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Spatial analysis of subsurface water quality: A case study from an arid region of India

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Abstract
This study assesses the physicochemical and heavy metal contamination of subsurface water in Bikaner City, Rajasthan. Samples were collected from various tube wells and analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-, NO_3^-), and heavy metals (Mn, Cu, Zn, Pb, Cr, U, As). The spatial distribution of these parameters was visualized using Inverse Distance Weighting (IDW) in QGIS. The results revealed that several regions exhibit high TDS and nitrate levels. Fluoride concentrations in some areas surpassed the permissible limit (1.5 mg/L), raising concerns about potential health risks associated with dental and skeletal fluorosis. Heavy metals such as uranium and manganese were detected at varying concentrations, with localized hotspots exceeding permissible limits. The findings emphasize the importance of addressing both natural and anthropogenic sources of contamination to safeguard public health and promote sustainable water use in the arid region.

Keywords: *Subsurface Water; Spatial Analysis, Arid Region, Fluoride, Nitrate.*

Introduction

Groundwater quality is a critical concern in arid regions, such as Bikaner, where it serves as a primary water source for drinking, agriculture, and industrial purposes. Due to limited surface water availability, people of arid regions rely heavily on groundwater to meet their daily water needs. However, the over-extraction of groundwater and contamination from natural and anthropogenic sources have raised significant concerns regarding water safety and quality. Previous studies in Rajasthan have documented widespread groundwater contamination (Bhakar and Singh, 2019; Coyte et al., 2019; Kumari and Rai, 2020; Rahman et al., 2020; Karimi et al., 2024), particularly with fluoride, which poses severe health risks, including dental and skeletal fluorosis (Jain et al., 2014). In addition, heavy metals such as arsenic, lead, and uranium have been reported in groundwater across different regions, further exacerbating public health risks (Gandhi et al., 2022). These contaminants often originate from geogenic sources, industrial activities, agricultural runoff, and improper waste disposal practices. Understanding the spatial distribution of groundwater contaminants and identifying potential hotspots is crucial for devising effective mitigation strategies. The Inverse Distance Weighting (IDW) interpolation technique has been widely used to create continuous surface maps of contaminant concentrations, allowing researchers to visualize contamination patterns and assess the extent of water quality issues (Singh et al., 2020). In recent years, Geographic Information System (GIS) has emerged as a powerful tool for the spatial analysis of groundwater contamination. GIS facilitates mapping geogenic contamination pat-

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terns, enabling better visualization and understanding of contamination sources and their spread (Nag and Das 2017). By integrating GIS and spatial interpolation techniques such as Kriging and Inverse Distance Weighting (IDW), researchers can predict the distribution of contaminants across areas that are not sampled. This method allows for more comprehensive assessments of water quality by interpolating data between measured points, thus offering a clearer picture of groundwater contamination trends. Several studies have successfully applied GIS and interpolation techniques to assess groundwater contamination. For instance, Nag and Das (2017) used GIS to evaluate fluoride contamination in West Bengal. GIS-based approaches not only help in understanding the spatial distribution of contaminants but also play a crucial role in decision-making for groundwater management and policy planning (Singh et al. 2020). Given the importance of groundwater for daily life and economic activities in Bikaner, conducting a comprehensive assessment of geogenic contamination is essential. This study utilizes GIS-based spatial analysis and interpolation methods to evaluate the extent of geogenic contamination in groundwater within Bikaner City, analyzing the concentrations of various contaminants. By identifying the sources and levels of geogenic contamination, this research seeks to inform strategies for improving groundwater quality and ensuring the safe use of this vital resource.

Methodology

Study Area

The Bikaner district, located in the north-western region of Rajasthan, India, spans latitudes 27°11' to 29°03' N and longitudes 71°52' to 74°15' E, covering approximately 30,247.90 km² area. It borders Sriganganagar to the north, Hanumangarh and Churu to the east, Nagaur and Jodhpur to the south, and Jaisalmer and Pakistan to the west. It has an arid climate with extreme temperatures. Annually, rainfall held 260-440 mm (90% during southwest monsoon from July to mid-September). The hottest and the coldest months are June (average 36°C and maximum temperature 48°C) and January (average 16°C and minimum 1°C) respectively. The highest humidity occurs in the month of August. Gradual temperature increases from April to June, followed by the monsoon season providing most of the annual rainfall.

Sampling sites

This study aimed to evaluate the geogenic contamination of groundwater in Bikaner City by collecting water samples from various tube wells. The sampling locations were carefully selected to provide a representtative overview of groundwater quality across different areas of the city. The specific sites for sampling are detailed in Table 1.

