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Integrated Spatial and Statistical Assessment of Groundwater Quality in Rupbas Tehsil of Bharatpur, Rajasthan: A WQI-Based Approach

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Abstract

This study presents a comprehensive evaluation of groundwater quality in Rupbas Tehsil of Bharatpur District, Rajasthan, through the application of the Water Quality Index (WQI) and hydrogeochemical techniques. A total of 32 groundwater samples, 16 collected during the pre-monsoon and 16 during the post-monsoon seasons, were analyzed for key physicochemical parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), oxidation-reduction potential (ORP), total hardness (TH), total alkalinity (TA), fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), and phosphate (PO_4^{3-}). Field measurements and laboratory analyses revealed seasonal variations in water quality, with several samples ranging from good to poor categories based on WQI values. Elevated values of EC, TDS, salinity, DO, Cl^-, TH and TA in certain locations indicate localized anthropogenic contamination, likely due to agricultural runoff and improper waste disposal. The findings suggest that while the groundwater is largely suitable for agricultural use, select samples may require treatment before being deemed safe for drinking. The study underscores the importance of continuous monitoring and the implementation of sustainable groundwater management practices to safeguard water resources in the region.

Keywords: Rupbas tehsil (bharatpur), groundwater, physicochemical characterization, water quality index (WQI), statistical analysis, irrigation suitability

INTRODUCTION

Water is an indispensable natural resource, fundamental to sustaining life, supporting economic development, and maintaining ecological balance. The availability of safe and potable water has become a pressing global concern, particularly in developing nations like India, where groundwater serves as the primary source for domestic, agricultural, and industrial needs [1–3]. The dual threats of over-extraction and contamination, restricting from both geogenic and anthropogenic sources, have knowingly compromised groundwater quality across various regions of India [4, 5].

Rajasthan, a semi-arid state in northwestern India, faces acute water scarcity due to limited surface water resources and erratic rainfall patterns [1, 4]. Consequently, groundwater has emerged as the dominant source of water supply. Bharatpur

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District, situated in eastern Rajasthan, exemplifies this dependency. The district has witnessed a steady decline in groundwater levels and deterioration in water quality, largely attributed to intensive agricultural practices, urban expansion, and inadequate natural recharge [6]. To evaluate groundwater quality effectively, the water quality index (WQI), hydrogeochemical and statistical tools has gained prominence as a robust tool. In recent years, WQI has been widely applied across Indian states, including Rajasthan, to assess groundwater for drinking and irrigation purposes [7, 8]. For instance, studies in Rajasthan and other semi-arid regions of India have demonstrated the utility of these methods in revealing seasonal variations and spatial distribution of contaminants like fluoride, nitrate, and phosphate [4, 9, 10]. Rupbas Tehsil is particularly vulnerable in Bharatpur (Rajasthan) due to its growing population and increasing irrigation demands, which exert considerable stress on local aquifers. Despite the strategic and agricultural significance of Rupbas Tehsil, focused groundwater quality assessments in this region remain limited.

The present study aims to conduct a comprehensive evaluation of the groundwater quality of Rupbas tehsil using WQI and hydrogeochemical analysis. A total of 32 groundwater samples, 16 each from pre- and post-monsoon seasons, were collected and analyzed for key parameters including pH, EC, TDS, salinity, DO, ORP, temperature, TH, TA, F^-, Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}. Statistical and graphical methods were employed to interpret geochemical evolution and assess the suitability of groundwater for domestic and agricultural use. This research not only provides critical insights into the status of groundwater in Rupbas Tehsil but also contributes to the broader discourse on sustainable water resource management in semi-arid regions. The findings are expected to serve as a valuable reference for formulating effective groundwater conservation and treatment strategies.

