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WATER QUALITY ASSESSMENT OF ALMORA AND CHAMOLI DISTRICTS OF UTTARAKHAND, INDIA

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ABSTRACT

Groundwater forms the backbone of drinking water supply in the Himalayan region, rendering its quality assessment essential for long-term sustainability. This study presents a comprehensive evaluation of groundwater quality in Chamoli and Almora districts of Uttarakhand, employing physico-chemical analysis, heavy metal concentration measurements, and Water Quality Index (WQI) determination. Total 84 samples have been collected out of which 46were collected from Chamoli and 38 samples from Almora (pre- and post-monsoon seasons in 2021), the parameters that have been analysed are pH, electrical conductivity (EC), total dissolved solids (TDS), major cations and anionsalong with heavy metals such as lead, zinc, manganese, nickel, copper, iron, and chromium, in accordance with “American Public Health Association” APHA (2005) standards and BIS guidelines. Results revealed that groundwater pH in Chamoli ranged from 6.52 to 7.59, with TDS levels between 70 and 602 mg/L, whereas Almora samples showed pH values from 5.92 to 8.21 and TDS from 58 to 426 mg/L; these figures were largely within permissible limits. Concentrations of major cations and anions were moderate, with bicarbonates being the most prevalent anion. Heavy metals were generally present in trace quantities, but a limited number of samples surpassed the desirable thresholds. WQI outcomes demonstrated that groundwater in both districts is predominantly classified as excellent, with Chamoli maintaining consistently high standards throughout both seasons. Almora exhibited minor seasonal variations, with several samples falling into the good quality category. In summary, groundwater in these regions is suitable for drinking and domestic purposes, though occasional instances of elevated heavy metals underscore the necessity for ongoing monitoring and effective management to ensure safe utilization of this vital resource.

INTRODUCTION

Water is a critical natural resource that sustains ecosystems, human health, and socio-economic development. Ensuring the availability of safe and clean water has become a global priority, particularly in regions that are ecologically sensitive and socio-economically dependent on natural water sources. In India, the Himalayan states play a pivotal role in feeding perennial rivers and groundwater reserves that serve large parts of the country. Uttarakhand, situated in the central Himalayas, is known for its abundant water resources originating from glaciers, rivers, and springs (Kumar et al. 2023). However, rapid urbanization, population growth, tourism, agricultural practices, and climate-induced changes have begun to exert pressure on the quality of these water resources. Ground water is mostly used for the consumption in the Himalayan region. In recent years it has been shown through various studies that groundwater quality is being degraded. The availability and usability of ground water in any region are largely influenced by its chemical composition. Hence, analyzing the physico-chemical properties of surface water is essential for determining its suitability for different applications. Groundwater, which serves as a vital source of water for human needs, is facing significant environmental stress due to developmental pressures (Nayar, 2020). Its vulnerability to pollution owing to the easy disposal of wastewater into accessible sources emphasizes the urgent need for effective control of water contamination and contin-

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uous monitoring of water quality. Groundwater degradation commonly results from human-induced factors such as improper waste management, poor sanitation, unregulated industrial and domestic discharges, and infiltration of agricultural chemicals (Salifu et al., 2013; Jain et al., 2010). Furthermore, spatial differences and temporal changes in precipitation, influence fluctuations in water quality. To prevent further decline, it is crucial to establish effective monitoring programs aimed at identifying pollution sources, assessing site-specific environmental conditions, and providing accurate data for better water resource management. Developing comprehensive water quality databases will ultimately support sustainable strategies for future water resource planning and utilization.

The districts of Almora and Chamoli, located in the Kumaon and Garhwal regions of Uttarakhand respectively, represent two distinct geographical and socio-environmental settings. Almora, with its mixed urban-rural character and reliance on spring-fed systems, faces challenges of increasing demand and localized contamination (Gopirajan et al. 2021). Chamoli, often referred to as the “Abode of Gods,” is characterized by its proximity to glacier-fed rivers and high-altitude streams, yet it too is increasingly exposed to pressures from expanding tourism, pilgrimage activities, and changing land-use patterns (Bisht, 1994). Assessing and comparing the water quality in these districts is therefore essential, not only for safeguarding community health but also for sustaining the ecological balance and supporting sustainable development in the Himalayan region. The Himalayas are usually considered to have the purest form of waters but with continuous increase in population, rise in tourism water quality concern is a major issue across the region (Singh et al. 2020). This study aims to assess the water quality of Almora and Chamoli districts by analyzing key physico-chemical and biological parameters. A comparative assessment will provide insights into the spatial variability of water quality between these regions and help identify major influencing factors. The findings are expected to contribute to developing region-specific water management strategies and to inform policymakers, local communities, and stakeholders about the current status and future needs for maintaining water security in Uttarakhand.

