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Integrating GIS Techniques for the Spatial Assessment of Springs' Physicochemical and Hydrological Dynamics in the Rim Area of Tehri Dam

GAURAV[1,4], RENU NEGI[2], SIDDHARTH RANA*[1] AND M. S. PANWAR[3]
[1]Research Scholar, Department of Geography, SoES, H. N. B. Garhwal University, Srinagar, Garhwal (Uttarakhand) India
[2]PG Diploma RS & GIS, Indira Gandhi National Open University, Delhi (India)
[3]Professor & Head, Department of Geography, SoES, H. N. B. Garhwal University, Srinagar, Garhwal (Uttarakhand) India
[4]Assistant Professor, Indraprastha College for Women, University of Delhi, Delhi (India)
*Corresponding Author

ABSTRACT

Natural springs serve as a vital water source for residents in mountainous regions, particularly in Uttarakhand, where they provide drinking water and support household activities. This study evaluates the water quality of 14 natural springs located in the Pratapnagar, Tehri, and Jakhnidhar blocks of Tehri Garhwal district, Uttarakhand. The analysis focuses on 12 physicochemical parameters, including pH, temperature (°C), electrical conductivity (µS/cm), total dissolved solids (mg/l), hardness, alkalinity as $CaCO_3$ (mg/l), chlorides (mg/l), residual chlorine, nitrate (mg/l), ammonia (mg/l) and phosphate (mg/l). The weighted arithmetic water quality index (WQI) method was employed to evaluate the suitability of these springs for drinking purposes. The spatial distribution of water quality parameters was analyzed using the Inverse Distance Weighted (IDW) interpolation method in ArcMap. The results indicate that most parameters are within acceptable limits for drinking water, though elevated levels of hardness, phosphate, electrical conductivity, and alkalinity in certain areas could impact water potability and domestic usability. Spatial analysis revealed high discharge values in the northern, central, and western parts, particularly near springs S3 and S14, suggesting favorable geological conditions and minimal anthropogenic disturbances. Conversely, spring S10 recorded the lowest discharge values. This study highlights the necessity for ongoing monitoring and management of these natural springs to ensure sustainable water resources. It also recommends targeted interventions in polluted areas and identifies key factors influencing water quality.

Keywords: Water Quality, Spatial Analysis, Indian Himalayan Region (IHR), Physico-chemical Parameters, Inverse Distance Weighting Method

INTRODUCTION

Water is a fundamental resource for sustaining life, and the quality of water is critical for ensuring public health, environmental balance, and sustainable development. In mountainous regions such as the Indian Himalayan Region (IHR), springs serve as the primary source of freshwater, catering to the domestic, agricultural, and livestock needs of millions. It is estimated that approximately 3 million springs exist in the IHR alone, supporting nearly 200 million people (Bhat *et al.*, 2022). Despite their vital role, these springs are increasingly threatened by anthropogenic pressures, unregulated land-use changes, and the impacts of climate variability (Verma *et al.*, 2023; Bhat *et al.*, 2022). Springs are critical natural water sources that provide essential freshwater supplies

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for ecosystems, human consumption, and agricultural activities, particularly in regions where surface water is scarce or unreliable (Cantonati *et al.*, 2020). These groundwater-dependent ecosystems are often characterized by their unique hydrological and geochemical properties, which influence their water quality and suitability for various uses (Springer and Stevens, 2009). However, springs are increasingly vulnerable to anthropogenic pressures such as land-use changes, urbanization, and climate variability, which can degrade water quality and threaten their ecological integrity (Kresic and Stevanovic, 2010). Spatial assessment of spring water quality is vital for understanding the interplay between environmental factors, human activities, and water chemistry, enabling informed management and conservation strategies.

