



Spatiotemporal assessment of groundwater quality in the Central Ganga Plain, India, using multivariate statistical tools

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Abstract In the present study, the water quality status of the Sadar block in Pratapgarh district of Uttar Pradesh, India, was calculated by Water Pollution Index (WPI) using 15 groundwater quality parameters (pH, turbidity, EC (electric conductivity), TDS (total dissolved solids), salinity, total hardness, Ca^{2+} , K^+ , Mg^{2+} , Na^+ , Cl^- , F^- , SO_4^{2-} , HCO_3^- , and NO_3^-) at 40 different study locations. It is found that 10%, 25%, and 65%, of samples, fall under the good, moderately polluted, and highly polluted category, respectively. Irrigation suitability of groundwater has also been evaluated by using irrigation suitability parameters, i.e., Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), Permeability Index (PI), Kelly Ratio (KR), Percentage Sodium (% Na), and Magnesium Hazards (MH). Based on the analysis, it was determined that most of the samples were suitable for irrigation in the area. Irrigation practices are found to be unsuitable for Kelly's ratio of 37.5%, MH 60%, and RSC 55% samples. WPI and Pearson's correlation matrix (PCA) have suggested a significant linear relationship among the water quality parameters based on the test results. The Gibbs

plot indicates that the majority of samples fall under the "evaporation dominance" category while the rest fall under the "rock weathering dominance" suggesting that the complex geochemical mechanisms are active in the study area. This study would be very helpful to government authorities and it would aid them to suggest alternate drinking water resources in affected areas.

Keywords Groundwater · Water pollution index · Irrigation suitability · Statistical analysis

Introduction

Water quality is one of the major challenges in the world. It has a great impact on domestic and agricultural production and the standard of living for humans. Consumption of contaminated water leads to many health-related problems, i.e., dental fluorosis due to the presence of excess fluoride (Kumar, 2017), arthritis, high blood pressure caused by the presence of salinity in the drinking water (Vineis et al., 2011) (methemoglobinemia), blue baby syndrome (Sadeq et al., 2008) caused by the presence of excess nitrate, and hyperkeratosis, melanosis vascular diseases, and lung diseases due to arsenic (Tsuji et al., 2014). In India, it remains an urgent need to have safe drinking water as its 30% urban and 90% rural populations rely entirely on surface and groundwater that

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has not been treated (Singh et al., 2014). In India, groundwater sources provide more than 80% of the domestic water requirements, and about 50% of its industrial, municipal, and irrigation water supplies (Tiwari et al., 2018). Water quality is usually poor in waterlogged areas and shows the trend of increasing salinity, sulfate, carbonate, and bicarbonate ions in groundwater (Kumar & Saxena, 2011). Waterlogging is a result of paleochannels and oxbow lakes caused by the Sai river in the study area. Defining water quality requires monitoring and analysis of several physicochemical parameters (pH, EC, TDS, total hardness, total cation, and total anions) and identifying contaminant sources. Many of the Central Gangetic Plains face problems related to groundwater quality and water scarcity. In addition, water quality is also deteriorating due to pollution and over-exploitation of its resources through various anthropogenic activities. The current study focuses on the Pratapgarh district of Uttar Pradesh, a part of the Central Gangetic Plain. The groundwater in this region is mainly being utilized for drinking and irrigation purposes. There is a growing concern about the deterioration of groundwater quality due to geogenic and anthropogenic activities in this region. The Pratapgarh district covers an area of 3730 km², mostly in the eastern portion of the Central Gangetic Plain of Uttar Pradesh. Kunda, Kalganj, Pratapgarh, Patti, and Raniganj are the five tehsils that make up the district, which is further divided into 17 development blocks. There has been an investigation conducted of the region spread over 193 km² to better understand the problems faced by residents due to poor quality water consumption. The groundwater availability in the region is 4759.23 ha-m, and a groundwater draft of 5184.92 ha-m is marked under the overexploited category (CGWB, 2019–20). According to the previous study, different areas (Sadar, Baba Belkherhath, Mandhata, Sandva Chandrika) of Pratapgarh have severe problems with groundwater depletion due to over-exploitation. The water tables are deepening in the central Ganga plain due to overexploitation of water resources; it is caused by changes in land use and land cover patterns (Ahmad & Nigar, 2020). In the future, only deeper groundwater characterized by high levels of Na, Cl, and TDS will be available for drinking and irrigation. Several health-related problems, i.e., dental fluorosis, gastric problems, high blood pressure,

arthritis, and so on, are evident in the region (Tiwari et al., 2018), which are largely caused by drinking bad quality water regularly. Many residents also reported difficulty in cooking, washing clothes, and daily use requirements, with the regular water they are getting in the region from other sources, i.e., packaged drinking water, a government-run water body (Jal Nigam Pratapgarh, available at a few locations in the block), and deep tube wells (depths greater than 200 feet). Sai river also passes through the block and many residents in the vicinity utilize its water for purposes other than drinking, during the rainy season. There are various methods used for the assessment of groundwater quality, including the National Sanitation Foundation Water Quality Index (Effendi, 2016; Lumb et al., 2011), the Water Quality Index of the Canadian Council of Ministers of the Environment (CCMEWQI), and the weighted arithmetic WQI method for the Oregon Water Quality Index (OWQI) (Singh et al., 2021; Tyagi et al., 2020). Other important methods are the Multi-Criteria Decision-Making (MCDM) Method (Akhtar et al., 2021), the Stream Health Index (SHI), a weighted WQI calculated by the Bureau of Indian Standards, and the landfill water pollution index (Singh et al., 2021). The WQI method has the disadvantage of using ideal values, especially for pH, where even a small change in pH results in significantly different groundwater quality. Hence, an integrated methodology (the Pollution Index of groundwater PIG) (Adimalla & Qian, 2019; Shukla & Saxena, 2021) and entropy weighted water quality index (Adimalla & Qian, 2019) can be used for the calculation of the groundwater quality index.

This study aims to conduct a complete evaluation of groundwater quality in the Sadar block of Pratapgarh district of the U.P, where the majority of the study locations are rural. During the field investigations, it was discovered that individuals are unaware of the water quality requirements and compliance standards with the water they consume. This research generates a WPI report for the Sadar block of Pratapgarh district, assessing the quality of groundwater for drinking and irrigation purposes. Continuous assessment of various groundwater contaminants removal provides chances for safe drinking water, and this might be achieved by integrating traditional knowledge with recent innovative technologies to develop future groundwater security.

Study area

Location, climate, and demography

In the middle of the west Ganga plain, the study area Sadar block of Pratapgarh district lies between 25°48' N and 26° N latitudes and 81°52' E and 82°3' E longitudes (Fig. 1). It covers 193 km², of which 61% is arable. Only 67% of this cultivable land is irrigated, while the rest is heavily dependent on monsoon rain (Mishra, 2018). According to the financial year 2019, the rural population of Sadar block is 209,727 (CGWB, 2019–20). Most of the area's climate is tropical, with cold winters and warm summers. During January, the minimum and maximum temperatures range from 7.5 to 24.1 °C, respectively, making it the coldest month. The hottest month is May, with a daily maximum temperature of 42.5 °C and a minimum temperature of 26.4 °C. Approximately 90% of rainfall occurs from June to September, with an average annual rainfall of 1180 cm, a potential

evapotranspiration rate of about 1400 mm, and a monthly relative humidity rate of 55.96% (Singh et al., 2016).

