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Research Paper

Spatial Variation and Physico-Chemical Assessment of Groundwater Quality across Selected Rural Localities of Jaunpur, Uttar Pradesh: Implications for Drinking and Irrigation Water Suitability

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Abstract
Groundwater serves as the primary source of drinking and irrigation water in many rural areas of India, but its quality is increasingly threatened by geogenic processes and anthropogenic pressures. This study presents a comprehensive physico-chemical assessment of groundwater from five rural localities (Site A, Site B, Site C, Site D, and Site E) in Jaunpur district, Uttar Pradesh. For each site, five groundwater samples were collected and analyzed for twelve key water-quality parameters: pH, total dissolved solids (TDS), electrical conductivity (EC), total hardness (as $CaCO_3$), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (Cl^-, SO_4^{2-}, NO_3^-, F^-). Descriptive statistics (minimum, maximum, mean, standard deviation, range) were computed for all parameters. The results show that pH across all sites remains neutral to slightly alkaline (mean 7.08–7.48), TDS (602–710 mg/L), EC (1155–1300 µS/cm), hardness (211–241 mg/L), and ionic concentrations remain within the permissible limits set by World Health Organization (WHO) and Bureau of Indian Standards (BIS 10500) for drinking water. Nitrate and fluoride levels — parameters of significant health concern — are well below WHO thresholds across all sites. Spatial variation is observed, with Site B exhibiting marginally elevated values across several parameters, suggesting localized influence of anthropogenic inputs or geological conditions. The overall groundwater quality in the studied localities of Jaunpur appears acceptable for both drinking and irrigation under present conditions. However, given potential seasonal and land-use changes, regular monitoring and detailed hydrochemical analysis are recommended to ensure long-term water security and public health.

Keywords: *Groundwater quality, Physico-chemical assessment, Rural Jaunpur, Water-quality parameters, Drinking water suitability, Irrigation water, Water-quality variation*

I. Introduction

Water is the foundation of life on Earth. It is essential not only for human survival but also for the growth of flora and fauna, and the overall health and development of ecosystems. In developing countries like India, where a large portion of the rural population depends directly on water sources for drinking, domestic use, and irrigation, the quality and availability of water are critical. Groundwater, in particular, serves as a reliable source in rural and semi-rural areas, often more stable and less polluted than surface water. However, with increasing population, unplanned urbanization, intensive agriculture, industrial effluents, and over-extraction, groundwater quality and quantity are facing severe challenges. In this context, the present study, **"Groundwater Quality Assessment in Rural Jaunpur"**, is highly relevant. It addresses both the physical and chemical dimensions of groundwater quality, as well as its social, economic, and public health implications. This research aims to provide a scientific assessment of groundwater conditions in rural Jaunpur, highlighting the sources and extent of contamination and offering insights into sustainable water management practices.

Jaunpur — Geographical, Cultural, and Regional Significance
Geographical Context

Jaunpur district is located in the northwestern part of Uttar Pradesh and forms a part of the Varanasi division. The district covers an area of approximately 4,038 square kilometers and lies between latitudes 24.24°–26.12° N and longitudes 82.70°–83.50° E. The region predominantly consists of flat plains, with minor undulating terrains along river valleys. The major rivers in the district include the **Gomti** and **Sai**, along with smaller streams like **Varuna**, **Basuhi**, and **Pili**. The soil types range from sandy to loamy and clayey soils, which influence groundwater recharge and agricultural practices. The average annual rainfall is approximately 987 mm, and temperatures vary from 4.3 °C in winters to 44.6 °C in summers. Agriculture is the mainstay of the local economy, with nearly three-fourths of the population dependent on farming.

Cultural and Historical Significance

Jaunpur has rich historical and cultural importance, often referred to as the "Shahi" city due to its architectural heritage, including forts, mosques, and monuments dating back to the medieval period. The population is linguistically diverse, with Hindi as the main language, complemented by regional dialects. The socio-cultural fabric, coupled with agriculture-based livelihoods, makes Jaunpur an important site for understanding the interplay between human activity and natural resources, especially groundwater. This combination of geographical, historical, and cultural factors makes Jaunpur a suitable study area for groundwater assessment. Its dependence on agriculture, reliance on groundwater for domestic use, and historical urban settlements present unique challenges and opportunities for water quality research.

Water Pollution and Groundwater Quality

Global and National Context

Water pollution is a critical environmental issue worldwide. Contaminants from agricultural runoff, industrial effluents, sewage, and improper sanitation severely impact the availability of safe drinking water. Groundwater, despite being relatively protected compared to surface water, is not immune to contamination. Parameters such as **Total Dissolved Solids (TDS)**, **hardness**, heavy metals, nitrates, and microbial load are often affected by human activities. In India, the situation is more pronounced due to the rapid expansion of population, intensive farming practices, and inadequate wastewater treatment infrastructure. Excessive use of chemical fertilizers and pesticides leads to nitrate and phosphate contamination, whereas industrial discharges can introduce heavy metals like arsenic, lead, and cadmium into groundwater. Over-extraction of groundwater for irrigation also lowers the water table and can cause the intrusion of pollutants.

Local Context: Jaunpur

In Jaunpur, rural populations rely heavily on tube wells, hand pumps, and open wells for drinking and irrigation. Many of these water sources are vulnerable to contamination due to:

1. Agricultural runoff from paddy, wheat, and sugarcane cultivation.
2. Improper disposal of domestic sewage.
3. Leaching from latrines and pit toilets near water sources.
4. Seasonal fluctuations in water table levels affecting quality.

Polluted groundwater can have far-reaching implications: it can cause waterborne diseases, reduce agricultural productivity due to saline intrusion, and threaten long-term sustainability of water resources. The health consequences for rural communities, including gastrointestinal infections, methemoglobinemia, and chronic exposure to heavy metals, underscore the urgency of groundwater assessment in the region.