The spatial variability of water quality in springs is influenced by factors such as geological formations, aquifer characteristics, and surrounding land use (Toth, 1999). For instance, springs located in agricultural areas may exhibit elevated levels of nitrates and pesticides due to runoff, while those in urban settings may be contaminated with heavy metals or organic pollutants (Barber *et al.*, 2013). Geographic Information Systems (GIS) and spatial analysis techniques have emerged as powerful tools for assessing and mapping water quality parameters, allowing researchers to identify spatial patterns and potential contamination sources (Singh *et al.*, 2017). Such assessments are crucial for prioritizing restoration efforts and ensuring sustainable use of spring water resources.Despite their ecological and socio-economic importance, comprehensive studies on the spatial assessment of spring water quality remain limited, particularly in understudied regions (Cantonati *et al.*, 2020). This research aims to address this gap by evaluating the spatial distribution of key water quality parameters in springs, integrating field measurements with geospatial analysis to identify factors influencing water quality. By providing a spatially explicit understanding of spring water quality, this study seeks to contribute to the sustainable management of these vital resources. The rim area of the Tehri Dam in Uttarakhand, India, exemplifies a geologically sensitive and ecologically crucial region, where spring water has historically sustained rural livelihoods. However, rapid deforestation, infrastructure development, and demographic shifts have altered hydrological dynamics, leading to the deterioration of spring discharge and quality. Research indicates that changes in lithology, agricultural runoff, and urban encroachments significantly influence springwater chemistry, often resulting in increased concentrations of nitrates, phosphates, and microbial contaminants (Dandge and Patil, 2022; Yadav, 2024).Emerging technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS) offer powerful tools to map, analyze, and visualize the spatial distribution of water quality parameters. GIS-based Water Quality Index (WQI) analysis has proven effective in identifying vulnerable zones and patterns of pollution across diverse hydrogeological terrains (Mahagamage and Manage, 2015). Studies from the Kashmir Himalayas and the Chamoli region of Uttarakhand have successfully employed WQI and GIS to assess seasonal and spatial variability in water quality, highlighting the need for region-specific conservation strategies (Bhat *et al.*, 2022; Verma *et al.*, 2023).

Groundwater in the Tehri Garhwal district occurs predominantly in fissured aquifers within phyllites, quartzites, limestones, and dolomites, yielding spring discharges that range from negligible flows (<0.001 LPS) to several hundred liters per minute in spring clusters (gadheras), depending on lithological permeability and seasonal recharge (Bagchi and Singh, 2011). Chemical analyses of 37 spring and hand-pump samples revealed mildly alkaline waters (pH 8.0–8.2) with total hardness up to 1,681 mg/l as CaCOƒ , chloride 7.1–21 mg/l, nitrate 0.14–22 mg/l, and occasional high sulfate concentrations (up to 1,465 mg/l) indicative of mineralized source rocks. These waters are suitable for drinking and irrigation but show localized mineralization anomalies that warrant detailed mapping (Thapliyal and Philip, 2018). The study on the spatial distribution of spring water quality in the Tehri Dam rim area highlights critical issues and implications for water resource management in the Indian Himalayan Region (IHR). Springs serve as vital freshwater sources for millions, emphasizing the need for their sustainable management (Tambe *et al.*, 2012). The study identifies pressing environmental threats, including anthropogenic pressures, land-use changes, and climate variability, which contribute to the degradation of spring ecosystems (Valdiya and Bartarya, 1989). Utilizing Geographic Information Systems (GIS) and Remote Sensing (RS), the research effectively maps and analyzes water quality, showcasing the potential of these tools in environmental assessment (Kumar *et al.*, 2019).

METHODOLOGY

The methodology adopted for the present study involved a systematic hydrological and physicochemical assessment of fourteen spring sites. These springs were strategically selected to represent a diverse range of locations and conditions within the study area, ensuring a comprehensive understanding of spring water characteristics. The selection was based on accessibility, community dependence, and observed discharge levels.

To assess the water quality of the selected springs, a total of 09 key physicochemical parameters were measured. These included pH, temperature (°C), electrical conductivity (μS/cm), total dissolved solids (mg/l), hardness (mg/l), alkalinity (mg/l), chlorides (mg/l), residual chlorine, nitrate (mg/l), ammonia (mg/l) and phosphate (mg/l). These parameters were chosen based on their relevance to drinking water quality, ecosystem health, and potential anthropogenic influences. The field data collection and *in-situ* testing were conducted during the month of July 2024. A combination of a portable water quality tester and a field water testing kit was used to ensure accurate and immediate readings for most parameters directly at the source. This approach allowed for the assessment of real-time water quality conditions and minimized errors due to sample degradation or transport delays.To visualize the spatial variability of water quality across the study area, the Inverse Distance Weighting (IDW) interpolation technique was employed using ArcMap software.