Geology, hydrology, and drainage features

The entire block is covered with unconsolidated Quaternary alluvium deposits, consisting mostly of fine to very fine sand Kanker intermixed along with varying amounts of calcareous nodules (Tiwari et al., 2018). In the study area 52 m below ground level (m bgl) depth, the quality of water is saline to very saline. The total groundwater availability in the block is 4759.23 ha-m, with the major sources of water for drinking and irrigation purposes being deep wells, tube wells, hand pumps, and river water. The village has 133 sources of drinking water, including wells, tube wells, hand pumps, and taps. The perennial river Sai, which runs through the heart of Pratapgarh district from west to east, flanks the block Sadar (Chilbila).

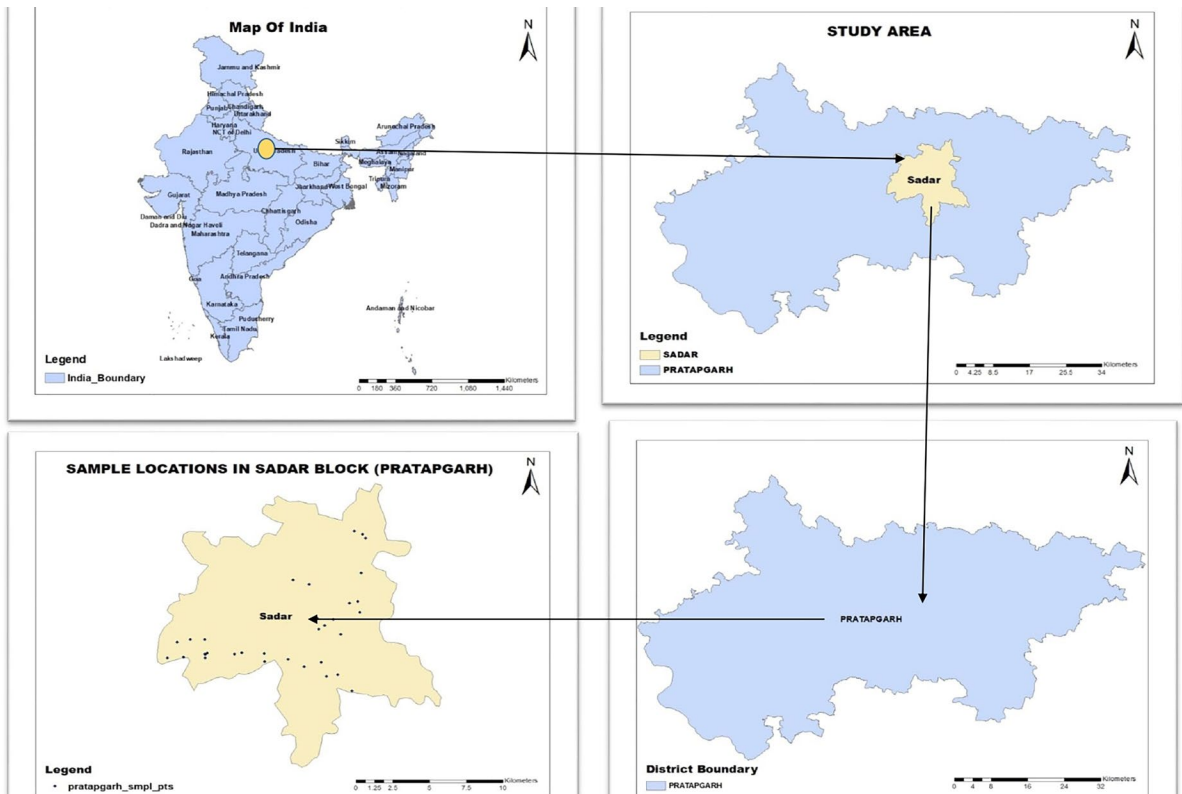


Fig. 1 Location map of Pratapgarh district in Uttar Pradesh

In the Jaunpur district, this river meets the Gomti river downstream and irrigates parts of the northern and southern Pratapgarh district. The district of Pratapgarh is dominated by agriculture and is the top fruit producer. It is one of the biggest cultivators of Aonla, owing to its plasticity due to growth in sandy, clayey, and loamy soil types in arid and semiarid climates, both deciduous and deep-rooted (Gantait et al., 2021). In salt-affected regions, *Emblica officinalis* has also proven to be a promising crop for commercial cultivation. In India, this tree covers as many as a million hectares of saline wastelands and ravine land (Gantait et al., 2021) and is an extremely valuable ingredient of various Ayurvedic medicines and an extremely rich source of Vitamin C in India.

Material and methods

Sample collection and analysis

Forty samples of groundwater (tube wells, hand pumps, dug well) were collected from some of the major locations during the pre-monsoon (Feb 2021) and post-monsoon (Jul 2021) seasons. To ensure accuracy and full confidence in the results, all the sampling bottles and glasses were soaked in a 5% nitric acid solution overnight, then rinsed 2–3 times with deionized water before sampling. Pre-washed 1-L polyethylene bottles with narrow mouths were used to collect the samples and GPS devices were used to determine the locations of all the 40 sampling points. These samples were immediately preserved and stored at 4 °C temperature, until analyzed (to prevent chemical reactions within the water) and transported to the laboratory of Shri Ramswaroop Memorial University, Barabanki, India, for further analysis. Physicochemical analysis of the samples was then performed. The pH, EC, TDS, and salinity properties of water can be measured directly in the field from hand pumps, dug wells, and tube wells, with a portable multi-parameter meter.

We used the titrimetric method (APHA, 2012) to analyze the carbonate, bicarbonate, and total hardness of the samples after the sample collection. In addition, the major cations potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+) were analyzed by the titrimetric method (APHA, 2012), after calibrating the flame photometer.

Using the silver nitrate solution, the concentration of chloride (Cl^-) was measured. Thereafter, ion-sensitive electrodes were used to measure fluoride (F^-) and nitrate (NO_3^-), and sulfate (SO_4^{2-}) was analyzed using an ultraviolet (UV) spectrophotometer as described in the American Public Health Association's standard methods for the examination of water and wastewater (APHA, 2012). Table 1 illustrates the statistical analysis of each parameter.

Accuracy of analytical data

Using the analytical data, we assessed the accuracy of ionic measurements by:

- (a) Estimating the percentage error of ion balance (APHA, 2012, Shukla & Saxena, 2020; Chen et al., 2017).
- (b) Calculating the EC and TDS ratios for accuracy and precision for the analytical data.

$$\%E = \left(\frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \right) \times 100 \quad (1)$$

In this case, anions and cations were mentioned in meq/L, and E is the error balance. The ideal value of percentage error of ion balance should be in the range of $\pm 5\%$ for ideal water quality analysis. It was found that the groundwater samples exhibited a good charge balance within the range of $\pm 5\%$, except for five samples where the “E” value was 8.2, –74, –8, –72, and 1, which was acceptable. The TDS/EC ratio (Shukla & Saxena, 2021) was within the range of 0.56 to 0.8, indicating high precision for the analytical data (APHA, 2012).

Water pollution index (WPI)

In the present study, we used the WPI proposed by Hossain and Patra (2020), which is one of the best methods based upon the difference between observed concentrations (C_i) and a standardized value (S_i) divided by respective S_i , to determine the increase or decrease in the pollution load (PL_i). In the case of pH, the minimum S_i limit is 6.5 for $pH < 7$, and the maximum S_i limit is 8.5 for $pH > 7$ (Wang et al., 2021). The small variation in pH results in a significantly different (acidic or alkaline) groundwater quality.

