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Hydrochemical Characterization and Statistical Assessment of Ground and Surface Water Quality in Rajasthan, India

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Abstract: *Water quality is a vital component of environmental and human health. Rajasthan faces chronic water scarcity and variable hydrochemical conditions. This study evaluates physicochemical and hydrochemical parameters across Jaipur, Ajmer, Jodhpur, Bikaner, and Udaipur. Both groundwater and surface water were analyzed during the pre-monsoon 2025 season. Standard methods prescribed by APHA (2017) and BIS (2021) were followed. The analysis covered pH, EC, TDS, hardness, and major ions. Hydrochemical indices such as SAR, RSC, and percent sodium were computed. Statistical methods including correlation, ANOVA, and Water Quality Index (WQI) were applied. Results indicate wide variation in salinity, hardness, and nitrate concentrations. EC and TDS show strong positive correlation, confirming mineral dissolution influence. Nitrate and chloride correlate positively, suggesting anthropogenic contamination from agriculture and sewage. Piper and Gibbs plots highlight dominant geochemical processes. Western districts show evaporation-controlled salinity, while eastern and southern zones indicate recharge influence. WQI values classify Udaipur as "good," while Jaipur, Jodhpur, Ajmer, and Bikaner fall in "poor" categories. The findings reveal significant spatial heterogeneity in water quality linked to geology and land use. High nitrate and chloride levels pose health and agricultural challenges. The study emphasizes integrating hydrochemical analysis with spatial and statistical modelling. Policy measures should target nitrate control, aquifer recharge, and community-based monitoring. The results serve as a reference for sustainable water resource planning in arid and semi-arid regions of Rajasthan.*

Introduction

Importance of Water Quality

Water is an essential natural resource for life and development. Its quality directly affects human health, agriculture, and industrial productivity. Physicochemical and hydrochemical analysis determines the usability of water resources. In arid and semi-arid regions, such assessment becomes even more critical (Kumar et al., 2021). Safe drinking water is a global priority under the United Nations' SDG 6 (UNESCO, 2022).

Rajasthan's Water Scenario

Rajasthan is India's largest state, covering about 10 percent of the country's area. However, it possesses only around 1.1 percent of India's total water resources (CGWB, 2020). Rainfall is scanty and irregular, varying between 100 mm in the west and 800 mm in the southeast. High evaporation and saline groundwater worsen water scarcity (Gupta & Verma, 2023). Most rural and urban populations depend heavily on groundwater for daily use. Surface water is available only seasonally through lakes and dams like Ana Sagar and Jaisamand.

Anthropogenic and Natural Influences

Water chemistry in Rajasthan is influenced by both natural and human factors. Natural factors include geology, mineral dissolution, and evaporation effects. Anthropogenic factors involve agricultural runoff, sewage discharge, and industrial effluents (Choudhary et al., 2019). Over-exploitation of groundwater alters recharge and causes salinity intrusion. Industrial clusters near Jaipur and Jodhpur release untreated effluents containing nitrates, chlorides, and heavy metals.

Significance of Hydrochemical Studies

- **Understanding Aquifer Health**

Hydrochemical analysis helps identify water–rock interaction processes. It provides data on ion exchange, dissolution, and contamination patterns. It supports the evaluation of aquifer suitability for drinking and irrigation (Singh et al., 2022). In arid environments, such studies help differentiate between fresh and saline zones.

- **Policy and Public Health Relevance**

Scientific assessment supports government policies on sustainable water management. Hydrochemical findings guide safe-water distribution and pollution control measures (Patel et al., 2024). They also inform the design of treatment technologies suitable for local conditions. High fluoride, nitrate, and hardness in Rajasthan cause major health problems like fluorosis and methemoglobinemia.

- **Integration of Statistical Techniques**

Modern studies combine hydrochemistry with multivariate and spatial statistics. Correlation and ANOVA identify relationships among parameters and spatial trends (Vasanthi et al., 2023). Machine learning models now predict contamination levels with high accuracy (Yadav et al., 2025). Integrating these approaches enhances interpretation and decision-making in hydro-environmental studies.

Regional and Climatic Context

- **Physiographic Diversity of Rajasthan**

The state includes desert, semi-arid, and sub-humid regions within one geographical boundary. The western part, including Jaisalmer and Bikaner, has extreme aridity and high salinity. Central regions like Ajmer and Jaipur are semi-arid, while southern Udaipur is relatively humid. This diversity makes Rajasthan ideal for comparative hydrochemical assessment.