Table 1. *Geospatial coordinates of subsurface water sampling sites in Bikaner City*

S.N.	Sampling Site	Geographical coordinates	
		Latitude	Longitude
1	Raisar	28.05255	73.4779
2	Naurangdesar	28.0727	73.5455
3	Sagar	28.0196	73.3906
4	Ridmalsar	28.0101	73.3762
5	Gadhwala	27.9221	73.4662
6	Sinthal	27.9653	73.5991
7	Napasar	27.9688	73.5558
8	Udasar	27.5619	73.2647
9	Naal	28.0306	73.1898
10	Gajner	27.9364	73.0621
11	Deshnokh	27.7851	73.3446
12	Palana	27.8470	73.2608
13	Udayramsar	27.9377	73.3016
14	Gangasahar	27.9795	73.3082
15	Patel nagar	28.0024	73.3410
16	Khara	28.1950	73.3868
17	Jamsar	28.2521	73.4068
18	Antyodaya Nagar	28.0221	73.2851
19	Binchwal	28.0854	73.3533
20	Karmisar	28.0020	73.2692

Sample analysis

Samples were collected from groundwater wells at depths ranging from 50 to 800 feet across Bikaner City. Clean 1.0 L bottles were used for each sample collection, filled completely with water and tightly sealed to prevent contamination. To ensure sample integrity, 50 mL aliquots of the water were filtered on-site using Whatman filter paper. These filtered samples were preserved with ultra-pure nitric acid (HNO_3). For further analysis, 100 mL of the filtered water was combined with 5 mL of concentrated nitric acid and 5 mL of concentrated sulfuric acid, then coo-

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led to room temperature. The final volume was adjusted to 100 mL with double-distilled water before being transported to the laboratory, where it was stored at 4°C until analysis. In the laboratory, various physicochemical parameters were measured. The groundwater's pH and electrical conductivity (EC) were determined using a pH meter and an electro-conductivity meter respectively. Major cations and anions were analyzed using established methods: sodium (Na) and potassium (K) concentrations were measured with a flame photometer, while magnesium (Mg) and calcium (Ca), along with total hardness (TH), were assessed using the EDTA titration method. Anions such as bicarbonate (HCO_3^-) were quantified via titration, and chloride (Cl^-) content was determined using silver nitrate titration. Fluoride (F^-) and nitrate (NO_3^-) concentrations were estimated using a UV-spectrophotometer, with fluoride measured by the SPADNS method. Heavy metals, including manganese (Mn), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), uranium (U), and arsenic (As) were analyzed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), following the manual.

All analyses adhered to the standard procedures outlined by the American Public Health Association (APHA 2017). The spatial distribution of groundwater quality parameters, including major cations, anions, and heavy metals, was assessed using the Inverse Distance Weighting (IDW) interpolation technique in QGIS 3.38.3 'Grenoble' software. IDW was applied to create continuous surface maps of contaminant concentrations across Bikaner City, enabling visualization of geogenic contamination patterns from sampled locations.

Results and Discussion

Spatial analysis of physico-chemical variables

The analysis of groundwater quality in Bikaner City reveals several key findings related to the physicochemical parameters of the water (Fig. 1 to Fig. 3). The pH of the groundwater samples ranged from 7.5 to 8.4, indicating an alkaline nature (Fig. 1). This alkaline pH is consistent with observations in similar arid and semi-arid regions, where groundwater often exhibits higher pH levels due to the dissolution of alkaline minerals such as calcite and dolomite. The pH levels are predominantly within acceptable limits for drinking water. The electrical conductivity (EC) values ranged from 1010 to 7400 μS/cm, reflecting the high mineral content typical of arid regions (Figure 1). Areas with EC values exceeding 3000 μS/cm, particularly in the central and southern parts of the city, suggest potential issues related to salinity and mineralization. The substantial variability in EC aligns with studies indicating increased salinity in groundwater due to evaporation and mineral dissolution (Rajmohan et al., 2021; Agbasi et al., 2025). Areas with high EC are often correlated with elevated TDS levels, reflecting higher mineralization (Krishan et al., 2020).

Groundwater salinization is a significant concern in arid and semi-arid regions, where evaporation and mineral dissolution play crucial roles in increasing salinity levels. The spatial variation of total dissolved solids (TDS) concentra-tions in groundwater at various sampling sites within Bikaner City, Rajasthan is also illustrated in Figure 1. The TDS values, ranging from 650 mg/L to 4540 mg/L, are categorized into five distinct zones repre-sented by different colours. The distribution indicates regions of high conta-mination, particularly in the northern and central parts of Bikaner City, where TDS levels exceed 4058 mg/L, posing potential risks for water usage. Several areas exceed the acceptable limit of 500 mg/L prescribed by the Bureau of Indian Standards (BIS, 2012). Elevated TDS levels are often attributed to the presence of dissolved salts and minerals, a common feature in desert environments where evaporation exceeds precipitation. The concentration of potas-sium (K^+) ranged from 3 to 8 mg/L, while sodium (Na^+) levels ranged from 105 to 890 mg/L (Fig. 2). The high concentrations of sodium and potassium could be due to evaporation process (Banerjee and Prasad, 2020). Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations ranged from 14 to 558 mg/L and 18 to 178 mg/L, respectively, indica- ting contributions from the weathering of calcite, dolomite, and magnesite.

