for precipitation and minimum temperature, trends were not statistically significant.

The precipitation indices indicated that annual total wet days precipitation (PRCPTOT), along with the number of days with 10 mm, 20 mm, and consecutive dry days (CDD) are decreasing slightly. In contrast, a slight increment in consecutive wet days (CWD) and a significant increment in extremely wet day precipitation (R99p) (3.2 mm/yr), is depicting the altered magnitude and frequency of the wet days. A further step assessment of temperature indices (Table S3) indicated that frost days (FD0), cool nights (TN10p), and warm nights (TN90p) are showing a slightly decreasing trend. There is a consequent significant increase in the monthly maximum daily temperature (TXx) by 0.07 °C/yr, monthly maximum daily minimum temperature (TNx) by 0.097 °C/yr, summer days (Su25) by 2.92 days/yr, warm days (TX90p) by 0.75 days/yr, and significantly decreasing cool days (TX10p) by 0.44 days/yr. These values and the overall increasing trend in maximum and minimum daily temperature indicate a warming climate in the adjoining locality.

The increasing trend in global temperature and variability in rainfall is a global phenomenon (IPCC, 2014; IPCC, 2022). Nepal's climate change scenarios indicate that the average annual maximum temperature has increased by 2.4 °C (0.056 °C/y) over 44 years

Table 6
Trends and statistical significance for climatic parameters of Dadeldhura station from 1980 to 2018.

Parameter	Definition	Mean	Slope	z	p-value
Tmax	Maximum annual temperature	21.1	0.1	5.6	0.00*
Tmin	Minimum annual temperature	11.4	0	0.3	0.74
Tan	Average annual temperature	16.2	0.1	5.4	0.00*
Ppt	Total annual precipitation	1385.9	-3.2	-0.8	0.45
Netppt	Net precipitation	240.8	-10.7	-2.4	0.02*
ET	Evapotranspiration	1152.1	7.6	4.1	0.00*

* $p<0.05$

from 1971 to 2014 (MoFE, 2019). Ongoing global warming is resulting in global consequences (IPCC, 2022), and its local manifestation in its varied forms is mostly visible as an impact on water resources (Nistor et al., 2016).

Communities in the mountain perceive the changes in climatic patterns, precipitation variability, and increase in extreme events (Karki et al., 2017). In addition to learning about changing climate from scientific sources, communities in the Rangun Khola watershed have observed evidence of the local climatic variation directly in the form of increasing temperature, declining precipitation, increasing natural disasters, and increasing water scarcity.

Local climate data assessment done at the Dadeldhura weather station revealed that community perceptions of local manifestation of climatic parameters are close to reality. The significantly decreasing number of days with precipitation more than or equal to 1 mm with concurrently increasing high-intensity rainfall (R99p) indicates the increasing frequency of localised high-intensity rainfall events (Talchabhadel et al., 2018). This alteration in magnitude and frequency of precipitation patterns in association with a significantly inclining temperature trend indicates the associated risk of extended dry periods in the adjoining localities (Bastakoti et al., 2017; Karki et al., 2017).

The significantly increasing temperature and slightly decreasing precipitation trend have consequently impacted the evapotranspiration and resultant net precipitation trend in the study area. The potential evapotranspiration trend shows a significant upsurge at a rate of 7.6 mm/yr. This increased evapotranspiration has diminished the availability of surface and subsurface flow to supplement groundwater in the locality, which is clear from the significantly falling net precipitation at the rate of 10 mm/yr (Fig. 11). The seasonal trend analysis done with net precipitation data indicated that the overall trend for all four seasons was declining with a significant reduction of net precipitation in the post-monsoon season. As a result, natural spring flow that receives input from rainfall as precipitation infiltrates and recharges the groundwater is also affected (Agarwal et al., 2012).

Furthermore, local climate change has higher variability than regional change. Warmer temperatures, prolonged monsoons, and sporadic rain events are common across the region. The data of the Dadeldhura station shows similarity with the regional trend, where the RCP4.5 projection indicated an increasing maximum temperature of Tmax (1–4.5 °C) at the present rate of 0.05 °C and showed large variability in both wet and dry precipitation pattern (Dhaubanjar et al., 2020). These changes are expected to distress almost every sector with severe implications on water demand and availability (MoPE, 2017).

Microclimatic variation directly impacts the spring hydrograph (Agarwal et al., 2012). The accumulated impact of increasing global temperature and altered local rainfall regime, contributing to variation in the amount of effective infiltration with direct implications on spring discharge (Fiorillo, 2009), was evident in the springs in the Rangun Khola watershed. The changing local climate has greater implications for seasonal springs (Negi and Joshi, 2004). However, the present level of visible changes in the spring flow pattern, with 1% of perennial springs already having dried up in the Rangun Khola watershed, underlined the severity of the water scarcity scenario (Valdiya and Bartarya, 1991). The local climate variability concurrent with drying spring sources appears to validate the community perception of decreasing water availability as a combined impact of changing climate (Pandit et al., 2016; Lamsal et al., 2017).