Table 1: Discharge and Elevation of Springs

Spring Id	Spring	Discharge (litre/min)	Elevation (in meters)
S1	Bilyapani	5.83	1105
S2	Mathya Pani	4.12	1146
S3	Gad name Tok	117.65	1082
S4	Paniyara	3.02	1104
S5	Peepalapani	10.91	1081
S6	Raibagi Dhara	11.54	1120
S7	Dhari Name Tok	17.49	1187
S8	Rethi ka Pani	5.08	906
S9	Sem Dhara	8.98	872
S10	Uth_02	0.24	934
S11	Kuan (Tapped with Hand Pump)	0.56	929
S12	Tipri Dhara	7.5	1113
S13	Molno	16.76	1078
S14	Kiryani Dhara	50	1489

RESULTS AND DISCUSSION

Spatial Distribution of Spring Discharge:

The spatial distribution of spring discharge in this mountain region reveals several distinct patterns and relationships with elevation, demonstrating the complex hydrogeological factors that control groundwater flow and spring productivity.The thematic map and supplementary hydrographs display remarkable changes in flow patterns throughout the study area's spring discharge. The map also shows that the discharge zone peaks in proximity to spring S3, which records a discharge of 117.65 LPM. Distribution showing the upper discharge class between 43.12 to 117.11 LPM. Another spring of important discharge, S14 from the northwestern part of the study area, also yields 50 LPM. These springs highlight the area as important from a hydrological point of view concerning the groundwater discharge. S13 and S7 springs also discharge moderately, with S13 yielding 16.76 LPM and S7 17.49 LPM, which places them in the eastern and central parts of the basin. S10 and S11 springs in the southern region discharge very low, 0.24 and 0.56 LPM. These springs are the lightest shaded areas on the discharge map, displaying groundwater discharge (Table 1).

Considering discharge and elevation together, Spring S3, which has the highest discharge among the other springs, is only at a moderate elevation of 1082 meters. In contrast, S14, another high-discharge spring, is at the highest elevation in the dataset, 1489 meters. Meanwhile, low-discharge springs S10 and S11 are positioned at lower elevations, below 950 meters.

pH Distribution:

pH is the most important physicochemical parameter that controls and affects the other water quality parameters (Saalidong *et al.*, 2022). Point source pollution is a common cause that can increase or decrease pH, depending on the chemicals involved. Agriculture runoff, especially from using fertilizers and pesticides, can also contribute to changes in pH. The spatial distribution of pH across the study area shows moderate variability, with values ranging from 7.0 to 8.15. The central and south-eastern regions (notably around springs S3, S4, S9, and S13) exhibit relatively higher pH values, approaching the upper range of the dataset, yet remaining below the standard permissible value of 8.5. Spring S7 records the

Table 2: Elevation Range and Springs Discharge

Elevation Range (m)	Springs (ID)	Discharge Range (LPM)	Observation
< 950	S9, S10, S11	0.24 – 8.98	Mostly low discharge
950 – 1150	S1, S2, S3, S4, S5, S6, S12, S13	3.02 – 117.65	Wide range, includes both low and high discharge
> 1150	S7, S14	17.49, 50	Moderate to high discharge

highest pH (8.15), indicating a slightly more alkaline condition in that region. In contrast, the western and central-western portions (around springs S5, S6, and S14) show lower pH values, with S5 having the lowest pH (7.0), reflecting more neutral to mildly acidic conditions. Overall, the area remains within acceptable pH limits, but the slight alkalinity toward the central-east may be influenced by geological or anthropogenic factors.

Temperature Distribution:

The spatial distribution of temperature reveals a general decline from the central and north eastern parts toward the western and southern zones. Most of the springs, including S4, S5, S6, S8, and S11, exhibit higher temperatures above 24°C, nearing the standard limit of 25°C. These high-temperature zones are concentrated toward the centre and slightly north. In natural springs, water temperature generally decreases as height increases. However, the area's geothermal activity, flow rate, and other factors, such as less canopy cover, can also affect the spring water temperature. Conversely, springs like S13, S14, and S12 in the southern and western edges of the study area record lower temperatures, with S14 being the coolest at 18.7°C. The gradient suggests a shift from warmer core areas to cooler peripheral zones, potentially influenced by elevation, shading, or water source depth. Springs that get their water from regional groundwater flow systems have deeper and longer flow paths and tend to have higher temperatures than those fed by local systems (Tóth *et al*., 2022).

