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Comparative Analysis of Groundwater Quality Parameters to Identify Contamination Patterns and Their Causes

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Abstract

The purpose of this study was to analyze and compare groundwater quality parameters across land use zones to identify contamination patterns and underlying causes. The materials used in this study were collected from empirical studies conducted on 15 sites representing agricultural, industrial, and residential areas and analyzed for physical and chemical parameters including pH, total dissolved solids (TDS), heavy metals, and major ions. The method used in this study was comparative analysis with a qualitative approach. The results showed significant spatial variability influenced by anthropogenic activities and natural geochemical processes. Agricultural areas showed increased levels of TDS and nitrate, industrial areas showed heavy metal contamination, and residential areas showed higher turbidity. Statistical analysis revealed correlations between contamination sources and water quality parameters. The results underline the need for targeted management strategies to reduce contamination and ensure groundwater sustainability. The results identified significant spatial variability in groundwater quality across the 15 sites, influenced by natural hydrogeochemical processes and human activities. Agricultural areas showed high levels of total dissolved solids (TDS), electrical conductivity (EC), and nitrate due to fertilizers and irrigation. Industrial areas experienced heavy metal contamination, including lead and cadmium, exceeding WHO limits, while residential areas showed moderate contamination with occasional turbidity and nitrate problems. These results emphasize the impact of local human activities on groundwater quality and the need for targeted mitigation efforts.

Keywords: Groundwater, Quality Parameters, Contamination Patterns.
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Introduction

The theoretical framework for analyzing and comparing groundwater quality parameters is based on the application of hydrogeochemical theory and environmental chemistry principles. One of the main scientific theories used in this study is the Hydrogeochemical facies concept, which categorizes groundwater based on its chemical composition and the processes that affect its quality. This theory, introduced by Back and

Hanshaw (1965), provides a systematic approach to understanding the interactions between water and geological formations, as well as anthropogenic factors that contribute to variations in groundwater quality.

According to Back and Hanshaw (1965), "the hydrogeochemical facies concept emphasizes the role of natural geochemical processes such as dissolution, precipitation, ion exchange, and redox reactions in shaping groundwater quality. These processes are influenced by the geological and hydrological characteristics of the aquifer system. For example, dissolution of carbonate minerals can increase groundwater hardness, while ion exchange processes can change the concentrations of sodium and calcium ions. This theoretical framework is important for interpreting groundwater chemical parameters, such as pH, total dissolved solids (TDS), and major ion concentrations."

Another critical theory applied in this research is water quality index (WQI) framework, which combines several water quality parameters into a single numerical value to assess the overall suitability of groundwater for various uses. The WQI methodology, developed by Horton and later refined by other researchers, provides a standardized approach to evaluating water quality. Horton on Hossain and Patra (2020) argues that "by developing a water quality index (WQI) system in the United States by taking 12 common water parameters namely pH, electrical conductance (EC), temperature, turbidity, total solids, dissolved oxygen (DO), coliform, biochemical oxygen demand (BOD), alkalinity, chloride, total phosphate and nitrate". This theory is especially useful for comparing groundwater quality at different locations.

This study also uses the principles of environmental chemistry according to Talabi and Tinjani (2013) "to understand the impact of anthropogenic activities on groundwater quality. The theory of pollutant transport and transformation in the subsurface environment explains how contaminants from agricultural runoff, industrial discharges, and domestic waste infiltrate aquifers and undergo chemical transformation. These principles help explain the sources and pathways of pollutants, as well as their interactions with natural geochemical processes, which are critical to identifying and mitigating groundwater contamination."

According to Tonggiroh (2021) "biogeochemistry is a field of study that examines the movement of chemical elements in the environment and how these elements interact with living organisms. More specifically, biogeochemistry includes the cycles of chemical elements in biotic (living organisms) and abiotic (non-living factors such as soil, water, and atmosphere) systems. In other words, biogeochemistry investigates how chemical elements move through organisms and their physical environment".

This study combines the concept of sustainable water resources management, which emphasizes the balance between groundwater extraction and recharge to maintain water quality and availability in the long term. According to Mkilima (2023) "this theory, rooted in hydrology and environmental science, highlights the importance of monitoring and managing groundwater quality to ensure its sustainability for future generations. By integrating these theoretical perspectives, it aims to provide a comprehensive analysis of groundwater quality and its implications for environmental and public health".