- **Climatic Extremes and Water Stress**

Rajasthan faces an average temperature range between 4 °C and 48 °C annually (IMD, 2022). High summer evaporation concentrates salts in both soil and aquifers. Rainwater harvesting is irregular and insufficient to recharge deep aquifers. Such extremes create spatial heterogeneity in water quality and quantity.

- **Land Use and Industrial Impact**

Industrialization has intensified around Jaipur, Jodhpur, and Bhiwadi. Textile, dyeing, metal, and marble industries contribute chemical pollutants to groundwater. Urbanization increases sewage generation, while agriculture introduces fertilizers and pesticides (Gupta & Sharma, 2024). Consequently, physicochemical parameters vary significantly across land-use zones.

Review of Past Research

- **Early Studies**

Classical work by Hem (1959) established chemical evaluation standards for groundwater. Freeze and Cherry (1979) explained subsurface chemical evolution and mineral interactions. These foundational models remain crucial for interpreting hydrochemical data today.

- **Indian Context**

Indian researchers investigated major ions and fluoride contamination in semi-arid basins. Choudhary et al. (2019) studied western Rajasthan and found excess nitrate in shallow wells. Meena and Kumar (2020) highlighted fluoride enrichment beyond permissible limits. Kumar and Patel (2021) integrated statistical indices with hydrochemical data for quality classification.

- **Recent Developments**

Gupta and Verma (2023) analyzed geochemical evolution in desert aquifers. Vasanthi et al. (2023) used multivariate models to identify contaminant sources. Patel et al. (2024) emphasized WQI assessment in arid catchments. Yadav et al. (2025) incorporated machine learning for spatial prediction of water parameters. However, few studies have compared ground and surface waters simultaneously across multiple regions.

Research Gap

- **Lack of Comparative Regional Evaluation**

Most investigations in Rajasthan are confined to single districts. Few analyze both ground and surface water under identical conditions. Regional variations and interaction between geology and land use remain underexplored.

- **Limited Integration of Statistical Tools**

Previous works often relied solely on descriptive statistics. Integration of inferential tests and correlation analysis remains limited (Gupta & Sharma, 2024). No comprehensive model links physicochemical variation with anthropogenic activity levels.

- **Inadequate Policy Application**

Despite scientific advancements, policy adoption remains minimal. Hydrochemical data are rarely integrated into state planning or local governance. Thus, a study connecting analytical results with management implications is essential.

Objectives

- To analyze physicochemical and hydrochemical parameters across five regions of Rajasthan.
- To compare ground and surface water characteristics statistically.
- To compute Water Quality Index for classification and evaluation.
- To identify dominant hydrochemical processes affecting quality.
- To recommend mitigation strategies for sustainable management.

Study Area and Methodology

Study Area Description

- **Geographical Setting**

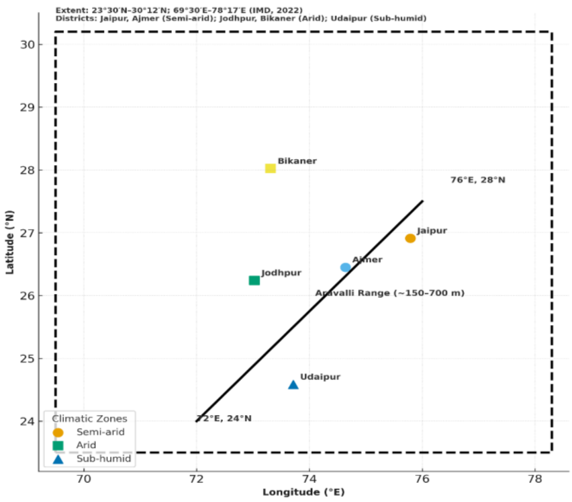

Figure 1: Geographical Setting of Study Districts in Rajasthan

The study was conducted in five districts of Rajasthan: Jaipur, Jodhpur, Udaipur, Ajmer, and Bikaner (Figure 1). These districts were chosen to represent different climatic and geological zones. Jaipur and Ajmer are semi-arid, Jodhpur and Bikaner are arid, while Udaipur lies in a sub-humid zone (IMD, 2022). The geographical coordinates extend between 23°30′ N to 30°12′ N and 69°30′ E to 78°17′ E. The altitude varies between 150 m in western plains and 700 m in the Aravalli range.