Table 1 Statistical summary of physicochemical parameters

S. No	Chemical parameters	WHO (2011)	BIS (2012)	Mean	Minimum	Maximum	Standard deviation
1	Turbidity	5	5	10.1455	0.9	122	19.50
2	pH	7.0–8.5	6.8–8.5	7.2675	6.7	7.9	0.28
3	Electric conductivity (EC)	750	750	1938.2	446	5257	1382.31
4	Total dissolved solids (TDS)	500	600	1020.3	232	3045	799.92
5	Salinity	100	100	1592.05	232	4411	1134.54
6	Fluoride (F ⁻)	1.5	1	1.265	0.2	3.4	0.63
7	Nitrate NO ₃ ⁻	45	45	25.2	0.9	54	13.16
8	Chloride(Cl ⁻)	250	250	607.9	35	1488	445.37
9	Sulfate (SO ₄ ⁻)	250	200	420.9	28	2660	455.82
10	Total hardness(TH)	250	600	593.25	160	1600	409.21
11	Bicarbonate (HCO ₃ ⁻)	500	500	273.6	18	760	214.88
12	Sodium(Na ⁺)	50	200	64.44	8	192	48.71
13	Potassium (K ⁺)	12	200	13.6	1.2	289	46.59
14	Calcium(Ca ²⁺)	75	100	45.5	12	201	48.40
15	Magnesium (Mg ²⁺)	30	30	45.6	11.6	116.5	30.50
16	WPI	-	-	2.01	0.2	7.8	1.52
17	CAI 1	-	-	16.82	-0.8	39	12.8
18	CAI 2	-	-	21.49	1.2	52	15.7

EC in μS/cm, turbidity nephelometric turbidity units (NTU), all other parameters in mg/L, except pH, salinity part per trillion (ppt), chloro-alkaline indices (CAI)

The pollution load of groundwater can be calculated by the water pollution index (WPI), where 15 water quality parameters are used, pH, turbidity, EC (electric conductivity), TDS (total dissolved solids), salinity, total hardness, Ca²⁺, K⁺, Mg²⁺, Na⁺, Cl⁻, F⁻, SO₄²⁻, HCO₃⁻, and NO₃⁻.

For all the abovementioned parameters (other than pH), pollution load, PL, is calculated as:

$$PL_i = -(1 - \frac{C_i}{S_i}) \tag{2}$$

where “i” represents different parameters of water quality, “Ci” represents the observed concentrations of the parameter, and “Si” represents the maximum value.

In the case of pH, the value of PL_i computed from Eq. (2) is considered problematic when pH is less than or greater than 7; hence, pollution load for different pH scales is calculated as:

$$PL_i = \frac{C_i - 7}{S_i - 7} \tag{3}$$

where the minimum S_i limit is 6.5 when pH < 7, and the maximum S_i limit is 8.5 when pH > 7.

Thereafter, the Water Pollution Index (WPI), with n number of parameters, can be calculated by taking an average of all pollution loads.

$$WPI = \frac{1}{n}(PL_i + PL_{i+1} + PL_n) \tag{4}$$

Irrigation suitability

A variety of ratios and parameters are used for agricultural water suitability, Sodium Absorbance Ratio (SAR), Residual Sodium Carbonate (RSC), sodium percentage (Na%), Magnesium Hazard (MH), Kelly Ratio (KR), and Permeability Index (PI). These indicators are explained as follows:

$$SAR = Na^+ / ((Ca^{2+} + Mg^{2+}) / 2)^{1/2} \tag{5}$$

$$RSC = (HCO_3^-) - (Ca^{2+} + Mg^{2+}) \tag{6}$$

$$MR = (Mg^{2+} / (Ca^{2+} + Mg^{2+})) * 100 \tag{7}$$

$$KR = (Na + / (Ca^{2+} + Mg^{2+})) * 100 \tag{8}$$

$$\text{Na\%} = \frac{(\text{Na}^+ + \text{K}^+)}{(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})} * 100 \quad (9)$$

$$\text{PI} = \frac{(\text{Na}^+ + (\text{HCO}_3^-)^{1/2})}{(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})} * 100 \quad (10)$$

Matrix pearson's correlation

The 15 physicochemical parameters have been used for Pearson's correlation study. The degree of linear correlation between two parameters is represented by the correlation coefficient "r" (Kothari et al., 2021). The correlation coefficient "r" varies from -1 (negative correlation) to +1 (positive correlation). If the values of "r" are zero between the parameters, then there exists no correlation (Singh et al., 2021).

Chloro-alkaline indices

The values of CAI 1 and CAI 2 in (meq/L) are given by Schoeller (1977), and the values of these indices can be positive or negative. Chloro-alkaline indices (CAIs) estimate ion-exchange reaction between groundwater and aquifer materials. The negative or positive values of chloro-alkaline indices depend on whether the exchange of Na^+ and K^+ is from water, with Mg^{2+} and Ca^{2+} in rock/soil or vice versa. A positive CAI value indicates hardening (direct ion exchange). If the process of reverse ion exchange is occurring, the CAI value will be negative (Sunkari et al., 2021). The CAI value is close to zero when there is no ion exchange in the aquifer materials. The CAI 1 and CAI 2 can be calculated by the following equations:

$$\text{CAI 1} = \frac{[\text{Cl}^- - (\text{Na}^+ + \text{K}^+)]}{\text{Cl}^-} \quad (11)$$

$$\text{CAI 2} = \frac{[\text{Cl}^- - (\text{Na}^+ + \text{K}^+)]}{(\text{SO}_4^{2-} + \text{HCO}_3^- + \text{CO}_3^{2-} + \text{NO}_3^-)} \quad (12)$$

Result and discussion

Tables 2 and 3 summarize the results of various physicochemical analyses of groundwater samples.

pH

The pH is one of the important physical parameters of groundwater. The acceptable limit of pH for drinking water is 6.5 to 8.4 (WHO, 11), and the range of pH values in the sample varies from 6.7 to 7.9 with a mean value of 7.26. According to World Health Organization (BIS, 2012), the groundwater in the study area is slightly alkaline.

Turbidity

Turbidity describes the optical properties of liquids and solids. The amount of light emitted is used to calculate the count of suspended particles in the water. The turbidity in the samples ranges from 0.9 to 122 NTU with a mean value of 10.1455 NTU, and this range is above the recommended level of 5 NTU.

Total dissolved solids (TDS)

The minimum and maximum TDS values in the sample ranged from 232 to 3040 mg/L with a mean value of 1020 mg/L. As per Indian standards (BIS, 2012), a water sample containing more than 500 mg/L of TDS is not suitable for drinking purposes. The elevated values of TDS in the sample are due to various types of minerals and organic matter dissolved in the water. Various salts, i.e., sodium, potassium, calcium, magnesium, bicarbonates, carbonates, chlorides, organic matter, phosphate, and other particles, might get dissolved in water. These parameters affect the osmoregulation of freshwater organics due to an increase in water density (Kumar, 2017; Saleem et al., 2018).

