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Seasonal Groundwater Quality Assessment in Lathiyani, Himachal Pradesh (India)

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Abstract

Groundwater is the primary source of drinking and domestic water in the Lathiyani region of Una district, Himachal Pradesh (India). The quality of water is substantially impacted by seasonally varying human activities, rainfall and groundwater recharge. The objective of this study was to assess the quality of groundwater for drinking purposes in the study area. This study is distinguished by its seasonal assessment of groundwater quality, which is substantiated by correlation analysis and estimating a Groundwater Quality Index (GWQI). A total of 96 groundwater samples were collected from six wells during the summer, monsoon, and winter seasons during 2023-2024. The GWQI and correlation heat maps were generated for the major physico-chemical parameters such as pH, electrical conductivity (EC), turbidity, total dissolved solids (TDS), dissolved oxygen (DO), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}). The results indicated a discernible seasonal variation in the groundwater quality parameters. The monsoon season was characterized by the highest turbidity (2.1-7.5 NTU) and DO (6.2-8.6 mg L^{-1}), while the pH of the water varied from 6.8 to 8.2. In summer, elevated EC (410-860 $\mu\text{S cm}^{-1}$), TDS (280-590 mg L^{-1}), Ca^{2+} (38-92 mg L^{-1}), Mg^{2+} (22-61 mg L^{-1}), Cl^- (24-86 mg L^{-1}), NO_3^- (4.5-19.2 mg L^{-1}), and PO_4^{3-} (0.12-0.35 mg L^{-1}) were observed, suggesting evaporative enrichment. The GWQI values, ranging from 48.6 in winter to 112.4 in summer, indicated very poor to excellent groundwater quality. The Spearman rank correlation-based assessment of seasonal hydrochemical relationships revealed a persistent and robust EC-TDS association ($r = 1.00$, $p < 0.01$), which suggested that dominant mineral dissolution processes of groundwater are vital in the area. However, the absence of significant EC- Cl^- and NO_3^- - PO_4^{3-} correlations suggested that multi-ionic regulation and variable nutrient mobility across seasons occurred. Overall, the groundwater was found suitable during the winter, moderately stressed during the rainy season, and deteriorated during the summer, highlighting the necessity of season-specific groundwater management.

Keywords: Groundwater quality index; seasonal variation; physico-chemical parameters; correlation matrix, heat map

Introduction

Groundwater is one of the most important freshwater resources, which is used for drinking and irrigation purposes along with maintenance of ecosystem throughout the world. In India, groundwater further becomes a vital resource for drinking, domestic, and agricultural requirements especially in areas where surface water is limited or unpredictable (Custodio, 2002; Reddy et al., 2019; Kumar and Maurya, 2023). In many areas, quality of the groundwater is more critical than its quantity. Nevertheless, managing groundwater quality has become increasingly difficult due to increasing anthropogenic activities, such as intensive agriculture, industry, and rapid urbanization (Lapworth et al., 2017; Ullah et al., 2022; El-Aassar et al., 2023).



The anthropogenic sources are the main causes of groundwater contamination, as the road runoff, municipal solid waste leachates, and insufficient wastewater treatment are some of the ways that urban activities contribute to aquifer contamination (Lapworth *et al.*, 2017; Khan *et al.*, 2021).

Britto *et al.* (2018) have extensively explored variations in the physical, chemical, and biological characteristics of groundwater, which are the results of natural processes or anthropogenic activities, to assess water quality. In general, water quality assessment involves the collection of samples at specific locations and the analysis of critical physico-chemical and biological parameters (Britto *et al.*, 2018; Tyagi *et al.*, 2013). In order to facilitate the interpretation of complex physio-chemical data, the groundwater quality index (GWQI) organizes the combined effects of geology, hydrogeochemical processes, land use, and anthropogenic influences into a single numerical value, thereby offering a comprehensive evaluation of groundwater suitability (Jha *et al.*, 2020; Nzama *et al.*, 2021; Shukla *et al.*, 2022; Ahmed *et al.*, 2023; Supriya *et al.*, 2025). Both Paun *et al.* (2016) and Singh *et al.* (2013) have reported that water quality index (WQI) models enable the rapid assessment of groundwater potability, spatial and temporal variations, the identification of pollution concentrations, and compliance with drinking water standards. The National Sanitation Foundation Water Quality Index (NSFWQI), the Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), the Oregon Water Quality Index (OWQI), and the Weighted Arithmetic Water Quality Index (WAWQI) (Paun *et al.*, 2016) are among the popular and widely-adopted GWQI models developed in different parts of the world. In this study, the appropriate GWQI model was chosen in accordance with the study objectives, regional drinking water standards, and data availability. In groundwater studies, variables like pH, electrical conductivity (EC), total dissolved solids (TDS), hardness, nitrate (NO_3^-), chloride (Cl^-), and fluoride (F^-) are frequently given priority due to their direct implications for drinking water suitability.

In areas with agricultural and industrial stressors, the techniques of GWQI are widely utilized to help guide decisions about sustainable water management (Garg *et al.*, 2022; Sharma *et al.*, 2024). According to anthropological needs and environmental sustainability, these metrics represent the general health and cleanliness of aquifers (Panneerselvam *et al.*, 2020; Supriya *et al.*, 2018a). Consequently, by considering the above-mentioned highlights, the present study was undertaken to evaluate the groundwater quality of underlying aquifer in a selected area, where such investigations did not take place in the previous studies. This study evaluated the quality of groundwater for drinking and household uses in a comprehensive and systematic manner and assessed seasonal fluctuations comparatively for summer, monsoon, and winter seasons by analyzing the major physico-chemical parameters in accordance with criteria established by the Bureau of Indian Standards (BIS, 2012) and the world health organization (WHO, 2017).

MATERIALS AND METHODS

Description of Study Area

Lathiyani region (study area) is located at latitude 31.69°N and longitude 76.52°E in Una district, which is situated in the southwestern part of Himachal Pradesh, India (Fig. 1). The study area is part of the lower Shivalik hills and shares boundaries with Punjab to the south and southwest, Kangra district to the north and northwest, and Bilaspur district to the east. The region is characterized by a humid subtropical climate, with an average annual rainfall from 100 to 140 cm and a mean annual temperature of 16.8°C . The summer temperature can reach as high as 32.4°C , while the winter temperature may fall below -0.5°C . The geological, hydrogeological, and climatic conditions collectively affect the availability, quality, and vulnerability of groundwater in the study area (IMD, 2018; CGWB, 2020).

The terrain of the area is predominantly hilly with small valleys and seasonal streams which significantly influence surface runoff and groundwater recharge. Geologically, the region is underlain by Shivalik group formations, mostly composed of poorly cemented and structurally disturbed sandstone, shale, siltstone, and conglomerates. While secondary porosity created by cracks, joints, and weathered zones controls groundwater storage and flow, these lithological units have low to moderate primary porosity (Kumar *et al.*, 2017a; CGWB, 2020). The Lathiyani region is selected due to significant dependence on groundwater for domestic purposes, as well as limited availability of surface water in the area. The vulnerability of groundwater is further exacerbated by agricultural activities and monsoonal discharge. In the present study, the distribution and variability of groundwater quality measures were assessed using descriptive statistical analysis. The Python was used to create box-and-whisker plots to show the median, interquartile range, dispersion, and any outliers of datasets. In order to assess the direction and intensity of correlations between the physicochemical parameters and to find potential associations with groundwater quality, correlation heat maps were also created using Python.