Study Area

The proposed study is conducted to evaluate the overall groundwater quality of the Chamoli and Almoradistricts of Uttarakhand. Almora is located at 29.5971°N 79.6591°E in Almoradistrict in Uttarakhand. Chamoli is located in coordinates of 30° 30’ 0’’ N and 79° 30’ 0 E. The study area lies in the Lesser Himalayan Region and Higher Himalayan region of Uttarakhand (Fig 1).

Geology

The study area lies at the junctions of Kumaun and Garhwal regions of Uttarakhand. The area lies between the lesser Himalayan and Higher Himalayan region. The Chamoli district lies in Almora Group and Berinag Group of rocks towards the Northern part it has Munsyari and Vaikrita Group and a small portion of the district lies in the Tethys Himalayan Region (Valdiya 1980).

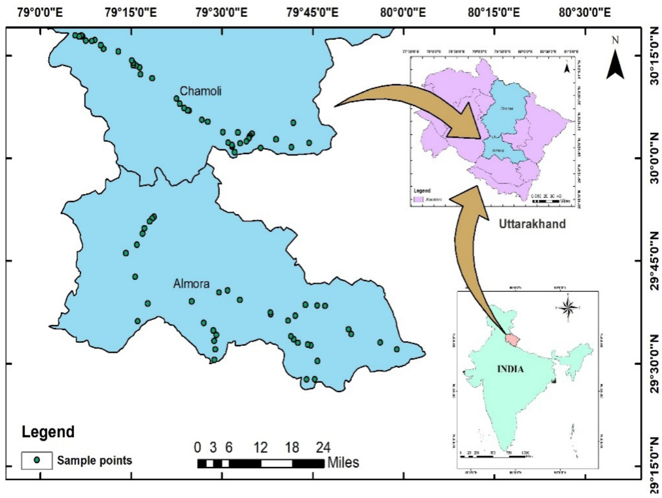

Fig.1. Location Map of Chamoli and Almora district of Uttarakhand.

REVIEW OF LITERATURE

Assessing water quality, especially in the Himalayan context, has been the focus of significant research over the past few decades, as the region provides essential water resources for millions and is highly sensitive to environmental change. Various studies in the Himalayan regions, including Uttarakhand, have utilized integrated approaches involving WQI, Geographic Information System (GIS) and Heavy Metal Pollution Index to evaluate regional differences and dominant influencing factors. For example, a recent assessment in the Himalayan springs incorporated nine physico-chemical parameters, revealing qualitative and spatial heterogeneity where issues such as high iron concentrations and elevated EC and TDS levels were observed. The study emphasized the utility of WQI for overall assessment and GIS for spatial visualizations, recommending these as essential tools for sustainable spring water resource management. Verma et al. (2023) conducted an analysis of spring water across villages in Chamoli, assessing 14 physico-chemical parameters and calculated WQI for both drinking and irrigation purposes. Their findings showed that while most samples were suitable for consumption, certain samples exhibited levels above recommended limits for parameters like TDS and hardness, varying between pre- and post-monsoon periods. Similar studies in adjacent regions have confirmed that anthropogenic pressures are leading to both quantitative and qualitative degradation of these fragile water sources.

The research conducted by Bhandari and Joshi, 2013 aimed to characterize the spring water in Almora district for its suitability in irrigation. The study involved collecting samples from 54 springs, representing both rural and urban locales, and analyzing them across pre-monsoon, monsoon, and post-monsoon periods for several chemical parameters such as pH, EC, TDS, and a range of major ions including sodium, potassium, calcium, magnesium, bicarbonate, chloride, and sulphate. Their findings indicated that, based on irrigation water quality parameters, almost all springs were deemed suitable for irrigation.

In another related study, Kothari et al. (2021) computed WQI values for water samples from villages across Tehri Gharwal, Bhilangna, Bageshwar, Chamoli, Nainital, and Ramgarh districts. Their assessment revealed that most villages had

WQI scores exceeding 100, indicating poor or very poor water quality, unsuitable for consumption without proper treatment. Only 15 villages out of 117 demonstrated excellent water quality, with six having good water quality. In samples from the Ghat block of Chamoli district, WQI was below 50, signifying excellent water quality.

These studies highlight that, while the majority of spring waters in Almora are suitable for irrigation, drinking water quality issues persist across several districts and many areas require adequate treatment or filtration prior to use. Thus, the literature points to the importance of ongoing monitoring, spatial analysis, and the use of composite indices for water quality assessment in the environmentally sensitive context of the Uttarakh and Himalayas. The comparative assessment of Almora and Chamoli districts will add value to this growing body of knowledge and inform adaptive management strategies for local communities.