Electric conductivity (EC)

The minimum and maximum values of EC in the test samples varied from 446 to 5257 $\mu\text{S}/\text{cm}$. The permissible limit of EC in drinking water is 750 $\mu\text{S}/\text{cm}$ with a mean value of 1938 $\mu\text{S}/\text{cm}$. The higher value of electric conductivity in water samples may be due to the presence of inorganic acids, bases, and salts. Various health-related issues, like the sour and unsuitable taste, arthritis, gastral and high blood pressure, hypertension, miscarriage among pregnant women, skin diseases, acute respiratory infection, renal failure, and pulmonary edema (Vineis et al., 2011), are

Table 2 Site-wise analytical summary of physico-chemical parameters for groundwater samples

Sample code	Date	Type	Turbidity	pH	EC	TDS	Salinity	Cl ⁻	F ⁻	NO ₃ ⁻	SO ₄ ²⁻	TH	HCO ₃ ⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	WPI
PG1	27-02-2021	Mark-II	3.2	7.9	446	232	232	35	1	23	86	320	56	42.2	1.2	18	25.1	0.2
PG2	27-02-2021	Mark-II	1.5	7.4	608	313	482	80	0.9	34	162	400	82	47.5	3.9	14	32.1	0.95
PG3	27-02-2021	Tubewell	2	7.2	761	388	570	35	0.4	21	82	200	86	37	5	12	15.6	0.64
PG4	27-02-2021	Mark-II	3.1	7.1	674	371	561	70	0.6	10	95	400	62	36.5	2.4	20	31.6	0.94
PG5	27-02-2021	Mark-II	2.1	7.1	691	351	512	106	0.5	12	120	440	79	16.1	2.1	24	34.6	0.97
PG6	27-02-2021	Mark-II	8.2	6.8	2048	611	1791	876	1	23	200	240	128	45.3	2.5	22	18.1	1.43
PG7	27-02-2021	Mark-II	14.2	6.7	4558	2765	3601	1418	1.8	32	880	800	760	95.7	2.7	36	63.6	3.60
PG8	27-02-2021	Mark-II	10.6	7	4455	2301	3681	1418	1.6	25	660	1080	662	87	3.9	87	82.75	3.75
PG9	27-02-2021	Mark-II	6.02	6.8	2551	1501	1815	875	1.4	20	610	520	260	37.9	4.1	24	41.3	2.12
PG10	27-02-2021	Mark-II	6	7.1	2587	1068	2112	565	1.5	41	850	840	226	56	8.1	32	67.3	2.58
PG 11	27-02-2021	Mark-II	4	7.3	617	310	455	35	1	20	120	400	50	8	2.6	18	31.8	0.89
PG12	27-02-2021	Mark-II	3	6.8	1200	611	881	177	0.9	10	124	440	80	13.6	2.3	23	34.7	1.18
PG13	27-02-2021	Dug well	42	7.1	5257	3045	4411	1240	3.2	45	2660	1480	720	88.4	10.7	158	110.1	5.61
PG14	27-02-2021	Mark-II	7.8	7.3	3512	2911	2881	957	2.1	42	860	1000	650	62.8	3	78	76.8	3.39
PG15	27-02-2021	Mark-II	3.1	7.2	871	451	650	921	1	0.9	210	680	22	42	4.2	30	54.1	1.64
PG16	27-02-2021	Mark-II	0.9	7.3	511	258	451	240	0.8	24	28	400	92	9.8	2.3	21	31.5	0.87
PG17	27-02-2021	Mark-II	1.9	7.1	611	311	451	380	0.2	30	82	240	86	45.1	4.1	22	18.1	0.77
PG18	27-02-2021	Mark-II	2.8	7.3	617	321	472	35	0.6	20	94	360	60	32.2	6.1	17	28.5	0.85
PG19	27-02-2021	Mark-II	5	7.4	771	392	575	78	0.5	21	83	280	112	20	2.1	19	21.7	0.76
PG20	27-02-2021	Mark-II	2	7.1	571	273	424	200	1	12	76	400	48	23.1	1.2	28	31	0.91
PG21	27-02-2021	Mark-II	2.3	6.8	471	321	341	137	1.1	14	56	240	18	18.2	2.4	18	18.5	0.69
PG22	18-07-2021	Mark-II	2.1	7.3	799	399	688	140	1.2	27	62	200	117	43.1	4.2	22	14.8	0.72
PG23	18-07-2021	Mark-II	4.8	7.4	1541	770	1450	600	1.4	14	69	160	320	56.8	6.7	20	11.6	1.07
PG24	18-07-2021	Mark-II	7.2	7.3	2050	1040	1890	870	1.5	12	620	230	520	46	4.2	18	17.6	1.58
Sample code	Date	Type	Turbidity	pH	EC	TDS	Salinity	Cl ⁻	F ⁻	NO ₃ ⁻	SO ₄ ²⁻	TH	HCO ₃ ⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	WPI
PG25	18-07-2021	Mark-II	5.1	7.6	1949	974	1840	780	1.5	42	560	240	480	62.4	21	16	18.7	1.62
PG26	18-07-2021	Mark-II	11	7.8	4245	2145	3125	709	2.1	46	630	600	460	160	10.6	25	47.9	2.81
PG27	18-07-2021	Mark-II	4.2	7.2	1454	727	1325	820	1.1	9	220	240	412	62	1.2	23	18.1	1.24
PG28	18-07-2021	Mark-II	8	7.3	2843	1421	2620	920	1.2	18	560	480	418	120	2.3	36	37.0	2.22
PG29	18-07-2021	Tubewell	16.1	7.3	2911	1455	2810	283	1.4	41	616	260	416	86.2	4.1	22	19.8	1.91
PG30	18-07-2021	Tubewell	12.2	7.6	2310	1155	2205	875	1.3	42	480	960	420	45.9	1.2	45	76.3	2.72
PG31	18-07-2021	Tubewell	16.4	7.4	3018	1509	2018	779	1.6	45	612	1080	512	160	85.4	120	80.0	3.66
PG32	18-07-2021	Mark-II	18.9	7.9	3347	1673	2216	1276	1.5	44	584	1400	412	192	10.2	168	102.7	3.88
PG33	18-07-2021	Mark-II	122	7.3	5050	2520	4025	1488	3.4	54	780	1600	518	177	289	201	116.6	7.87

Table 2 (continued)

Sample code	Date	Type	Turbidity	pH	EC	TDS	Salinity	Cl ⁻	F ⁻	NO ₃ ⁻	SO ₄ ²⁻	TH	HCO ₃ ⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	WPI
PG34	18-07-2021	Mark-II	8.9	7.4	2090	1045	1190	1000	1.4	23	620	800	320	180	8.2	35	63.8	2.52
PG35	18-07-2021	Mark-II	4.2	7.2	2025	1012	1995	532	1.2	20	460	400	218	82.4	4.2	21	31.6	1.68
PG36	18-07-2021	Mark-II	3.1	7.6	2112	1010	2010	960	1.4	24	580	1080	220	61.2	2.2	82	83.2	2.72
PG37	18-07-2021	Tubewell	6.2	7.4	1740	874	1620	878	1	10	442	1400	112	45.2	8.6	160	103.3	3.02
PG38	18-07-2021	Mark-II	8.1	7.2	976	488	746	875	1	22	260	240	280	52	2.3	18	18.5	1.16
PG39	18-07-2021	Mark-II	9.2	7.4	1900	1100	1890	354	1.4	30	514	960	322	61	4	42	76.5	2.50
PG40	18-07-2021	Mark-II	6.4	7.3	780	390	670	300	0.9	20	29	240	128	20	1.2	26	17.8	0.78

EC in $\mu\text{S/cm}$, turbidity (NTU), all other parameters in mg/L, except pH

caused due to ingesting salty water containing a large number of dissolved minerals. The most affected area which was severely affected by TDS and EC is PG33 (3045 mg/L and 5257 $\mu\text{S/cm}$) which indicates a high pollution load at this sampling site.

Total hardness (TH)

The total hardness (TH) of the analyzed groundwater varies from 160 to 1600 mg/L with a mean value of 593 mg/L, indicating moderately hard to very hard types of groundwater recorded in sample PG33 (Mohanganj village, Sadar block). The maximum permissible limit of hardness in groundwater is 500 mg/L. Intake of very hard water for a long time may result in an elevated occurrence of anencephaly, urolithiasis, pre-natal mortality, a few forms of cancer, and cardiovascular diseases (Durvey et al., 1991; Tiwari et al., 2018).