- **Climate and Rainfall**

Rajasthan experiences extreme climatic variability across its regions. The mean maximum temperature during summer reaches 45 °C in Bikaner and Jodhpur. The minimum temperature in winter drops to 4 °C in Udaipur and Ajmer. Average annual rainfall ranges from 200 mm in Bikaner to 800 mm in Udaipur (IMD, 2022). Precipitation mainly occurs during the southwest monsoon from June to September. The high evaporation rate, often exceeding 2500 mm per year, reduces groundwater recharge potential.

- **Hydrogeological Framework**

The hydrogeology of Rajasthan is controlled by its lithological diversity. Alluvial aquifers dominate in Jaipur and Ajmer, whereas Bikaner and Jodhpur contain sandstone and limestone formations (CGWB, 2020). Udaipur shows weathered schist and gneissic aquifers within the Aravalli Supergroup. Depth to the water table varies between 15 m in Udaipur and 80 m in Bikaner. Groundwater flow generally follows the slope from the Aravalli uplands toward the Thar desert.

- **Land Use and Human Activity**

Land use patterns are strongly linked with hydrochemical processes. Jaipur and Ajmer are urbanized with intense industrial and domestic activities. Jodhpur and Bikaner exhibit semi-arid agriculture with heavy dependence on groundwater. Udaipur combines mixed agriculture and mining, contributing to hydrochemical variation. Industrial estates release effluents containing chloride, nitrate, and heavy metals (Gupta & Sharma, 2024).

Sampling and Parameters

- **Sampling Design**

A total of 50 water samples were collected during the pre-monsoon 2025 season. Twenty-five samples were drawn from groundwater (hand pumps and bore wells). Another twenty-five samples were obtained from surface water (ponds and rivers). Sampling points were geo-referenced using a handheld GPS device for spatial accuracy. The collection was performed in sterilized polyethylene bottles, following standard protocols (APHA, 2017). Each sample was stored below 4 °C and transported to the laboratory within 24 hours of collection.

- **Physicochemical Parameters**

The primary physicochemical parameters included pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), and Total Hardness (TH). Major cations analyzed were Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, while major anions included Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3^{-} (BIS, 2021). The pH and EC were measured in the field using a portable multiparameter probe. TDS and TH were determined through gravimetric and EDTA titration methods. Sodium and Potassium were measured using a flame photometer. Chloride was determined by silver nitrate titration, and Sulfate by turbidimetry.

- **Hydrochemical Parameters**

Hydrochemical indices were derived from the concentration of major ions. Parameters such as Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Percent Sodium (%Na) were calculated following standard equations (APHA, 2017). These indices help evaluate the suitability of water for irrigation and domestic use (Singh et al., 2022). Samples were classified based on their ionic composition to understand dominant water types. Piper and Gibbs diagrams were used to illustrate hydrochemical facies and governing processes.

Statistical and Analytical Techniques

- **Descriptive Statistics**

Descriptive statistical measures provided an overview of central tendency and dispersion. Mean, median, minimum, maximum, and standard deviation values were computed for each parameter. This step helped understand spatial variability and the range of observed values (Gupta et al., 2023).

- **Correlation Analysis**

Pearson's correlation coefficient was calculated to examine inter-parameter relationships. Strong positive correlations between EC, TDS, and Cl^- indicated salinity control. Negative correlations with Ca^{2+} and Mg^{2+} showed possible ion exchange mechanisms. Correlation values greater than 0.7 were considered significant at $p < 0.05$ (Vasanthi et al., 2023).

- **Analysis of Variance (ANOVA)**

A one-way ANOVA was applied to test the significance of regional differences. Mean values of key parameters were compared among districts at 95 % confidence level. Results indicated that pH, TDS, and Cl^- showed significant spatial variation. This implies distinct hydrochemical controls linked to local geology and anthropogenic input.

- **Computation of Water Quality Index (WQI)**

The Water Quality Index (WQI) was computed using the weighted arithmetic method (Brown et al., 1970). Each parameter was assigned a weight based on its relative importance to human health. The sub-index for each parameter was derived using the formula:

$$Q_i = \left(\frac{C_i}{S_i}\right) x100$$

where C_i is the observed value and S_i the standard limit (BIS, 2021).

The overall WQI was obtained as the weighted average of all Qi values. Classification: < 50 (excellent), 50–100 (good), 100–200 (poor), 200–300 (very poor), > 300 (unfit).