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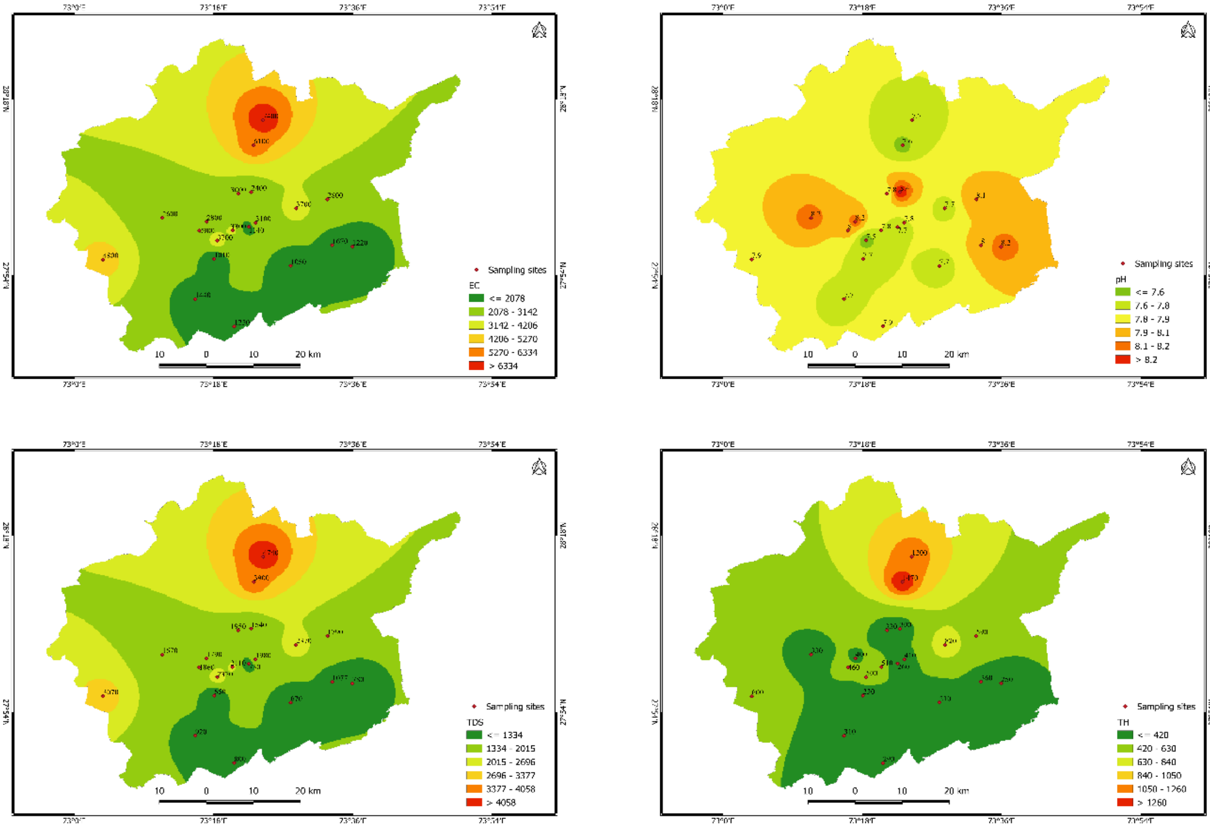