Groundwater Sampling and Analysis

In this study, groundwater samples were collected from six representative wells (W1 to W6) ensuring sufficient spatial coverage in three seasons, i.e., pre-monsoon, monsoon, and post-monsoon, during April 2023-January 2024 (Fig. 1 and Table 1). In order to get representative groundwater samples, each well was purged for 5-10 minutes

before sampling. The high-density polyethylene (HDPE) bottles that had been previously washed and rinsed two or three times with groundwater were used to collect the samples. The pumping outlet that corresponded to the well depth was directly removed in order to collect groundwater. The remaining samples were left unpreserved, while those meant for cation analysis were preserved by acidification with ultrapure nitric acid ($\text{pH} < 2$). During the sampling process, all samples were brought to the laboratory, where physicochemical analyses were finished within 24 to 48 hours following sample collection, and kept in an icebox at about 4°C . The samples were analyzed in the laboratory of Department of Environmental Sciences, HPU, Summerhill, Shimla (India), for 10 physico-chemical variables, which included pH, EC, turbidity, TDS, dissolved oxygen (DO), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^{-}), nitrate (NO_3^{-}) and phosphate (PO_4^{3-}). The standard grab sampling procedures, instruments, and analytical methodologies as detailed in Tables 2 and 3 were utilized in accordance with APHA (2021). The results were interpreted in accordance with the drinking water standards of the world health organization (WHO, 2017) and Bureau of Indian Standards (BIS, 2012), as outlined in Table 4.

Calculation of Ground Water Quality Index

In this study, an index-based approach was implemented to consolidate the cumulative impact of different groundwater quality parameters into a single representative value using following equations. The weighted arithmetic approach was used to calculate the groundwater quality index (GWQI), as expressed below (Horton, 1965) (Table 5).

$$\text{GWQI} = \sum Sli \quad (1)$$

$$Sli = Wi \times qi \quad (2)$$

where, Sli = sub-index of i^{th} water quality parameter; Wi = unit weight assigned to the i^{th} water quality parameter; qi = rating based on concentration of i^{th} parameter; and in GWQI calculation.

$$Wi = \frac{wi}{\sum wi} \quad (3)$$

where, Wi = relative weight of the i^{th} parameter, wi = assigned weight of each parameter based on importance in water quality evaluation and $\sum wi$ = sum of assigned weights of all parameters.

$$qi = \left(\frac{Ci}{Si} \right) \times 100 \quad (4)$$

where, qi = quality rating of the i^{th} parameter (unitless), Ci = concentration of each chemical parameter in each groundwater sample (mg L^{-1}), and Si = standard permissible limit of the i^{th} parameter (mg L^{-1}).

The quality rating (qi) for each parameter was determined separately for each groundwater sample based on the observed concentration (Ci) and the matching standard permitted value. Subsequently, the sub-index (Sli) was created by multiplying the quality rating (qi) with the relative weight (Wi) of the relevant parameter and this was done in order to acquire the score. The groundwater quality index (GWQI) for each groundwater sample was then calculated by adding up the sub-indices of all of the parameters that were chosen.

Results and Discussion

Box-Whisker Plot Analysis

Pre-Monsoon (Summer season)

The present study showed that the mean and median pH values for the summer were 7.12 and 7.10, respectively, suggesting a roughly symmetric distribution. There may be a few comparatively higher observations, as indicated by the skewness score of 0.35, which indicates a minor positive skewness. It has been observed that there was one upper outlier (~ 7.4), and the whiskers ranged about from 6.9 to 7.2. (Figure 2). The close relationship between mean and median showed low variability and a reasonably consistent pH across the sampling wells. In the present investigation, the mean and median values of turbidity were 0.76 and 0.70 NTU, respectively. The findings revealed that due to a few higher observations, the distribution is slightly biased to the right, as indicated by the positive skewness (0.37). In figure 2, the box-whisker plot showed an outlier (~ 1.2 NTU), however the majority of samples had concentrations below 1 NTU. It has been observed that the narrow interquartile range suggests limited variation among groundwater samples. The EC measured a median of $1300 \mu\text{S cm}^{-1}$ and a mean of $1430 \mu\text{S cm}^{-1}$. It is clear that the distribution is highly positively skewed because the difference between the mean and the median is rather substantial, and the skewness value is high (1.49). The study findings showed that the mean value was raised by the existence of an outlier about $2000 \mu\text{S cm}^{-1}$, the broader box and whiskers show more variation in the ionic concentrations of the sampled wells (Figure 2). In the summer season, TDS showed a median of 320 mg L^{-1}

and a mean of 338 mg L⁻¹. The distribution is right-skewed due to one relatively high observation (470 mg L⁻¹), as indicated by the positive skewness (1.31).

Table 1. Detailed information on the selected wells and seasonal samples collected from the study area

ID	Sample location	Latitude (North)	Longitude (East)	Well Depth (m)	Sampling depth (m) ^a	Summer (2023)	Rainy (2023)	Winter (2023-24)	Number of samples
W1	DAV Lathiyani	31°32'42"	76°24'16"	18	10	6	5	5	16
W2	Bajwar Kundu	31°32'41"	76°24'00"	45	30	6	5	5	16
W3	Ghatti	31°32'25"	76°24'26"	22	12	5	6	5	16
W4	Sasan	31°32'43"	76°24'47"	50	35	5	6	5	16
W5	Hanuman Temple	31°32'32"	76°24'53"	20	10	5	5	6	16
W6	Karasi	31°32'29"	76°25'05"	40	25	5	5	6	16

^aSampling depth = m below ground level (bgl).

Table 2. Analytical methods and instruments used for the analysis of physico-chemical parameters (APHA, 2021)

Parameter	Unit	Analytical method / Instrument
pH	°	Digital pH meter (Systronics 335)
Turbidity (NTU)	°	Nephelometric method (turbidity meter)
Electrical Conductivity (EC)	µS cm ⁻¹	Conductivity meter (Systronics 304)
Total Dissolved Solids (TDS)	mg L ⁻¹	Gravimetric method (calculated from EC)
Dissolved Oxygen (DO)	mg L ⁻¹	Winkler iodometric method
Calcium (Ca ²⁺)	mg L ⁻¹	EDTA titrimetric method
Magnesium (Mg ²⁺)	mg L ⁻¹	EDTA titrimetric method (calculated)
Nitrate (NO ₃ ⁻)	mg L ⁻¹	UV-Visible spectrophotometric method
Phosphate (PO ₄ ³⁻)	mg L ⁻¹	Ascorbic acid spectrophotometric method
Chloride (Cl ⁻)	mg L ⁻¹	Argentometric titration method