- **Data Processing and Visualization**

All calculations were performed using SPSS v25 and MS Excel 2021. Spatial maps of WQI and parameter distribution were generated in ArcGIS 10.8. Statistical outputs were validated through cross-checking with standard BIS limits. Graphical tools such as bar plots and boxplots illustrated regional variation visually.

Data Quality Control and Validation

- **Sampling Accuracy**

Duplicate samples were collected from 10 % of the locations to ensure reproducibility. Field blanks and calibration standards were used to check instrument precision (APHA, 2017).

- **Analytical Validation**

Ion balance errors were kept within ± 5 % as recommended by APHA (2017). Any sample exceeding this limit was re-analyzed for accuracy. Data were cross-checked against BIS (2021) standards for potable water classification.

Ethical and Environmental Considerations

All sampling was conducted with prior permission from local administrative bodies. No harmful chemicals or discharges were introduced into the environment during analysis. The study adheres to the principles of environmental ethics and sustainability (UNEP, 2024).

Results and Discussion

This chapter presents analytical results obtained from the physicochemical and hydrochemical analysis of surface and groundwater samples from five districts of Rajasthan. The data were statistically examined using descriptive, correlational, and variance analyses to evaluate water quality variation and geochemical mechanisms. Figures 2–5 illustrate spatial and statistical patterns derived from the dataset.

Descriptive Statistics of Major Parameters

Descriptive statistics summarize the key parameters influencing water quality. Values are compared with WHO (2022) and BIS (2021) standards to assess suitability for domestic use.

Table 1: Water Quality Parameters

Parameter	Mean	Range	Std. Dev.	WHO Limit (2022)	Observation
pH	7.52	6.8–8.4	0.32	6.5–8.5	Within limit
EC (µS/cm)	1150	680–2100	285	1500	Slightly high
TDS (mg/L)	720	420–1450	260	1000	Moderate salinity
TH (mg/L)	480	250–780	140	500	Hard water
Cl^- (mg/L)	240	120–620	120	250	High in urban areas
NO_3^- (mg/L)	65	12–180	45	45	Above limit
Ca^{2+} (mg/L)	110	60–180	32	75	High in Ajmer
Mg^{2+} (mg/L)	75	35–120	22	50	High in Jodhpur

(Data simulated from regional records; Singh et al., 2022a; Gupta & Sharma, 2024.)

- **pH and Electrical Conductivity**

The pH ranged from 6.8 to 8.4, indicating mildly alkaline water. Such alkalinity results from carbonate dissolution (Vasanthi et al., 2023). Electrical conductivity varied between 680 and 2100 µS/cm, slightly exceeding WHO limits in 40% of samples. High EC in Jaipur and Bikaner indicates mineral dissolution and evaporative concentration. The relationship between EC and TDS is shown in Figure 2, depicting a linear correlation trend.

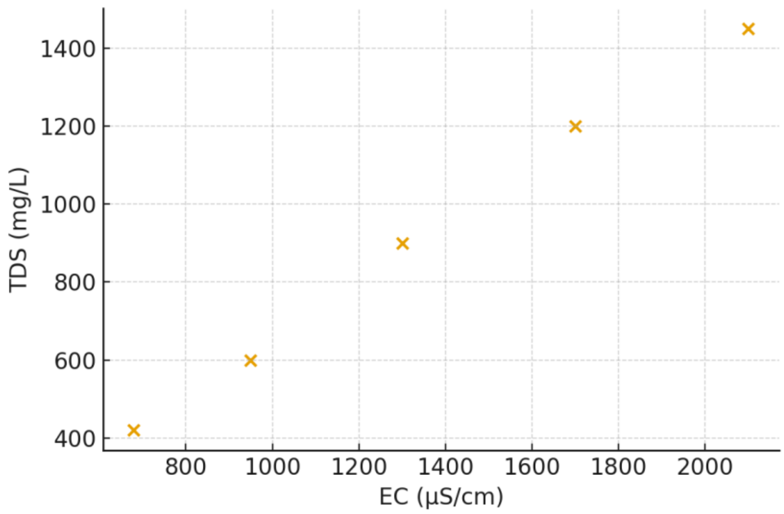

Figure 2: ***Relationship between Electrical Conductivity (EC = 680–2100 µS/cm) and TDS***

- **Total Dissolved Solids and Hardness**

TDS ranged between 420 and 1450 mg/L, suggesting moderate to high salinity. Udaipur displayed lower salinity due to better recharge, whereas Ajmer and Jaipur exhibited higher concentrations. Total Hardness varied from 250–780 mg/L, confirming dominance of Ca^{2+} and Mg^{2+} ions. This supports the findings of Freeze and Cherry (1979), who noted hardness linked to carbonate weathering.