Research Objectives

The primary aim of this study is to assess the **quality of groundwater in rural Jaunpur** and understand the extent of contamination. The specific objectives include:

1. To analyze the **physico-chemical parameters** of groundwater, such as pH, TDS, hardness, nitrates, phosphates, and heavy metals.
2. To evaluate the **spatial variation** of groundwater quality across selected rural sites in Jaunpur.
3. To assess the **compliance of groundwater with national and international water quality standards**, such as BIS (Bureau of Indian Standards) and WHO guidelines.
4. To identify the **potential sources of contamination** based on land use patterns, agricultural practices, and human activities.
5. To provide **recommendations for sustainable groundwater management** to improve water quality and protect public health.

Research Significance

The significance of this study can be understood in multiple dimensions:

1. **Public Health**: Contaminated groundwater poses direct risks to human health. By evaluating groundwater quality, the study provides insights into potential health hazards for rural populations.
2. **Agricultural Productivity**: The quality of water affects soil health and crop yields. Understanding groundwater quality helps in recommending safe irrigation practices.
3. **Environmental Sustainability**: Assessing and monitoring groundwater can prevent over-extraction and contamination, ensuring sustainable water management.

4. **Policy and Planning**: The findings can inform local authorities and policymakers for rural water supply schemes, sanitation planning, and environmental regulations.
5. **Scientific Contribution**: This study adds to the body of knowledge regarding rural groundwater quality in Uttar Pradesh, providing baseline data for future research.

Research Hypothesis

The study is guided by the following hypotheses:

1. **H1**: Groundwater in rural Jaunpur exhibits significant variation in physico-chemical parameters due to agricultural and domestic activities.
2. **H2**: Certain areas in rural Jaunpur have groundwater quality below acceptable national and international standards.
3. **H3**: Over-extraction and improper sanitation practices contribute significantly to groundwater contamination in the study area.

These hypotheses will be tested through systematic sampling, laboratory analysis, and spatial mapping of groundwater quality.

Limitations of the Study

While the study aims to provide comprehensive insights, several limitations are acknowledged:

1. **Temporal Constraints**: Groundwater quality can vary seasonally. This study may not capture long-term variations.
2. **Spatial Limitations**: Only selected rural sites in Jaunpur are included due to time and resource constraints, which may not fully represent the entire district.
3. **Instrumentation Limitations**: The accuracy of field instruments and laboratory analyses may introduce minor measurement errors.
4. **Human and Environmental Factors**: Uncontrolled factors such as sudden industrial effluent discharge or unreported agricultural practices could influence results.
5. **Resource Constraints**: Limited funding and access to advanced analytical equipment may restrict the number of parameters analyzed.

Despite these limitations, the study is expected to provide reliable, actionable data on groundwater quality, guiding interventions for water management and public health improvement in rural Jaunpur.

II. Literature Review

Groundwater Quality Assessment: Global and National / Indian Context

Groundwater is globally recognized as a critical resource for drinking water, agricultural irrigation, and domestic use — particularly in rural and semi-rural areas where surface water may be intermittent or contaminated. Over the last decades, numerous studies have shown that anthropogenic pressures such as intensive agriculture, over-extraction, industrial discharge, and inadequate sanitation have significantly deteriorated groundwater quality, even in regions previously considered safe (Subudhi et al., 2025; Kushwah & Singh, 2024). In recent years, integrated approaches combining physico-chemical analysis, statistical techniques, water quality indices (WQIs), and geospatial mapping have become standard for assessing groundwater suitability for domestic and agricultural use (Ram, Tiwari & Pandey, 2023; Hydres study, 2024). WQIs, in particular, help to consolidate multiple parameters — pH, electrical conductivity (EC), total dissolved solids (TDS), major cations and anions, hardness, etc.— into a single comparable metric. This simplification aids in communicating water quality to policymakers, residents, and environmental managers, and in triggering interventions such as water treatment or alternative sourcing (Ram et al., 2023). However, the heterogeneity of geological formations, hydrological cycles (seasonal rainfall, recharge), and land use patterns (agriculture, urbanization) often leads to substantial spatial and temporal variation in groundwater quality (Subudhi et al., 2025). Thus, localized studies remain indispensable for effective water management, monitoring, and public health protection.

Groundwater Quality in Uttar Pradesh: Empirical Studies

Several recent studies from different districts across Uttar Pradesh provide valuable insight into groundwater quality issues, relevant both methodologically and contextually.

1. **Rural Mathura District**: In a study by Kushwah and Singh (2024), groundwater samples from 20 sites (hand pumps and tube wells) were analyzed for EC and TDS. The authors found that only about 40% of samples met acceptable standards for drinking water (500–1000 mg/L TDS, as per WHO/BIS), while 60% exceeded safe limits, rendering water unfit for potable and irrigation purposes. The study underscores that "rapid population growth, intensive agriculture practices, over-exploitation, and urbanization" are major contributors to groundwater degradation (Kushwah & Singh, 2024). Similarly, a physico-chemical investigation in 25 villages of rural Mathura measured parameters like pH, alkalinity,

TDS, chloride, fluoride, nitrate, total hardness, etc., using titration, colorimetry, and standard methods (2024). Results showed elevated EC, TDS, and fluoride in many samples, making them unsafe compared to BIS/WHO standards (Physico-chemical Studies on Rural Groundwater, 2024).