Figure 1. *Spatial distribution of EC, pH, TDS and TH in groundwater*

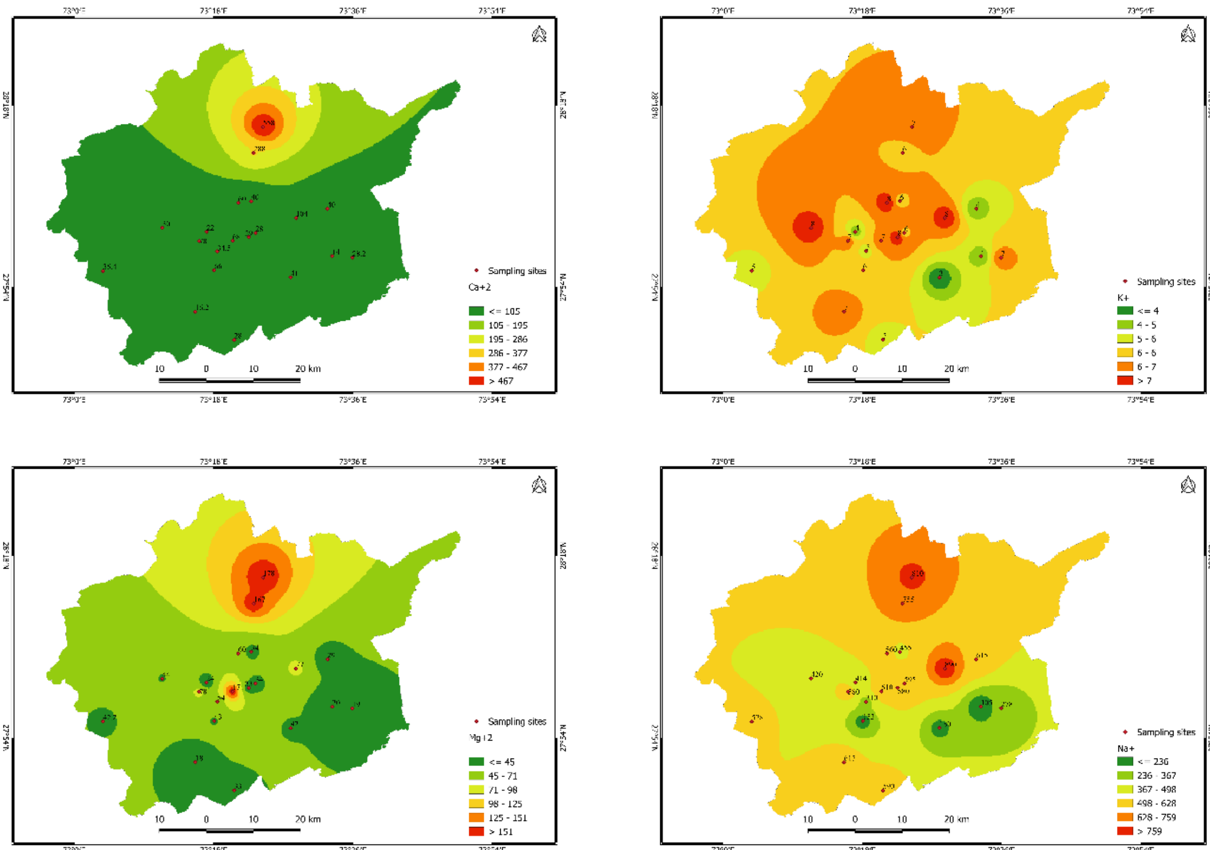

Figure 2. *Spatial distribution of cations (Na, K, Ca and Mg) in groundwater*

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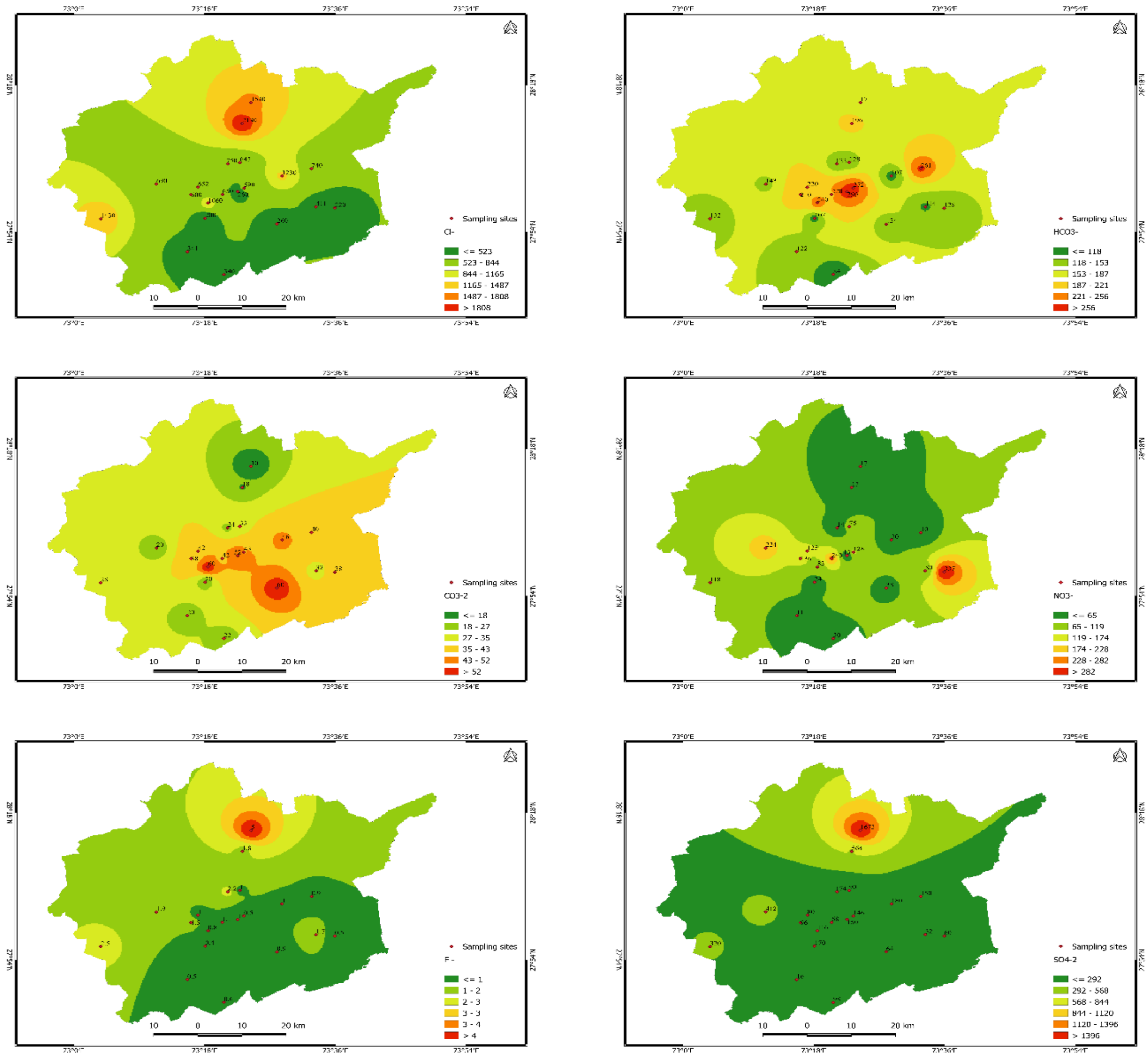