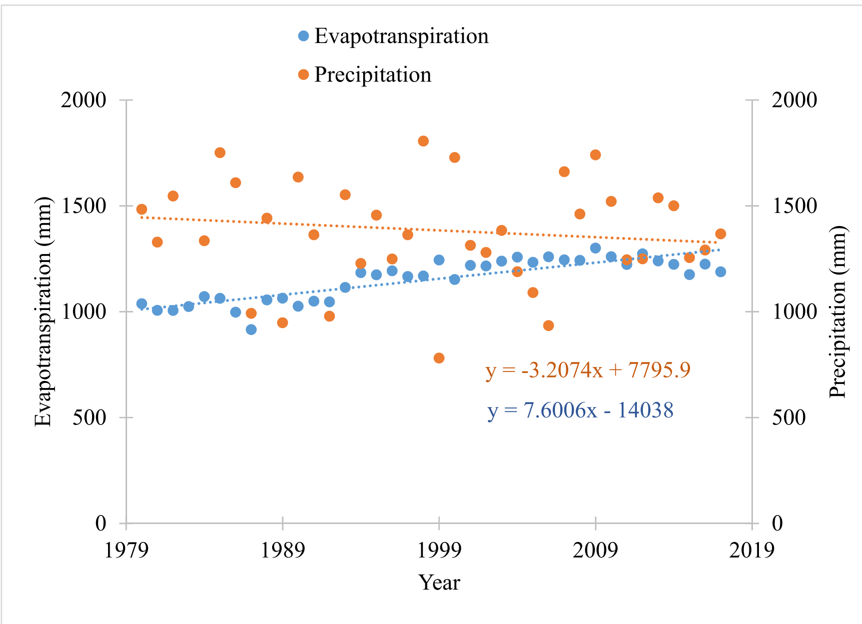

Fig. 11. A slight decreasing trend in precipitation and a significantly increasing trend in evapotranspiration between 1979 and 2018 indicate a significant reduction in the difference between the two or net precipitation.

4.4. Anthropogenic drivers of change

The population growth of Dadeldhura, which almost doubled in 40 years (CBS, 2011), followed by flourishing urban development (Portnov et al., 2007), is one of the major anthropogenic pressures on the available water resources. Even though no significant direct relation was observed between population density and changing spring flow, the associated implication of urban growth on spring sources should not be discounted. For example, a significant increment in the number of drying spring sources occurred concurrently with the expanding unplanned road network in Parashuram municipality, which revealed that drying spring sources may be associated with road expansion. However, further in-depth research is needed to establish the relationship between unplanned road construction and drying spring sources.

Under the new Constitution 2015, Nepal has adopted a three-tier structure of federalism: federal, provincial (7), and local (753) bodies further divided into 6740 wards as the lowest units of the government. After the 2017 election, federalism came into operation (Babu and Sah, 2019). The federal political system decentralised the responsibility and power to the local level along with ownership of public investments (Paudel and Waglé, 2019).

The unlocked opportunity was seized by local leaders, who were equipped with power as well as under pressure to satisfy the local need for infrastructure development, especially in the road sector (e.g., track opening, road expansion, and new construction). The road extension resulted in 682 documented road expansions in the Rangun Khola watershed. The area lies geologically in the lesser Himalayas and is characterised by highly fractured rocks (Dhital, 2015), which increases the geological vulnerability to anthropogenic changes to the land surface.

Past research has shown that the hydrogeological alteration resulting from vegetation change has a higher possibility of recovery than hill slope hydrology resulting from road construction (Jones and Grant, 1996; La Marche and Lettenmaier, 2001). The haphazard road construction on the hill slopes has a combined effect of obstructed infiltration and aggravated surface flow, triggering soil erosion, which ultimately alters the hydrological processes and ecosystem functioning in the watershed (Saraswati et al., 2020). The triggered extensive haphazard road construction in the watershed has thus led to significant implications on natural resources, especially visible in the hydrological system in the form of drying springs on hill slopes.

4.5. Implication of the drivers on spring resources in mountain

4.5.1. Ecosystem and livelihood implications

The changing climate directly affects the agriculture-based livelihood of communities in the Rangun Khola watershed. Considering the perceptions of these implications by households, drying water sources was the most prominent issue reported by 65% of the households, followed by impacts on plant phenology (59%), agricultural productivity (53%), time for water collection (45%), and indirect implications on a range of livelihood activities as reported by almost one-third of the households (Fig. 12).