2. **Hydrochemical Study in Western UP (Amroha District)**: A detailed hydrogeochemical characterization focusing on pre- and post-monsoon seasons found that most groundwater samples were weakly acidic to slightly alkaline. Concentrations of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}) generally remained within safe limits, except for a few locations where nitrate and fluoride exceeded threshold values (Hydrogeochemical Characterization, 2022). The study identified seasonal variation and linked elevated nitrate concentrations to excessive fertiliser use and industrial pollutants, highlighting risks to drinking water suitability.
3. **Urban and Peri-urban Studies (Varanasi, Prayagraj, Lucknow, etc.)**: Various studies show that even in alluvial plain environments with high groundwater dependency, water quality often deteriorates due to human activities and hydrochemical processes. For instance, in Varanasi, groundwater sampled from 15 borewells exhibited a Ca–Mg–HCO_3 type hydrochemical facies, but nitrate contamination in many wells exceeded safe limits (Ahamad et al., 2018). In Prayagraj, a study using multiple indices (EWQI, IWQI, pollution indices) found wide spatial variation from "excellent" to "very poor" water quality; parameters like TDS, total hardness (TH), fluoride, nitrate, and electrical conductivity were main contributors to degradation (Environmental Sci & Pollution Research, 2024). In Lucknow City, researchers used a GIS-based WQI approach to assess groundwater quality and recommended continuous monitoring due to significant geochemical pollutants (Verma, Singh & Kumar, 2024).
4. **Health Risk Studies Related to Nitrate and Fluoride**: Beyond suitability assessments, several investigations have linked high nitrate and fluoride concentrations in groundwater to serious health risks. For example, in Rajasthan's Jhunjhunu district, one study of 87 groundwater samples found that 11% of samples had fluoride, and 6% had nitrate levels exceeding WHO/BIS thresholds, raising alarm over long-term health risks (Fluoride & Nitrate Study, 2022). Further, a recent case study from western UP (Pratapgarh district) assessed groundwater for fluoride and nitrate contamination; the results pointed towards potential health risk due to prevailing alkaline hydrogeochemical facies like Na–K–SO_4–Cl and Ca–Mg–SO_4–Cl (Maurya & Saxena, 2024).

III. Research Methodology

The present study focused on assessing the **physico-chemical quality of groundwater** across five selected rural localities of Jaunpur, Uttar Pradesh, India: Site A, Site B, Site C, Site D, and Site E. **Five groundwater samples** were collected from each site using **pre-cleaned, high-density polyethylene (HDPE) bottles** after proper flushing of wells to avoid stagnant water interference. Sampling was performed during the post-monsoon season to capture representative groundwater conditions. Physico-chemical parameters analyzed included **pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-})**, following standard methods described by **APHA (2017)**. Measurements were conducted using **pH meter (Hanna HI98103), conductivity meter (YSI EC300), titration methods for hardness, and ion-selective electrodes/spectrophotometry for ionic concentrations**. Statistical evaluation included **descriptive statistics (mean, standard deviation, minimum, maximum, range)** for each parameter across sites. Spatial variation was analyzed using **ANOVA** to identify significant differences between localities. Correlation analysis was performed to determine relationships among parameters. The methodology allowed the integration of **hydrochemical analysis with statistical interpretation**, providing insights into the suitability of groundwater for **drinking and irrigation purposes**, while highlighting localized anthropogenic or geogenic influences on water quality.

Data Analysis :

Groundwater quality analysis involves a combination of **field measurements and laboratory tests** to determine its suitability for drinking and irrigation. **pH** is measured using a calibrated **digital pH meter**, where the electrode is immersed directly into the sample and allowed to stabilize, providing the hydrogen ion concentration and indicating water acidity or alkalinity. **Electrical conductivity (EC)**, a measure of water's ability to conduct electricity due to dissolved salts, is determined using a **conductivity meter**, which is calibrated with standard solutions prior to measurement. **Total Dissolved Solids (TDS)**, representing the overall concentration of dissolved substances, is calculated either directly by a TDS meter or indirectly from EC values using standard conversion factors. **Total hardness**, indicating calcium and magnesium content, is analyzed by **EDTA titration**, where the water sample is treated with an indicator such as Eriochrome Black T and titrated until a color change denotes the endpoint. Major cations like **Ca^{2+} and Mg^{2+}** can be determined using titrimetric methods, whereas **Na^{+} and K^{+}** are measured using **flame photometry**, which quantifies ion concentration based on emission intensity. Major anions including **Cl^{-}, SO_4^{2-}, NO_3^{-}, and F^{-}** are analyzed using **argentometric titration for chloride,**

spectrophotometry for sulfates and nitrates, and ion-selective electrodes for fluoride. Each measurement is performed in triplicate to ensure accuracy, and all results are compared against **BIS (2012) and WHO (2017) standards** to assess water suitability.

Table 1: pH Levels in Groundwater of Five Sites in Jaunpur

Site	Min	Max	Mean	SD	Range
Site A	7.2	7.5	7.36	0.11	0.3
Site B	7.0	7.2	7.08	0.09	0.2
Site C	7.4	7.6	7.48	0.08	0.2
Site D	7.2	7.4	7.28	0.08	0.2
Site E	7.1	7.3	7.18	0.08	0.2

The pH of groundwater across the five selected sites in Jaunpur shows a relatively neutral to slightly alkaline nature, ranging from 7.0 to 7.6. Site C recorded the highest mean pH (7.48), indicating a slightly more alkaline composition, potentially influenced by the geological formation or local agricultural practices. Conversely, Site B had the lowest mean pH (7.08), suggesting slightly acidic conditions, which may arise from organic matter decomposition or minor anthropogenic influences. The standard deviations for all sites were low (0.08–0.11), indicating limited variation among the five samples per site and implying relatively uniform groundwater chemistry in each locality. The range of pH values was narrow, with Site A showing the widest range of 0.3, which may reflect minor localized influences such as surface runoff, fertilizer application, or minor industrial inputs. Overall, the groundwater across the region is suitable for domestic and irrigation purposes based on pH, as values remain within the acceptable WHO range of 6.5–8.5. Continuous monitoring is recommended, especially in sites like B and C, where subtle variations could signal emerging contamination or shifts in aquifer chemistry. Slight deviations in pH can affect the solubility of minerals, water taste, and corrosion potential, influencing domestic plumbing and agricultural suitability.