METHODOLOGY

Groundwater samples were collected from 84 locations from Chamoli 2021,46 samples during post-monsoon 2020 and 38 samples during pre-monsoon 2021 from Almora of the study area using Global Positioning System (GPS). The samples have been collected in 250 ml polypropylene water bottles. The sample collection was done accordance with the APHA Recommended Procedure 2005. The samples have been added with 10% (HNO_3) for the preservation of the samples.The physio chemical parameters pH, TDS, EC, sodium, potassium, calcium, magnesium and nitrate, chloride, fluoride and bicarbonates are measured,heavy metal analysis such as lead, chromium, zinc, iron, manganese and copper were measured using AAS, the results have been and compared with BIS.

RESULTS AND DISCUSSION

The analysis of Chamoli and Almora district of Physio chemical parameters,cations and anions and heavy metal pollution are as follows:

Physio Chemical Parameters

In Chamoli district the values of potential of hydrogen pH ranges from 6.62-7.59 (7.21) SD value 0.48 during pre-monsoon whereas, it ranges from 6.52-7.58 (7.2) SD value 0.30 during post-monsoon,total dissolved solids 70-602 (263) SD value 131 during pre-monsoon whereas, it ranges from 90-594(151) SD value 77 during post-monsoon,electrical conductivity ranges from 109-938(411) SD value 205 during pre-monsoon whereas, it ranges from 141-928(236) SD value 120 during post-monsoon.

In Almora district the values of potential of hydrogen pH ranges from 5.92-8.21 (6.97) SD value 0.47 during pre-monsoon 2021 whereas, it ranges from 6.12-8.15 (7.13) SD value 0.48 during post-monsoon 2020, total dissolved solids 64-426 (161) SD value 99 during pre-monsoon 2021 whereas, it ranges from 58-269 (134) SD value 56 during post-monsoon 2020, electrical conductivity ranges from 100-647(248) SD value 152 during pre-monsoon 2021 whereas, it ranges from 96-412 (208) SD value 85 during post-monsoon 2020.

Major Cation

In Chamoli district the values of sodium ranges from 2.07-81.73 (14.11) SD value 16.71 during pre-monsoon whereas, it ranges from 2.29-73.94 (12.93) SD value 15.6 during post-monsoon, potassiumranges from 0.03-5.31 mg/l (1.42) SD value 1.19during pre-monsoon whereas, it ranges from 0.26-11.62(3.00) SD value 2.36 during post-monsoon, calciumranges from 4.24-82.51 (33.3) SD value 21.19 during pre-monsoon whereas, it ranges from 2.65-80.06 (30.95) SD value 19.85 during post-monsoon, magnesiumranges from 2.16-47.64 (10.67)SD value 9.69during pre-monsoon whereas, it ranges from 1.9-40.27 (9.4) SD value 8.13during post-monsoon(Table 1 & 2).

In Almora district the values of sodium ranges from 2.0-86.7 (16.18) SD value 18.86 during pre-monsoon 2021 whereas, it ranges from 2.2-71.6 (12.99) SD value 14.98 during post-monsoon 2020, potassium ranges from 0.2-37.10 mg/l (8.45) SD value 9.09 during pre-monsoon 2021 whereas, it ranges from 0.3-24.4 (5.7) SD value 5.59 during post-monsoon 2020, calcium ranges from 4.19-98.16 (35.92) SD value 24.58 during pre-monsoon 2021 whereas, it ranges from 3.6-82.2 (29.55) SD value 20.17 during post-monsoon 2020, magnesium ranges from 2.25-48.71 (10.36) SD value 9.20 during pre-monsoon 2021 whereas, it ranges from 1.9-34.9 (8.7) SD value 7.57 during post-monsoon 2020(Table 1 & 2).

Major Anions

In Chamoli district the values of Nitrateranges from 2.04-61.16 (10.35)SD value 18.47during pre-monsoon whereas, it ranges from 0.00-51.77(9.33)SD value 14.13 during post-monsoon, fluoride ranges from 0.00-1.3 (0.29)SD value 0.46during pre-monsoon whereas, it ranges from 0.00-1.3(2.23) SD value 0.5during post-monsoon, bicarbonate ranges from 50-468 (149.4) SD value 103during pre-monsoon whereas, it ranges from 48-402(136.76)SD value 92.56during post-monsoon,sulphate ranges from 3.98-60.51 (12.31)SD value 11.19 during pre-monsoon whereas, it ranges from 3.52-4.71 (10.96)SD value 9.10 during post-monsoon,chloride ranges from 2.04-80.94 (21.06)SD value 17.47during pre-monsoon whereas, it ranges from 2.22-70.85 (18.19) SD value 14.99during post-monsoon(Table 1 & 2).