Experimental Section

1. *Study area:* Rupbas Tehsil is in the southern part of Bharatpur District, Rajasthan, India. It is geographically coordinated between latitudes 26°48′N to 27°05′N and longitudes 77°00′E to 77°20′E. The region experiences a semi-arid climate, characterized by hot summers, mild winters, and seasonal rainfall concentrated during the monsoon months (June to September). Average annual rainfall is relatively low, and evapotranspiration rates are high, contributing to water stress in the area.
   a. *Geology and geomorphology:* The geological framework of Rupbas Tehsil comprises formations belonging to the Delhi Supergroup and Quaternary alluvium. The subsurface lithology is dominated by unconsolidated alluvial deposits such as sand, silt, and clay, which are interspersed with older metamorphic rocks like quartzite and schist, particularly in the south-western parts of the tehsil. These geological units serve as potential aquifers, with the alluvial layers supporting shallow to moderately deep groundwater reserves. The geomorphology is relatively flat to gently undulating, facilitating surface runoff and infiltration in certain zones. Groundwater is typically accessed through hand pumps, tube wells, and bore wells, depending on the depth and yield of the aquifer.
   b. *Hydrogeology:* Groundwater in Rupbas Tehsil occurs under both confined and unconfined conditions, depending on the local geology and depth of the aquifer. The primary source of recharge is precipitation, which infiltrates through permeable sandy soils and alluvial layers. The aquifer system is composed of alluvial deposits and weathered rock zones, which vary in thickness and hydraulic conductivity. The depth to water table fluctuates seasonally, generally ranging from 10 to 30 meters below ground level, with deeper levels observed during the pre-monsoon period due to reduced recharge.

      The region faces significant challenges due to overexploitation of groundwater, primarily for agricultural irrigation, which has led to a gradual decline in water levels. Additionally, the absence of substantial surface water bodies forces the rural population to rely almost exclusively on groundwater for drinking and domestic use. This dependence, coupled with contamination from agricultural runoff, domestic waste, and geogenic sources, has raised concerns about water quality and public health.

Given these challenges, regular monitoring and scientific assessment of groundwater quality are essential to ensure its sustainability. The present study aims to address this need by evaluating the physicochemical characteristics of groundwater in Rupbas Tehsil and identifying the geochemical processes influencing its composition.

2. *Groundwater sampling:* A systematic groundwater sampling strategy was adopted to ensure spatial representation across Rupbas Tehsil. The study area was divided into grids measuring 6 × 6 km², and sampling locations were selected preferably from the center of each grid. In cases where the grid center was inaccessible due to terrain or infrastructure limitations, the most populated area within the grid was chosen as an alternative sampling point to reflect human exposure and usage patterns. Groundwater samples were collected from commonly used sources such as hand pumps, tube wells, open wells, and submersible pumps, which serve both drinking and irrigation needs in the region. To ensure sample integrity and minimize contamination, acid-washed polyethylene bottles were used. These bottles were pre-treated by immersion in 10% nitric acid overnight, followed by thorough rinsing with distilled water to eliminate residual impurities.

   Prior to sample collection, the water source was allowed to run for 2–3 minutes to flush out stagnant water and obtain a fresh, representative sample. Additionally, each bottle was rinsed with the source water before final collection to remove any traces of acid or distilled water, thereby reducing the risk of analytical errors.

   In total, 32 groundwater samples were collected during two distinct seasons, 16 collected during the pre-monsoon (April 2021) and 16 during the post-monsoon seasons (January 2019). Location of samples with water source is detailed in **ESI Table S1**. This dual-seasonal approach enabled a more comprehensive understanding of the hydrogeochemical dynamics and anthropogenic influences affecting groundwater in Rupbas Tehsil.
3. *Physicochemical analysis of water quality parameters:* To evaluate the potability and overall quality of groundwater in Rupbas Tehsil, a total of 14 physicochemical parameters were analyzed. These included both in situ measurements and laboratory-based analyses, following standardized protocols to ensure accuracy and reliability. During fieldwork, seven key physicochemical parameters were measured in situ using portable water quality testing kit. These included: pH, EC, TDS, salinity, DO, ORP, and Temperature. Multiparameter PCSTestr™ 35 (Eutech, Thermo Scientific, USA) used for pH, EC, TDS, salinity, and temperature, Waterproof ORPTestr® 10 (Eutech, Thermo Scientific, USA) used for ORP, and DO6+ meter (Eutech, Thermo Scientific, USA) used for DO. All instruments were calibrated using certified standards in the Chemistry Laboratory of R. R. College, Alwar, prior to field deployment to ensure measurement precision.