Major anionic chemistry

The study area Sadar (Chilbila, Mohanganj) is flanked by the perennial river Sai; the water with long residence time led to leaching of the soil horizon and increases the major ionic concentration of Na, K, Cl, and HCO₃ (Tiwari et al., 2017, 2018). The order of the anion abundance in groundwater was found to be HCO₃⁻ > Cl⁻ > SO₄⁻ > NO₃⁻ > F⁻.

Bicarbonate (HCO₃⁻)

The concentration of bicarbonate varied from a minimum of 18 mg/L to a maximum value of 760 mg/L with a mean value of 274 mg/L, which is mainly derived from the soil zone by carbon dioxide (CO₂), dissolution of carbonates, and silicates minerals (Tiwari et al., 2018). The results from ion chemistry show that HCO₃⁻ is the leading anion in the study area associated with kankar or caliche formation. Bicarbonate levels may be higher due to the decomposition of rocks during heavy rainfall and groundwater movement (Mishra et al., 2016; Misra & Mishra, 2006).

Chloride (Cl⁻)

The high chloride concentration of 35 mg/L to 1488 mg/L with a mean value of 608 mg/L suggests that the study area has been adversely affected by

Table 3 Analytical summary of physicochemical parameters for groundwater samples of most contaminated sites in the study area (in March_2019)

S.N	Location	Types of sources	pH	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ⁻	HCO ₃ ⁻	Hardness	Turbidity	EC	TDS	Na ⁺	K ⁺	WPI
1	Pure Khusai	Deep tubewell	7.6	1.3	945	30	960	660	480	11.82	3884	2486	82	10.2	2.42
2	Pure Khusai	Deep tubewell	7.5	1	524	29	1980	710	1040	21	5672	3630	95	9.2	4.10
3	Pure Khusai	Deep tubewell	7.7	1	823	0.8	1800	650	860	92	5528	3538	86	12.2	6.98
4	Pure Khusai	Deep tubewell	7.6	0.8	798	25	1500	590	860	274	5031	3220	190	36	2.42
5	Pure Khusai	Deep tubewell	8	1.5	298	2.6	610	480	430	7.09	2250	1440	62	7.5	1.63
6	Pure Khusai	Deep tubewell	7.4	1.1	621	40	850	570	970	27	3950	2528	52	8	1.96
7	Pure Khusai	Deep tubewell	8	2.2	377	45	1140	780	340	8.29	4203	2690	120	26	2.25
8	Pure Khusai	Deep tubewell	8.6	1.2	367	22	1240	830	320	14.7	4375	2800	212	98	2.56
9	Pure Khusai	Deep tubewell	7.9	1.3	426	29	1320	800	370	2.6	4609	2950	96	43	2.70
10	Pure Khusai	Deep tubewell	8	3.2	308	43	820	780	270	37.5	3563	2280	88	20	2.81
11	Pure Loka	Deep tubewell	7.6	0.8	675	0	770	530	470	66	3903	2498	82	22	7.99
12	Pure Loka	Deep tubewell	7.5	0.4	1284	0.2	1360	430	1220	364	5938	3800	195	95	5.29
13	Sitkaha	Deep tubewell	8	1	823	2	1300	470	740	126	4813	3080	292	160	4.38
14	Sitkaha	Deep tubewell	7.4	0.7	1400	4.4	1820	490	1400	47	6972	4462	280	175	6.89
15	Sitkaha	Deep tubewell	7.9	1	872	51	1800	872	1300	148	6350	4064	302	190	5.01
16	Sitkaha	Deep tubewell	7.4	0.9	1073	171	1920	550	1440	33	7219	4620	320	120	4.64
17	Sitkaha	Deep tubewell	7.6	1.1	671	40	1680	510	1110	20	5609	3590	262	112	3.90
18	Sitkaha	Deep tubewell	7.6	0.8	921	31	2670	510	1350	13	7803	4994	286	114	5.0
19	Sitkaha	Deep tubewell	7.5	0.8	970	35	2760	530	1260	36	7859	5030	302	160	4.32
20	Chilbila	Deep tubewell	7.8	0.41	743	58.3	48.1	420	812	0.84	3080	2033	120	86	2.21
21	Bus stop	Deep tubewell	7.2	1.2	720	42	820	450	1200	12	3262	2680	42	8	1.37

EC in $\mu\text{S/cm}$, turbidity (NTU), all other parameters in mg/L, except pH

groundwater salinity. Chloride is an inorganic anion of great importance, and its presence in groundwater is most often caused by improper hygiene practices, methods of irrigation, improper disposal of untreated sewage, and linkage of the septic tank to underground water (Shukla & Saxena, 2020). People who are not accustomed to drinking water that contains high levels of Cl^- will notice a salty taste and a laxative effect (Singh et al., 2008).

Sulfate (SO_4^{2-})

According to WHO guidelines, the maximum permissible value of sulfate in water is 250 mg/L. The concentration of sulfate in the test sample in the study area varies between 28 and 2660 mg/L, with a mean value of 421 mg/L. Groundwater generally contains sulfate due to mineral deposition in the rock and untreated sewage discharge. In addition to pyrite, gypsum and anhydrite are also able to form sulfate in water due to oxidative weathering of sulfide minerals (Han et al., 2013). Drinking water with high sulfate levels can cause a bad taste and respiratory disorder (Rao, 1993).

Nitrate (NO_3^-)

The concentration of NO_3^- in groundwater samples varies from 0.9 to 54 mg/L, with a mean value of 25.2 mg/L. According to WHO guidelines, the acceptable range of nitrate in drinking water is 45 mg/L. The high concentration of NO_3^- in village Sitkaha Mohanganj may be due to excessive application of nitrogenous fertilizer in the intensive cropping system (> 250%) and higher net irrigated area (Tiwari et al., 2017).

Fluoride (F^-)

The values of fluoride in the samples vary from 0.2 to 3.4 mg/L, with a mean value of 1.265 mg/L. The maximum concentration of F^- was found at site PG33 (3.20 mg/L), where the geogenic sources could be the possible reason behind the increased level of fluoride. According to WHO guidelines, the acceptable range of fluoride is 1.5 mg/L in drinking water. Drinking water with F^- a level greater than 1.5 mg/L may cause dental fluorosis (Gaikwad et al., 2020). During

the public interaction in the study area, fluorosis was found to be a problem in several residents.

Major cationic chemistry

The order of cation abundance in groundwater was found to be $\text{Mg}^{2+} > \text{Na}^+ > \text{Ca}^{2+} > \text{K}^+$

Magnesium (Mg^{2+})

The minimum and maximum values of magnesium vary from 11.6 to 116 mg/L, with a mean value of 45.6 mg/L. The elevated level of magnesium in drinking water causes heart ailments, high blood pressure, and even causes death (Singh et al., 2021).

Sodium (Na^{2+})

The sodium concentration in groundwater is 8 mg/L to 192 mg/L, with a mean value of 64 mg/L, which suggests that the study area has been adversely affected by groundwater salinity. An excess of potassium can cause congenital diseases, kidney problems, and neurological issues (Adimalla & Qian, 2019; Shukla & Saxena, 2021).

Calcium (Ca^{2+})

The minimum and maximum values of calcium in groundwater were found between 12 and 201 mg/L with a mean value of 46 mg/L. The desirable limit of calcium in groundwater is 75 mg/L. The calcium and magnesium ions are mainly released in water due to the weathering of silicate minerals (Tiwari et al., 2018).