Table 3. WHO and the BIS drinking water quality standards

Parameter	Unit	WHO (2017)	BIS 10500 (2012)
pH	-	6.5–8.5	6.5–8.5
Turbidity (NTU)	-	≤ 5	5 (desirable), 10 (permissible)
Electrical Conductivity (EC)	µS cm ⁻¹	-	1,500 (permissible)
Total Dissolved Solids (TDS)	mg L ⁻¹	≤ 1,000	500 (desirable), 2000 (permissible)
Dissolved Oxygen (DO)	mg L ⁻¹	≥ 5	–
Calcium (Ca ²⁺)	mg L ⁻¹	–	75 (desirable), 200 (permissible)
Magnesium (Mg ²⁺)	mg L ⁻¹	–	30 (desirable), 100 (permissible)
Chloride (Cl ⁻)	mg L ⁻¹	250	250 (desirable), 1,000 (permissible)
Nitrate (NO ₃ ⁻)	mg L ⁻¹	50	45 (desirable), 100 (permissible)
Phosphate (PO ₄ ³⁻)	mg L ⁻¹	–	0.1–0.2 (desirable)

The observations showed the majority of samples showed modest variability, concentrated between roughly 280 and 350 mg L⁻¹. The distribution of DO was almost symmetrical, with a mean of 3.78 mg L⁻¹ and a median of 3.75 mg L⁻¹. The results for DO reveal that there is slight positive skewness observed, as indicated by the skewness value of 0.19, while there was one greater outlier (~4.5 mg L⁻¹) and the majority of data were contained within a small range. In the investigation, calcium had the greatest summer mean content of 135 mg L⁻¹ and a median of 135 mg L⁻¹. In figure 2 the box-whisker plot the skewness value of 0.10 implies a nearly symmetric distribution, the whiskers showed substantial heterogeneity between wells, extending around from 110 to 160 mg L⁻¹. The mean and median values of nitrate were identical (17.0 mg L⁻¹). The findings showed a small positive skewness value of 0.30, the majority of samples remained clustered between 13 and 18 mg L⁻¹, showing modest variance with the exception of an upper outlier (~22 mg L⁻¹). The concentration of Cl⁻ showed a median of 25.0 mg L⁻¹ and a mean of 24.5 mg L⁻¹. The findings revealed that a somewhat positive skewness is indicated by the skewness value of 0.72, with concentrations ranging roughly from 18 to 30 mg L⁻¹, the distribution displayed moderate variability. It has been observed that the mean and median concentrations of phosphate were the same (0.47 mg L⁻¹). A distribution that is almost symmetric is shown by the skewness value of 0.13. The majority of samples were dispersed within a small concentration range, with the exception of one upper outlier (~0.50 mg L⁻¹). In figure no 2, the box-whisker plots showed higher variability in EC (skewness = 1.49) and TDS (skewness = 1.31) throughout the summer, suggesting localized enrichment of dissolved ions in some groundwater wells. The observations showed that the magnesium

(skewness = 0), calcium (0.10), and phosphate (0.13), on the other hand, showed comparatively symmetric distributions, indicating more consistent concentrations throughout the study region. The results revealed that the localized hydrogeochemical variability and potential human impacts are further indicated by the presence of outliers in EC, TDS, nitrate, turbidity, and DO. These findings, correlated with the elevated concentrations of calcium, magnesium, and nitrate that were observed during the summer, provide further support to the influence of decreased recharge, increased evaporation, and enhanced mineral dissolution under pre-monsoon conditions. These results are in accordance with the findings of previous research carried out in Himalayan and sub-Himalayan groundwater systems (Singh and Ghosh, 2020; Gogoi *et al.*, 2023; Raut *et al.*, 2025; Mapoma and Abdullateef, 2024; Ha *et al.*, 2021; Agrawal *et al.*, 2024).

Table 4. Groundwater Quality Index (GWQI) categorization (Brown *et al.*, 1972)

WQI range	Water quality category	Water use suitability
0 – 50	Good	Suitable for drinking
51 – 70	Poor	Requires treatment before use
71 – 100	Very Poor	Unsuitable for drinking
> 100	Unfit	Not suitable for domestic use

Table 5. Seasonal categorization of well water quality in the study area using GWQI

ID	Pre monsoon		Monsoon		Post monsoon	
	GWQI (Calculated)	GWQI (Category)	GWQI (Calculated)	GWQI (Category)	GWQI (Calculated)	GWQI (Category)
W1	54.4	Poor (51–70)	50.1	Poor (51–70)	47.3	Good (0–50)
W2	47.8	Good (0–50)	52.3	Poor (51–70)	50.8	Poor (51–70)
W3	58.6	Poor (51–70)	55.8	Poor (51–70)	55.2	Poor (51–70)
W4	63.5	Poor (51–70)	57.2	Poor (51–70)	60.5	Poor (51–70)
W5	90.7	Very Poor (71–100)	82.5	Very Poor (71–100)	85.1	Very Poor (71–100)
W6	49.6	Good (0–50)	49.0	Good (0–50)	48.9	Good (0–50)

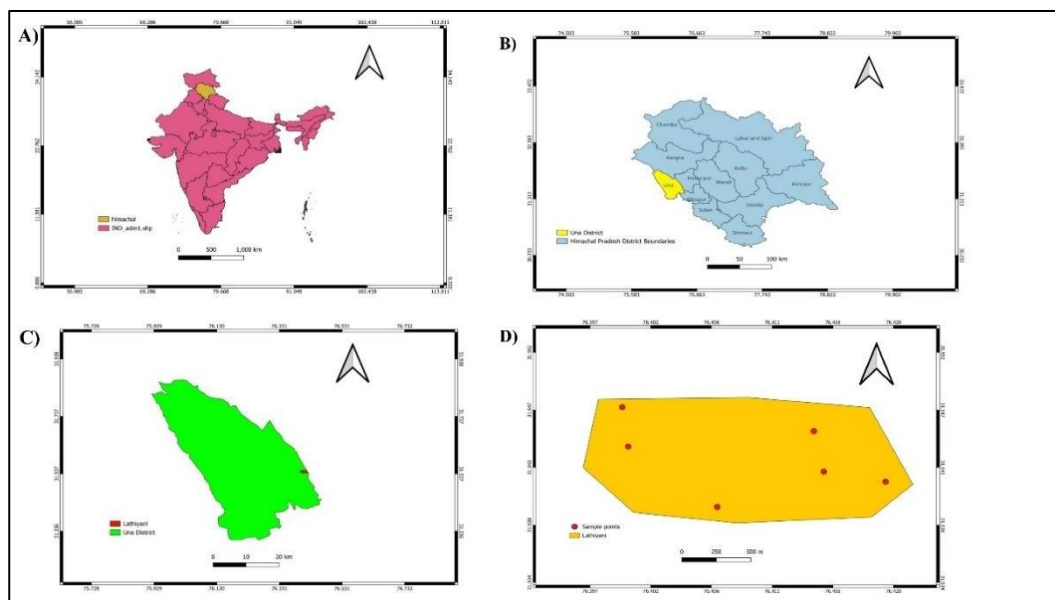


Fig. 1. QGIS generated location map of the study area

Post monsoon (Winter season)

The current study found that the mean and median pH values during the post-monsoon (winter) season were 7.32 and 7.30, respectively, indicating a nearly symmetrical distribution. The skewness value of 0.35 indicated slightly positive skewness, suggesting the presence of a few substantially higher observations. The whiskers ranged from 7.1 to 7.6, with no significant outliers (Figure 2). The close proximity of the mean and median readings showed low variability and rather consistent pH levels across the sampling wells. In the present investigation, turbidity exhibited a mean value of 0.22 NTU and a median of 0.20 NTU during the post-monsoon season. The positive skewness value of 0.37 suggested that the distribution was slightly right-skewed due to a few higher-order observations. The box-whisker plot demonstrated a relatively narrow interquartile range, indicating that the groundwater samples were rather stable Figure 2. It has been observed that the turbidity levels remained significantly lower than the allowed limit throughout the season, indicating good water clarity. The EC recorded a mean of 1714 $\mu\text{S cm}^{-1}$ and a median of 1520 $\mu\text{S cm}^{-1}$. The results showed a strongly positively skewed distribution, as seen by the comparatively wide

difference between mean and median values and the high skewness score of 1.49. The existence of an upper outlier ($\sim 2550 \mu\text{S cm}^{-1}$) raised the average EC concentration.