   For laboratory analysis, two five-hundred-millilitre samples were collected from each site and transported to the laboratory. One bottle was used to determine TH and TA, while the second bottle was analyzed for major anions including: Cl^-, F^-, SO_4^{2-}, NO_3^-, and PO_4^{3-}. TH and TA were determined via titration methods following APHA 2005 standards [11]. TH was measured using EDTA titration, with calcium hardness calculated directly and magnesium hardness obtained by subtracting calcium hardness from TH. TA was measured using sulfuric acid titration, and carbonate and bicarbonate concentrations were computed using standard alkalinity formulas. Cl^- was analyzed using the argentometric method. F^-, SO_4^{2-}, NO_3^-, and PO_4^{3-} concentrations were measured using UV-Visible spectrophotometry (Antech). To ensure analytical accuracy, procedure blanks, standardization with known solutions, spiked samples, and duplicate analyses were routinely performed.

4. *Geospatial mapping:* The geographic coordinates of each sampling location were recorded using a handheld GPS device. These coordinates were later imported into GIS software to generate spatial distribution maps of groundwater quality parameters across Rupbas Tehsil, enabling visual interpretation of contamination hotspots and seasonal variations.
5. *Water quality index (WQI):* WQI is a widely accepted method for evaluating the overall quality of water by integrating multiple physicochemical parameters into a single numerical value (ESI Table S2). This approach simplifies complex water quality data and helps classify water sources based on their suitability for various uses, such as drinking, irrigation, and industrial applications. In this study, the Weighted Arithmetic Index Method proposed by Brown and co-authors (1970) was employed to compute the WQI (ESI Table S3; [12]. The WQI is calculated using the following formula:

$$WQI = \frac{\sum(W_n \times Q_n)}{\sum W_n}$$

Where, W_n = unit weight of the n^{th} parameter, and Q_n = quality rating of the n^{th} parameter.
Unit weight (W_n) for each parameter is calculated using the following formula:

$$W_n = \frac{k}{S_n}$$

Where, k = proportionality constant, and S_n = standard permissible limit for the n^{th} parameter as per WHO guidelines [13].

Proportionality constant (k) is determined using the following formula:

$$k = \frac{1}{\sum\left(\frac{1}{S_n}\right)}$$

Quality rating (Q_n) for each parameter is calculated using the following formula:

$$Q_n = \left(\frac{P_n - C_i}{S_n - C_i}\right) \times 100$$

Where, P_n = measured concentration of the n^{th} parameter, and C_i = ideal value of the parameter (usually 0, except for pH and DO, which are considered 7.0 and 14.6 mg/L, respectively).
6. *Statistical Analysis:* And all the parameters are taken in triplicate and the mean value is reported.

RESULTS AND DISCUSSION

Rupbas tehsil, located in Bharatpur district of Rajasthan, is geographically coordinated between latitudes 26°48′N to 27°05′N and longitudes 77°00′E to 77°20′E. It is about 38 km from Bharatpur city along the Bharatpur-Dholpur road. The region has a semi-arid climate, experiencing hot summers, mild winters, and seasonal rainfall concentrated during the monsoon months from June to September. It is predominantly populated and surrounded by agricultural land. Therefore, it is necessary to assess the quality of its groundwater, with a special focus on the impact of contaminants on agricultural practices.

For the quality assessment of groundwater of Rupbas tehsil, 32 groundwater samples were collected during pre- and post-monsoon. The sample were taken from the center of each 6 × 6 km^2 grid. Initially, the groundwater samples were analyzed for pH, EC, TDS, salinity, DO, ORP, and temperature at the sample collection site. Subsequent laboratory analysis was conducted to determine the concentrations of F^-, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, TH and TA. These analyses were performed using APHA 2005 standard methods [11]. The observed groundwater quality parameters for Rupbas tehsil are presented and discussed below, with a comparison against the acceptable drinking water standards established by the WHO and BIS [13,14].

The pH of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, pH values ranged from pH 6.8 to pH 8.1 (Table

1), with a mean of pH 7.3. In the post-monsoon season, the range was pH 6.4 to pH 7.5 (Table 2), with a mean of pH 7.2. These results indicate that the groundwater in the study area is slightly acidic to alkaline in nature. The key finding is that the pH values from all 16 sampling sites and their respective mean values across both seasons fall within the permissible limits for drinking water, as defined by both the WHO and BIS [13,14]. This suggests that pH is not a limiting factor for the groundwater's potability in this region.