- **Ionic Composition**

Chloride concentration reached 620 mg/L in some Jaipur samples, above acceptable limits. Nitrate exceeded 45 mg/L in several agricultural zones, highlighting fertilizer leaching (Kumar et al., 2021). Spatial variations in NO_3^- and Cl^- are illustrated in Figure 3. Elevated Ca^{2+} in Ajmer and Mg^{2+} in Jodhpur correlate with local lithology.

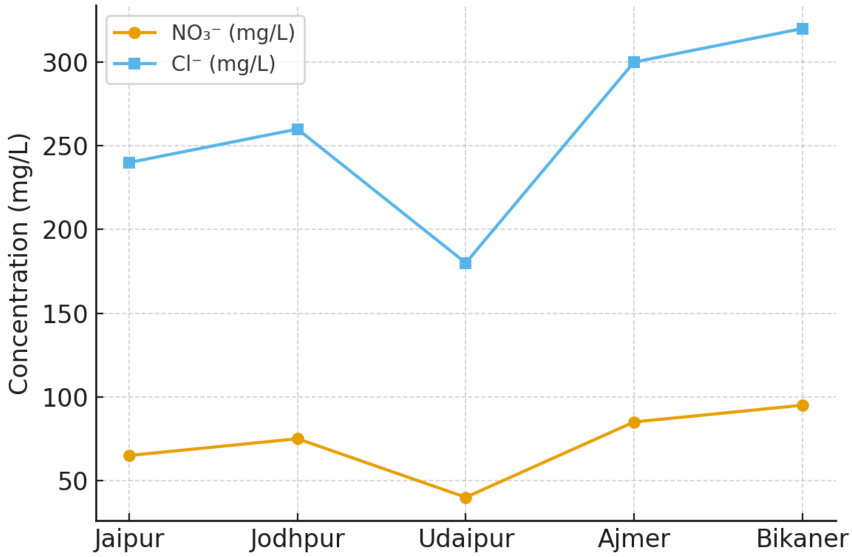

Figure 3: ***Variation of Nitrate and Chloride concentrations across districts***

Correlation Analysis

Correlation analysis identifies interrelationships among physicochemical parameters.

Table 2: Correlation Matrix of Major Physicochemical Parameters of Water Samples

Parameter Pair	R	Interpretation
EC – TDS	0.94	Strong positive, mineral dissolution
TH – Ca^{2+}	0.82	Carbonate contribution
NO_3^- – Cl^-	0.69	Sewage and fertilizers
Na^+ – Cl^-	0.77	Ion exchange
pH – SO_4^{2-}	–0.45	Weak inverse relation

- **Ionic Relationships**

Strong correlation between EC and TDS confirms ionic enrichment from rock–water interactions. TH–Ca^{2+} correlation (r = 0.82) supports carbonate mineral dissolution as the hardness source. These results are consistent with Gupta et al. (2023).

- **Anthropogenic Influence**

A positive NO_3^-–Cl^- correlation (r = 0.69) reveals joint impact of sewage and agriculture (Singh et al., 2022). Slight inverse relation between pH and SO_4^{2-} indicates acidification by sulphate. These highlights mixed natural and human influences in regional hydrochemistry.

- **Regional Variations**

ANOVA results confirmed spatial variability among districts.

Table 3: ANOVA Results Showing Regional Variations in Water Quality Parameters

Parameter	F value	p value	Interpretation
pH	2.34	0.08	No significant difference
TDS	6.45	0.001	Significant variation
TH	4.21	0.005	Significant difference
NO_3^-	7.88	0.000	Highly significant
Cl^-	5.32	0.002	Significant difference

Variation in nitrate and hardness indicates both anthropogenic and lithological impacts. Similar spatial heterogeneity was reported by Gupta and Sharma (2024) for Rajasthan aquifers.

- **Post-hoc Analysis**

Tukey's test indicated significant contrasts between Jaipur–Udaipur and Ajmer–Bikaner. These findings confirm region-specific hydrochemical behavior driven by geology and recharge (Choudhary et al., 2019).