In Almora District the values of Nitrate ranges from 2.09-59.23 (17.29)SD value 15.74 during pre-monsoon whereas, it ranges from 4.18-63.94 (15.96) SD value 14.43 during post-monsoon, fluoride ranges from -0.31-1.15 (0.19)SD value 0.4 during pre-monsoon whereas, it ranges from -0.5 -1(0.03) SD value 0.4 during post-monsoon, bicarbonate ranges from 23-427 (130) SD value 102during pre-monsoon whereas, it ranges from 17-410 (137) SD value 99during post-monsoon, sulphate ranges from 3.71-59 (10.96) SD value 9.94 during pre-monsoon whereas, it ranges from 3.20-53.20 (10.78) SD value 8.57 during post-monsoon, chloride ranges from 2.20-83 (21.20)SD value 17.61during pre-monsoon whereas, it ranges from 2.20-67.50 (17.82) SD value 13.42 during post-monsoon(Table 1 & 2).

Heavy metals

In Chamoli District the values of lead ranges from 0.001-0.021 (0.009) SD value 0.004 during pre-monsoon whereas, it ranges from 0.001-0.017(0.006) SD value 0.004during post-monsoon,zinc ranges from 0-9.28 (1.1) SD value 2.31 during pre-monsoon whereas, it ranges from 0-16.87 (1.20) SD value

3.32during post-monsoon,manganese ranges from 0-0.11 (0.02)SD value 0.03 during pre-monsoon whereas, it ranges from 0-0.32 (0.05) SD value 0.08during post-monsoon,nickel ranges from 0-0.02 (0.004)SD value 0.01 during pre-monsoon whereas, it ranges from 0.001-0.06 (0.01) SD value 0.02 during post-monsoon, copper ranges from 0.00-0.09 (0.01)SD value 0.02during pre-monsoon whereas, it ranges from 0.00-0.04 (0.007)SD value 0.01 during post-monsoon, iron ranges from 0.01-0.81 (0.05)SD value 0.13during pre-monsoon whereas, it ranges from 0.00-0.38(0.06)SD value 0.07 during post-monsoon. Chromium ranges from 0.001-0.081 (0.031)SD value 0.02 during pre-monsoon whereas, it ranges from 0.009-0.05 (0.021) SD value 0.01 during post-monsoon(Table 1 & 2).

In Almora district the values of lead ranges from -0.02-0.16 (0.09) SD value 0.04 during pre-monsoon whereas, it ranges from -0.03-0.06 (0.03) SD value 0.03 during post-monsoon, zinc ranges from -0.45-16.59 (2.5) SD value 3.73 during pre-monsoon whereas, it ranges from-0.64-5.73 (0.78) SD value 1.04 during post-monsoon, manganese ranges from -0.14-0.27 (0.03) SD value 0.08 during pre-monsoon whereas, it ranges from-0.01-0.25 (0.04) SD value 0.06 during post-monsoon, nickel ranges from -0.01-0.05 (0.01) SD value 0.02 during pre-monsoon whereas, it ranges from-0.07-0.03 (0.00) SD value 0.03 during post-monsoon, copper ranges from -0.04-0.09 (0.01)SD value 0.04 during pre-monsoon whereas, it ranges from -0.02-0.02 (0.00) SD value 0.01 during post-monsoon, iron ranges from -0.26-0.58 (0.12)SD value 0.34 during pre-monsoon whereas, it ranges from -0.29-0.73 (0.06) SD value 0.28 during post-monsoon. Chromium ranges from -0.03-0.04 (0.02)SD value 0.01during pre-monsoon whereas, it ranges from -0.01-0.04(0.78) SD value 0.01 during post-monsoon(Table 1 & 2).

Water Quality Index

The water quality index (WQI) method is calculated for drinking water quality in different geological terrains (Horton, 1965). It tells composite influence on different water quality parameters (Sahu and Sikdar, 2008). In this study, the Weighted Arithmetic Index method is applicable as proposed by Brown et al. (1972) and WQI is calculated by following steps:

$$\mathrm{WQI} = \sum_{i=1}^{n} \frac{\mathrm{Wiqi}}{\mathrm{Wi}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

q_i= sub index for the ith parameter and w_i=unit weight for the ith parameter.
The calculation of quality rating or sub index (Qi) is expressed as:

$$qi = \frac{(V_n - V_i)}{(V_s - V_i)} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where, V_n represents the observed value of the i-th parameter in a water sample, V_s denotes the standard permissible value of the same parameter, and vi refers to its ideal value (which is considered as 0 for all parameters, except for pH where the ideal value is 7.0).