Potassium (K^+)

Potassium is also one of the most important cationic parameters. The concentration of potassium in the sample varies from 1.2 to 289 mg/L, with a mean value of 13.6 mg/L in the study area. Potassium plays an important role in osmoregulation, but its exceeded level may have a bad impact on human health. According to Misra and Mishra (2006), the ions of Na^+ , K^+ , Cl^- , and HCO_3^- are released directly into the soil through phosphate fertilizers (an important source of contamination of agricultural soil).

Water Pollution Index (WPI)

Water Pollution Index (WPI) is an indexing parameter of water quality. In the study area, it was found that the values of WPI vary from 0.6 to 7.8. Out of 40 groundwater samples, only 10% of samples were categorized as “good” quality water at sites PG1, PG3, PG21, and PG22, where the range varies from 0.5 to 0.75 (Table 4). In the area, 25% of samples were “moderately” polluted at sites PG2, PG4, PG5, PG11, PG16, PG17, PG18, PG19, PG20, and PG40, where the WPI varies from 0.75 to 1 (Table 4). Although the water at these moderately polluted sites was not suitable for drinking purposes, it can be used for cleaning and other such purposes. Sixty-five percent of the samples were classified as “highly polluted” at sites PG7, PG8, PG13, PG26, and PG33. The value of WPI at these sites was found to be greater than 1 and hence the water was not fit for drinking purposes. At site PG33, Mohanganj Sitkaha village, all the parameters were found to be more than the permissible limits, and an alarmingly high WPI value of 7.8 was noted. Samples with $WPI > 1$ (Hossain & Patra, 2020) are categorized as “highly polluted” and cannot be used for drinking, domestic purposes, and cattle feeding purposes. The correlation matrix verifies that WPI shows a good correlation with turbidity, salinity, EC, TH, TDS, F^- , Ca^{2+} , and Mg^{2+} ($r=0.81$ to 0.88), suggesting the importance of these parameters in shaping the drinking water quality. Notably, the percentage of samples in “excellent” categories is not identified in the region. The WPI values may be classified, based on the “n” number of parameters into four different categories as mentioned in Table 4, and the water pollution index of these sample sites is graphically represented (Fig. 2).

Table 4 Water quality classification method concerning WPI score

S. No	WPI value	Category of water	Total contaminated sample	% Pollution
1	<0.5	Excellent water	0	0% site
2	0.5–0.75	Good	4	10% site
3	0.75–1	Moderately polluted	10	25% site
4	> 1	Highly polluted	26	65% site

Pearson’s correlation matrix

Fifteen physicochemical parameters have been used for the study of Pearson’s correlation. A strong correlation exists between TDS and EC, salinity, calcium, magnesium, and bicarbonate ($r=0.96$), which indicates that the aquifer system is undergoing oxidation/reduction or positive direct ion exchange. TDS, salinity, chloride, and sulfate are all negatively correlated with pH. The fluoride has a good ($r=0.7-0.8$) correlation with sulfate and bicarbonate, whereas hardness has a good correlation with calcium and magnesium. Having a strong or good correlation suggests that they are derived from the same source and exhibit similar geochemical behavior during different processes. The majority of these ions are derived from human activities, i.e., municipal sewage discharge, septic tanks, and the use of fertilizer (Singh et al., 2021). Potassium shows weak correlation ($r < 0.5$) with all parameters. Major physicochemical analysis results of groundwater in the study area are expressed in Table 5.

Chloro-alkaline indices

The range of CAI 1 values in the study area varies from -0.82 to 39 meq/L with a mean value of 16.82 meq/L and CAI 2 values vary from 1.2 to 52 meq/L with a mean value of 21.50 meq/L (Table 1). In this process, Mg^{2+} and Ca^{2+} ions are released from aquifer materials. In the study area, 90% of samples show direction exchange. In this region, only 10% of samples (PG1, PG3, and PG18) show softening process due to the release of sodium and potassium ions from aquifer materials. The results of these processes are shown in Fig. 3.

Gibbs plot

Gibb’s plots are commonly used to recognize the composition of water with their respective aquifer attributes, evaporation dominance, which might be due to anthropogenic activities, and rock weathering dominance (mainly geogenic activities). When the sample falls between rock dominance and evaporation dominance zones, there will be the dominance of precipitation for groundwater. The Gibbs diagram represents the $(Cl^- + NO_3^-) / (Cl^- + NO_3^- + HCO_3^-)$ and $(Na^+ + K^+) / (Na^+ + K^+ + Ca^{2+})$ ratio with reference to

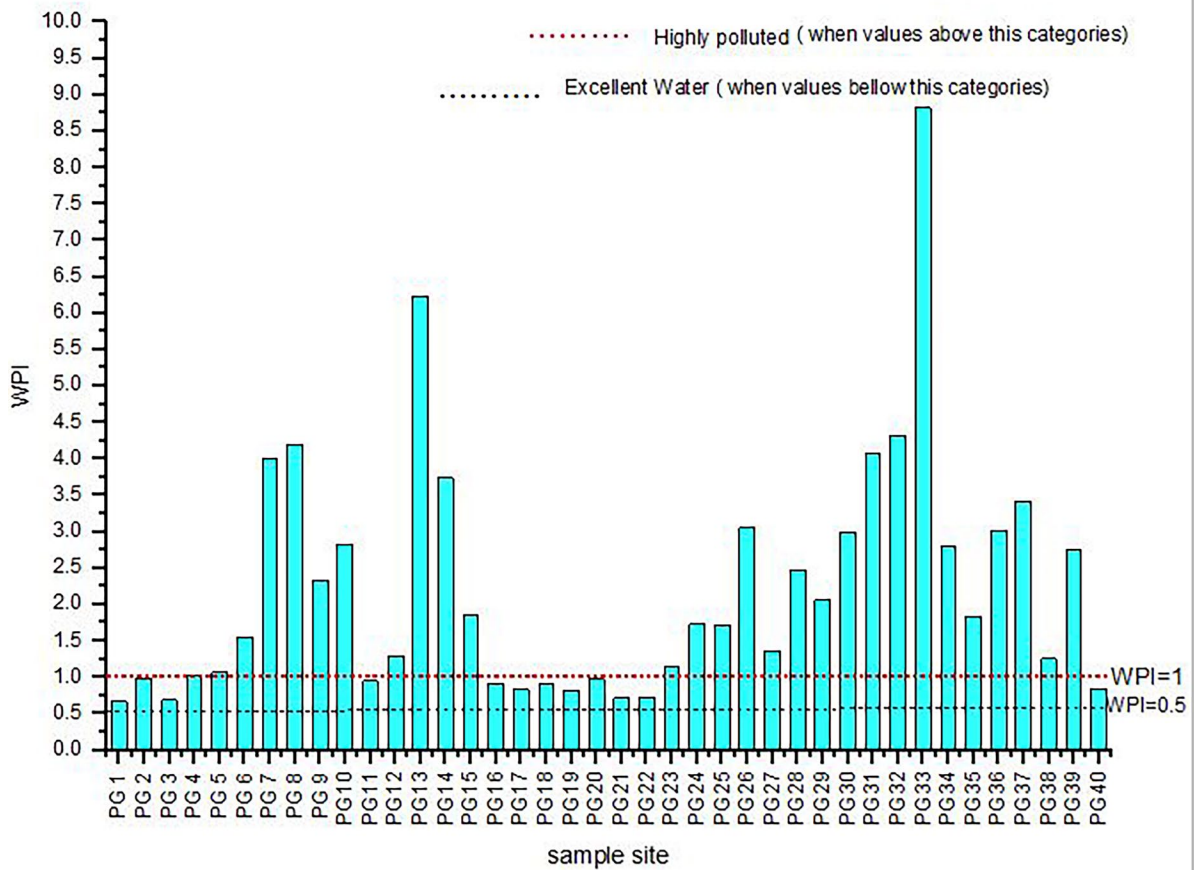


Fig. 2 Site-wise variation of Water Pollution Index (WPI)

TDS. Figure 4 shows that 80% of samples fall under the evaporation dominance zone and the remaining fall under rock weathering dominance. There is no precipitation dominance in any of these samples. The physicochemical data on Gibbs's plot shows the evaporation and rock weathering as a major motive power, mainly controlled by complex geochemical mechanisms in the study area. A similar analysis was conducted in a few other recent and previous studies (Baloch et al., 2021; Rashid et al., 2020).