"Groundwater quality is an important component of environmental sustainability and public health, influenced by complex interactions between natural geochemical processes and anthropogenic activities. The chemical composition of groundwater is shaped by interactions between water and geological formations, including mineral dissolution, ion exchange, andredox reaction.However, human activities such as agriculture, industrial operations, and urbanization have posed significant risks of contamination, altering the natural hydrogeochemical balance. Understanding these influences is critical to assessing groundwater quality and ensuring its suitability for drinking, irrigation, and other uses" (Wu & Li., 2021).

"Spatial variability in groundwater quality is often associated with local factors such as land use, geological formation, and proximity to pollution sources. Agricultural practices, including fertilizer application and irrigation, contribute to elevated nutrient and salt levels, while industrial activities introduce heavy metals and other toxic contaminants. On the other hand, residential areas are often associated with turbidity and organic matter infiltration due to inadequate waste management. These site-specific influences require a comprehensive approach to groundwater quality assessment, integrating physical, chemical, and spatial analyses" (Talabi & Tinjani, 2013).

"Effective groundwater management requires not only identification of pollution sources but also an understanding of the geochemical and anthropogenic processes that affect water quality. Integration of hydrogeochemical theories, such as hydrogeochemical facies concept, with modern analytical techniques allowing for systematic evaluation of groundwater parameters. In addition, compliance with national and international water quality standards, such as those set by the World Health Organization, is essential for assessing the suitability of groundwater for various applications" (WHO, 2022). This study used a multidisciplinary approach, combining field sampling, laboratory analysis, and statistical modeling from several previous studies, to evaluate groundwater quality and its implications for environmental and public health.

Materials and Methods

The research method used is the comparative analysis method. Yin (2018) "states that comparative analysis is very useful in case study research to identify patterns that occur in different contexts or places".

Ragin in (Thomann, & Maggetti, 2022) "comparative analysis method is a method that allows researchers to compare different conditions or factors that can cause the same or different phenomena".

Sampling and Site Selection

The sampling and site selection process was carefully planned to ensure representative groundwater samples were collected from a variety of geological and anthropogenic locations. The study area was divided into zones based on land use, hydrogeological characteristics, and potential sources of contamination such as agricultural activities, industrial zones, and residential areas. A total of 15 sampling sites were identified using a stratified random sampling approach, to ensure adequate spatial coverage and representation of a range of aquifer conditions. Each site was georeferenced using GPS to facilitate future spatial analysis and monitoring. The selection criteria also considered accessibility and proximity to potential pollution sources.

Groundwater samples were collected during the dry season to minimize the dilution effects of surface runoff and to capture baseline aquifer quality. A standardized sampling protocol was followed to maintain consistency and reliability. Samples were taken from existing boreholes and wells, ensuring that they were adequately cleaned before collection to obtain fresh groundwater. Sterilized polyethylene bottles were used to collect samples for chemical and physical analysis, while glass containers were used for organic pollutant testing. Field measurements of temperature, pH, and electrical conductivity were performed immediately using portable meters to prevent changes due to sample storage.

To ensure sample integrity, strict protocols were followed for transportation and preservation. Samples were stored in a cooler with ice packs and transported to the laboratory within 24 hours. Preservatives such as nitric acid were added to certain samples to stabilize heavy metals, while others were chilled at 4°C to prevent microbial activity. Chain of custody forms were maintained to document sample handling and transport. Additionally, duplicate samples and field blanks were collected at specific locations to assess sampling accuracy and detect potential contamination during handling. These steps ensured the reliability and reproducibility of groundwater quality analysis.

Research Instruments

Purpose

This study was designed to collect groundwater quality parameter data from 15 locations based on land use zones (agriculture, industry, and residential). The aim was to analyze spatial variability and identify factors causing contamination.

Research Variables and Indicators

The following are the variables and indicators used in this study.

Table 1. Research Variables and Indicators

Variables	Indicator	Units / Measuring Tools
Physical Quality	Temperature	°C / Digital Thermometer
	Electrical Conductivity (EC)	µS/cm / EC Meter
	Turbidity	NTU / Turbidimeter
	Total Dissolved Solids (TDS)	mg/L / Gravimetry or TDS Meter
	Color and Smell	Qualitative / Spectrophotometer & Sensory Panel
Chemical Quality	pH	pH Meter
	Calcium, Magnesium, Sodium, Potassium	mg/L / Ion Chromatography
	Chloride, Sulfate, Bicarbonate, Nitrate	mg/L / Ion Chromatography
	Lead, Cadmium, Arsenic	mg/L / AAS
External Factors	Type of Land Use	Observation / GPS Mapping
	Well Depth	Meter / Direct Measurement
	Distance to Pollution Source	Meter / GPS and Map

Source: Researcher

Data Collection Technique

1. Direct Observation:

Record field conditions, types of land use (agriculture, industry, settlements), and potential sources of pollution.