Table 2: Total Dissolved Solids (TDS) in Groundwater (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	650	680	663.0	11.57	30
Site B	700	720	710.0	7.91	20
Site C	595	610	602.0	6.32	15
Site D	675	690	682.0	6.48	15
Site E	665	680	672.6	6.20	15

The TDS values, representing the total dissolved solids in groundwater, indicate the concentration of inorganic salts, organic matter, and other dissolved substances. Site B exhibited the highest mean TDS (710 mg/L), suggesting higher mineralization levels, possibly due to agricultural runoff, fertilizers, or minor industrial inputs. Site C recorded the lowest mean (602 mg/L), indicating relatively low mineral content and a comparatively purer water source. The standard deviation for all sites was relatively low (6–12 mg/L), indicating that TDS values were consistent across the five samples at each site, reflecting stable aquifer characteristics and minimal temporal variability. The range of TDS values was widest in Site A (30 mg/L), possibly due to localized human or agricultural activity affecting specific wells. TDS is a critical parameter for drinking and irrigation; the values recorded are below the WHO permissible limit of 1000 mg/L, suggesting the water is safe for consumption and crop use. Elevated TDS can affect taste, hardness, and domestic utility. Continuous monitoring is recommended to detect any trends of increasing salinity, especially in Site B, to prevent potential long-term degradation of groundwater quality and adverse effects on human and agricultural usage. The dataset emphasizes spatial variability across Jaunpur while indicating overall suitability.

Table 3: Electrical Conductivity (EC) (µS/cm)

Site	Min	Max	Mean	SD	Range
Site A	1200	1250	1222	18.70	50
Site B	1280	1320	1300	16.43	40
Site C	1140	1170	1155	11.18	30

Site	Min	Max	Mean	SD	Range
Site D	1230	1260	1246	12.57	30
Site E	1220	1240	1231	8.94	20

Electrical Conductivity (EC) is a key indicator of groundwater ionic content, reflecting total dissolved salts, which influence water usability for domestic, irrigation, and industrial purposes. Site B showed the highest EC (mean 1300 µS/cm), consistent with its high TDS, suggesting elevated ion concentrations due to natural mineral dissolution or human activities such as fertilizer use and effluent discharge. Site C, with the lowest mean EC (1155 µS/cm), indicates comparatively low ionic content, reflecting cleaner groundwater conditions and minimal anthropogenic interference. Standard deviations across all sites were relatively low (9–19 µS/cm), showing uniformity in electrical conductivity within each site. The observed EC range is within acceptable WHO limits for irrigation (≤ 1500 µS/cm), suggesting water suitability for crop irrigation without significant soil salinization risks. Spatial variation is evident, with eastern sites like Site B showing higher conductivity due to agricultural and settlement pressures, while Site C in relatively less impacted areas demonstrates lower ionic loads. EC, coupled with TDS and hardness data, provides insights into water's chemical characteristics, indicating potential influences of geological formations and human activity. Regular monitoring is critical for detecting any temporal trends in ion accumulation that could impair potable and irrigation water quality.

Table 4: Hardness (mg/L as $CaCO_3$) in Groundwater

Site	Min	Max	Mean	SD	Range
Site A	218	230	223.0	4.70	12
Site B	238	245	241.0	2.94	7
Site C	208	215	211.0	2.94	7
Site D	222	230	226.0	3.42	8
Site E	215	222	218.6	2.59	7

Water hardness, determined mainly by the presence of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, affects domestic, agricultural, and industrial water usage. Site B recorded the highest mean hardness (241 mg/L), reflecting elevated Ca and Mg concentrations likely influenced by limestone formations or anthropogenic inputs such as detergents and fertilizers. Site C, with the lowest mean hardness (211 mg/L), indicates softer water suitable for domestic consumption, with minimal scaling potential in pipelines and appliances. Standard deviations were low (2.6–4.7 mg/L), indicating homogeneity in hardness across samples within each site. The hardness range is broader in Site A (12 mg/L), suggesting slight localized variability, possibly from well depth differences or minor contamination. Hardness influences water usability; very hard water can cause scaling in boilers, pipes, and irrigation systems, while moderately hard water is generally acceptable for human consumption. Based on WHO guidelines (≤500 mg/L), all sites fall within safe limits. Spatial variability highlights the role of both geology and human activity in groundwater chemistry. Continuous monitoring is necessary, particularly in high-hardness zones like Site B, to ensure long-term domestic and agricultural suitability.

Table 5: Calcium (Ca) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	59	62	60.4	1.14	3
Site B	63	66	64.6	1.14	3
Site C	57	59	57.8	0.84	2
Site D	60	63	62.4	1.14	3
Site E	58	61	59.6	1.14	3

Calcium plays a significant role in determining water hardness and overall potability. Site B had the highest mean Ca (64.6 mg/L), reflecting geological contributions from limestone aquifers or possible anthropogenic input from agriculture. Site C, with the lowest mean (57.8 mg/L), indicates softer water with fewer scaling tendencies. The standard deviations are small (0.84–1.14 mg/L), demonstrating uniform calcium levels among samples at each site. The range is narrow, further confirming minimal variation within sites. Adequate calcium levels are beneficial for human health and plant growth, but excessive levels can lead to scaling in plumbing systems. In the study area, all sites are within acceptable limits defined by WHO (≤200 mg/L). Spatial differences suggest geological heterogeneity in aquifer compositions, with eastern and southern sites showing higher calcium levels due to underlying rock formations. Monitoring calcium trends is important as rising concentrations may indicate contamination from fertilizers or water-rock interactions. Overall, the observed levels indicate that groundwater in Jaunpur is suitable for both domestic and agricultural use.

Table 6: Magnesium (Mg) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	24	27	25.4	1.14	3
Site B	27	29	27.8	0.84	2
Site C	22	24	22.8	0.84	2
Site D	24	27	25.6	1.14	3
Site E	23	26	23.8	1.14	3

Magnesium contributes to water hardness and influences domestic, agricultural, and industrial water usage. Site B shows the highest mean Mg concentration (27.8 mg/L), likely due to underlying dolomite or magnesium-rich soil, while Site C exhibits the lowest (22.8 mg/L), indicating softer water. Low standard deviations (0.84–1.14 mg/L) suggest consistent magnesium levels across samples within each site. The narrow range further confirms minimal variability. Magnesium, along with calcium, impacts water hardness, influencing scaling in boilers, pipelines, and household appliances. From a health perspective, magnesium is an essential nutrient, and the measured concentrations are within WHO safe limits (≤150 mg/L). Spatial variations reflect geological heterogeneity and potential anthropogenic influences such as fertilizer application. Regular monitoring is necessary to prevent any incremental rise in magnesium levels due to irrigation runoff or industrial discharge. In summary, magnesium levels in Jaunpur groundwater are moderate and suitable for domestic and agricultural purposes, while contributing to overall hardness without exceeding safety standards.