Unit weight (W_i) for an ith parameter:

$$W_i = \frac{K}{S_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Where, k = proportionality constant and s_i=standard permissible limit of the ith parameter. Calculation of proportionality constant:

$$K = \frac{1}{\sum \frac{1}{S_i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

The weights are assigned for each chemical parameters significance and which tells about the water quality parameter for drinking purposes. The parameter having highest significance of weight 5 and least of 2 is assigned. WQI standards of drinking water is divided into five categories namely, Excellent (< 25); Good (26–50); Poor (51–75), Very Poor (76-100), and Unsuitable (>100)(Mahdav et al. 2018, Yadavetal.2010).

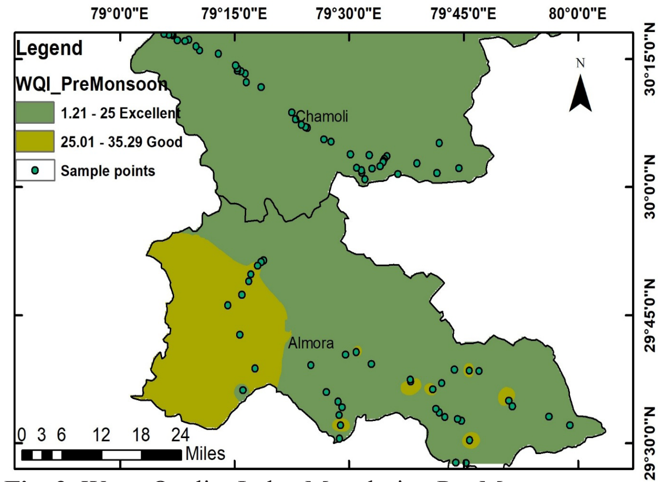

Fig. 2. Water Quality Index Map during Pre Monsoon season of Chamoli and Almora district of Uttarakhand.

In Chamoli District during Pre-Monsoon 2021, out of 46 samples 45 samples lie in the *Excellent* category, and only 01 sample fall in the *Good* category of WQI (Fig 2). While during Post-Monsoon all samples lie in the *Excellent* category (Fig 3 &Table3). While during Pre-Monsoon 2021, out of 38 samples 25 samples lie in the *Excellent* category, and 13 samples in *Good* category of WQI(Fig 2).In Almora District during Post-Monsoon, out of 38 samples 30 samples lie in the *Excellent* category, and 08 samples fall in the *Good* category of WQI (Fig.3 &Table 3)

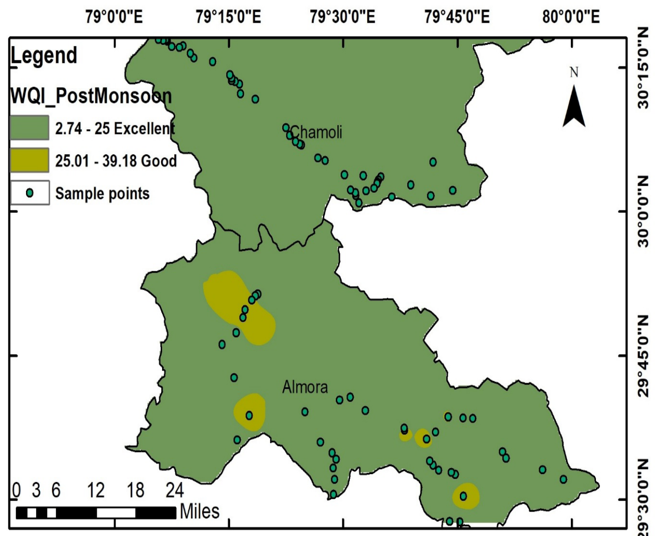

Fig. 3. Water Quality Index Map during Post Monsoon season of Chamoli and Almora district of Uttarakhand.