Irrigation suitability of groundwater

Sodium absorbance ratio (SAR)

The sodium absorption ratio is an indexing parameter of water irrigation. In the study area, values of sodium absorption ratio vary from 1.3 to 22.8 (Table 6).

Seventy percent of samples are in excellent categories, 25% samples are in good categories, and the remaining 5% are in doubtful categories. According to sodium absorption ratio, none of the samples fall into unfit categories. Ninety-five percent of samples are suitable for irrigation and only 12% of samples are unsuitable for irrigation purposes. In the groundwater, there is an increase in sodium absorption ratio values due to the combined effects of evaporation and calcite precipitation (Marghade et al., 2021).

Residual sodium carbonate (RSC)

The residual sodium carbonate is an indexing parameter of water irrigation, depending on bicarbonates, calcium, and magnesium. The range of RSC values in the study area varies from 0.4 to 14 (Table 6). Fifteen percent of samples are of good categories, 22%

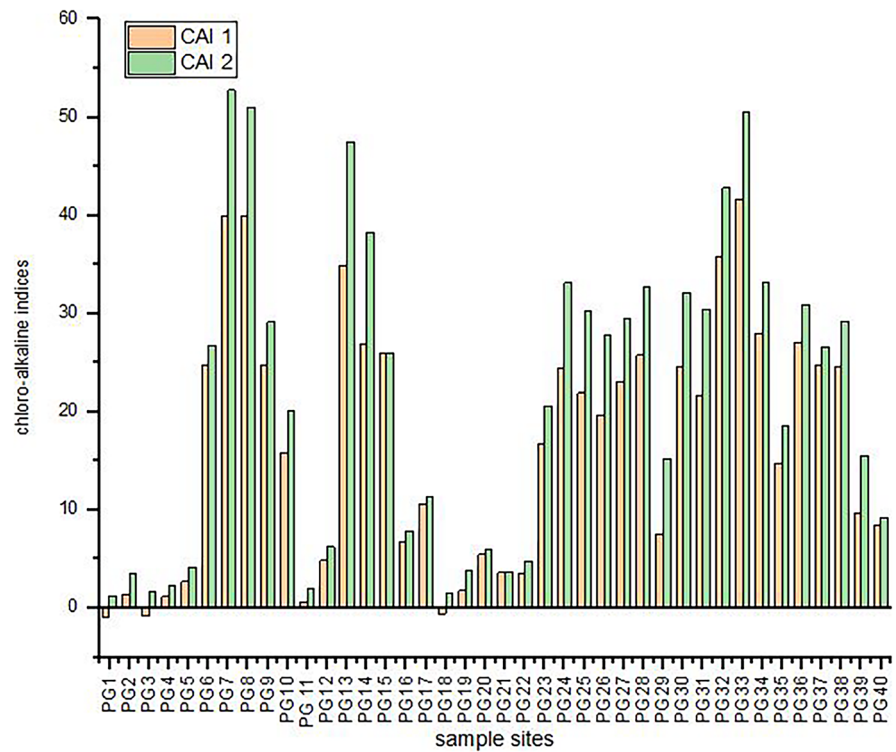
Table 5 Pearson's linear correlation matrix for groundwater quality parameters in the study area

Parameter	Turbidity	PH	EC	TDS	Salinity	F ⁻	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	TH	HCO ₃ ⁻	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	WPI
Turbidity	1															
PH	0.039	1														
EC	0.604	0.007	1													
TDS	0.541	-0.021	0.965	1												
Salinity	0.582	-0.005	0.981	0.946	1											
F ⁻	0.749	0.094	0.863	0.851	0.850	1										
NO ₃ ⁻	0.523	0.341	0.660	0.633	0.629	0.640	1									
Cl ⁻	0.495	-0.010	0.812	0.770	0.791	0.693	0.376	1								
SO ₄ ²⁻	0.440	-0.024	0.802	0.811	0.807	0.794	0.552	0.627	1							
TH	0.578	0.188	0.698	0.684	0.660	0.669	0.505	0.668	0.648	1						
HCO ₃ ⁻	0.422	0.059	0.883	0.901	0.885	0.759	0.590	0.774	0.735	0.505	1					
Na ⁺	0.529	0.361	0.710	0.628	0.626	0.610	0.599	0.643	0.455	0.569	0.609	1				
K ⁺	0.922	0.066	0.414	0.343	0.377	0.579	0.443	0.349	0.175	0.457	0.253	0.480	1			
Ca ²⁺	0.690	0.208	0.637	0.604	0.598	0.654	0.466	0.627	0.569	0.904	0.454	0.576	0.592	1		
Mg ²⁺	0.555	0.183	0.697	0.684	0.659	0.661	0.503	0.664	0.650	0.998	0.505	0.560	0.432	0.878	1	
WPI	0.815	0.067	0.889	0.851	0.860	0.878	0.643	0.791	0.743	0.883	0.719	0.701	0.676	0.857	0.874	1

The bold values indicate a strong positive correlation with r > 0.9

TH Total hardness, TDS Total Dissolved Solids, WPI Water Pollution Index

Fig. 3 CAI-1 against CAI-2 shows positive and reverse ion exchange processes



samples are in doubtful categories, and 55% samples are unfit for irrigation practices. Calcium and magnesium ions have less soluble content than carbonate and bicarbonate ions, as indicated by the positive values of RSC. By accumulating sodium carbonate in the soil, high RSC water might make it sterile (Marghade et al., 2021).

Sodium percentage (Na %)

It is an irrigation indexing parameter used for the irrigation suitability of water. In the study area, the range of Na% varies from 0.1 to 2.1 (Table 6). Only 37.5% of samples are of excellent categories, 37.5% of samples are good categories, 32.5% are of permissible categories,