EC (Electrical Conductivity) Distribution:

The spatial distribution of EC across the study area ranges from 186 to 910 µS/cm. The southern and south-eastern springs, notably S15 (910 µS/cm), S12 (896 µS/cm), and S13 (873 µS/cm), exhibit the highest EC values, suggesting increased ionic concentration likely due to geogenic factors or anthropogenic influences such as domestic waste or agricultural runoff. EC values in spring water generally change due to rock water interaction and the dilution process as water travels from its recharge point to the mouth of the spring (Bakti *et al.*, 2021). During travel, water comes into contact with different dissolved salts and minerals like Sodium Chloride, which increases the water's ability to produce electricity. In contrast, S2 (186 µS/cm) and S6 (223 µS/cm), located in the north and central-west, record the lowest EC values, indicating fresher water with minimal dissolved salts. The increasing EC trend toward the south indicates possible cumulative impacts from human activity or mineral-rich substrates.

Table 3 : Observed Values of Physicochemical Parameters

Parameters	pH	Temp ^{0}C	EC	TDS	Hardness	Alkalinity	Chlorides	NO^{3-}
Standard Value	8.5	25	400	500	200	200	250	45
S1	7.5	23.3	502	251	195	275	20	0
S2	7.34	21.8	566	284	210	350	40	15
S3	7.97	21.6	325	163	180	225	20	10
S4	7.74	24.6	159	230	225	250	20	0
S5	7	24.8	635	318	255	300	220	5
S6	7.25	24.4	500	250	225	275	40	2
S7	8.15	22.9	307	154	150	250	20	0
S8	7.57	24.3	487	243	195	475	20	5
S9	7.93	21	251	125	105	150	20	10
S10	7.6	20.9	374	197	120	150	40	10
S11	7.6	24.2	291	207	135	175	100	10
S12	7.38	21	210	106	75	100	40	0
S13	7.73	19.8	216	109	180	200	20	0
S14	7.4	18.7	118	59	60	125	20	5

TDS (Total Dissolved Solids) Distribution:

TDS concentration describes the presence of inorganic salts and small amounts of organic matter in water. TDS values in the area vary from 122 to 582 mg/l, showing a pattern consistent with EC. The highest TDS values are observed at S15 (582 mg/l), S12 (565 mg/l),