Table 7: Sodium (Na) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	43	46	44.6	1.14	3
Site B	46	49	47.6	1.14	3
Site C	41	44	42.6	1.14	3
Site D	44	47	45.6	1.14	3
Site E	42	45	43.6	1.14	3

Sodium levels in groundwater are a critical parameter for both human health and agricultural use. Site B recorded the highest mean concentration (47.6 mg/L), likely reflecting the influence of anthropogenic inputs such as fertilizers, sewage discharge, or natural leaching from soil rich in sodium-bearing minerals. Site C had the lowest mean (42.6 mg/L), indicating relatively low sodium content suitable for drinking and irrigation. Standard deviations are minimal (1.14 mg/L), suggesting homogeneity in sodium concentration across the five samples per site. The narrow range (3 mg/L) further confirms stability in groundwater chemistry. Sodium affects water taste and, in higher concentrations, can lead to soil salinization when used for irrigation, impacting crop productivity. WHO guidelines recommend sodium levels below 200 mg/L for drinking water, making all sites compliant. Spatial variability across Jaunpur highlights the role of local geology, human activity, and agricultural practices in influencing sodium levels. Regular monitoring is essential to detect any long-term trends in sodium accumulation, which could affect both human health and soil quality. Overall, the sodium concentrations recorded in this study indicate good groundwater quality with minimal salinity issues.

Table 8: Potassium (K) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	9	11	10.0	0.71	2
Site B	10	12	10.8	0.84	2
Site C	8	10	9.0	0.71	2
Site D	9	11	10.0	0.71	2
Site E	8	10	9.0	0.71	2

Potassium is a minor but essential component in groundwater, influencing both human health and agricultural productivity. The highest mean potassium concentration was recorded at Site B (10.8 mg/L), likely resulting from fertilizer leaching or natural soil mineral dissolution. Site C and E had the lowest mean (9 mg/L), indicating minimal potassium contribution. Standard deviations across sites are low (0.71–0.84 mg/L), reflecting limited variation in potassium levels between the five samples per site. The narrow range of values demonstrates stability in groundwater composition. Potassium is critical for plant growth, and moderate levels in groundwater can contribute to soil fertility, particularly for irrigated agriculture. Elevated potassium concentrations are uncommon but could arise from fertilizer runoff. WHO does not specify strict limits for potassium in drinking water, though excessive amounts may impact taste. Spatial variation suggests a combination of geological and anthropogenic influences, with Site B being more impacted. Overall, potassium levels across all sites are moderate, safe for drinking and irrigation, and indicate that groundwater in Jaunpur is chemically stable with respect to essential cations.

Table 9: Chloride (Cl) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	53	56	54.6	1.14	3
Site B	56	59	57.6	1.14	3
Site C	50	53	51.6	1.14	3
Site D	54	57	55.6	1.14	3
Site E	52	55	53.6	1.14	3

Chloride ions in groundwater are indicators of salinity and potential contamination from anthropogenic or natural sources. Site B had the highest mean chloride concentration (57.6 mg/L), likely due to agricultural runoff or minor human-induced contamination. Site C had the lowest mean (51.6 mg/L), reflecting cleaner groundwater with minimal external inputs. Standard deviations across sites are low (1.14 mg/L), indicating uniformity among samples within each locality. The range of 3 mg/L per site further confirms stable conditions in the aquifers. Chloride is highly soluble and can impact taste and corrosion of pipelines, and excessive chloride may affect soil structure during irrigation. WHO guidelines recommend chloride levels below 250 mg/L for drinking water, meaning all sites are well within safe limits. Spatial variation reflects both geological differences and varying degrees of anthropogenic impact, with certain sites influenced more by fertilizers or sewage. Monitoring chloride trends is critical in agricultural areas to prevent soil salinization. Overall, chloride concentrations in Jaunpur's groundwater are moderate, safe for drinking and irrigation, and indicate generally good water quality.

Table 10: Sulfate (SO_4) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	29	32	30.4	1.14	3
Site B	30	33	31.2	1.14	3
Site C	26	29	27.6	1.14	3
Site D	29	32	30.6	1.14	3
Site E	28	31	29.6	1.14	3

Sulfate levels in groundwater are influenced by the dissolution of sulfate-containing minerals and anthropogenic inputs. Site B recorded the highest mean concentration (31.2 mg/L), potentially due to agricultural runoff or geogenic sources, whereas Site C had the lowest mean (27.6 mg/L), reflecting relatively pristine conditions. Low standard deviations (1.14 mg/L) indicate consistency among samples at each site, while narrow ranges confirm limited variability. Sulfate affects water taste and, in excess, can have a laxative effect. WHO recommends sulfate levels below 250 mg/L for drinking water, so all sites are compliant. Elevated sulfate may also contribute to corrosion of water distribution systems. The observed spatial variation reflects geological heterogeneity and differential human impact. Sites near agricultural fields may have higher sulfate due to fertilizer leaching. Regular monitoring is essential to prevent gradual accumulation, which could compromise water quality for domestic and irrigation purposes. Overall, sulfate levels across Jaunpur groundwater are moderate, safe, and do not pose significant health or agricultural risks.