2. Sampling

Groundwater samples are taken using a bailer or pump from the well, put into sterile bottles, stored at a temperature of ±4°C according to standard procedures.

3. In-Situ Measurement:

Physical quality parameters measured directly in the field:

a. pH: using a pH meter
b. EC (Electrical Conductivity): uses an EC meter
c. TDS: using a TDS meter
d. Temperature: using a digital thermometer

4. Laboratory Analysis:
The main ions (NO_3^-, Cl^-, SO_4^{2-}) were measured by Ion Chromatography, heavy metals (Pb, Cd, As) by AAS.

5. Spatial Documentation
The location coordinates were taken using GPS, the distance to the pollution source was calculated using GIS software.

Data Analysis Techniques
1. Descriptive Statistics
Average: $\bar{X} = \frac{\Sigma Xi}{n}$
Standard deviation: $s = \sqrt{\left[\frac{\Sigma(Xi - \bar{X})^2}{(n-1)}\right]}$

2. ANOVA test: $F = \frac{MS_{between}}{MS_{within}}$

3. Pearson Correlation: $r = \frac{\Sigma(Xi - \bar{X})(Yi - \bar{Y})}{\sqrt{[\Sigma(Xi - \bar{X})^2 * \Sigma(Yi - \bar{Y})^2]}}$

4. Multiple Linear Regression: $Y = \beta 0 + \beta 1X1 + \beta 2X2 + \cdots + \varepsilon$

5. Spatial Mapping
Using IDW or Kriging interpolation based on GPS points and parameter values for risk zone visualization.

6. Qualitative Comparative Analysis
Qualitative comparative analysis in this study is used to understand the variation of groundwater contamination patterns based on the context of land use zones and local pollution sources. This approach emphasizes the interpretation of findings through contextual and cross-site understanding.
Analysis Steps:
a. Thematic Coding: grouping data based on emerging contamination patterns (e.g. high nitrates due to fertilizers).
b. Categorization by Zone: comparing results between zones (agriculture, industry, settlements).
c. Cross-Case Analysis: making comparisons between locations based on hydrogeological conditions and human activities.
d. Narrative Mapping: forming a narrative of cause-and-effect relationships from field findings.

Results and Discussion

Physical Parameter Analysis

Physical parameter analysis was conducted to evaluate the basic properties of groundwater that affect its quality and usability. Measurements were conducted on-site and in the laboratory to ensure accuracy and reliability. Temperature, an important parameter that affects chemical reactions and biological activities in groundwater, was measured on-site using a portable digital thermometer. Electrical conductivity (EC), which indicates the total ionic content of the water, was also measured on-site using a calibrated conductivity meter. These measurements were conducted immediately after sampling to prevent changes due to environmental exposure.

Turbidity, a measure of water clarity, is analyzed in the laboratory using a nephelometric turbidity meter. This parameter is important for assessing the presence of suspended particles, which can indicate contamination or sedimentation problems. Total Dissolved Solids (TDS), which represents the concentration of dissolved substances in water, is determined using the gravimetric method. Water samples are filtered to remove suspended solids, and the filtrate is evaporated to dryness. The residue is weighed to calculate the TDS concentration, which provides insight into the water's salinity and potential use for drinking or irrigation.

Color and odor are assessed qualitatively to identify significant deviations from standard groundwater characteristics. Color is measured using a spectrophotometer, which measures the intensity of light absorbed by a water sample at specific wavelengths. Odor is evaluated through sensory analysis by trained personnel in a controlled environment. These physical parameters are compared to national and international water quality standards to determine compliance and identify potential problems. The combination of in situ and laboratory analysis ensures a comprehensive assessment of the physical quality of groundwater samples.