Figure 3. *Spatial distribution of anions (Cl, F, NO_3, HCO_3, CO_3 and SO_4) in groundwater*

The strong correlation bet-ween sodium, potassium, magnesium (Mg^{2+}), and calcium (Ca^{2+}) suggests a common source of these ions, likely related to the dissolution of geological minerals. Spatial distribution of anions (Cl, F, NO_3, HCO_3, CO_3 and SO_4) in groundwater is depicted in Figure 3. The concen-tration of bicarbonates in groundwater ranged from 84 to 290 mg/l, primarily due to the dissolution of CO_2 and the weathering of carbonate rocks. Higher concentrations are observed in the northwest regions. These findings are consistent with previous studies that show bicarbonate levels influenced by both natural processes and the geochemical characteristics of aquifers (Rahman et al. 2020, Meena 2022). Sulfate concentrations range from 16 mg/L to 580 mg/L, with a clear gradient shown through color-coded zones. The highest sulfate is concentrated in the northern and western parts of Bikaner City, with values exceeding 486 mg/L in some regions. The source of high sulfate ion is dissolution of sulfate minerals such as gypsum in groundwater. The results are supported by Tanwer et al. (2023) who found high sulfate ion concentrations in groundwater of Churu district of Rajasthan. Chloride concentrations range from 200 mg/L to 2130 mg/L, with sources including atmospheric deposition and the dissolution of chloride-containing minerals. High chloride levels, particularly in the central regions, surpass the WHO guideline of 250 mg/L. The high chloride levels observed are consistent with Kincaid and Findlay (2009) showing elevated chloride concentrations in areas with significant evaporation. Fluoride concen-

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areas with significant evaporation. Fluoride concentrations varied from 0.4 to 5.0 mg/l, with fluoride primarily sourced from the weathering of fluorapatite and other fluoride-bearing rocks. Several areas, particularly in the northeast, exhibit fluoride levels exceeding the WHO limit of 1.5 mg/L, raising concerns about the potential health risks of dental and skeletal fluorosis. The range of fluoride in the present study aligns with previous findings in Rajasthan, where fluoride levels often exceed recommended limits due to geological factors (Vikas et al. 2013, Keesari et al. 2021). Fluoride dissolution in groundwater is controlled by the geological formations. The main geological formations of the area are sandstone, limestone-evaporite sequence, sandstone-clay-sandstone sequence, aeolian sand and river flood deposits. The major minerals are calcite, dolomite, gypsum, anhydrite, halite and salts of potassium and magnesium. The key water carrying formations are alluvium, sandstone, tertiary sandstone, and limestone. Nitrate ion (NO_3^-) concentrations in groundwater across the depicted area ranged from 10 to 337 mg/L; the highest nitrate concentrations, exceeding 282 mg/L, are localized in the western and southeastern parts of the region. Lower concentrations below 65 mg/L are predominant in the central and eastern parts. This observation supports potential contributions from agricultural runoff and urban sources such as chemical fertilizers (such as sodium nitrate) and animal manure on nitrate contamination. Levels exceeding 50 mg/L pose a risk of methemoglobinemia, especially in infants (Rahman et al., 2021). Overall, the groundwater quality in Bikaner City is generally within permissible limits set by the World Health Organization (WHO 2011) and Indian standards (BIS 2012). Key parameters such as pH, EC, SO_4^{2-}, HCO_3^-, CO_3^{2-}, Ca^{2+}, and NO_3^- are within acceptable ranges, indicating that the water is generally suitable for consumption and use. However, salinity is primarily due to evaporation process in the study areas. The precipitation of carbonate minerals at high salinity levels due to evaporation may reduce calcium activity in the groundwater, triggering the solubility of gypsum and fluorite through the common ion effect. Additionally, repeated irrigation practices with high salinity groundwater can cause salt accumulation, which could be subsequently flushed by irrigation events, resulting in higher salinity and nitrate levels in the groundwater. The variations in specific parameters underscores the need for ongoing monitoring and management to ensure water safety and sustainability in this arid region.