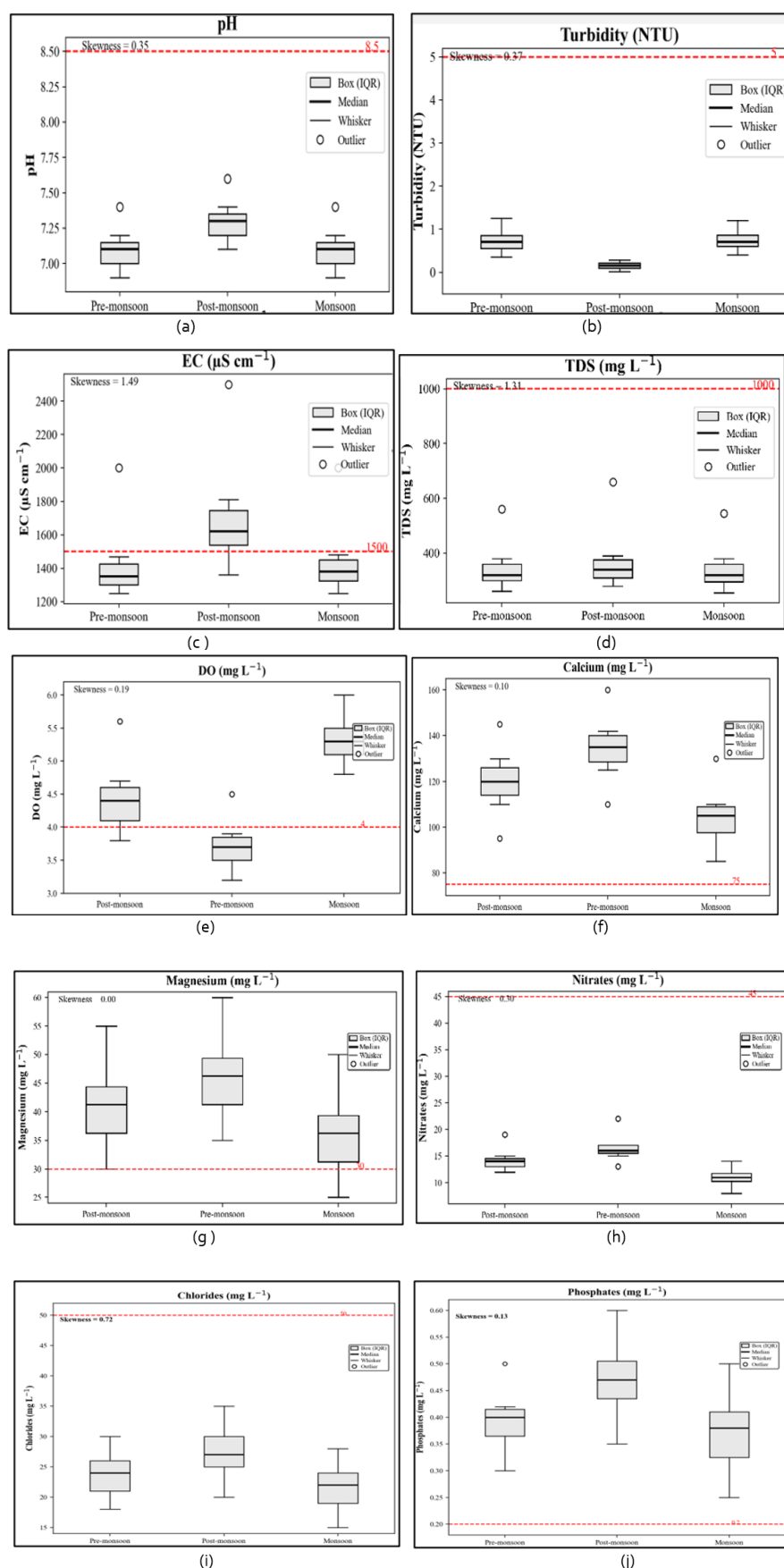
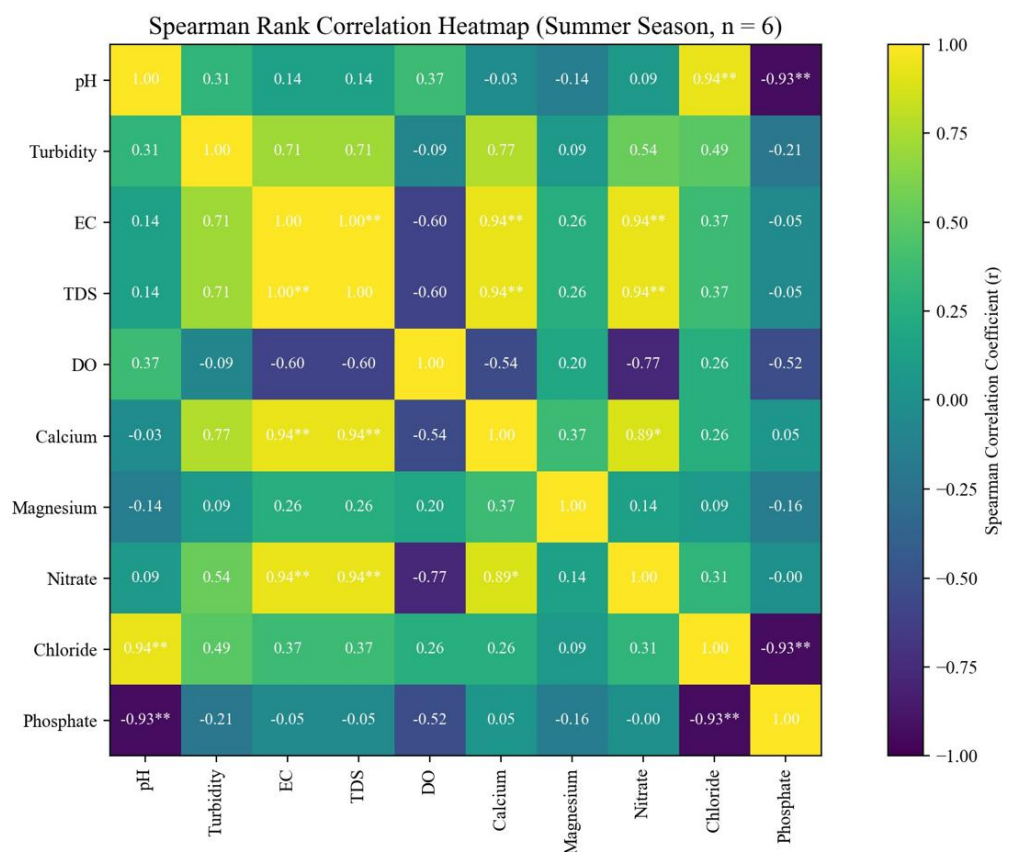
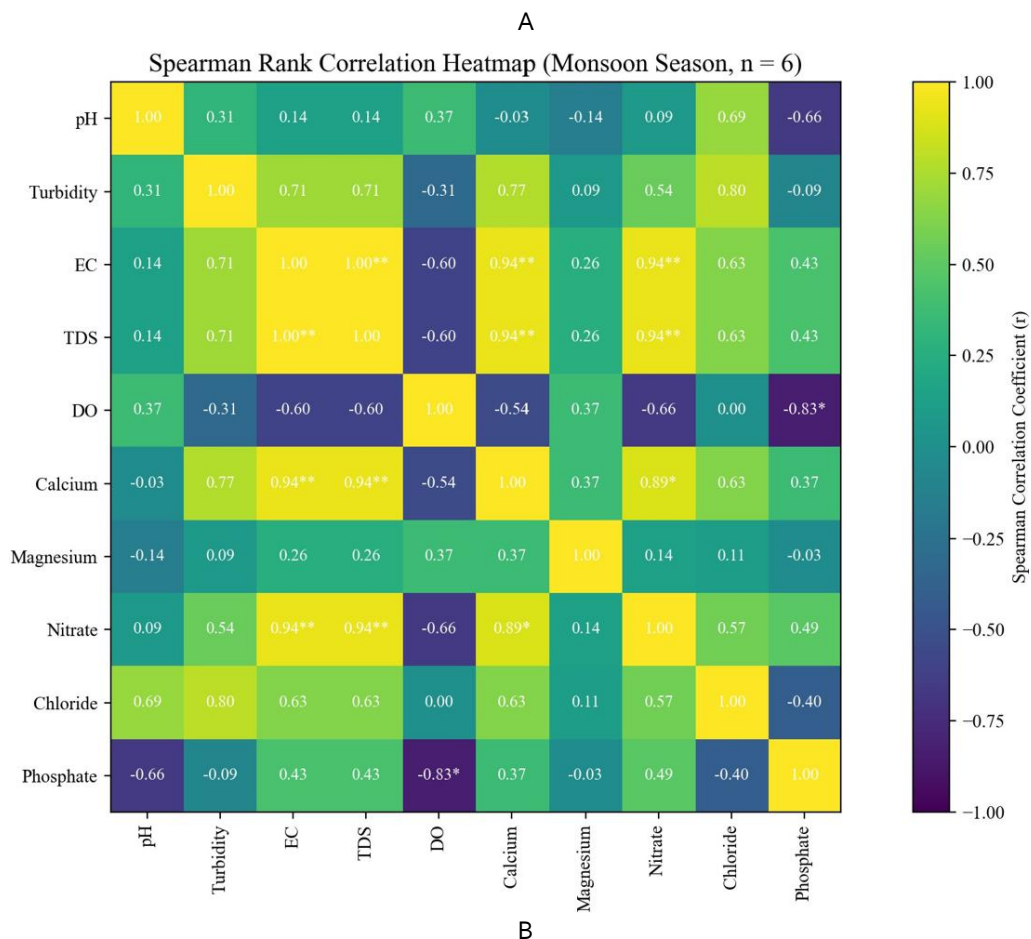