Table 1. Descriptive data with comparison of two districts in Pre-Monsoon season

Parameter	Acceptable limit as BIS 10500-2012	Permissible limit as BIS 10500-2012	Chamoli Pre Monsoon						Almora Pre Monsoon					
			Min	Max	Mean	SD	No. of Sm.	% Sample	Min	Max	Mean	SD	No. of Sm.	% Sample
pH	6.5-8.5	No Relaxation	7.21	7.59	-	0.48	-		5.92	8.21	6.97	0.47	6	15.79
EC (µS/cm)	-	-	411.7	938	-	205	-		100	647	248	152	-	-
TDS (mg/l)	500 mg/l	2000 mg/l	263.5	602	-	131	2	4.35	64	426	161	99	-	-
K (mg/l)	-	-	1.26	5.31	-	1.19	-		0.20	37.10	8.45	9.09	-	-
Na (mg/l)	-	-	2.07	81.73	14.11	16.71	-	-	2.00	86.70	16.18	18.86	-	-
Mg (mg/l)	30 mg/l	100 mg/l	2.16	47.64	10.67	9.69	2	4.35	2.25	48.71	10.36	9.20	2	5.26
Ca^{2+} (mg/l)	75 mg/l	200 mg/l	4.24	82.51	33.35	21.19	2	4.35	4.19	98.16	35.92	24.58	4	10.53
Cl^{-} (mg/l)	250 mg/l	1000 mg/l	6.62	7.59	7.21	17.47	-	-	2.20	83.00	21.20	17.61	-	-
NO_3^{-} (mg/l)	45 mg/l	No Relaxation	0	61.16	10.35	18.47	4	16	2.09	59.23	17.29	15.74	2	10.00
F^{-} (mg/l)	1.0 mg/l	1.5 mg/l	0	1.3	0.29	0.46	-	-	-0.31	1.15	0.19	0.40	2	5.26
SO_4^{2-} (mg/l)	200 mg/l	400 mg/l	3.98	60.51	12.31	11.19	-	-	3.71	59.00	10.96	9.94	-	-
HCO_3^{-} (mg/l)	30 mg/l	600 mg/l	50	468	149.04	103	-	-	23	427	130	102	2	5.26
Ni (mg/l)	0.02 (mg/l)	No Relaxation	0	0.028	0.004261	0.01	1	2.17	-0.01	0.05	0.01	0.02	18	47.37
Mn (mg/l)	0.1 (mg/l)	0.3 (µg/l)	0	0.118	0.025	0.03	-	-	-0.14	0.27	0.03	0.08	6	15.79
Fe (mg/l)	0.3 (mg/l)	No Relaxation	0.01	0.816	0.056	0.13	1	2.17	-0.26	0.58	0.12	0.34	19	50.00
Pb (mg/l)	0.01 (mg/l)	No Relaxation	0.001	0.021	0.009	0.00	13	28.26	-0.02	0.16	0.09	0.04	37	97.37
Cu (mg/l)	0.05 (mg/l)	1.5 (mg/l)	0	0.092	0.018	0.02	-	-	-0.04	0.09	0.01	0.04	7	18.42
Cr (mg/l)	0.05 (mg/l)	No Relaxation	0.001	0.081	0.031	0.02	7	15.22	-0.03	0.04	0.02	0.01	-	-
Zn (mg/l)	5(mg/l)	15 (mg/l)	0	9.287	1.104	2.31	-	-	-0.45	16.79	2.50	3.73	10	26.32

Table 2. Descriptive data withcomparison of two districts in PostMonsoon season

Parameter	Acceptable limit as BIS 10500-2012	Permissible limit as BIS 10500-2012	Chamoli PostMonsoon						Almora Post Monsoon					
			Min	Max	Mean	SD	No. of Sm.	% Sample	Min	Max	Mean	SD	No. of Sm.	% Sample
pH	6.5-8.5	No Relaxation	6.52	7.58	7.2	0.30	-	-	6.12	8.15	7.13	0.48	4	10.26
EC (µS/cm)	-	-	141	928	235.63	120.24	-	-	96	412	208	85	-	-
TDS (mg/l)	500 mg/l	2000 mg/l	90	594	150.87	76.96	1	2.17	58	269	134	56	5	12.82
K (mg/l)	-	-	0.26	11.62	3	2.36	-	-	0.30	24.40	5.70	5.59	-	-
Na (mg/l)	-	-	2.29	73.94	12.93	15.60	-	-	2.20	71.60	12.99	14.98	-	-
Mg (mg/l)	30 mg/l	100 mg/l	1.9	40.27	9.42	8.13	2	4.35	1.90	34.90	8.70	7.57	1	2.56
Ca^{2+}(mg/l)	75 mg/l	200 mg/l	2.65	80.06	30.95	19.85	2	4.35	3.60	82.20	29.55	20.17	1	2.56
Cl^{-} (mg/l)	250 mg/l	1000 mg/l	2.22	70.85	18.19	14.99	-	-	2.20	67.50	17.82	13.42	-	-
NO_3^{-} (mg/l)	45 mg/l	No Relaxation	0	51.77	9.33	14.13	2	8	4.18	63.94	15.96	14.43	1	4.00
F^{-} (mg/l)	1.0 mg/l	1.5 mg/l	0	1.3	0.23	0.50	-	-	-0.50	1.00	0.03	0.40	-	-
SO_4^{2-} (mg/l)	200 mg/l	400 mg/l	3.32	47.1	10.96	9.10	-	-	3.20	53.20	10.78	8.57	-	-
HCO_3^{-} (mg/l)	300 mg/l	600 mg/l	38	402	147.56	92.56	-	-	17	410	137	99	1	2.56
Ni (µg/l)	0.02 (mg/l)	No Relaxation	0.001	0.062	0.016	0.02	7	15.22	-0.07	0.03	0.00	0.03	18	46.15
Mn (µg/l)	0.1 (mg/l)	0.3 (µg/l)	0	0.328	0.058	0.08	1	2.17	-0.01	0.25	0.04	0.06	4	10.26
Fe (µg/l)	0.3 (mg/l)	No Relaxation	0	0.386	0.061	0.07	1	2.17	-0.29	0.73	0.06	0.28	9	23.08
Pb (µg/l)	0.01 (mg/l)	No Relaxation	0.001	0.017	0.006	0.00	8	17.39	-0.03	0.06	0.03	0.03	33	84.62
Cu (µg/l)	0.05 (mg/l)	1.5 (µg/l)	0	0.04	0.004	0.01	-	-	-0.02	0.02	0.00	0.01	-	-
Cr (µg/l)	0.05 (mg/l)	No Relaxation	0.009	0.05	0.021	0.01	-	-	-0.01	0.04	0.01	0.01	-	-
Zn (µg/l)	5(mg/l)	15 (mg/l)	0	16.877	1.208	3.32	1	2.17	-0.64	5.73	0.78	1.04	1	2.56