Spatial analysis of heavy metals

The analysis of groundwater samples from 20 locations around Bikaner, Rajasthan, revealed significant findings concerning the presence of heavy metals and metalloids. The results showed that Arsenic (As), Chromium (Cr), Copper (Cu), and Lead (Pb) were non-detectable (ND) across all sampled locations. Manganese (Mn) was detected in only one location i.e., Naal (0.03 mg/L) (Figure 4). Heavy metals, including zinc (Zn) and uranium (U), were found within relatively low ranges, with zinc ranging from 0.01 to 0.09 mg/L and uranium from 0.02 to 0.22 mg/L (Fig. 5 and Fig. 6). The absence of significant levels of chromium and arsenic in the samples is consistent with findings from similar regions where these contaminants are less prevalent. These outcomes incorporate earlier studies in similar arid regions where the average or below presence of these metals has been reported (Duggal et al. 2014). The lack of detectable chromium, a known carcinogen, suggests that the groundwater sources are currently free from industrial contamination, a positive indicator for public health in this region. The uranium (U) results showed varied concentrations across the well locations, with the highest concentration recorded at Khara (0.22 mg/L). The presence of uranium is particularly concerning as it poses both chemical toxicity and radiological hazards. Studies in the Thar Desert and similar arid regions have previously documented the occurrence of uranium in groundwater, attributed to natural leaching from bedrock. The findings from Khara align with Gandhi et al. (2022), highlighting the need for regular monitoring and possible mitigation strategies to ensure the safety of drinking water. Zinc (Zn) was detected in only three locations: Sinthal (0.02 mg/L), Napasar (0.01 mg/L), and Udayramsar (0.05 mg/L). These concentrations are relatively low and do not pose an immediate health risk. As suggested by previous research in the region, zinc's presence in these specific locations might be linked to localized anthropogenic activities, such as agricultural runoff. Arsenic (As) was non-detectable in all locations, which is a positive finding given the severe health risks associated with Arsenic contamination. Previous studies in the Thar Desert have occasionally reported elevated levels of arsenic, particularly in areas influenced by industrial or agricultural activities. The absence of detectable arsenic in the sampled wells

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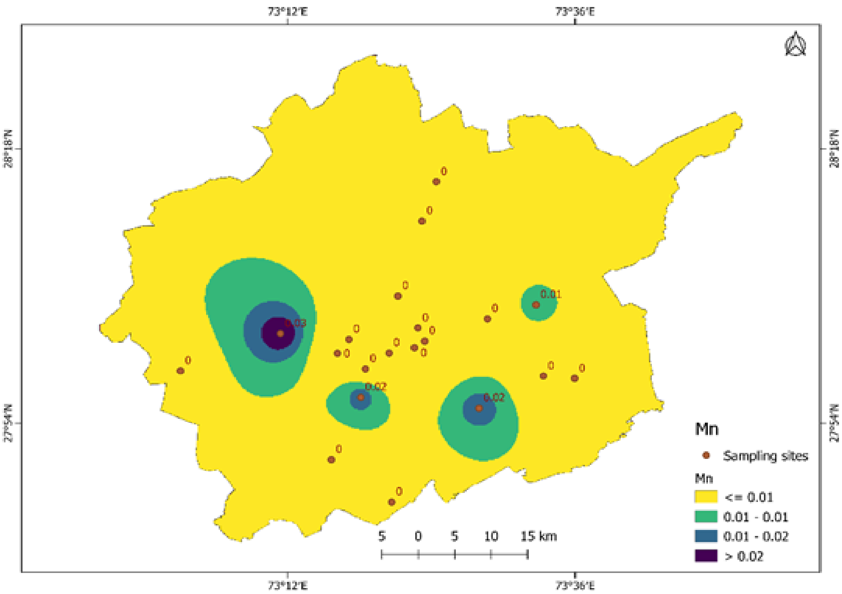