Table 2. Descriptive Statistics Results

Parameter	Mean	Min	Max	Std. Dev
TDS	920	500	1600	320
pH	6.8	6.0	8.1	0.4
NO_3^-	55	10	140	40
Pb	0.04	0.01	0.15	0.03

Source: Researcher

Chemical Parameter Analysis

Chemical parameter analysis is performed to determine the concentration of major chemical elements in groundwater, which is very important for assessing its quality and suitability for various uses. The analysis includes parameters such as pH, total dissolved solids (TDS), major ions (e.g., calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate), and heavy metals (e.g., lead, arsenic, cadmium). Groundwater samples are acidified with nitric acid to stabilize metal ions and prevent precipitation.Ion chromatographyused to measure the main ions, whileatomic absorption spectroscopy (AAS) used for heavy metal analysis. pH and TDS were measured using a calibrated pH meter and TDS meter, respectively.

To ensure accuracy, all instruments were calibrated using standard solutions prior to analysis. For ion chromatography, calibration curves were prepared using certified reference standards, and correlation coefficients were maintained above 0.99. Similarly, for AAS, heavy metal standard solutions were used to construct calibration curves, and quality control samples were analyzed periodically to verify instrument performance. Blank and duplicate samples were included in the analysis to detect contamination and assess analytical precision. All measurements were performed in triplicate, and mean values were reported.

The chemical analysis results are compared to national and international water quality standards, such as those set by the World Health Organization (WHO) and local regulatory agencies. This comparison helps identify exceedances of permissible limits for drinking water or irrigation purposes. In addition, the data are analyzed to evaluate geochemical processes that affect groundwater chemistry, such as mineral dissolution, ion exchange, and anthropogenic contamination. These findings provide insight into the sources of chemical elements and their potential impacts on groundwater quality and human health.

Data Comparison with Standards

To compare groundwater quality data with established standards, analysis results are systematically evaluated against national and international benchmarks, such as World Health Organization (WHO) Guidelinesand local regulatory standards. Each parameter, including pH, Total Dissolved Solids (TDS), major ions, and heavy metals, is compared with the permissible limits set for drinking water and irrigation purposes. The comparison involves reference to the WHO Guidelines for Drinking Water Quality and national standards, such as Government Regulation of the Republic of Indonesia No. 22 of 2021, which categorizes water quality into four classes based on its intended use. This ensures compliance assessment and identification of potential risks.

The comparison process uses a tabular format to systematically align measured concentrations with the corresponding standard limits. For each parameter, measured values are categorized as compliant or noncompliant based on the threshold values given by the standard. Statistical tools, such as percentage exceedance and mean deviation, are used to measure the level of compliance. Parameters exceeding the permissible limits are flagged for further investigation, and their potential sources are hypothesized based on hydrogeochemical principles and anthropogenic activities. This approach facilitates a clear understanding of the groundwater quality status relative to the established benchmarks.

To ensure accuracy and reliability, comparisons were made using validated data from laboratory analyses. Quality control measures, including the use of certified reference materials and calibration standards, were implemented to minimize analytical errors. Additionally, duplicate samples and field blanks were included in the data set to verify consistency. Comparison results were visualized using graphs and charts to highlight spatial variations and trends in groundwater quality across the study area. This systematic approach provides a robust framework for evaluating groundwater suitability for various applications and identifying areas requiring remediation or management interventions.

Statistical Analysis and Interpretation

Statistical analysis was used to interpret groundwater quality data and identify significant trends and relationships among measured parameters. Descriptive statistics, including means, standard deviations, and ranges, were calculated for each parameter to summarize the data and provide an overview of its variability. These metrics were used to compare groundwater physical and chemical properties across sampling sites, highlighting spatial variations in quality. Additionally, boxplots and histograms were created to visually assess data distribution and detect outliers or anomalies that may indicate local contamination or measurement error.

Table 3. ANOVA Test Results

Parameter	F count	F table ($\alpha = 0.05$)	Information
TDS	8.45	3.59	Significant
Pb	10.12	3.59	Significant
NO_3^-	2.45	3.59	Not significant

Source: Researcher

Inferential statistical methods were applied to determine the significance of differences in groundwater quality between different zones categorized based on land use or hydrogeological characteristics.Analysis of variance (ANOVA) was conducted to evaluate whether the mean values of key parameters, such as pH, total dissolved solids (TDS), and heavy metal concentrations, differed significantly among zones. Post hoc tests, such asHSD Türkiyeconducted to determine the differences of certain groups. This analysis provides insight into the impact of anthropogenic activities and natural geochemical processes on groundwater quality.