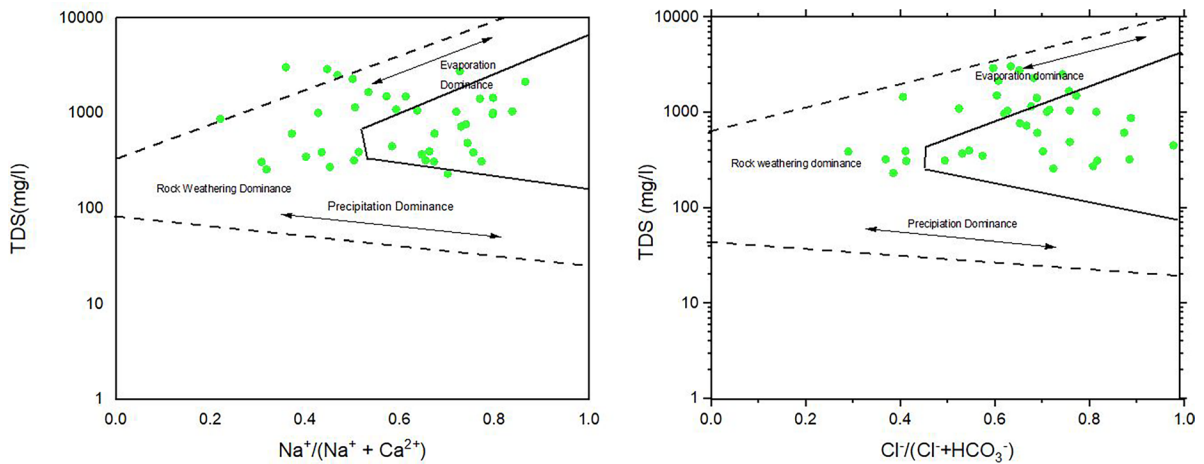


Fig. 4 Gibbs diagram showing the mechanism controlling the geochemistry of groundwater in the study area

Table 6 Classification of groundwater for irrigation purposes in the study area

Parameter	Min	Max	Classification	Water class	No of samples	% of samples
Sodium adsorption ratio (SAR)	1.3	22.8	0–10	Excellent	28	70
			10–18	Good	10	25
			18–26	Doubtful	2	5
			> 26	Unfit	0	0
Residual sodium carbonate (RSC)	0.4	14	< 1.25	Good	6	15
			1.25–2.5	Doubtful	12	30
			> 2.5	Unfit	22	55
Permeability Index (PI)	20	169.1	> 75	Class-I	16	40
			25–75	Class-2	23	57.5
			< 25	Class-3	1	2.5
Magnesium hazards (MH)	36	69.6	< 50	Suitable	16	40
			> 50	Unsuitable	24	60
Sodium percentage (Na%)	16	68	< 20	Excellent	3	7.5
			20–40	Good	15	37.5
			40–60	Permissible	13	32.5
			60–80	Doubtful	9	22.5
			> 80	Unfit	0	0
Kelley’s ratio (KR)	0.1	2.1	< 1	Suitable	25	62.5
			> 1	Unsuitable	15	37.5

22.5% are in doubtful categories, and no samples are identified in unfit categories for irrigation purposes in this region. In Fig. 5 Wilcox plot (Wilcox, 1955) between soluble sodium percentage and electric conductivity suggested that groundwater quality of the study area is in excellent to good and good to permissible categories, but some samples are also coming in doubtful to unsuitable categories. High sodium percentage (Na %) in the soil impacts the porosity of the soil texture, resulting in depletion of drainage capacity.

Magnesium hazard (MH)

The range of magnesium hazards varies from 36 to 69.6 (Table 6). In this region, due to the increased level of MH, only 40% of samples are in suitable categories and the other 60% are not suitable for irrigation purposes. A high percentage of magnesium ions in soil reduces the infiltration capacity and crop yield of soil, which may also lead to damage to the crop.

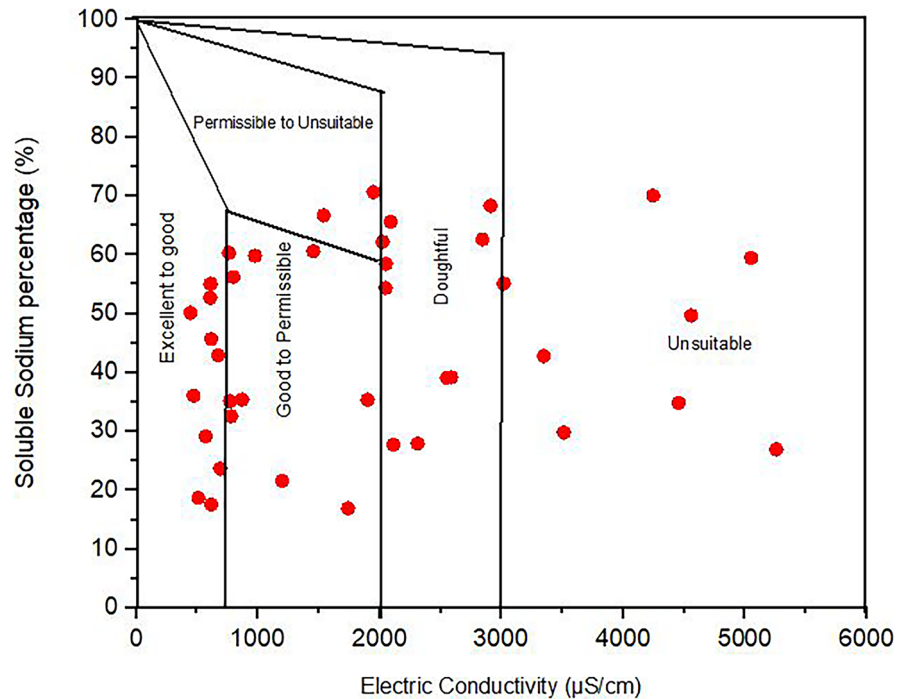
Kelley’s ratio

In the study area, Kelly’s ratio varies from 0.1 to 2.1 (Table 6). In this region, 63% of samples are suitable and fit for irrigation purposes, and the remaining 38% are in unsuitable categories that might be fit for irrigation due to sodium enhancement.

Permeability index (PI)

The value of the permeability index varies from 20 to 169 (Table 6). Doneen (1964) proposed three-class indexing for evaluating the suitability of water for irrigation. In this region, 40% of samples are of class first categories which are more suitable for groundwater, 57.5% in class second categories, and the remaining 2.5% samples are in class third categories which are considered less suitable for irrigation.

Fig. 5 Sodium percent versus electrical conductivity plot



Conclusion

WPI and irrigation suitability indices were applied to evaluate the groundwater quality for drinking and irrigation purposes in the study area. The maximum water WPI was reported to be 7.8 from the sample collected at the Mohanganj Sadar block (site PG33). A total of 25% of samples were in the poor category and 65% of samples were in the very poor category according to WPI. All result analysis suggests that 65% of water is not suitable for drinking purposes due to the occurrence of higher concentrations of TDS, EC, calcium, and chloride in the groundwater of the area. The crop growth in the region will be adversely affected by higher irrigation indices. Geogenic and agricultural activities may be responsible for the contamination. However, no major industrial activity was seen in the Sadar block of Pratapgarh district that could cause water contamination. The ratio plot of $(\text{Cl}^- + \text{NO}_3^-) / (\text{Cl}^- + \text{NO}_3^- + \text{HCO}_3^-)$ and $(\text{Na}^+ + \text{K}^+) / (\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+})$ with reference to TDS suggests evaporation and rock weathering dominant process that may be active in the study area. Using the chloro-alkaline index, it was found that 80% of the samples are under the influence of the hardening process.

Based on these findings, it appears that the rural and urban populations living in the study area are at risk for potential health problems from drinking the contaminated groundwater. For the implementation of effective water management programs, it is necessary to determine the geogenic and anthropogenic sources of water contamination. A groundwater contamination study would assist in spreading awareness about anthropogenic interventions. Moreover, it will raise awareness of the harmful effects of contaminated water among residents and medical professionals in rural areas. Thereafter, there is an urgent need to take some remedial measures for water pollution control and to improve the quality of water in the study area.

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Author contribution SM conducted the investigation, developed the suitable methodology and approach, and was involved with the writing (original draft) of the manuscript. AS provided supervision in the presented work and helped in the review and editing of the manuscript.

Data availability Data shall be made available on request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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