Figure 4.
Spatial distribution of manganese in groundwater across Bikaner City

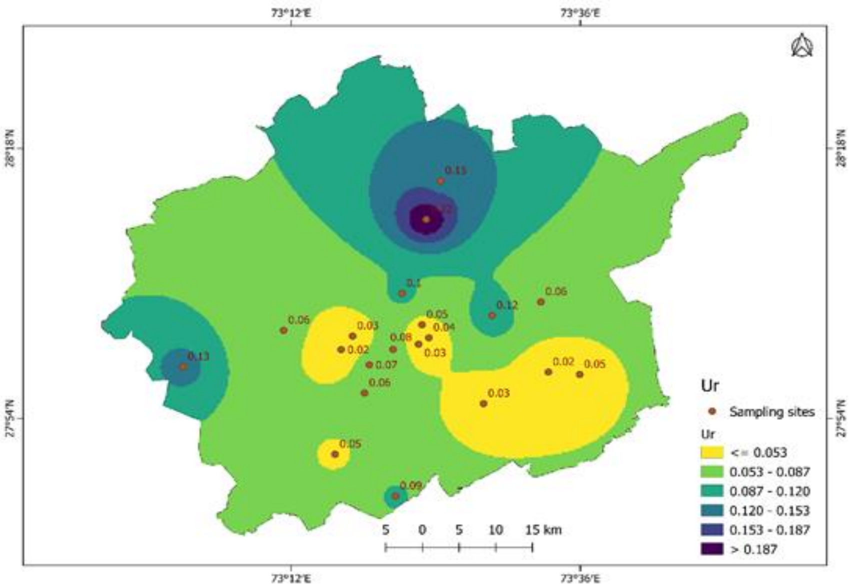

Figure 5.
Spatial distribution of uranium in groundwater across Bikaner City

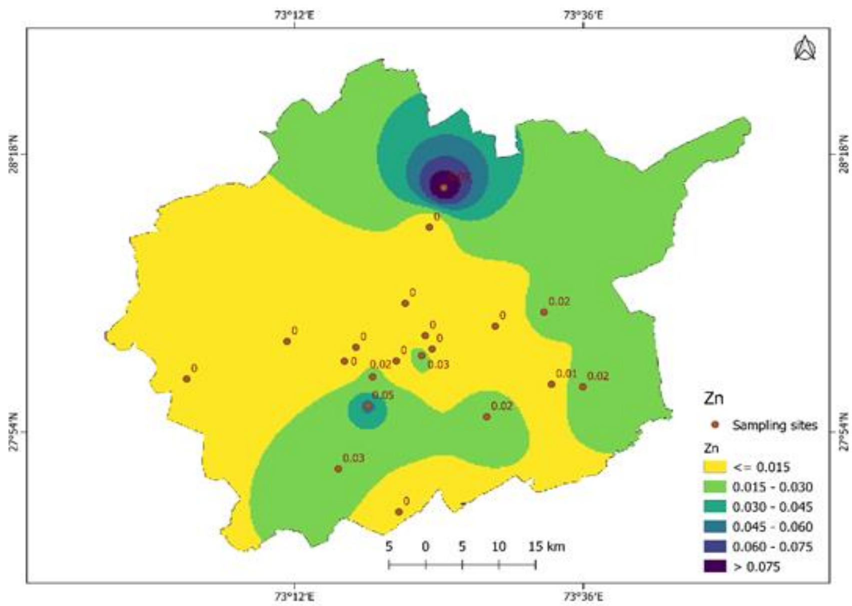

Figure 6.
Spatial distribution of zinc in groundwater across Bikaner City

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suggests that such activities have not impacted these locations. Additionally, while the overall groundwater quality appears to be within safe limits for most heavy metals and metalloids, detecting uranium in certain wells warrants further attention. These findings emphasize the importance of ongoing monitoring and research to safeguard water quality in the region.

Correlation analysis

The correlation analysis of groundwater quality parameters in Bikaner City reveals several significant relationships that shed light on the underlying water chemistry and potential sources of contamination (Table 2). The pH of the groundwater, which ranged from 7.5 to 8.4, exhibited a negative correlation with both Total Dissolved Solids (TDS) and Electrical Conductivity (EC) (r = -0.2634 and r = -0.26368, respectively). This suggests that as the groundwater becomes more alkaline, dissolved solids and EC levels tend to decrease. This inverse relationship aligns with the understanding that higher pH can influence groundwater's solubility and ionic strength. A near-perfect positive correlation between TDS and EC (r = 0.999977) indicates a strong relationship between these two parameters. This finding confirms that EC is a reliable measure of the concentration of dissolved solids in groundwater, as higher EC values correspond to increased levels of TDS. Similarly, Total Hardness (TH) shows a significant positive correlation with both TDS (r = 0.893203) and EC (r = 0.89426), indicating that increased hardness is associated with higher levels of dissolved salts and conductivity. This relationship is consistent with the fact that hardness-causing ions, such as calcium and magnesium, contribute to the overall mineral content in water. Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) are crucial parameters for assessing water hardness. Calcium exhibits a strong positive correlation with magnesium (r = 0.78149) and sulfate (SO_4^{2-}) (r = 0.94268). This high correlation with sulfate suggests that calcium may be sourced from the dissolution of sulfate-containing minerals, such as gypsum. The positive correlation between magnesium and calcium further supports the link between these hardness-causing ions, often derived from the weathering of minerals like dolomite and magnesite. Chloride (Cl^-) also demonstrates a strong positive correlation with both TDS = 0.928034) and EC (r = 0.928346), highlighting its significant role in groundwater salinity. The correlation with hardness (r = 0.922366) suggests that chloride concentrations increase with higher levels of total hardness, reflecting its contribution to the mineral load in groundwater. Sulphate (SO_4^{2-}) is positively correlated with calcium (r = 0.94268) and bicarbonate (HCO_3^-) (r = 0.020023), indicating that sulfate dissolution contributes to the calcium content in groundwater and may interact with bicarbonate ions. The presence of sulfate in groundwater is often linked to the dissolution of sulfate-bearing minerals, which can influence overall water chemistry. Nitrate (NO_3^-) shows a positive correlation with pH (r = 0.479744), suggesting that higher pH levels might be associated with increased nitrate concentrations. This relationship may be attributed to agricultural practices and fertilizer use, which can affect both pH and nitrate levels in groundwater. Fluoride (F^-) demonstrates a positive correlation with calcium (r = 0.79861) and magnesium (r = 0.57926), suggesting that the presence of these cations influences fluoride levels. Fluoride typically originates from the weathering of fluoride-bearing minerals, which can release calcium and magnesium into groundwater.