The EC of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, EC values ranged from 921 µS/cm and 8170 µS/cm (Table 1), with a mean of 3671.2 µS/cm. In the post-monsoon season, the range was 892 µS/cm and 8310 µS/cm (Table 2), with a mean of 3518 µS/cm. Significantly, the EC values from all 16 sampling sites of both seasons, including the mean, exceeded the maximum permissible limits for drinking water recommended by the WHO [13]. The elevated EC values throughout Rupbas tehsil indicated a high concentration of dissolved ionic solids, which can be attributed to mineral dissolution and geogenic factors.

The TDS of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, TDS values ranged from 654 mg/L to 5800 mg/L (Table 1), with a mean of 2593 mg/L. In the post-monsoon season, the range was 626 mg/L to 5890 mg/L (Table 2), with a mean of 2460 mg/L. Significantly, the TDS values from all 16 sampling sites of both seasons, including the mean, exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14]. The high TDS concentration indicates a significant presence of dissolved inorganic salts in groundwater, which can be attributed to various factors such as mineral dissolution and the geological composition of the aquifer.

The DO of groundwater collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, DO values ranged from 2.38 mg/L to 5.10 mg/L (Table 1), with a mean of 3.80 mg/L. In the post-monsoon season, the range was 1.16 mg/L to 4.60 mg/L (Table 2), with a mean of 3.49 mg/L. Significantly, the DO values for few sampling sites of both seasons are within the permissible limits, while the mean value of both seasons below the permissible limits for drinking water recommended by the WHO and BIS [13,14]. This indicates that, on average, the groundwater in the Rupbas tehsil is oxygen-deficient, which can be a sign of increased microbial activity and/or contamination from organic matter.

The ORP of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, ORP values ranged from 19 mV to 145 mV (Table 1), with a mean of 87.6 mV. In the post-monsoon season, the range was 9 mV to 369 mV (Table 2), with a mean of 167.1 mV. The results indicated a notable increase from pre-monsoon to post-monsoon groundwater ORP values. This increment in groundwater ORP suggests that the hydrological changes associated with the monsoon, such as increased recharge and altered microbial activity, likely influence the redox conditions of the aquifer. The higher post-monsoon ORP values could point to more oxidizing conditions in the groundwater system, which may have implications for the mobility and concentration of various dissolved chemical species.

The F^- of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, F^- values ranged from 0.04 mg/L to 1.12 mg/L (Table 1), with a mean of 0.43 mg/L. In the post-monsoon season, the range was 0.04 mg/L to 1.12 mg/L (Table 2), with a mean of 0.66 mg/L. The results indicated a notable increase from pre-monsoon to post-monsoon groundwater F^- values. Significantly, the F^- values for all 16 sampling sites of both seasons, including the mean, doesn't exceed the maximum permissible limits for drinking water recommended by the WHO and BIS[13,14].

Table 1. Groundwater quality parameters for Rupbas tehsil (Bharatpur, Rajasthan) during the pre-monsoon season of 2021.