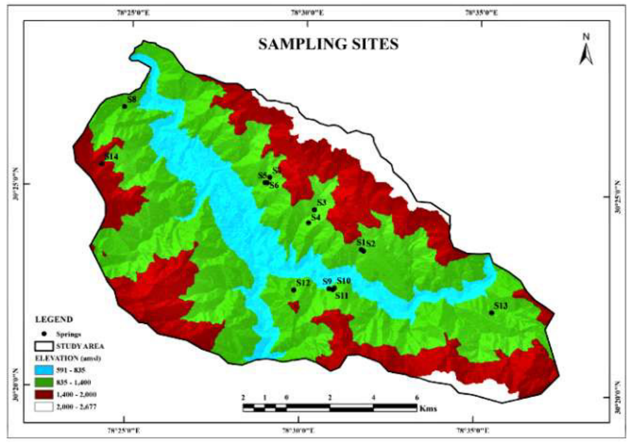

Fig. 1 : Springs Sites and Elevation

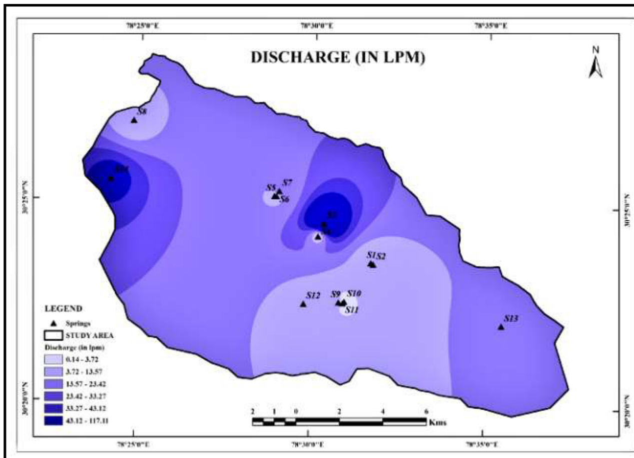

Fig. 2 : Spatial Distribution of Discharge

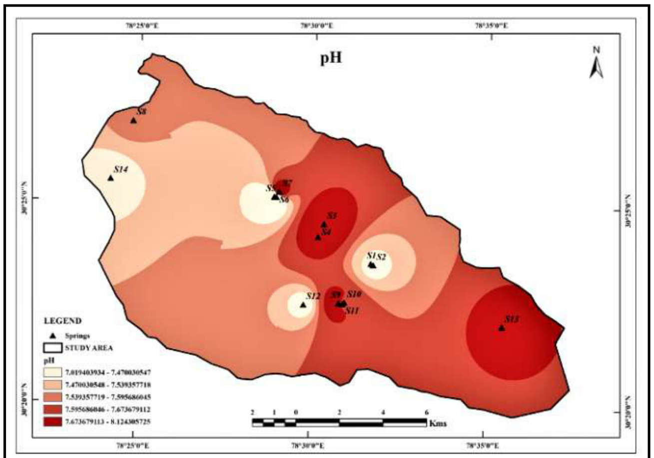

Fig. 3 : Spatial Distribution of pH

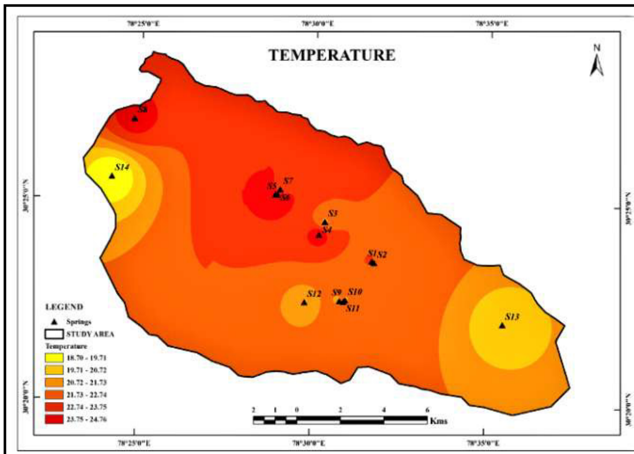

Fig. 4 : Spatial Distribution of Temperature

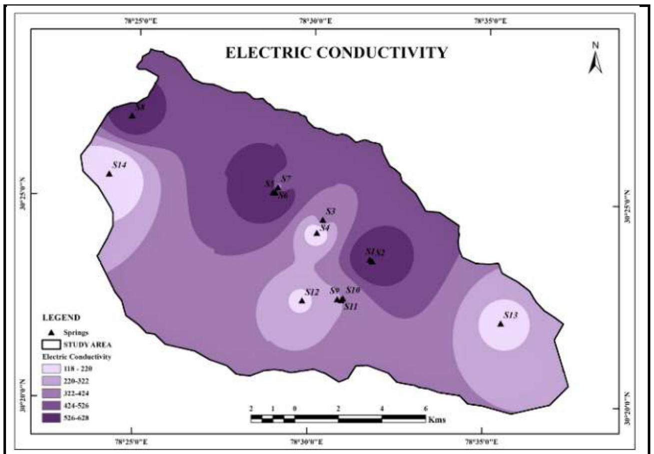

Fig. 5 : Spatial Distribution of EC

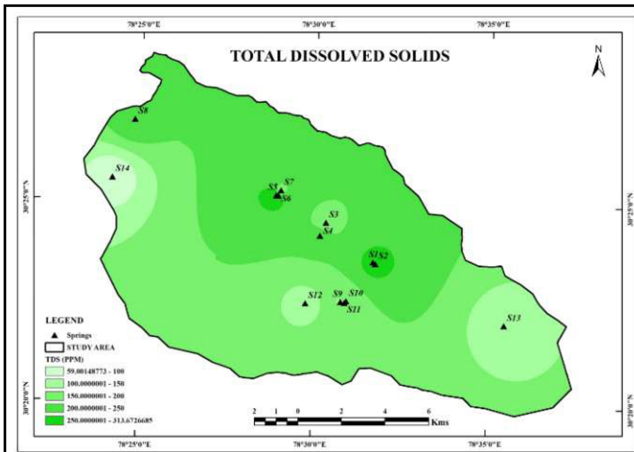

Fig. 6 : Spatial Distribution of TDS

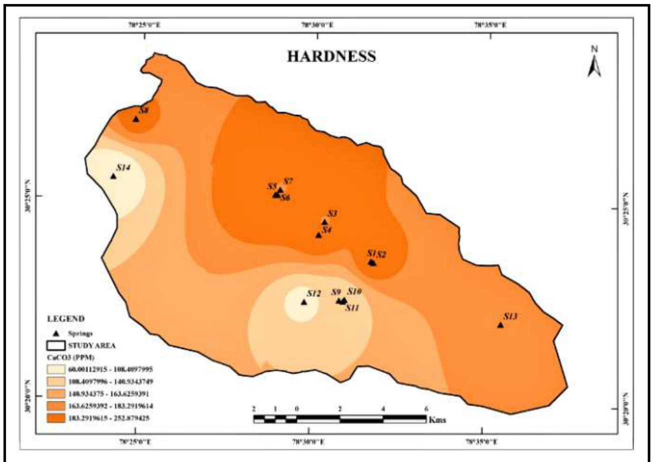

Fig. 7 : Spatial Distribution of Hardness

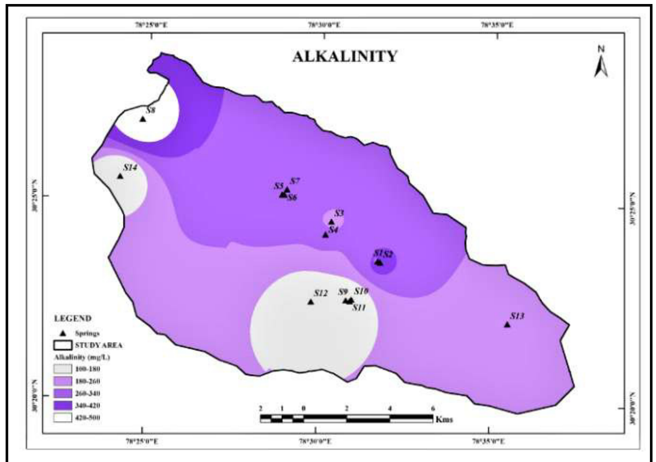

Fig. 8 : Spatial Distribution of Alkalinity