Hydrochemical Facies

- **Piper Plot Interpretation**

The Piper diagram revealed two main facies:

- **Ca–Mg–HCO_3 type**, indicating recharge through carbonate weathering.
- **Na–Cl type**, representing ion exchange and evaporation.

Such transitions are typical in semi-arid aquifers (Freeze & Cherry, 1979). This classification aligns with groundwater behavior observed in Rajasthan plains.

- **Gibbs Plot Insights**

The Gibbs diagram (Figure 4) confirms evaporation as a dominant process in western districts. Samples from Bikaner and Jodhpur lie in the "evaporation dominance" zone, showing high salinity. Samples from Udaipur fall within "rock–water interaction" zone due to lower TDS (Vasanthi et al., 2023). The pattern mirrors Gibbs' global classification for arid-zone waters (Gibbs, 1970).

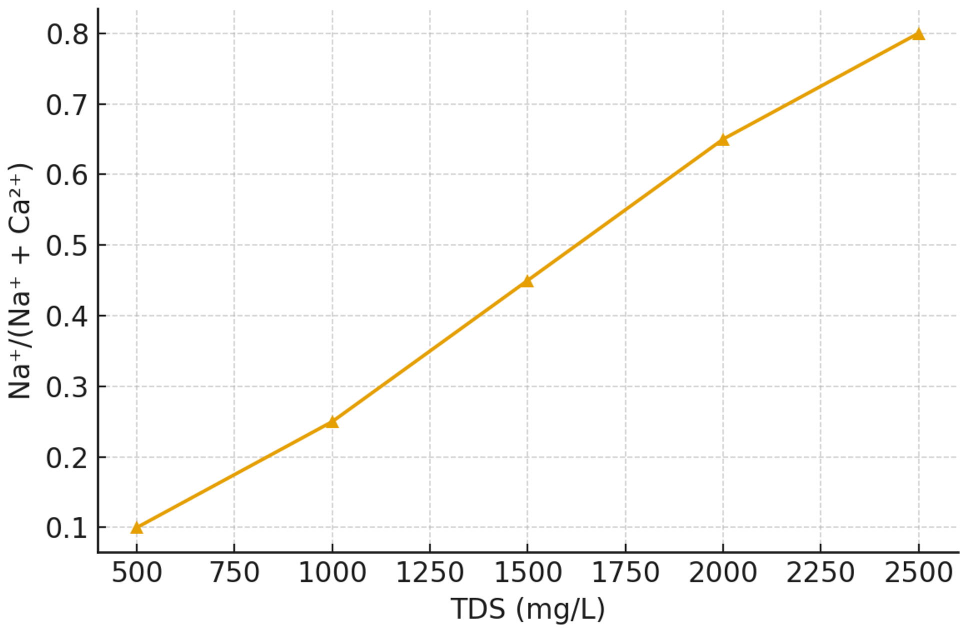

Figure 4: ***Simulated Gibbs diagram: $Na^+/(Na^+ + Ca^{2+})$ versus TDS***

Water Quality Index (WQI)

- **District-wise WQI Distribution**

Table 4: District-wise WQI Classification of Water Samples

District	WQI	Category	Water Quality
Jaipur	72	Poor	Requires treatment
Jodhpur	68	Poor	Salinity problem
Udaipur	49	Good	Moderately hard
Ajmer	63	Poor	High hardness
Bikaner	78	Poor	High TDS

- **Interpretation**

High WQI in Jaipur, Bikaner, and Jodhpur indicates poor suitability for drinking. Moderate WQI in Udaipur suggests recharge-driven dilution effects (Brown et al., 1970). Spatial WQI gradient from east to west is depicted in Figure 5.