The mountain ecosystem is highly sensitive to LULC (Nahib et al., 2021) and climate change (Mahamuni and Kulkarni, 2012). Accelerated LULC change, meticulously allied with the human development pathway, has sectorial impacts on land and water resources, leading to subsequent implications on ecosystem services delivery (Li and Deng, 2017). Extensive deforestation in the past, along with agricultural land expansion cumulating with local and global change factors (e.g., population, urbanisation, development

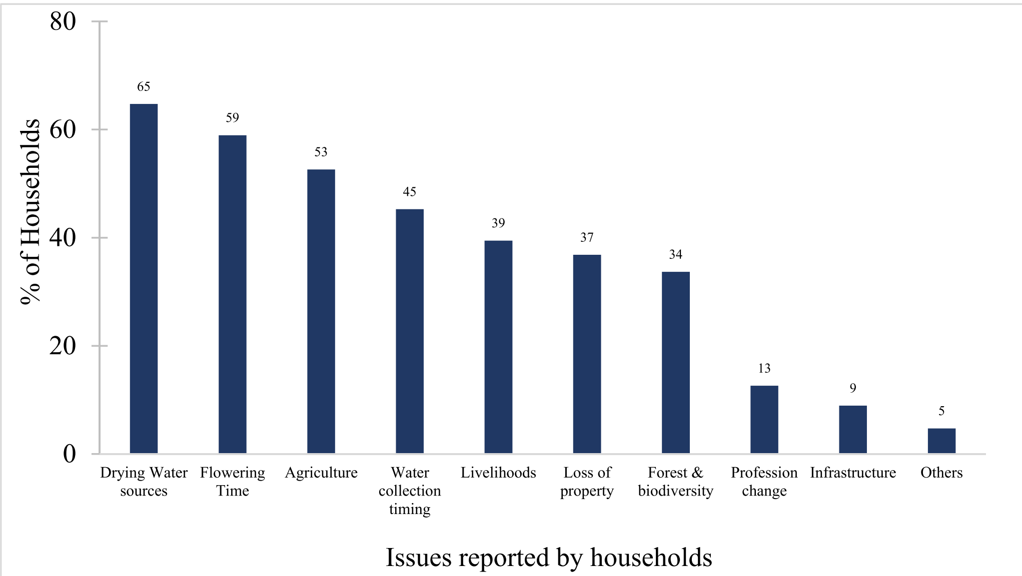

Fig. 12. Sectoral impact of climate change from a community lens, indicating the prominent implication on water resources and the agricultural sector.

intervention, climate change) (Li et al., 2017) has resulted in impacts on ecosystem services, especially water resources (Li and Deng, 2017). The effect of decreasing water availability from natural causes is exacerbated by increasing demand from anthropogenic pressure on the limited water sources in the Rangun Khola watershed.

The increasing water shortages in the watershed, observable as decreased spring discharge and drying spring sources, resemble studies done in other parts of the Himalayan region (Tambe et al., 2012; Sharma et al., 2016; Poudel and Duex, 2017). The drying sources and degrading spring flows have adversely impacted the quality, quantity, and timing of water availability, affecting local lives and livelihoods (MoPE, 2017). In terms of spring discharge change trend, irrespective of size, discharge reduction is a common phenomenon in the western Himalayas (Kc and Rijal, 2017).

However, the pronounced impact was more visible in smaller sources. Unlike the extensive spring restoration activities followed by action research in the western Himalayas (Tambe et al., 2012, Sharma et al., 2019), communities in the Rangun Khola watershed limit activities to short-term risk aversion interventions. The larger dependency of most of the population on the declining spring sources (Mahamuni and Kulkarni, 2012), combined with limited short-term coping mechanisms and risk aversion interventions, suggests a higher vulnerability associated with climate change implications in the Rangun Khola watershed.

4.5.2. Social implication

Almost 43% of households in the Rangun Khola watershed invest more than 15 minutes for water collection, while almost 15% invest up to 15 minutes. Increases in water collection time were among the top climate change implications reported by the households in the Rangun Khola watershed. The drying water sources are expected to be a serious concern for households already investing a lot of time in fetching water (Chapagain and Gentle, 2015). Women are the lead in household water management in mountain communities (WECS, 2011); concomitantly, in the Rangun Khola watershed, women are responsible for domestic water management in 87% of the households and agricultural water management in 48% of the households. In the case of droughts and reduced water availability, women as primary water managers need to spend considerable time collecting drinking water, so they are certainly directly affected (WECS, 2011). The altered water collection time is expected to add to their existing workload and lead to greater implications on gender roles and economic productivity (Udas et al., 2019).