S.N.	Name of sampling site	Source type	Groundwater quality parameters											
			pH	*EC*	*TDS*	*DO*	*ORP*	F^-	Cl^-	NO_3^-	SO_4^{2-}	PO_4^{3-}	*TH*	*TA*
1	Rajpura	Handpump	7.2	1530	1160	2.90	27	0.15	259.9	15.0	54.2	0.03	460	385
2	Roopbas	Borewell	7.2	2680	1690	3.90	132	0.04	272.4	46.2	53.1	0.08	485	395
3	Ghata	Borewell	7.9	1324	945	4.33	45	0.29	82.5	35.5	68.6	0.04	555	275
4	Khanuaa	Handpump	8.1	921	654	3.94	109	0.23	105.0	0.1	77.8	0.09	245	300
5	Ghanoli	Borewell	7.5	2540	1800	4.04	126	0.34	499.8	3.6	198.1	0.09	620	540
6	Khansurjapur	Borewell	7.3	8020	5680	3.23	118	0.79	1579.4	49.1	281.8	0.01	1310	1670
7	Ibrahimpur	Handpump	6.8	7250	5140	4.32	87	0.24	1616.9	48.8	309.1	0.09	1395	1740
8	Chakora	Handpump	7.0	8170	5800	4.02	145	0.69	1726.8	43.3	293.0	0.12	1545	1880
9	Samahad	Handpump	7.5	1178	896	2.80	19	0.42	282.4	2.4	12.7	0.02	320	450
10	Mahalpur Khachhi	Borewell	7.6	3090	2200	5.10	97	0.29	479.8	21.2	227.8	0.01	315	730
11	Biratha	Handpump	7.2	1096	777	2.38	135	0.26	102.5	24.8	67.6	0.08	470	380
12	Kurka	Borewell	6.9	2550	1670	3.80	54	1.12	427.3	26.1	122.8	0.02	525	635
13	Mudhera	Handpump	7.1	2870	2040	3.39	25	0.41	542.3	16.0	202.4	0.03	735	560
14	Kharera	Borewell	7.1	6440	4570	4.08	135	0.31	1859.3	17.1	275.8	0.01	520	635
15	Kamasi	Borewell	7.0	6140	4360	5.01	102	0.36	1641.8	37.7	248.8	0.07	735	550
16	Shehna	Handpump	7.6	2940	2100	3.58	45	0.89	274.9	2.9	242.3	0.04	450	390
Mean value			7.3	3671.2	2592.6	3.80	87.6	0.43	734.6	24.3	171.0	0.05	667.8	719.7
WHO Std.*			6.5-8.5	400	600	4.0-6.0	-	1.50	250	50	250	-	300	300
BIS Std.**			6.5-8.5	-	500	4.0-6.0	-	1.00	250	45	200	-	200	200

Note: *EC measure in µS/cm; TDS, DO,* F^-, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, *TH and TA measures in mg/L or ppm; ORP measures in mV; * WHO drinking water standards (WHO, 2017); and ** BIS-2012 (IS 10500: 2012) drinking water standards (BIS, 2012).*

Table 2. Groundwater quality parameters for Rupbas tehsil (Bharatpur, Rajasthan) during the post-monsoon season of 2019.

Sr. No.	Name of sampling site	Source type	Groundwater quality parameters											
			pH	***EC***	***TDS***	***DO***	***ORP***	***F^-***	***Cl^-***	***NO_3^-***	***SO_4^{2-}***	***PO_4^{3-}***	***TH***	***TA***
1	Rajpura	Handpump	7.3	1580	1100	2.19	9	0.42	299.9	32.7	43.7	0.015	490	220
2	Roopbas	Borewell	7.0	2680	1880	4.44	193	0.04	274.1	46.2	53.1	0.084	460	340
3	Ghata	Borewell	7.2	1130	778	4.60	198	0.79	65.0	27.3	141.4	0.056	130	385
4	Khanuaa	Handpump	7.4	892	626	3.97	252	0.10	118.2	4.2	16.5	0.039	450	320
5	Ghanoli	Borewell	7.2	3760	2620	4.60	214	0.31	519.8	7.4	212.0	0.047	790	390
6	Khansurjapur	Borewell	7.0	7310	5080	2.90	137	1.06	145.7	46.3	27.1	0.022	1025	710
7	Ibrahimpur	Handpump	6.7	7450	5210	2.98	99	1.12	241.2	9.3	19.1	0.046	1185	750
8	Chakora	Handpump	7.1	5680	3940	2.44	369	0.33	265.1	0.26	110.0	0.015	890	700
9	Samahad	Handpump	7.4	1220	860	3.80	43	0.85	120.0	29.0	45.7	0.008	445	325
10	Mahalpur Khachhi	Borewell	7.5	2660	1850	4.20	174	0.32	564.8	19.7	224.7	0.006	460	450
11	Biratha	Handpump	7.2	1680	1190	3.16	189	0.75	182.4	14.3	27.1	0.002	450	350
12	Kurka	Borewell	7.0	2550	1780	3.44	183	1.12	75.0	26.1	53.1	0.004	570	300
13	Mudhera	Handpump	6.4	3090	2160	1.16	83	0.85	149.9	8.3	49.2	0.005	520	340
14	Kharera	Borewell	7.4	8310	5890	4.32	223	0.41	247.4	42.3	78.2	0.014	1690	845
15	Kamasi	Borewell	7.5	3900	2720	4.60	224	0.40	779.3	34.7	246.2	0.091	1330	240
16	Shehna	Handpump	7.4	2390	1680	3.10	83	0.83	549.8	2.4	238.4	0.068	290	680
Mean Value			7.2	3517.6	1730.1	3.49	167.1	0.66	287.3	21.9	99.1	0.03	698.4	459.1
WHO Std.*			6.5-8.5	400	600	4.0-6.0	-	1.50	250	50	250	-	300	300
BIS Std.**			6.5-8.5	-	500	4.0-6.0	-	1.00	250	45	200	-	200	200