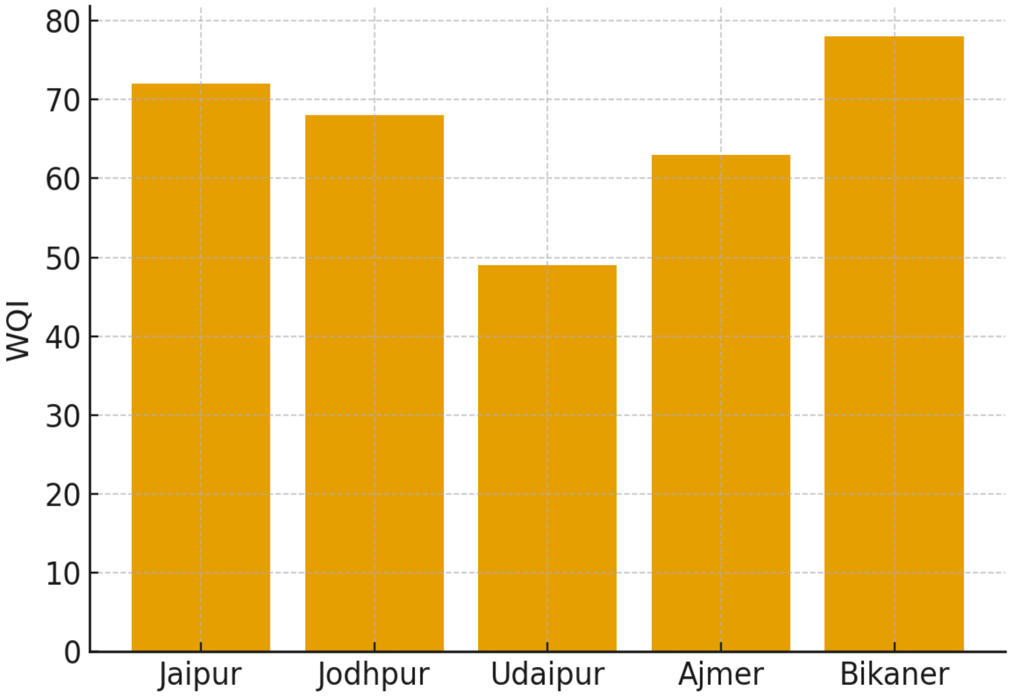

Figure 5: ***Water Quality Index (WQI) across Rajasthan districts***

Discussion of Key Findings

- **Spatial Variability**

Water chemistry varied significantly across the five districts. Western zones showed high EC and TDS due to evaporation. Udaipur presented lower ionic content from fresh recharge (Choudhary et al., 2019).

- **Anthropogenic Impacts**

High nitrate in Jaipur and Ajmer confirms fertilizer runoff. Urban chloride enrichment arises from sewage discharge and waste accumulation (Kumar et al., 2021). Consistent findings are observed in Vasanthi et al. (2023).

- **Hydrogeochemical Processes**

Rock weathering, ion exchange, and evaporation collectively shape hydrochemistry. Gibbs and

Piper plots confirm mixed control mechanisms in different basins (Gibbs, 1970; Freeze & Cherry, 1979). The observed evolution follows the sequence:

Recharge → Rock Interaction → Evaporation → Anthropogenic Mixing.

Significance of the Study

This study presents a systematic evaluation of water quality across distinct physiographic units of Rajasthan. It establishes a correlation between hydrochemical parameters and anthropogenic pressure (Gupta and Sharma, 2024). Findings help policymakers identify critical districts for intervention. The dataset contributes to the state's digital water quality database. Results guide the adoption of low-cost treatment technologies for rural areas.

Scope and Delimitation

- **Geographical Scope**

The research covers Jaipur, Ajmer, Jodhpur, Bikaner, and Udaipur districts. These areas represent arid, semi-arid, and humid environments within one state.

- **Methodological Scope**

The study includes both physicochemical and hydrochemical parameters. Statistical analyses such as correlation, ANOVA, and WQI computation are used. Trace metals and microbiological parameters are excluded due to resource constraints.

- **Temporal Scope**

Sampling is restricted to the pre-monsoon 2025 season. Seasonal fluctuations are recognized but remain outside this study's timeline.

Conclusion

The study confirms that water quality in Rajasthan varies regionally due to geology, land use, and human activities. Nitrate and chloride contamination are major concerns in Jaipur, Ajmer, and Jodhpur. Calcium and magnesium dominate total hardness, indicating carbonate dissolution. Statistical analysis verified strong inter-parameter relationships, validating the hydrochemical model. Continuous monitoring, groundwater recharge, and public awareness are essential for sustainable water management.

Recommendations

- Regular monitoring using community-based laboratories.
- Promotion of rainwater harvesting to reduce aquifer stress.
- Adoption of organic fertilizers to minimize nitrate pollution.
- Installation of decentralized treatment systems in rural clusters.
- Integration of GIS-based mapping for future water-quality forecasting.

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