Sodium (Na^+) has a positive correlation with potassium (K^+) (r = 0.489619), indicating that both ions may have similar sources or be influenced by similar factors in groundwater. However, sodium negatively correlates with pH (r = -0.22534), reflecting its varying behaviour compared to potassium. Carbonate (CO_3^{2-}) shows a negative correlation with bicarbonate (r = -0.02339), suggesting that carbonate levels tend to decrease as bicarbonate levels increase. This dynamic reflects the equilibrium between carbonate and bicarbonate in groundwater systems, where changes in one can impact the concentration of the other. The correlation analysis revealed a strong positive correlation between EC and TDS (r = 0.99), indicating that TDS is a reliable measure of salinity. Additionally, a positive correlation between calcium and sulfate (r = 0.94) suggests that gypsum dissolution may influence calcium availability in the groundwater. These correlations provide a detailed understanding of the interactions between groundwater quality parameters in Bikaner City. The strong relationships between TDS, EC, and hardness highlight the importance of monitoring these indicators to assess overall water quality. The positive correlations between calcium, sulfate, and chloride underline the influence of geological factors on groundwater composition. Overall, the results indicate that while the groundwater in Bikaner City generally meets permissible limits for most parameters, ongoing monitoring is essential to manage variations in parameters such as

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Table 2. *Correlation matrix of groundwater parameters of the study area.*

	pH	TDS	EC	TH	Ca^{+2}	Mg^{+2}	Cl^-	SO_4^{-2}	NO_3^-	F^-	Na^+	K^+	CO_3^{-2}	HCO_3^-
pH	1													
TDS	-0.2634	1												
EC	-0.26368	0.999977	1											
TH	-0.35565	0.893203	0.89426	1										
Ca^{+2}	-0.31999	0.797168	0.797017	0.806992	1									
Mg^{+2}	-0.40243	0.754289	0.754432	0.776281	0.78149	1								
Cl^-	-0.29937	0.928034	0.928346	0.922366	0.65568	0.66416	1							
SO_4^{-2}	-0.21597	0.777984	0.777576	0.693776	0.94268	0.645076	0.603824	1						
NO_3^-	0.479744	-0.12626	-0.12512	-0.25236	-0.26013	-0.028	-0.20703	-0.19437	1					
F^-	-0.09292	0.765918	0.763735	0.587458	0.79861	0.57926	0.594919	0.881216	-0.14175	1				
Na^+	-0.22534	0.605105	0.605588	0.639065	0.495458	0.537462	0.581616	0.43278	-0.2641	0.348414	1			
K^+	-0.09706	0.139519	0.13712	0.104158	0.199298	0.288391	0.084679	0.212449	0.166527	0.184627	0.489619	1		
CO_3^{-2}	-0.10309	-0.32929	-0.32751	-0.33476	-0.47069	-0.27492	-0.28256	-0.51939	0.137686	-0.49116	-0.24675	-0.29137	1	
HCO_3^-	-0.13416	0.192793	0.194961	0.153389	0.025546	0.153472	0.106589	0.020023	0.042465	-0.06529	0.214908	-0.02339	0.468731	1

TDS and to ensure the sustainability of groundwater resources in this arid region.

Conclusions

The geogenic contamination analysis of groundwater in Bikaner City reveals that the water is predominantly alkaline. While specific parameters such as pH, chloride, potassium, carbonate, and bicarbonate fall within acceptable limits in 95% of the samples, other critical parameters like TDS, total hardness, calcium, magnesium, sulfate, fluoride, nitrate, and electrical conductivity (EC) exceed the maximum permissible limits. The elevated levels of these elements, along with heavy metals, sometimes surpass the WHO's recommended maximum concentration levels. The high concentration of uranium is particularly concerning, which indicates that the groundwater in these regions poses significant health risks and is unsuitable for drinking. The hazard quotient analysis of the twenty groundwater samples studied suggests that the values exceed the WHO's recommended safety threshold (unity). This implies a considerable health risk to the local population, who primarily rely on hand-dug wells and boreholes for their water supply. The findings underscore that while the groundwater may not be fit for drinking, it could be used for irrigation. Anthropogenic activities, such as sewage discharge, likely influence the contamination. However, further investigation is required to comprehensively understand the geogenic and anthropogenic processes impacting groundwater quality in Bikaner City, Rajasthan.

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