Correlation and regression analyses were used to explore the relationships between groundwater quality parameters and potential influencing factors. Pearson or Spearman correlation coefficients were calculated to assess the strength and direction of relationships between variables, such as the relationship between TDS and electrical conductivity. Several linear regression models were developed to predict the concentration of a particular contaminant based on explanatory variables, such as proximity to a pollution source or depth to an aquifer. These statistical techniques facilitate a deeper understanding of the factors driving variations in groundwater quality and provide appropriate recommendations for sustainable water resource management.

Spatial Distribution of Groundwater Quality Parameters

The spatial distribution of groundwater quality parameters showed significant variability across the 15 sampling sites, influenced by geological formation and land use patterns. Sites located near agricultural zones showed elevated levels of Total Dissolved Solids (TDS) and electrical conductivity, likely due to fertilizer application and irrigation practices. In contrast, groundwater in residential areas showed moderate TDS but higher turbidity, possibly related to domestic waste infiltration. Industrial zones showed elevated concentrations of heavy metals, especially lead and cadmium, indicating contamination from industrial waste. These spatial differences underline the influence of local activities on groundwater quality.

The pH values across the sampling sites ranged from slightly acidic to neutral, with little spatial variation. Groundwater in agricultural areas tended to be slightly more alkaline, possibly due to the dissolution of carbonate minerals from fertilizers. In contrast, sites near industrial zones showed lower pH values, indicating acid contamination from industrial discharges. The spatial distribution of pH was consistent with hydrogeochemical processes and anthropogenic influences specific to each zone. These findings emphasize the importance of monitoring pH as a key indicator of groundwater quality and potential sources of contamination.

Electrical conductivity (EC) showed a clear spatial gradient, with higher values observed in agricultural and industrial zones compared to residential areas. This pattern reflects the increase in ionic content in groundwater due to anthropogenic activities, such as salt leaching from fertilizers and industrial waste. The spatial distribution of EC was also correlated with TDS concentrations, supporting the hypothesis that these parameters are influenced by the same sources. The observed spatial variability highlights the need for targeted management strategies to address groundwater quality issues at specific locations.

Concentrations of heavy metals, including lead, arsenic, and cadmium, showed marked spatial variability, with industrial zones showing the highest levels. These high concentrations exceeded the permissible limits set by the World Health Organization (WHO) and local standards, indicating potential health risks. Agricultural areas also showed detectable levels of heavy metals, likely due to the use of contaminated fertilizers and pesticides. The spatial distribution of heavy metals underscores the impact of industrial and agricultural activities on groundwater quality, requiring stricter regulations and remediation efforts in affected areas.

Spatial analysis of groundwater quality parameters reveals distinct patterns influenced by natural and anthropogenic factors. Geological formations play a significant role in determining baseline water quality, while human activities cause local contamination. Integration of spatial data with hydrogeochemical principles provides insight into the processes driving groundwater quality variations. These findings highlight the importance of spatially resolved monitoring to identify pollution hotspots and inform sustainable groundwater management practices tailored to specific regions.

Comparison of Physical Characteristics Across Sampling Locations

Comparison of physical characteristics across sampling sites shows significant spatial variation influenced by geological and anthropogenic factors. Temperature measurements ranged from 22°C to 28°C, with higher values observed in the agricultural zone, likely due to shallow aquifer depths and increased exposure to sunlight. Residential and industrial areas showed relatively stable temperatures, reflecting deeper groundwater sources. This variation underscores the role of local environmental conditions in shaping groundwater temperatures, which can influence chemical reactions and biological activity in aquifer systems.