Note: *EC measure in µS/cm; TDS, DO, F^-, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, TH and TA measures in mg/L or ppm; ORP measures in mV; * WHO drinking water standards (WHO, 2017); and ** BIS-2012 (IS 10500: 2012) drinking water standards (BIS, 2012).*

The Cl^- of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, Cl^- values ranged from 82.5 mg/L to 1859.3 mg/L (Table 1), with a mean of 734.6 mg/L. In the post-monsoon season, the range was 65.0 mg/L to 779.3 mg/L (Table 2), with a mean of 287.3 mg/L. The results indicated a notable increase from pre-monsoon to post-monsoon groundwater Cl^- values. Significantly, the Cl^- values for few sampling sites of both seasons, including the mean, exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14].

The NO_3^- of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, NO_3^- values ranged from 0.1 mg/L to 49.1 mg/L (Table 1), with a mean of 24.31 mg/L. In the post-monsoon season, the range was 0.3 mg/L to 46.3 mg/L (Table 2), with a mean of 21.9 mg/L. Significantly, the NO_3^- values for all 16 sampling sites of both seasons, including the mean, do not exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14].

The SO_4^{2-} of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, SO_4^{2-} values ranged from 12.7 mg/L to 309.1 mg/L (Table 1), with a mean of 171.0 mg/L. In the post-monsoon season, the range was 16.5 mg/L to 246.2 mg/L (Table 2), with a mean of 99.1 mg/L. The results indicated a decrease in both the overall range and the mean concentration of sulphate in the groundwater after the monsoon season. Significantly, the SO_4^{2-} values for few sampling sites of both seasons, including the mean, exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14].

The PO_4^{3-} of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, PO_4^{3-} values ranged from 0.01 mg/L to 0.120 mg/L (Table 1), with a mean of 0.052 mg/L. In the post-monsoon season, the range was 0.002 mg/L to 0.091 mg/L (Table 2), with a mean of 0.033 mg/L. The results indicated a decrease in both the overall range and the mean concentration of sulphate in the groundwater after the monsoon season.

The TH of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, TH values ranged from 245 mg/L to 1545 mg/L (Table 1), with a mean of 667.8 mg/L. In the post-monsoon season, the range was 130 mg/L to 1690 mg/L (Table 2), with a mean of 698.4 mg/L. The results indicated an increase in both the overall range and the mean concentration of TH in the groundwater after the monsoon season. This suggests that post-monsoon recharge can be contributed to higher TH. Significantly, the TH values of several sampling sites of both seasons, including the mean, exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14].

The TA of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons. During the pre-monsoon period, TA values ranged from 275 mg/L to 1880 mg/L (Table 1), with a mean of 719.7 mg/L. In the post-monsoon season, the range was 220 mg/L to 845 mg/L (Table 2), with a mean of 459.1 mg/L. The results indicated a decrease in both the overall range and the mean concentration of TA in the groundwater after the monsoon season. Significantly, the TA values for few sampling sites of both seasons, including the mean, exceed the maximum permissible limits for drinking water recommended by the WHO and BIS [13,14].