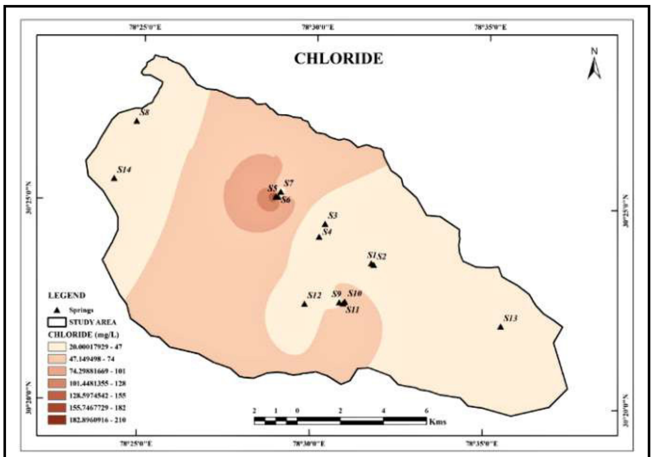

Fig. 9 : Spatial Distribution of Chloride

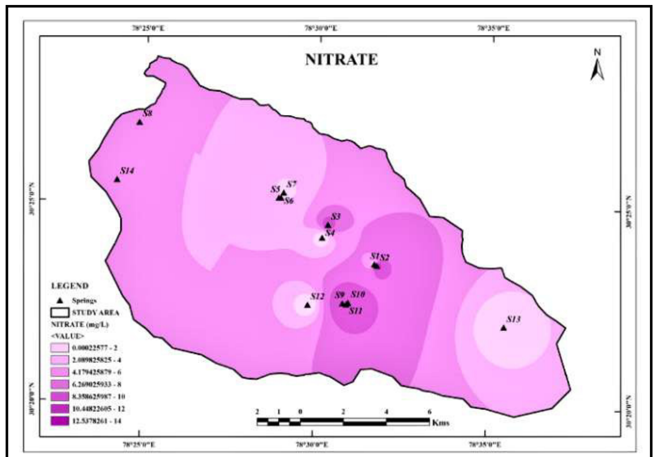

Fig. 10 : Spatial Distribution of Nitrate

and S13 (558 mg/l), concentrated in the southern region, possibly due to prolonged water-rock interaction or surface contamination. Springs such as S2 (122 mg/l) and S6 (146mg/l) in the north and northwest display the lowest TDS, reflecting high-quality water. This spatial gradient highlight increasing mineralization toward the southern part of the study area. Faster-moving water can dissolve more minerals from soils and rocks, which can result in higher TDS values.