Fig. 2. Box-Whisker plots showing seasonal variation in ground water parameters across the study area

The larger box and whiskers indicated significant diversity in ionic concentrations among groundwater wells. During the post-monsoon season, TDS concentrations averaged 378 mg L^{-1} with a median of 320 mg L^{-1} . The positive

skewness score of 1.31 indicates a right-skewed distribution due to a single high observation ($\sim 590 \text{ mg L}^{-1}$). The majority of groundwater samples were concentrated between 280 and 380 mg L^{-1} , demonstrating moderate heterogeneity among sampling locations. The distribution of DO concentration exhibited a mean value 4.50 mg L^{-1} , with a median of 4.40 mg L^{-1} .



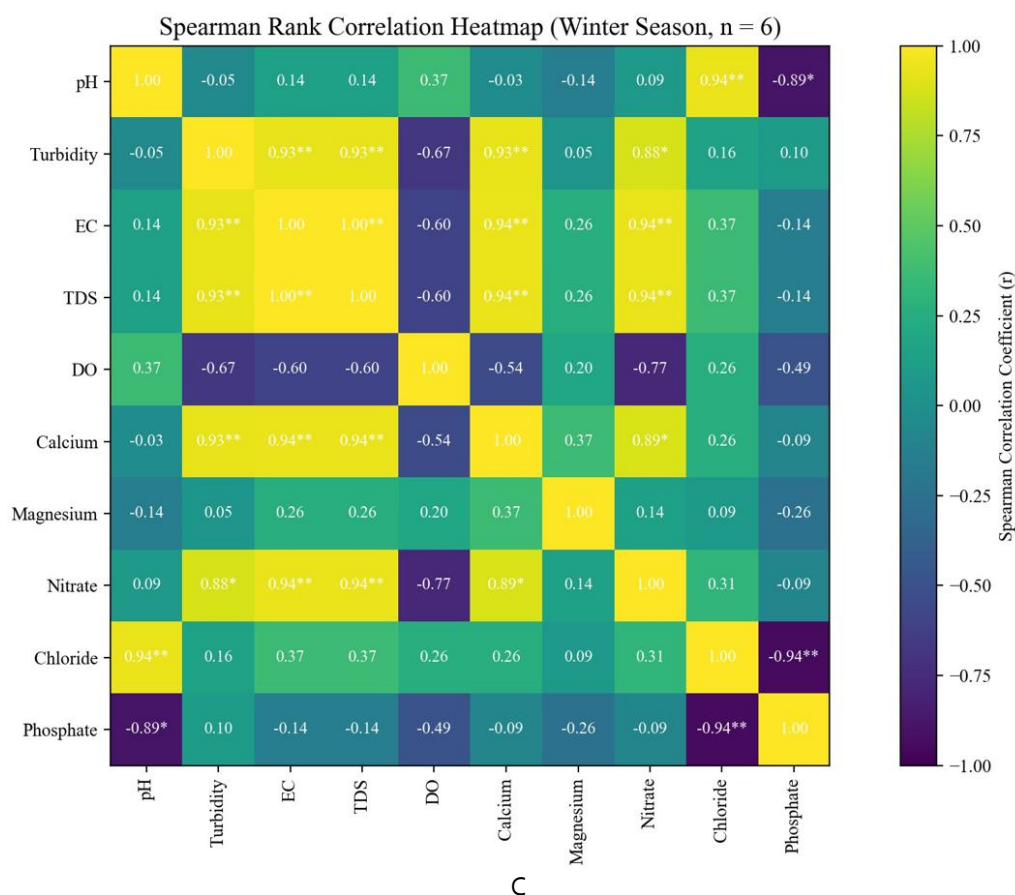


Fig. 3. Season-wise heat maps depicting the strength and direction of correlation among physico-chemical variables in six wells: (a) Pre-monsoon season, (b) Monsoon season and (c) Post-monsoon season, and temporal dynamics in ground water quality