Table 3. Comparative data of Almora and Chamoli District showing WQI value of Pre and Post Monsoon season.

District	Yadav.et.al.2010	Type	Pre-Monsoon		Post- Monsoon	
			No. of Samples	% sample	No. of Samples	% sample
Chamoli	0-25	Excellent	45	97.82	46	100
	26-50	Good	1	2.17		
	51-75	Poor	-	-	-	-
	76-100	Very Poor	-	-	-	-
	> 100	Unfit for drinking	-	-	-	-
Almora	0-25	Excellent	25	65.78	30	78.94
	26-50	Good	13	34.21	8	21.05
	51-75	Poor	-	-	-	-
	76-100	Very Poor	-	-	-	-
	> 100	Unfit for drinking	-	-	-	-

Heavy Metal Pollution Index

HPI calculates the impact of heavy metals on the overall water quality. The HPI is calculated on the basis of weighted arithmetic quality mean methods. It establishes a rating scale which is based on the weights of the heavy metals. The rating scale value lies between 0 and 1 which depends upon the importance of metals affecting the water quality (Horton 1965, Mohan et al., 1996; Rajkumar et al., 2020). The HPI model is calculated by using the following equation:

$$HPI = \frac{\sum_{i=1}^{i=n}(Q_i \times W_i)}{\sum_{i=1}^{i=n} W_i} \quad \ldots\ldots 5$$

$$Q_i = \sum_{i=1}^{i=n} \frac{|M_i - I_i|}{(S_i - I_i)} \times 100 \quad \ldots\ldots 6$$

Where, Q_i is the sub-index of the i^{th} metal,

W_i = unit weightage of ith metal is the number of metals considered,

M_i = calculated value of the heavy metal,

I_i is the ideal value,

Si denotes the standard permissible value of the i^{th} metal. The negative sign, which represents the difference between two values, is not considered in the calculation. For drinking water, the maximum allowable HPI threshold is fixed at 100. (Mohan *et al.* 1996; Prasad & Bose 2001).

The value of Heavy metal pollution in the Chamoli district during Pre-Monsoon 2021 out of 46 samples 42 samples lie in the *low* grade, and only 04 samples in *Medium* grade contamination (Fig 4).Whereas in Post-Monsoon out of 46 samples 28 samples lie in the *low* grade, 13 samples in *Medium* grade and 05 samples fall in the *High* grade contamination. It shows that all the values lie in Low to Medium range of Heavy metal pollution only 10.86% of samples lie in the High Heavy metal pollution zone. (Fig 5 &Table 4). In Almora District Pre-Monsoon 2021 out of 38 samples 20 samples lie in the *low* grade, 3 samples in *Medium* grade and 15 samples fall in the *High* grade contamination (Fig 5).Whereas during Post-Monsoon, out of 38 samples 16 samples lie in the *low* grade, and 22 samples in *Medium* grade(Fig 5&Table 4).