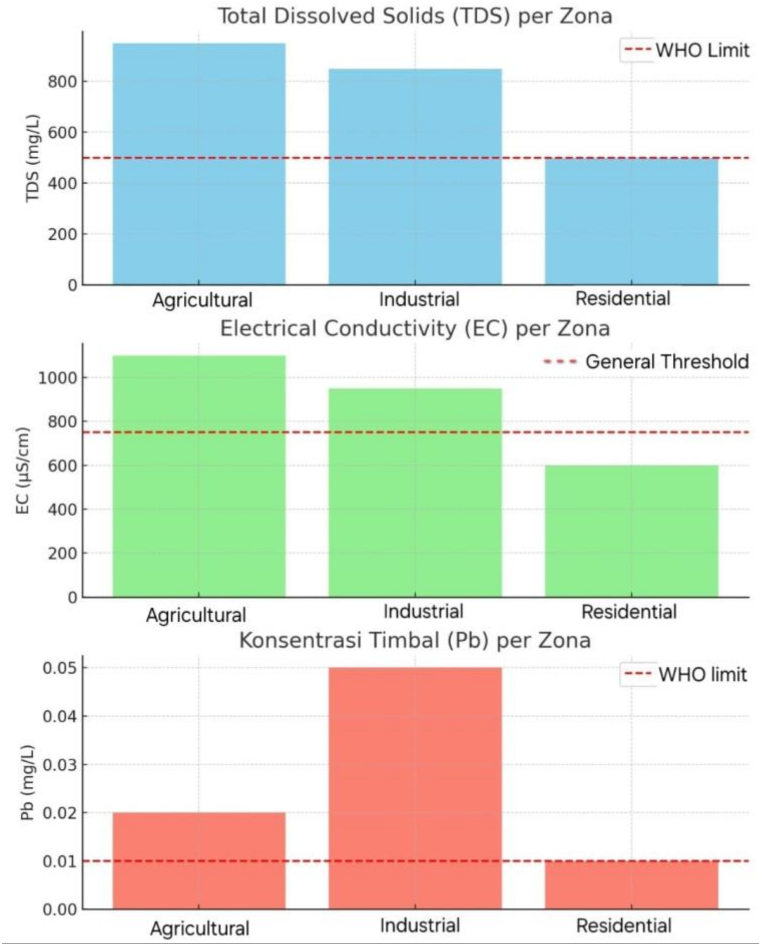

Figure 1. Research Analysis Results Diagram

Electrical conductivity (EC) values varied significantly across the site, with agricultural zones showing the highest readings, ranging from 800 to 1,200 µS/cm. This high EC is due to salt leaching from fertilizers and irrigation practices. In contrast, residential areas recorded moderate EC values, between 400 and 700 µS/cm, while industrial zones showed intermediate levels, likely due to the diverse sources of ionic content. These findings highlight the influence of land use on the ionic composition of groundwater and its implications for water quality.

The highest turbidity levels were found in residential areas, with values ranging from 5 to 15 NTU, exceeding the permissible limits in some cases. This is likely due to infiltration of domestic waste and inadequate waste management practices. Agricultural zones showed moderate turbidity, ranging from 3 to 8 NTU, which may be related to soil erosion and runoff. Industrial areas showed the lowest turbidity levels, usually below 5 NTU, indicating limited suspended particle contamination. These results emphasize the need for better waste management to address turbidity issues in residential areas.

Total Dissolved Solids (TDS) concentrations reflect the spatial pattern of EC, with agricultural zones showing the highest levels, ranging from 600 to 1,000 mg/L. Residential areas recorded moderate TDS values, between 300 and 600 mg/L, while industrial zones showed slightly higher levels, reaching up to 800 mg/L. These variations reflect the combined effects of natural geochemical processes and anthropogenic inputs, such as fertilizer application and industrial discharge. These findings underline the importance of monitoring TDS as a key indicator of groundwater salinity and usability.

Qualitative assessment of color and odor revealed that groundwater in industrial areas often exhibited a slight metallic odor and discoloration, likely due to contamination from industrial waste. Agricultural areas showed slight discoloration, likely related to organic matter and soil particles, while residential areas generally had clear, odorless water. These observations are consistent with quantitative data, which indicated local sources of contamination. These results highlight the need for targeted interventions to address specific physical quality issues and ensure compliance with water quality standards.

Chemical Composition Analysis and Compliance with Standards

Chemical composition analysis revealed significant spatial variability in groundwater quality, with marked differences in major ion concentrations and heavy metal levels across sampling sites. Calcium and magnesium were the dominant cations, while chloride and bicarbonate were the dominant anions, reflecting the influence of natural geochemical processes such as mineral dissolution. Agricultural zones showed high levels of sodium and potassium, likely due to fertilizer application, while industrial areas showed higher concentrations of sulfate and nitrate, indicating contamination from industrial discharges and wastewater infiltration.