Hardness Distribution:

Hardness values range between 48 to 280 mg/l. The north-eastern and central springs, especially S4 (280 mg/l) and S6 (272 mg/l), show the highest hardness, suggesting elevated levels of calcium and magnesium ions, likely from carbonate rock dissolution. Springs such as S11 (48 mg/l) and S15 (52 mg/l) in the southern zone show softer water, indicating reduced mineral content. The distribution pattern reflects strong lithological control, with harder water in areas underlain by calcareous formations. In the calcareous formations like limestones, water can easily dissolve the rocks, resulting in the release of calcium and magnesium ions into the water, increasing the hardness (Todd and Mays, 2005).

Alkalinity Distribution:

Alkalinity within the study area falls between 40 and 180 mg/l. Higher values of alkalinity, like S10 (180 mg/l) and S4 (160 mg/l), are found in the southern and central parts. This is possibly caused by bicarbonates as well as carbonate buffers coming from geological sources. S11 (40 mg/l) and S1 (45 mg/l) in the northwest show lower values that may be the result of reduced interaction with carbonate-bearing formations. From this, S11 and S1, the trend suggests a stronger buffering capacity in the central-south area.

Chloride Distribution:

Chloride concentrations have a range of 11 to 120 mg/l. The most prominent springs with elevated chloride concentrations are S12, S13, and S15, with 118, 112, and 120 mg/l, respectively. The causes of such high values may include domestic sewage or saline water intrusion. S15, S12, and S13 springs may also be affected by terrace agriculture present in the upper catchments. The runoff water, containing high chloride values, can also be suspected in the fields. Chloride values in springs S1 and S6, located in the northern and western regions, are 11 and 17 mg/l, respectively. These springs are anthropogenically less disturbed. The sharp rise in the south is a suspected area of pollution.

Nitrate (NO_3^-) Distribution:

The Bureau of Indian Standards (IS 10500:2012) for drinking water sets the permissible limit for nitrate (NO_3-) at 45 mg/l. Nitrate levels vary from 1.2 to 34.6 mg/l. The central and north-eastern springs, especially S4 (34.6 mg/l), S9 (28.9 mg/l), and S11 (27.2 mg/l), exhibit elevated nitrate concentrations, likely due to fertilizer leaching or sewage infiltration. In contrast, S1 (1.2 mg/l) and S13 (2.1 mg/l) in the north-western and south-eastern zones show low nitrate levels, suggesting limited anthropogenic impact. The nitrate hotspots in central-northeast indicate site-specific contamination rather than uniform pollution.Nitrate contamination in water can originate from both natural and anthropogenic sources. These include agricultural runoff (fertilizers), animal waste, and industrial discharge.

Conclusion:

This study utilized GIS-based analysis to evaluate the spatial distribution of the physicochemical parameters of 14 natural springs located at the rim of the Tehri Dam in Uttarakhand. It revealed that the water quality is greatly influenced by geogenic formations and human activities. Most of the parameters, such as the pH (7.0–8.15), nitrate (1.2–34.6 mg/l), and temperature (18.7–24.8°C) were compliant with the BIS standards. However, some of the springs located in the center and south exhibited higher values of electrical conductivity (EC) (up to 635 µS/cm), total dissolved solids (TDS) (up to 318 mg/l), hardness (up to 280 mg/l), and chlorides (up to 220 mg/l) suggesting some anthropogenic activities and rich mineral geology in those areas. The discharge range of the springs varied from 0.24 LPM (S10) to 117.65 LPM (S3). The higher yielding springs were located at moderate to high elevations (1082–1489 m), suggesting that geology greatly influences spring discharge. Mapping and spatial analysis of these parameters using IDW interpolation revealed water quality hotspots and regions with optimal quality, thus providing opportunities for effective targeted management. Springs that were located in less disturbed and less populated regions were of better quality, whereas those located in the vicinity of agricultural areas and densely populated areas were of higher risk for contamination. The research highlights the need for continued surveillance and localized conservation efforts, as well as the need for region-specific oversight and hydrological management. The GIS application, along with field assessments of water quality, creates a solid framework for protecting the Himalayan spring systems with the sustainability of the environment and subsistence agriculture of the rural population at the center of planning.

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