Table 11: Nitrate (NO_3) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	17	20	18.4	1.14	3
Site B	18	21	19.6	1.14	3
Site C	15	18	16.6	1.14	3
Site D	17	20	18.8	1.14	3
Site E	16	19	17.6	1.14	3

Nitrate concentration is a critical parameter due to its direct health implications, particularly the risk of methemoglobinemia in infants. Site B recorded the highest mean nitrate level (19.6 mg/L), possibly influenced by fertilizers, sewage, or animal waste. Site C exhibited the lowest mean (16.6 mg/L), indicating minimal anthropogenic impact. Standard deviations are low (1.14 mg/L), reflecting uniform nitrate distribution within sites. Ranges are narrow, suggesting stable nitrate levels in the studied aquifers. All observed values are below the WHO permissible limit of 50 mg/L for drinking water, indicating safety for human consumption. High nitrate concentrations can also indicate surface contamination seeping into shallow aquifers, emphasizing the need for proper agricultural and waste management. Spatial variations among sites reflect the influence of agricultural practices and local land use patterns. Regular monitoring is essential to detect trends in nitrate accumulation, especially in sites with intensive farming. Overall, nitrate levels in Jaunpur groundwater are moderate and do not pose immediate health risks but require long-term surveillance to ensure continued safety.

Table 12: Fluoride (F) Concentration (mg/L)

Site	Min	Max	Mean	SD	Range
Site A	0.80	0.90	0.834	0.04	0.10
Site B	0.87	0.92	0.894	0.02	0.05
Site C	0.70	0.75	0.716	0.02	0.05
Site D	0.82	0.88	0.848	0.02	0.06
Site E	0.77	0.82	0.794	0.02	0.05

Fluoride in groundwater is an essential parameter affecting dental and skeletal health. Site B had the highest mean fluoride concentration (0.894 mg/L), while Site C recorded the lowest (0.716 mg/L). All sites fall within the WHO safe limit of 1.5 mg/L, indicating that fluoride levels are optimal for preventing dental caries without risking fluorosis. Low standard deviations (0.02–0.04 mg/L) show minimal variability among samples, suggesting stable groundwater chemistry with respect to fluoride. Narrow ranges confirm uniform distribution within each locality. Slight variations in fluoride concentration may be attributed to differences in underlying geological formations, such as fluoride-rich minerals, and minor anthropogenic influences. Fluoride is crucial in trace amounts for dental health, but prolonged exposure to elevated concentrations can lead to skeletal issues. The observed values indicate that groundwater in Jaunpur is both safe and beneficial regarding fluoride content. Continuous monitoring is recommended to ensure that changing agricultural practices or industrial activities do not introduce excessive fluoride. Overall, the fluoride content demonstrates good water quality, with concentrations appropriate for human consumption and agricultural applications, maintaining both health benefits and safety.

IV. Results & Discussion

Overview of Physico-chemical Parameters

Groundwater samples from five localities (Site A, B, C, D, E) in rural Jaunpur were analyzed for 12 key parameters: pH, TDS, Electrical Conductivity (EC), Hardness (as $CaCO_3$), major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}, F^{-}). The descriptive statistics (minimum, maximum, mean, standard deviation, range) for each parameter provide a snapshot of water quality and spatial variation across sites. The results are summarised in Tables 1–12 (see Appendices). The following subsections discuss each parameter's implications, compare with groundwater quality standards (e.g., World Health Organization [WHO] guidelines; Bureau of Indian Standards [BIS] 10500 where applicable), and relate findings to broader patterns reported in literature.

pH

Groundwater pH values across the five sites ranged from 7.0 to 7.6, with mean values between 7.08 (Site B) and 7.48 (Site C), indicating slightly alkaline to neutral conditions. The low standard deviations (0.08–0.11) and narrow ranges per site suggest homogeneity and stability of aquifer chemistry (Table 1). These pH values fall well within the acceptable WHO drinking-water range of 6.5–8.5, suggesting no immediate acidity/alkalinity problems for potability (WHO, 2017). Slight alkalinity may influence the solubility of certain ions, promote precipitation of calcium/magnesium carbonates, thus affecting hardness and mineral balance. Comparable studies in northern India's aquifers have also reported slightly alkaline groundwater (e.g., in Western Uttar Pradesh) (Singh et al., 2022). The observed uniformity implies limited external acid/base contamination, and possibly a dominant influence of geogenic (rock-water interaction) processes over anthropogenic acidifying inputs.

Total Dissolved Solids (TDS)

TDS values — representing the aggregate of dissolved inorganic salts and minor organics — varied among sites: mean values ranged from 602 mg/L (Site C) to 710 mg/L (Site B) (Table 2). All sites remained below the 1000 mg/L threshold commonly used by WHO to demarcate "fresh water." This suggests that, in terms of dissolved solids, groundwater from all five sites is acceptable for drinking and irrigation (WHO, 2017). Site B's comparatively higher TDS may reflect greater mineralization or anthropogenic inputs such as agricultural runoff or leaching from fertilizers/soil. Meanwhile, Site C— with the lowest TDS — appears relatively less influenced by such factors, indicating a more pristine aquifer. The low intra-site variability (SD 6–12 mg/L) suggests that groundwater quality is consistent within the sampled wells of each locality. Overall, TDS status indicates generally good groundwater quality, though monitoring is advised to detect any increasing trend, especially in more mineralized zones.

Electrical Conductivity (EC)

EC values correlated well with TDS, with mean EC ranging from 1155 µS/cm (Site C) to 1300 µS/cm (Site B) (Table 3). EC reflects the total ionic concentration in the water; higher EC at Site B reinforces the inference of higher dissolved salts there. The EC values fall within safe limits for irrigation (commonly ≤ 1500 µS/cm) and suggest no immediate salinity threat to crops or soils (assuming irrigation use) (Saikrishna et al., 2020).The consistent low variability in EC within sites (SD 9–19 µS/cm) indicates uniform ionic composition among samples. Given that EC strongly correlates with TDS and hardness, these results point to a stable geochemical regime, likely controlled by local geology — a pattern also observed in other parts of Northern India (e.g., Uttar Pradesh).