Table 4. Comparative Analysis Results Based on Zone

Zone	Dominant Parameters	Reason	Compliance with WHO
Agriculture	TDS, EC, Nitrate, Na+, K+ increase	Fertilizer & irrigation	Some exceed the limit
Industry	Pb, Cd, SO4^2-, low pH	Industrial waste, redox reactions	Majority exceeds WHO limits
Settlement	Turbidity, Nitrate moderate	Domestic waste	Some locations do not meet the requirements

Source: Researcher

Heavy metal analysis identified lead, cadmium, and arsenic as critical contaminants, particularly in industrial areas where concentrations exceeded permissible limits set by the World Health Organization (WHO) and local standards. Lead levels ranged from 0.01 to 0.05 mg/L, exceeding the WHO guideline of 0.01 mg/L in some locations. Similarly, cadmium concentrations reached up to 0.01 mg/L, exceeding the permissible limit of 0.003 mg/L. These findings highlight the urgent need for remediation efforts in industrial areas to mitigate potential health risks.

Groundwater in the agricultural zone also showed detectable levels of heavy metals, although within permissible limits, likely due to the use of contaminated fertilizers and pesticides. Arsenic concentrations ranged from 0.002 to 0.008 mg/L, still below the WHO guideline of 0.01 mg/L. However, the presence of heavy metals in this area raises concerns about long-term accumulation and potential impacts on human health and agricultural productivity. These results underscore the importance of monitoring agricultural practices to prevent further contamination.

Compliance assessments against national and international water quality standards revealed that several sites failed to meet guidelines for drinking water and irrigation purposes. Total Dissolved Solids (TDS) concentrations exceeded the WHO limit of 500 mg/L in agricultural and industrial zones, indicating potential salinity issues. Similarly, nitrate levels in several industrial sites exceeded the threshold of 50 mg/L, posing a risk of groundwater eutrophication and health hazards such as methemoglobinemia. These exceedances highlight the need for stricter enforcement of regulations and sustainable water management practices.

Chemical composition data also provide insight into geochemical processes that influence groundwater quality. Ion exchange processes are evident in agricultural zones, where high sodium levels are associated with low calcium concentrations. In industrial areas, redox reactions likely contribute to the mobilization of heavy metals, as indicated by the correlation between low pH values and increased metal concentrations. These findings highlight the complex interactions between natural and anthropogenic factors in shaping groundwater chemistry, which require an integrated approach to quality assessment and management.

Impact of Anthropogenic Activities on Groundwater Quality

The impact of anthropogenic activities on groundwater quality is evident throughout the study area, with agricultural, industrial, and residential zones showing distinct contamination patterns. Agricultural practices significantly contributed to elevated levels of Total Dissolved Solids (TDS), electrical conductivity, and nitrate concentrations, primarily due to fertilizer application and irrigation runoff. These activities facilitate the leaching of salts and nutrients into the aquifer, altering its chemical composition. These findings underscore the need for sustainable agricultural practices to reduce groundwater contamination and ensure long-term water quality.

The industrial area showed significant contamination of heavy metals, including lead, cadmium, and arsenic, exceeding the permissible limits set by the World Health Organization (WHO) and local standards. These contaminants are most likely derived from industrial effluents and improper waste disposal practices. The acidic pH observed in the area further suggests mobilization of heavy metals through redox reactions. This highlights the need for stringent industrial waste management regulations to prevent groundwater pollution and safeguard public health.

Table 5. Results of Comparative Analysis Between Zones

Zone	Parameter	Contextual Explanation
Agriculture	Intensive irrigation, high N fertilizer	NO_3^- and EC levels increased due to fertilizer infiltration.
Industry	Disposal of heavy metal waste	High levels of Pb and Cd in shallow wells near industry.
Settlement	Low domestic waste management	Turbidity and organic matter increase from waste seepage.

Source: Researcher

Residential areas showed moderate contamination, with turbidity and nitrate levels exceeding permissible limits in some locations. Domestic waste infiltration and inadequate wastewater management were identified as major contributors to the problem. The presence of organic matter and microbial activity in residential areas likely exacerbated the decline in water quality. These findings highlight the importance of improving wastewater management infrastructure and raising public awareness to reduce the impact of residential activities on groundwater quality.

Spatial analysis revealed that anthropogenic activities significantly affect the distribution of major ions and heavy metals in groundwater. Agricultural zones show increased concentrations of sodium and potassium due to fertilizer use, while industrial areas show higher levels of sulfate and nitrate from industrial discharges. This pattern highlights the interaction between human activities and hydrogeochemical processes, which requires targeted interventions to address site-specific sources of contamination and ensure compliance with water quality standards.