The WQI of groundwater samples collected from Rupbas tehsil varied between the pre-monsoon and post-monsoon seasons (Figure 1). During the pre-monsoon period, WQI values ranged from 9.5 to 65.1, with a mean of 30.5. In the post-monsoon season, the range was 7.5 to 65.3, with a mean of 40.8. A comparative analysis indicated that there was a slight increase in the WQI from the pre-monsoon to the post-monsoon season, suggesting a potential deterioration of groundwater quality after the monsoon, possibly due to the flushing of contaminants from the surface into the groundwater system. This trend is a key finding attributable to the monsoon's influence, which can lead to the infiltration of surface runoff carrying contaminants, such as agricultural fertilizers and other pollutants, into the shallow groundwater system. This finding is significant and highlights a key mechanism influencing the groundwater quality in the region, warranting further investigation into the specific sources and pathways of contamination.

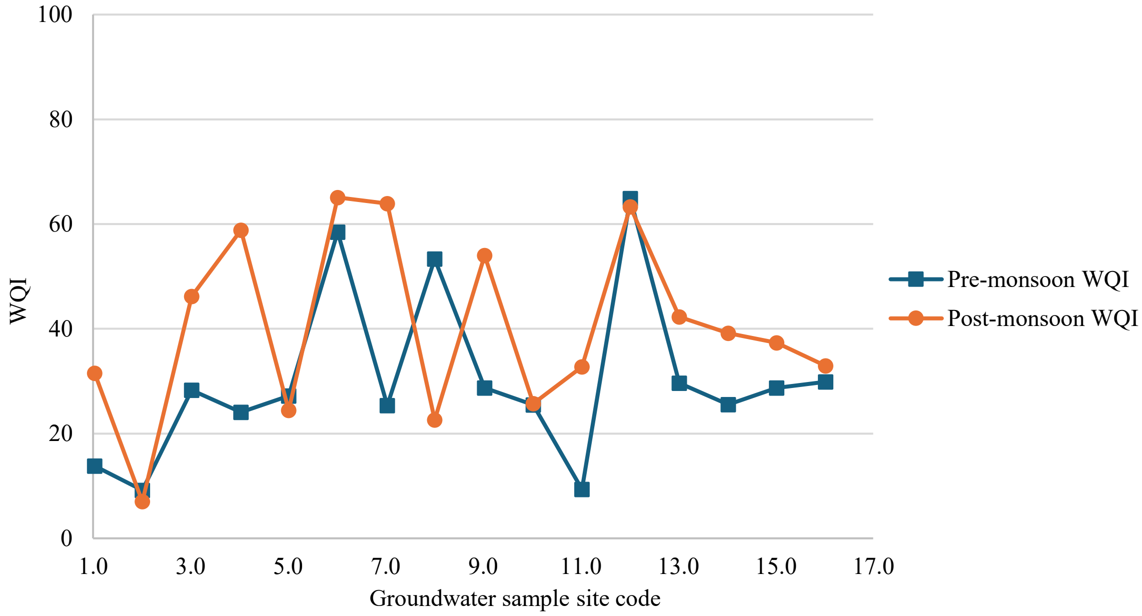

Figure 1. Groundwater WQI of Rupbas Tehsil during pre-monsoon and post-monsoon seasons along with their trendlines to visualize seasonal changes.

CONCLUSION

This comprehensive investigation into the groundwater quality of Rupbas Tehsil, Bharatpur District, has successfully utilized a multi-faceted approach, combining Water Quality Index (WQI) assessment with detailed hydrogeochemical analysis. The research reveals that the groundwater quality is not uniform and exhibits significant seasonal fluctuations, particularly between the pre-monsoon and post-monsoon periods. Based on the WQI, a majority of the groundwater samples were classified as suitable for various uses, falling into the "good" to "fair" categories. However, the study also identified distinct areas of localized contamination. Elevated concentrations of key physicochemical parameters, including electrical conductivity (EC), total dissolved solids (TDS), salinity, chloride (Cl^-), total hardness (TH), and total alkalinity (TA), are clear indicators of human impact. These pollutants are attributed to prevalent agricultural practices, such as the application of fertilizers and pesticides, as well as the improper disposal of domestic waste.

A critical finding is that while the groundwater is largely acceptable for agricultural irrigation, a subset of samples falls outside the safety standards for drinking water and would require treatment before consumption. This research establishes a vital baseline for the region's hydrogeological state and underscores the urgent need for a proactive groundwater management strategy. Implementing continuous monitoring programs, promoting responsible agricultural methods, and enhancing waste management infrastructure are essential steps to protect this invaluable resource for the long-term sustainability of the region.

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