In addition to the direct impact on the health and well-being of women and girls, threats to their safety, decreasing productivity in other areas like farming, and reducing the time available for schooling and other productive activities are the associated gendered implications of climate change on society (Chapagain and Gentle, 2015; Macchi et al., 2015).

The drying up of springs in the mountainous region is one of the reasons for community displacement in some areas of the country (Chapagain and Gentle, 2015), adversely affecting the region's economy (Agarwal et al., 2012). At present, seasonal outmigration is one of the secondary livelihood options people are relying on for survival. Chapagain and Gentle (2015) have exposed that the drying up of springs in the mountain is one of the growing causes of outmigration from mountain communities to areas with more water availability.

The ongoing depletion of spring sources in the Rangun Khola watershed without restoration intervention poses a high risk of further adverse impacts on livelihoods and ecosystems over time. Addressing these issues is crucial not only for gender equality but also for the overall well-being and sustainable development of the affected communities.

4.6. Policy gap

The Niti Aayog of India documented the restoration of springs in the mountain region as one of the priority areas, which brought some positive messages to the Hindu Kush Himalaya member countries (NITI, 2018). In the case of Nepal, in the process of stabilising restructured institutional arrangement and policy harmonisation, water resource management comes under all three government structures, and many plans and policies are still in the process of finalisation (Nepal et al., 2021).

There are some policies, such as Drinking Water Rules, and the Water Resources Act 1992, which are acting as umbrella policies covering the areas of water supply and consumer licensing. Despite the Local Government Operation Act, 2017 mandating local governments to manage water sources, the lack of priority on springs conservation and restoration persists, hindering effective implementation.

In the policy, programme, and budgeting of the fiscal year 2022/23, the government of Nepal emphasised spring protection and restoration for the first time in a policy document. However, the implementation was quite unsatisfactory. National WASH Policy 2078 (draft) has included the springs' protection and restoration issues with high priority. Besides, different tiers of Nepal's government have taken a few initiatives in integrated water resource management.

Watershed management is considered one of the important components of the Municipal Environment Protection and Natural Resource Management Act 2017. The Climate Change Policy, 2019 has highlighted the importance of recharge ponds for recharging groundwater. Likewise, in the fiscal year 2019/20 budget, the plans for constructing 200 ponds in the Siwalik and Mahabharat region to recharge groundwater were mentioned under President Chure's Conservation Program. Similarly, some local governments have also initiated a spring restoration program.

Despite federal emphasis on spring source management, gaps exist in prioritisation according to the Local Government Operation Act. In the Rangun Khola watershed, vacant municipal environmental monitoring positions impede impact assessments. For instance, The rural municipality of Alital approved the construction of 30 major road projects, among which only one, a 6.5 km road, underwent an environmental impact assessment, reflecting broader ineffective implementation, aligning with the findings of Regmi and Shrestha (2018) on the incapacity of local institutions in addressing contemporary issues.

Furthermore, there is a significant gap in the institutional levels for ensuring the funding allocation for action research and sustainable development activities (Joshi and Joshi, 2019), which is one of the greatest hindrances to spring resources management in the Himalayas. Reviving springs support ecosystems and livelihoods in Himalayan regions; hence, it is highly recommended to incorporate springshed management into yearly plans in order to meet the Sustainable Development Goals (Kulkarni et al., 2021).

5. Conclusions

In the Rangun Khola watershed, most springs (73%) had flow rates below 0.01 l/s, indicating a significant decline in water flow from 1998 to 2018. A 37% decrease was observed in springs with flow rates >0.1 l/s, while springs with flow rates <0.1 l/s increased by 60%. The household questionnaire survey confirmed this trend, revealing prolonged water collection times for households.

Land use and local climate change are two examples of natural causes contributing to spring resource loss. The Chi-square test has unveiled a robust association between changing spring flow dynamics, changing land use patterns, and forest decline. This underscores the critical role of undisturbed vegetation in protecting spring resources, as there is a clear correlation between a decrease in spring flow and increased land cover disturbance. However, human activities make this deterioration worse, including population increase, development interventions, and haphazard road construction. Despite recognising the water scarcity issue, there is a notable lack of effective mitigation and protection measures by both the government and communities.

Neglecting spring resource management in Rangun Khola and similar Himalayan watersheds could lead to severe ecological and economic consequences, including social conflicts, reduced agricultural productivity, and community displacement. Urgent, scientific-based interventions are needed for sustainable spring management in mountainous regions.

CRediT authorship contribution statement

Anju Pandit: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Okke Batelaan:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Vishnu Prasad Pandey:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Sanot Adhikari:** Writing – review & editing, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Editor-in-Chief Journal of Hydrology: Regional Studies - O.B. If there are other authors, they 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 A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101752.

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