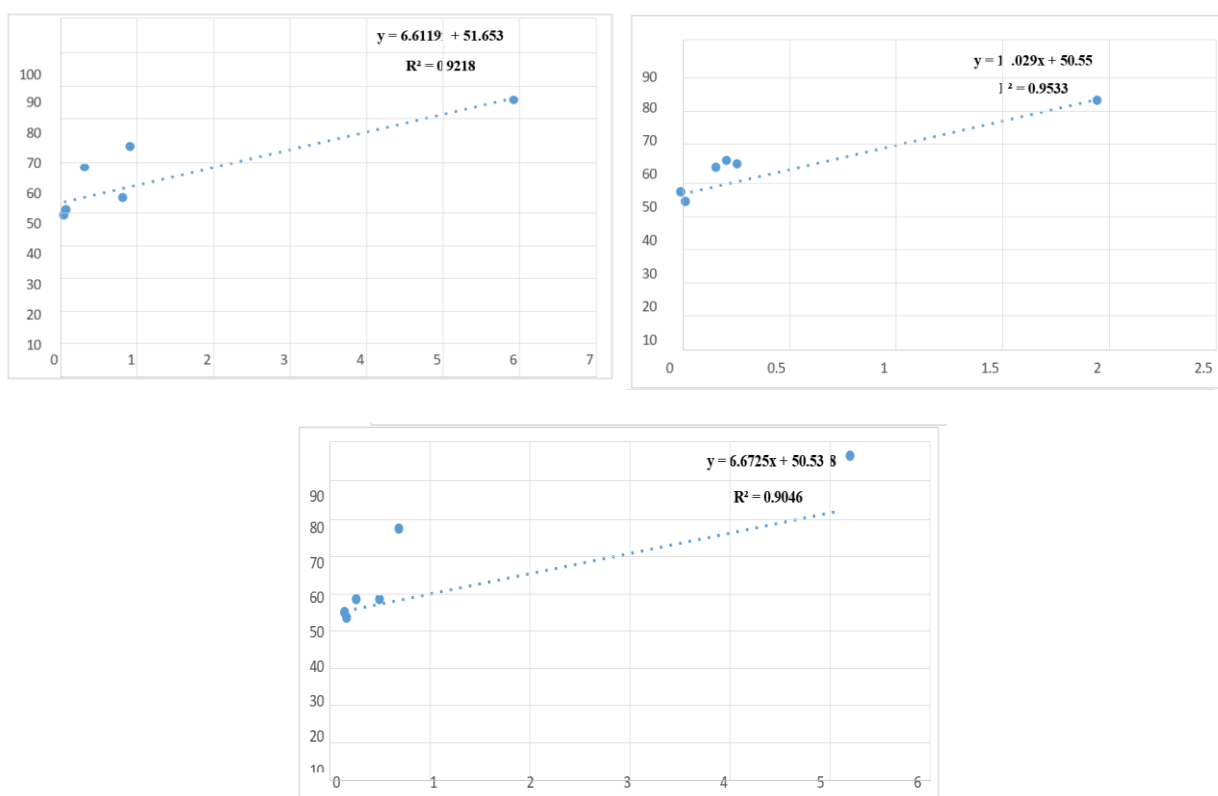


Fig. 4. Scatter plots showing the relationship between nitrate concentration and groundwater quality Index (GWQI) of pre-monsoon (a), monsoon (b) and post-monsoon (c)

The skewness value of 0.19 suggested a minor positive skew. The majority of observations fell within a small range, with one outlier ($\sim 5.6 \text{ mg L}^{-1}$). The good agreement between mean and median values indicated that DO concentrations were reasonably homogeneous across the research area. During the post-monsoon season, calcium concentrations averaged 120 mg L^{-1} , with a median of 120 mg L^{-1} . The skewness value of 0.10 indicated a relatively symmetric distribution. The whiskers ranged from 95 to 145 mg L^{-1} , showing substantial variability between groundwater samples (Figure 2). The average and median magnesium values were the same (42.5 mg L^{-1}). The skewness value of zero confirmed a perfectly symmetric distribution. It has been observed that the magnesium concentrations were uniformly distributed among sampled wells, ranging from 30 to 55 mg L^{-1} , as seen by the Box-Whisker plot. The mean and median concentrations of nitrate were found to be 14.33 mg L^{-1} and 14.00 mg L^{-1} respectively (Fig. 2).

The skewness value of 0.30 suggested a slight positive skewness. The majority of observations ranged between 12 and 15 mg L^{-1} , with an upper outlier ($\sim 19 \text{ mg L}^{-1}$) causing moderate variability among groundwater samples. The Cl^{-} concentration averaged 27.50 mg L^{-1} , with a median of 27.00 mg L^{-1} . The skewness value of 0.72 suggested a significant positive skew. The values ranged from 20 to 35 mg L^{-1} , indicating substantial dispersion across the sampling wells. During the post-monsoon season, mean and median phosphate concentrations were identical (0.47 mg L^{-1}). The skewness value of 0.13 suggested a roughly symmetric distribution. The majority of samples were within a narrow concentration range, although the box-whisker plot revealed a higher observation ($\sim 0.60 \text{ mg L}^{-1}$). Overall, the box-whisker plots showed that during the post-monsoon season, EC (skewness = 1.49) and TDS (skewness = 1.31) showed the maximum positive skewness and variability, suggesting localized enrichment of dissolved ions in certain groundwater wells (Figure 2). On the other hand, the distributions of magnesium (skewness = 0), calcium (0.10), phosphate (0.13), and DO (0.19) were more symmetrical, indicating that their amounts were more consistent throughout the research region. In groundwater quality, the presence of outliers in EC, TDS, nitrate, turbidity, and DO is indicative of the presence of localized hydrogeochemical variability as well as possible anthropogenic impacts. These results, along with the increased concentrations of pH, EC, TDS, Cl^{-} , and phosphate seen during the post-monsoon period, suggest to improved water-rock interaction and groundwater chemical stabilization after monsoon recharge. Similar post-monsoon enrichment and seasonal variations in groundwater quality parameters have been reported from Himalayan and sub-Himalayan aquifers by Supriya et al. (2018a; 2018b), Rawat et al. (2021), Verma and Chauhan (2020), Sharma et al. (2023), Patel et al. (2025), Kumar et al. (2025), Verma et al. (2024), and Agrawal et al. (2024). These findings were brought to light by the researchers who conducted the research.