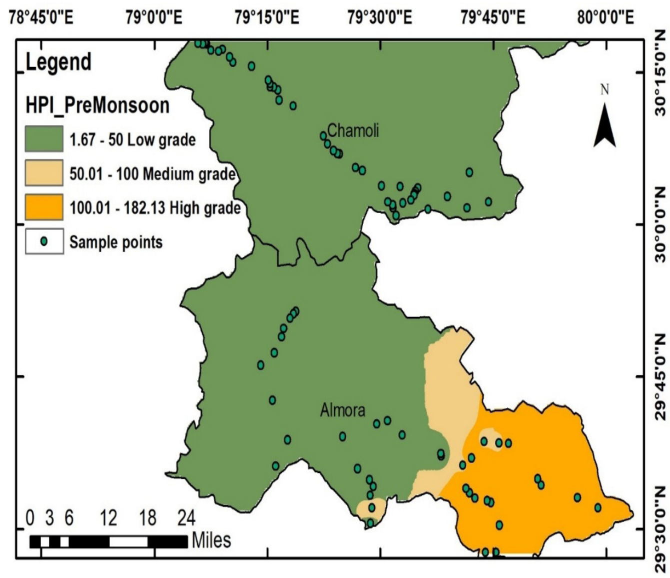

Fig. 4. Heavy Metal Pollution Index Map during Pre Monsoon season of Chamoli and Almora district of Uttarakhand.

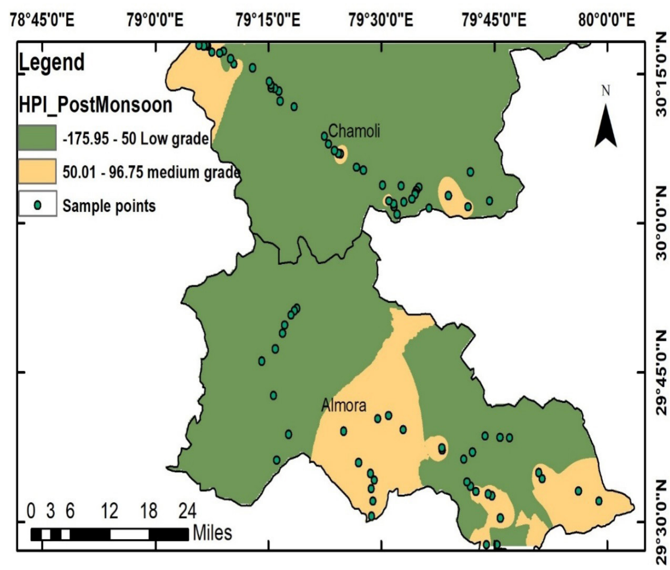

Table 4. Comparative data of Almora and Chamoli District showing HPI value of Pre and Post Monsoon season.

District	Indian Standard	Type	Pre-Monsoon		Post- Monsoon	
			No. of Samples	% sample	No. of Samples	% sample
Chamoli	0-50	Low	42	91.30	28	60.86
	50-100	Medium	4	8.69	13	28.26
	>100	High			5	10.86
Almora	0-50	Low	20	52.63	16	42.10
	50-100	Medium	3	7.89	22	57.89
	>100	High	15	39.47		

Fig. 5. Heavy Metal Pollution Index Map during Post Monsoon season of Chamoli and Almora district of Uttarakhand.

CONCLUSION

Groundwater quality in Chamoli and Almora districts of the Lesser Himalaya exhibits clear seasonal variations, with higher mineralization during pre-monsoon and dilution after monsoonal recharge. The hydrochemistry is primarily controlled by carbonate weathering, recharge dynamics, and localized anthropogenic inputs such as agriculture and sanitation. The WQI assessment shows that most samples fall in the excellent category, with a few in the good range, confirming the general suitability of groundwater for drinking and irrigation purposes.

However, the Heavy Metal Pollution Index (HPI) highlights localized risks. In Chamoli, although most samples remain in the low to medium range, post-monsoon 2021 recorded 10.9% of samples in the high contamination category. Almora presents an even greater concern, with 39.5% of pre-monsoon 2021 samples falling in the high contamination zone, mainly due to elevated heavy metal concentrations. These findings suggest that while groundwater is broadly safe, localized enrichment of nitrate and heavy metals poses potential health hazards.

Overall, the study underscores the combined influence of geology, recharge, and anthropogenic activities in shaping groundwater chemistry in the Lesser Himalaya. It is suggested from the study that long-term monitoring, particularly of heavy metals, is essential to detect seasonal fluctuations and emerging risks. Awareness among farmers for the use of controlled fertilizer, strengthening waste management, and adopting community-based safe drinking practices are recommended to minimize contamination risks to ensure the long-term sustainability of groundwater resources in the region.

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