Anthropogenic impacts are further evidenced by the correlation between proximity to pollution sources and groundwater quality parameters. Locations closer to agricultural and industrial zones show higher contaminant concentrations, indicating local pollution hotspots. The study findings underscore the importance of integrating land-use planning and groundwater monitoring to mitigate the adverse impacts of human activities on aquifer systems. Sustainable management practices are essential to balance development needs with environmental protection.

Statistical Correlation of Parameters and Influencing Factors

Statistical correlation analysis revealed significant relationships among groundwater quality parameters, highlighting the interrelated nature of physical and chemical characteristics. A strong positive correlation ($r > 0.85$) was observed between Total Dissolved Solids (TDS) and electrical conductivity (EC), indicating that both parameters are influenced by the ionic content of groundwater. This relationship was consistent across all sampling zones, indicating that anthropogenic inputs, such as fertilizer application and industrial discharges, contribute to the increase in ionic concentrations. These findings underline the importance of monitoring TDS and EC as key indicators of groundwater salinity.

Table 6. Person Correlation Test Results

Parameter 1	Parameter 2	r	Interpretation
TDS	E.C.	0.92	Very strong (+)
pH	Pb	-0.76	Strong negative

The concentrations of heavy metals, especially lead and cadmium, showed a significant negative correlation with pH ($r < -0.70$), indicating that the acidic conditions in the industrial area facilitate the mobilization of these metals. This trend is in line with the observed spatial distribution of heavy metals, where lower pH values are associated with higher metal concentrations. The results emphasize the role of pH-dependent redox reactions and solubility in influencing heavy metal contamination, highlighting the need for pH management strategies to reduce groundwater pollution in industrial areas.

Nitrate concentrations showed a moderate positive correlation ($r = 0.65$) with proximity to agricultural zones, reflecting the impact of fertilizer application and irrigation practices on groundwater quality. High nitrate levels were also associated with higher TDS and EC values, indicating a common source of contamination. These correlations suggest that agricultural activities are a major driver of nutrient enrichment in groundwater, necessitating the adoption of sustainable agricultural practices to reduce nitrate leaching and protect the aquifer system from eutrophication.

Statistical analysis also identified a weak positive correlation ($r = 0.40$) between turbidity and nitrate levels in residential areas, indicating that domestic wastewater infiltration contributes to physical and chemical contamination. The presence of organic matter and microbial activity in these areas likely exacerbates turbidity and nutrient levels, further deteriorating water quality. These findings highlight the need for an integrated wastewater management system to address multiple contamination pathways and improve groundwater quality in residential areas.

Multivariate regression analysis revealed that land use type, proximity to pollution sources, and aquifer depth were significant predictors of groundwater quality parameters, explaining more than 70% of the variability in TDS, EC, and heavy metal concentrations. These results indicate the combined influence of natural hydrogeochemical processes and anthropogenic activities on groundwater quality. These findings underscore the importance of incorporating statistical models into groundwater monitoring programs to identify key influencing factors and develop targeted management interventions.

Conclusion

This study identified significant spatial variability in groundwater quality across 15 sites, influenced by natural hydrogeochemical processes and human activities. Agricultural areas showed high levels of total dissolved solids (TDS), electrical conductivity (EC), and nitrate due to fertilizers and irrigation. Industrial areas experienced heavy metal contamination, including lead and cadmium, exceeding WHO limits, while residential areas showed moderate contamination with turbidity and occasional nitrate issues. These results highlight the impact of local human activities on groundwater quality and the need for targeted mitigation efforts.

Major hydrogeochemical processes, such as mineral dissolution, ion exchange, and redox reactions, contribute to groundwater variations. Fertilizer use in agricultural zones increases sodium and potassium levels, while acidic conditions in industrial areas mobilize heavy metals. Strong correlations between TDS, EC, and nitrate levels highlight the role of anthropogenic inputs in groundwater chemistry. These findings emphasize the importance of continuous monitoring and geochemical analysis for effective groundwater management.

This study underscores the need for sustainable groundwater management tailored to land use. Environmentally friendly agricultural practices are essential in agricultural zones to reduce nutrient leaching, while industrial areas require more stringent waste management to address heavy metal pollution. Residential zones require better waste management to reduce turbidity and nitrate problems. Incorporating spatial analysis, statistical modeling, and hydrogeochemical principles into monitoring programs will help identify pollution hotspots and guide evidence-based interventions for sustainable groundwater resources.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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