Monsoon (Rainy season)

The current study found that the mean and median pH values throughout the monsoon season were 7.08 and 7.00, indicating a roughly symmetric distribution. The skewness value of 0.35 indicated slight positive skewness, suggesting the presence of a few comparatively higher observations. The whiskers ranged from 6.8 to 7.3, with no significant outliers. It has been observed that the close proximity of the mean and median values showed that the groundwater samples had low variability and rather steady pH conditions during the wet season. During the monsoon season, turbidity averaged 0.78 NTU and had a median of 0.75 NTU. The positive skewness value of 0.37 suggested that the distribution was slightly right-skewed due to a few higher-order observations. The box-whisker plot showed a high outlier ($\sim 1.3 \text{ NTU}$), with the majority of samples lying below 1 NTU (Figure 2). The limited interquartile range indicated that there was relatively little variation across the groundwater samples, despite the fact that seasonal rainfall patterns were present. The EC exhibited a mean of $1480 \mu\text{S cm}^{-1}$ and a median of $1350 \mu\text{S cm}^{-1}$. The findings showed a strongly positively skewed distribution, as evidenced by the significant gap between mean and median values and the high skewness value of 1.49. The presence of an upper outlier, which was around $2200 \mu\text{S cm}^{-1}$, resulted in an increase in the mean EC concentration. There was a significant amount of variation in the ionic concentrations among the groundwater wells that were analyzed, as demonstrated by the broader box and whiskers, respectively (Fig. 2). During the monsoon season, TDS concentrations averaged 338 mg L^{-1} and reached a median of 300 mg L^{-1} . The positive skewness value of 1.31 indicates a right-skewed distribution due to a single high observation ($\sim 520 \text{ mg L}^{-1}$). The majority of groundwater samples were concentrated between 250 and 350 mg L^{-1} , demonstrating moderate heterogeneity among sampling locations. The distribution of DO concentration exhibited a mean value 5.37 mg L^{-1} and a median of 5.30 mg L^{-1} . The skewness value of 0.19 demonstrated a minor positive skew. The majority of observations fell within a small range, with only one outlier ($\sim 6.4 \text{ mg L}^{-1}$). There was a high degree of concordance between the mean and median results, which indicated that the DO concentrations were reasonably consistent throughout the research area. During the monsoon season, calcium concentrations averaged 105.83 mg L^{-1} , with a median of 105 mg L^{-1} . The skewness value of 0.10 indicated a relatively symmetric distribution. The whiskers ranged from 85 to 130 mg L^{-1} , demonstrating substantial variability between groundwater samples. During the monsoon season, calcium concentrations averaged 105.83 mg L^{-1} , with a median of 105 mg L^{-1} . The skewness value of 0.10 indicated a relatively symmetric distribution. The whiskers ranged from 85 to 130 mg L^{-1} , demonstrating substantial variability between groundwater samples. In the study area, magnesium concentrations were measured to be 37.50 mg L^{-1} on average respectively. The skewness

value of 0.00 indicated a symmetric distribution. The findings showed the magnesium concentrations were uniformly distributed among sampled wells, ranging from 28 to 48 mg L⁻¹, as seen by the Box-Whisker plot. It has been found that the mean concentration of nitrate was 11.33 mg L⁻¹, while the median value was 11.00 mg L⁻¹. The skewness value of 0.30 suggested a slight positive skewness. The study findings showed the majority of observations were between 9 and 13 mg L⁻¹, with an upper outlier (~16 mg L⁻¹) contributing to considerable variability among groundwater samples. The Cl⁻ concentration averaged 21.50 mg L⁻¹, with a median of 21.00 mg L⁻¹. The skewness value of 0.72 suggested a significant positive skew. It has been observed that the values ranged from 16 to 27 mg L⁻¹, indicating considerable dispersion across the sampling wells. The Box-Whisker plots showed that, despite the dilution effect of rainfall recharge, EC (skewness = 1.49) and TDS (skewness = 1.31) showed the highest positive skewness and variability during the monsoon season, indicating localized enrichment of dissolved ions in selected groundwater wells. The observation revealed that the magnesium (skewness = 0.00), calcium (0.10), phosphate (0.13), and DO (0.19), on the other hand, showed comparatively symmetric distributions, indicating more consistent concentrations throughout the research region. In groundwater quality, the presence of outliers in EC, TDS, nitrate, turbidity, and DO is indicative of the presence of localized hydrogeochemical variability as well as possible anthropogenic impacts. The influence of seasonal recharge and dilution processes on groundwater chemistry is highlighted by these data, and these findings, when combined with the lower concentrations of the majority of dissolved constituents and the greater levels of DO during the monsoon season, demonstrate the significance of these processes. In Himalayan and sub-Himalayan aquifers, similar monsoon-driven hydrochemical fluctuations have been documented by Rawat et al. (2021), Kumar and Singh (2022), Sharma and Kumar (2018), Supriya et al. (2025), Wagh et al. (2025), Sharma et al. (2023), Verma and Chauhan (2020), Agrawal et al. (2024), and Bhatt and Malla (2025).

Seasonal Spearman Rank Correlation of Groundwater Parameters

In the summer (Fig. 3a), concentration-driven ionic control was demonstrated by the very significant positive correlations that EC showed with TDS ($r = 1.00$, $p < 0.01$), calcium ($r = 0.94$, $p < 0.01$), and nitrate ($r = 0.94$, $p < 0.01$). But in contrast to what is usually expected from hydrochemistry, EC did not exhibit a significant correlation with Cl⁻ ($r = 0.37$, $p > 0.05$). Similarly, there was no significant association between phosphate and nitrate ($r \approx 0.00$, $p > 0.05$), indicating separate origins and mobility. The phosphate and pH showed a high negative association ($r = -0.93$, $p < 0.01$), indicating pH-dependent phosphate behaviour. During the monsoon season (Fig. 3b), EC had a high positive correlation with TDS ($r = 1.00$, $p < 0.01$) and substantial relationships with calcium ($r = 0.94$, $p < 0.01$) and nitrate ($r = 0.94$, $p < 0.01$), showing ongoing ionic dependency. However, EC did not exhibit a significant association with Cl⁻ ($r = 0.63$, $p > 0.05$), implying that Cl⁻ was not the primary determinant of conductivity during rainfall. In addition, there was no significant correlation between nitrate and phosphate ($r = 0.49$, $p > 0.05$), which may be indicative of differential mobility and potential dilution effects (Kumar et al., 2017a, Supriya et al., 2018b and Giri et al., 2025). It was revealed that there was a significant negative connection between dissolved oxygen and phosphorus ($r = -0.83$, $p < 0.05$). This suggests that the two parameters exhibited opposite trending patterns during the monsoon season. It was observed that there was a correlation between higher concentrations of DO and lower levels of phosphate, which is undoubtedly associated with the effects of recharging and dilution that are caused by rainfall (Bairwa et al., 2024). During the winter season, as depicted in Fig. 3c, the EC exhibited a strong positive correlation with TDS ($r = 1.00$, $p < 0.01$), calcium ($r = 0.94$, $p < 0.01$), and nitrate ($r = 0.94$, $p < 0.01$). These correlations suggest that the EC of groundwater is primarily controlled by dissolved ionic constituents that are an outcome of water-rock interactions. According to the observations, a further confirmation that dissolved solids were the primary contributors to groundwater salinity during the post-monsoon period is provided by the strong correlation that exists between EC and TDS. It is expected that geological processes, in addition to possible agricultural inputs, are responsible for the positive association that exists between calcium and nitrate in specific wells. On the other hand, the EC did not exhibit a significant correlation with Cl⁻ ($r = 0.37$, $p > 0.05$), which suggests that chloride was not as relevant in terms of its contribution to fluctuations in conductivity as other dissolved ions. Additionally, nitrate and phosphate showed a weak and non-significant negative correlation ($r \approx -0.09$, $p > 0.05$), indicating that these nutrients came from various sources within the groundwater system and were regulated by different hydrogeochemical processes. A significant negative association ($r = -0.94$, $p < 0.01$) was found between Cl⁻ and phosphate, showing distinct seasonal patterns. Across all seasons, EC and TDS had a substantial correlation ($r = 1.00$, $p < 0.01$), suggesting mineral dissolution control (Ha et al., 2021, Supriya et al., 2025 and Zhang et al., 2022). However, the absence of strong correlations between EC- Cl⁻ and nitrate-phosphate supports multi-ionic control and distinct nutritional behaviour (Pitchaimani et al. 2024). This pattern has also been observed in the studies by Sayyed and Bhosle (2011), Kumar et al. (2017b), Liu et al. (2021), He et al. (2021), Nguyen and Huynh (2023), and Wang et al. (2023).