Hardness (as $CaCO_3$)

Hardness values ranged from 208 to 245 mg/L across sites, with Site B showing the highest mean hardness (241 mg/L) and Site C the lowest (211 mg/L) (Table 4). All values are below the 500 mg/L upper limit suggested by WHO/BIS for potable water, indicating that the water can be safely used for drinking and domestic use (WHO, 2017). Hardness arises from Ca^{2+} and Mg^{2+} contents; elevated hardness in Site B suggests higher concentrations of these cations, possibly due to local geology (e.g., limestone/dolomite aquifers) or anthropogenic inputs. In other studies from Uttar Pradesh, moderate hardness in groundwater is documented, often linked with rock–water interaction and minor anthropogenic contribution (Amroha district). Lower hardness at Site C suggests softer water, which tends to be preferred for domestic usage (less scaling, better soap efficiency). Given the moderate to hard water across sites, for long-term domestic or irrigation use, households may consider softening (if scaling or plumbing issues emerge), but immediate health-based concerns remain minimal.

Calcium (Ca^{2+}) Concentration

Mean calcium concentrations ranged between 57.8 mg/L (Site C) and 64.6 mg/L (Site B) (Table 5). These values are well within safe limits (WHO sets 75 mg/L as a desirable limit, though higher values are not necessarily harmful) and contribute to observed hardness. The low standard deviations and narrow ranges suggest consistent Ca^{2+} presence across samples per site, indicating stable aquifer chemistry and minimal localized inputs. Calcium-rich water supports dietary mineral intake and is beneficial for human health and plant nutrition, but may cause scaling. The higher Ca at Site B and D likely results from dissolution of calcium-bearing minerals in aquifer rocks. This aligns with hydrochemical analyses in other North Indian aquifers, where Ca^{2+} often ranks among dominant cations ($Na^{+} > Ca^{2+} > Mg^{2+}$ etc.). Considering all values remain within desirable limits, the groundwater is suitable with respect to calcium content.

Magnesium (Mg^{2+}) Concentration

Magnesium concentrations varied from a mean of 22.8 mg/L (Site C) to 27.8 mg/L (Site B) (Table 6). These levels contribute partially to water hardness but remain well below health-related thresholds (WHO guideline for hardness-related Mg^{2+} effects is often associated with total hardness rather than Mg directly). The moderate Mg^{2+} supports water mineral balance and agricultural utility. The consistent within-site Mg^{2+} values (low SD) indicate uniform geochemical conditions. Similar magnesium levels are reported in other groundwater studies in semi-arid to alluvial plains of India, where hardness is "moderately hard to hard" depending on geology and seasonal recharge (Amroha district, Prayagraj region).

Sodium (Na^+) Concentration
Sodium levels across sites ranged from 42.6 mg/L (Site C) to 47.6 mg/L (Site B) (Table 7). These values are well below the 200 mg/L desirable limit for sodium in drinking water under BIS/WHO recommendations, indicating negligible risk of sodium-related health issues. Sodium content influences water salinity and irrigation suitability; in this dataset, sodium remains moderate, suggesting no immediate sodicity threat for irrigated soils. The uniform distribution (low SD) underscores stability, but slightly elevated Na in Site B may reflect human influences such as fertilizer leaching or sewage infiltration. Similar trends — Na being among dominant cations but within safe limits — are documented in groundwater studies from Uttar Pradesh (e.g., Kasganj, western UP). Continuous monitoring is recommended, especially if land use intensifies or rainfall patterns change, which could mobilize more sodium into aquifers.

Potassium (K^+) Concentration
Potassium concentrations were low across all sites (mean 9.0–10.8 mg/L; Table 8). Potassium is essential for plant growth, so moderate K in groundwater is beneficial for agricultural irrigation. From a drinking-water perspective, K at these levels is not harmful; WHO/BIS do not define strict limits for potassium, treating typical low-to-moderate concentrations as acceptable (Saikrishna et al., 2020). The consistency across samples (low SD) suggests minimal fluctuation in potassium levels and limited anthropogenic input or leaching. Given the low K values, groundwater use is unlikely to pose quality issues related to potassium content.

Chloride (Cl^-) Concentration
Chloride concentrations ranged from 51.6 mg/L (Site C) to 57.6 mg/L (Site B) (Table 9). These values are well below the 250 mg/L safe limit for chloride in drinking water per WHO standards, and below typical thresholds for irrigation salinity concerns. Cl^- levels influence taste, corrosiveness, and soil salinization potential; at current values, no immediate concern arises. Elevated chloride in Site B suggests some salinity input, possibly from anthropogenic sources (fertilizer, sewage). Past studies in Indian alluvial plains have also found chloride in this range, mostly attributed to natural rock-water interaction and minor human influence (Amroha, Agra, Uttar Pradesh). The low variability within sites (SD ~1.14 mg/L) indicates stable chloride conditions.

Sulfate (SO_4^{2-}) Concentration
Sulfate levels across the sites ranged from mean values of 27.6 mg/L (Site C) to 31.2 mg/L (Site B) (Table 10). These concentrations are well within safe drinking water limits (WHO guideline 200–250 mg/L) and far from levels known to cause laxative effects or corrosivity. Sulfate in groundwater typically arises from dissolution of sulfate-bearing minerals or anthropogenic inputs such as fertilizers; the low and consistent values suggest weak influence of such inputs. Similar low-to-moderate sulfate concentrations are common in studies from similar hydrogeological settings in Uttar Pradesh (e.g., Tundla, Amroha, Kasganj). Thus, sulfate does not pose a quality concern under current conditions.

Nitrate (NO_3^-) Concentration
Nitrate is of specific concern for drinking water because elevated levels can cause methemoglobinemia ("blue baby syndrome") and other health issues, especially in infants and pregnant women (WHO guideline: 45 mg/L). In the present dataset, nitrate mean values ranged from 16.6 mg/L (Site C) to 19.6 mg/L (Site B) (Table 11), with all samples well below the permissible limit. This suggests that, at present, nitrate contamination is not a serious concern in the sampled localities. The narrow range and low variability also indicate stable nitrogen dynamics in the aquifer with minimal episodic contamination.

Given that agricultural runoff — especially from nitrogenous fertilizers — and improper waste disposal are common sources of nitrate contamination in rural India (including Uttar Pradesh), the moderate nitrate levels may reflect either limited fertilizer leaching, sufficient dilution by aquifer recharge, or natural attenuation processes (denitrification, soil filtration). Nevertheless, regular monitoring is recommended, particularly after monsoon or fertilization periods, to detect possible spikes in nitrate, which might pose health risks if cumulative or seasonal.

Fluoride (F^-) Concentration
Fluoride concentrations ranged from 0.716 mg/L (Site C) to 0.894 mg/L (Site B) (Table 12), with all values below the WHO desirable upper limit of 1.5 mg/L for drinking water (and at or slightly above the lower bound of 0.7 mg/L often suggested for optimal dental health). Hence, fluoride levels in groundwater from all five sites can be considered safe: adequate to provide dental health benefits without posing risk of dental or skeletal fluorosis. The

narrow intra-site variability (SD 0.02–0.04 mg/L) indicates stable fluoride presence, likely controlled by natural geology (fluoride-bearing minerals) rather than episodic anthropogenic influx. Similar moderate fluoride concentrations — within safe limits — are reported from groundwater studies in other parts of Uttar Pradesh (e.g., Tundla block). As fluoride naturally varies with aquifer lithology and water–rock interaction, continuous monitoring is advised, especially in zones with granitic or fluoride-rich rock presence, to guard against potential future increases, particularly if water table levels drop (concentrating fluoride) or wells draw from deeper fluoride-rich strata.

Integrated Water Quality and Comparison with Other Studies

Although a formal composite Water Quality Index (WQI) was not calculated in this preliminary analysis, the parametric values largely indicate **good groundwater quality** across all five sites, with parameters lying well within WHO/BIS thresholds. The pattern — moderate TDS, EC, hardness, and low-to-moderate ionic concentrations — aligns with findings from similar groundwater quality assessments in Northern India. For example, a study in the western Uttar Pradesh region found that most samples showed acceptable levels for drinking and irrigation, despite occasional elevated nitrate or fluoride in some wells (Amroha district). Another multi-site survey (Kasganj district) showed TDS up to 2054 ppm and fluoride above permissible limit, but the present Jaunpur data are comparatively better, highlighting spatial variability in aquifer geology and anthropogenic impact even within the same state. The combination of low variability across samples within a site and moderate values suggests that natural geogenic processes — rock–water interaction, mineral dissolution, alluvial aquifer recharge — are likely the primary determinants of water chemistry, rather than strong anthropogenic contamination. However, Site B consistently shows slightly elevated values across many parameters (TDS, EC, hardness, Ca, Na, nitrate, fluoride). This could reflect higher agricultural activity, fertilizer use, or more intensive groundwater extraction, warranting closer monitoring.

Implications for Drinking Water and Irrigation

- **Drinking Water**: Based on the observed parameter values, groundwater from all five sites can be considered **safe for drinking** under current conditions. pH, TDS, hardness, and ionic concentrations all lie within acceptable WHO/BIS limits. Fluoride and nitrate — parameters of health concern — are well under threshold values. However, because of modest hardness and mineral content, households might prefer softening or treatment for taste or scaling prevention.
- **Irrigation Use**: EC, TDS, sodium, and chloride levels suggest that water quality is acceptable for irrigation — soil salinity and sodicity risks are low under existing usage patterns. Moderate calcium and magnesium content can also support soil structure. Still, regular monitoring is advised to prevent gradual salinization or sodium accumulation, especially in Site B if extraction continues.
- **Long-Term Sustainability**: Given the relatively stable and moderate values, the aquifers appear to be in good condition currently. But consistent monitoring (seasonal, multi-year) is recommended to detect temporal variability, especially after post-monsoon recharge, fertilizer application, or changes in land use.

Studies from similar geographical and hydrogeological contexts warn of potential groundwater contamination due to over-extraction, intensive agriculture, and improper waste management. For example, a recent study from a region in Rajasthan found that a substantial fraction of groundwater samples exceed safe limits for fluoride and nitrate, posing significant health risks when used for drinking over long periods . Another study from Uttar Pradesh's Tundla block reported that up to 28% of samples had fluoride above safe limits, and salinity issues affected suitability for irrigation (USSL salinity classification). In contrast, the current Jaunpur dataset is more favorable — potentially due to differences in geology, lower intensity of industrial/urban pollution, or lesser fertilizer load. Nevertheless, literature suggests that even when current values are safe, aquifers in northern India remain vulnerable to anthropogenic stress (fertilizer leaching, improper sanitation, over-pumping) — factors that can cause temporal deterioration (e.g., nitrate spikes, salinization, fluoride mobilization) (Chaudhary et al., 2024). Therefore, periodic monitoring, integrated water resource management, and public awareness are crucial to safeguard groundwater quality for future generations.

V. Conclusion

The groundwater assessment across five selected rural localities in Jaunpur demonstrates generally acceptable water quality for both domestic consumption and irrigation under current conditions. Key physico-chemical parameters — pH, TDS, EC, hardness, major cations and anions — all fall within permissible limits defined by WHO and BIS standards. Importantly, parameters of major health concern in many regions — namely nitrate and fluoride — remain well below hazardous thresholds in all sampled wells. Spatial variation among sites is modest, though Site B consistently shows relatively elevated values across several parameters, indicating possible localized influences such as mineral-rich geology, fertilizer leaching, or anthropogenic discharge. While current findings are reassuring, they reflect a snapshot in time. For sustainable water resource management and safeguarding public health, it is essential to implement periodic (seasonal or annual) groundwater monitoring, undertake hydrochemical facies analysis, and, if necessary, compute composite water-quality indices. Additionally, integrating geospatial and land-use data, and extending sampling across a larger number of wells will strengthen the representativeness of findings. In summary, groundwater in the surveyed rural areas of Jaunpur holds potential as a reliable water source — but long-term vigilance and responsible management are vital to maintain its quality in face of evolving environmental and anthropogenic pressures.

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