Ground Water Quality Index (GWQI)

The GWQI values of six wells under investigation during the summer season ranged from 47.8 to 90.7 (Table 5). The GWQI classified wells W₂ (47.8) and W₆ (49.6) as acceptable water quality (GWQI: 0-50) according to the Brown et al. (1972). According to Brown et al. (1972), wells W₁ (54.4), W₃ (58.6), and W₄ (63.5) had significantly deteriorating groundwater quality throughout the pre-monsoon period, classified into the poor groundwater quality range

(GWQI: 51–75). On the other hand, well W5 displayed very poor groundwater quality, with a GWQI score of 90.7 (GWQI: 71–100). These findings revealed that the water quality has significantly deteriorated in comparison to the other wells that were sampled. According to Brown *et al.* (1972), the dominance of poor to very poor groundwater quality categories during the summer season may be attributed to increased evaporation, lower groundwater recharge, and the subsequent concentration of dissolved elements. The GWQI values varied from 49.0 to 82.5 during the rainfall (monsoon) season. According to the categorization standards, wells W1 (50.1), W2 (52.3), W3 (55.8), and W4 (57.2) were classified as poor, but well W6 (49.0) remained within the acceptable range. Additionally, well W5 (82.5) was rated as extremely poor, indicating a worse degradation in water quality. The persistence of unsatisfactory groundwater quality in the majority of wells during the rainy season suggested that the aquifer system is influenced by surface discharge, leaching of contaminants, and the mobilization of dissolved ions and nutrients, particularly in wells W1 to W4. The findings showed that the continuous decrease in groundwater quality in well W5 is indication of localized pollution, which may have been caused by agricultural operations, household wastewater inputs, and surface runoff from the areas that are close to the well. The GWQI values ranged from 47.3 to 85.1 during the winter (post-monsoon) season. The high quality of the groundwater in wells W1 (47.3), W2 (50.8), and W6 (48.9) was indicative of the enhanced conditions that occurred as a result of dilution and recharge following the monsoon. The water quality of well W5 (85.1) remained extremely poor, while wells W3 (55.2) and W4 (60.5) remained in the poor category. The beneficial effect of post-monsoon recharge and reduced anthropogenic pressure is underscored by the overall improvement observed in several wells during winter. The groundwater quality was generally deemed to be at its lowest during the summer and rainy seasons, as indicated by a higher GWQI values and a greater number of wells classified as "poor" or "very poor" (Table 5). On the contrary, the winter season exhibited relatively reduced GWQI values, suggesting that the quality of the groundwater had improved. This seasonal pattern is in accordance with Tyagi *et al.* (2013), Sener *et al.* (2017) and Nath *et al.* (2024). During the pre-monsoon and monsoon periods, elevated GWQI values were linked to evaporation-induced concentration of ions and runoff-driven contamination, while post-monsoon recharge resulted in dilution and enhancement of water quality (Supriya *et al.*, 2018a; Kumar *et al.*, 2025).

Validation of Groundwater Quality Index (GWQI)

In the current study, linear regression analysis between nitrate (NO_3^-) concentration and GWQI values for the pre-monsoon, monsoon, and post-monsoon seasons was used to assess the GWQI's reliability. The nitrate was selected as a validation parameter because it is widely recognized as an important indicator of groundwater contamination resulting from anthropogenic activities such as agricultural runoff, fertilizer leaching, and domestic wastewater infiltration. The regression analysis showed that nitrate content and GWQI were strongly positively correlated throughout all seasons. There was a high degree of concordance between the nitrate concentration and the GWQI values, as indicated by the coefficient of determination (R^2) values that were obtained, which were 0.92 (pre-monsoon), 0.95 (monsoon), and 0.90 (post-monsoon). These findings demonstrated that fluctuations in nitrate concentration throughout the corresponding seasons account for 92.18%, 95.33%, and 90.46% of the variation in GWQI. The strong correlation between nitrate content and GWQI was further supported by the high R^2 values seen during the pre-monsoon ($R^2 = 0.92$) and post-monsoon ($R^2 = 0.90$) seasons. The observations showed that the strong regression associations throughout all seasons show that rising nitrate concentrations were correlated with rising GWQI values, indicating a decline in groundwater quality. The GWQI effectively detects seasonal variations in groundwater quality and reacts sensitively to changes in nitrate concentration, as demonstrated by the consistently high coefficients of determination. Consequently, the reliability, applicability, and dependability of the GWQI model as a useful tool for evaluating groundwater quality in the research region are supported by the regression-based validation (Fig. 3).

Conclusions

In the Lathiyani area of Himachal Pradesh, the current study found significant seasonal fluctuations in groundwater quality. It has been revealed that the quality of the groundwater ranged from good to very bad, with GWQI values ranging from 47.8–90.7 (pre-monsoon), 49.0–82.5 (monsoon), and 47.3–85.1 (post-monsoon). As a result, wells W3, W4, and especially W5 displayed groundwater quality that ranged from bad to extremely poor during the course of the investigation. The findings showed wells W2 and W6 remained consistently within the satisfactory category. The continued localized groundwater deterioration is shown by the highest GWQI values that were measured at W5 (90.7, 82.5, and 85.1). The seasonal fluctuation revealed that while post-monsoon recharge enhanced groundwater quality through dilution, evaporation, decreased recharge, and pollutant leaching caused groundwater quality to degrade throughout the pre-monsoon and monsoon seasons. The results of the Spearman correlation analysis revealed a significant link between EC and TDS, calcium, and nitrate ($r = 0.94$ – 1.00 , $p < 0.01$). This suggests that dissolved ionic elements were primarily responsible for controlling the chemical composition of groundwater. The validation of the GWQI with nitrate showed strong coefficients of determination ($R^2 = 0.9218$, 0.9533 , and 0.9046), proving its dependability for seasonal groundwater quality evaluation. These results highlight the need of systematic groundwater management and regular monitoring, particularly for sensitive wells like W5.

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Author Contributions

Kalyani Supriya: Investigation, Data analysis, Supervision, Reviewing and Editing; **Nandita Sharma, Sanya Dogra:** Writing-Original Draft; **RK Aggarwal:** Formal analysis, Data curation. KS, NS, SD, RKA conceived the concept, wrote and approved the manuscript.

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Competing interest

The authors declare no competing interests.

Ethics approval

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