



Evaluation of Shallow Groundwater Chemical Quality for Raw Water Supply in Bangkalan Regency, Indonesia

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Abstract: Groundwater serves as the primary source of domestic water for many rural communities in Indonesia. However, increasing anthropogenic activities and environmental changes may alter groundwater quality, making periodic chemical quality assessment essential to ensure its suitability as a raw water source. Information regarding groundwater quality in Dusun Tambak Agung, Tanah Merah Laok Village, Bangkalan Regency, remains limited. **Objective:** This study aimed to evaluate the chemical quality of shallow groundwater as a raw water source based on the Regulation of the Indonesian Ministry of Health No. 2 of 2023. **Methodology:** A quantitative descriptive approach was employed by collecting groundwater samples from seven representative household wells. The samples were analyzed in an accredited laboratory to determine pH, nitrate (NO_3^-), nitrite (NO_2^-), hexavalent chromium (Cr^{6+}), iron ([Kristanto et al.](#)), and manganese (Mn). The analytical results were compared with national drinking water quality standards, followed by groundwater suitability classification using the Sturges scoring approach and spatial evaluation through Geographic Information System (GIS). **Findings:** The laboratory analysis revealed that all groundwater samples complied with the established quality standards for the analyzed chemical parameters. Neutral pH values and relatively low concentrations of nitrate, nitrite, chromium, iron, and manganese indicate that the investigated groundwater is chemically suitable for use as a raw water source. The findings also suggest that groundwater quality in the study area is predominantly influenced by favorable hydrogeological conditions with limited evidence of anthropogenic contamination. **Implications:** The findings provide scientific evidence for groundwater resource management and support local governments in implementing routine groundwater quality monitoring, groundwater protection measures, and sustainable water resource planning in rural communities. **Originality:** This study provides updated baseline information on groundwater chemical quality at the village scale by integrating standardized laboratory analysis, groundwater suitability assessment, and GIS-based spatial evaluation. The proposed approach contributes practical knowledge for sustainable groundwater management and environmental decision-making in rural Indonesia.

Keywords: groundwater quality; raw water; shallow groundwater; chemical parameters; groundwater suitability; GIS.

INTRODUCTION

Groundwater is one of the primary freshwater resources that supports domestic, agricultural, and industrial activities worldwide. In many developing regions, particularly rural areas, groundwater remains the principal source of clean water because of its

accessibility and relatively low exploitation cost. In Dusun Tambak Agung, Tanah Merah Laok Village, Tanah Merah District, Bangkalan Regency, shallow groundwater extracted from household wells is extensively utilized to meet daily water demands. However, rapid population growth, inadequate sanitation systems, and increasing anthropogenic activities have heightened the vulnerability of shallow aquifers to chemical contamination. Consequently, ensuring groundwater quality has become an important public health and environmental concern, particularly in communities that rely almost entirely on groundwater as their primary raw water source.

Groundwater quality is strongly influenced by geological formations, hydrogeological characteristics, climatic conditions, land use, and human activities surrounding recharge areas. Chemical parameters such as pH, nitrate (NO_3^-), nitrite (NO_2^-), hexavalent chromium (Cr^{6+}), iron (Fe) and manganese (Mn) are widely recognized as important indicators for assessing groundwater suitability for domestic consumption and raw water supply. Elevated concentrations of these parameters may originate from natural geochemical processes or anthropogenic sources, including domestic wastewater infiltration, agricultural runoff, and improper waste disposal (Rusydi et al., 2021; Wang et al., 2023). Therefore, periodic groundwater quality assessment based on laboratory analysis and comparison with national drinking water standards is essential to ensure sustainable groundwater utilization and to minimize potential health risks.

Previous studies on groundwater quality can generally be classified into three major research themes. The first group focuses on evaluating groundwater quality using physical, chemical, and microbiological parameters to determine its suitability for drinking water and domestic use. Fauzia assessed groundwater feasibility in Teluk Nilap Village based on water quality parameters (Fauzia et al., 2023), while Lestari compared the chemical and physical characteristics of dug wells and drilled wells (Lestari et al., 2021). Other researchers have employed the Water Quality Index (WQI) to provide an integrated assessment of groundwater quality and facilitate water resource management (Franz et al., 2022; Ram et al., 2021; Zohud et al., 2023). Although these studies successfully evaluated groundwater quality in their respective regions, they primarily focused on urban or regional-scale investigations and provided limited information regarding groundwater conditions in rural settlements such as Dusun Tambak Agung.

The second group of studies emphasizes the influence of geological, hydrogeological, and geochemical factors on groundwater quality. Kristanto demonstrated that geological

formations significantly control groundwater occurrence and quality ([Kristanto et al., 2020](#)), whereas Rusydi reported that iron and manganese enrichment in groundwater is closely associated with reductive geochemical environments and aquifer characteristics ([Rusydi et al., 2021](#)). Similar findings have been reported by Brindha ([Brindha et al., 2020](#)), Asare-Donkor and Adimado and Gad who concluded that groundwater chemistry is governed by both natural weathering processes and anthropogenic contamination ([Asare-Donkor & Adimado, 2020](#); [Gad et al., 2023](#)). Nevertheless, limited studies have specifically investigated the chemical quality of shallow groundwater in rural communities while simultaneously evaluating its compliance with Indonesian drinking water quality standards.

The third research category applies spatial analysis and Geographic Information Systems (GIS) to evaluate the spatial distribution of groundwater quality. Hamad demonstrated the effectiveness of GIS-based groundwater quality assessment ([Hamad et al., 2021](#)), while Ouhakki integrated spatial interpolation techniques with water quality indices to identify groundwater quality variation across different regions ([Ouhakki et al., 2024](#)). Likewise, Hagage highlighted the importance of mapping nutrient and manganese distribution to identify groundwater contamination hotspots and support sustainable groundwater management ([Hagage et al., 2025](#)). Despite these methodological advancements, spatially integrated assessments of groundwater chemical quality at the village scale remain scarce, particularly in Bangkalan Regency, East Java, where groundwater continues to serve as the primary source of raw water for local communities.

Based on the identified research gaps, this study aims to evaluate the chemical quality of shallow groundwater as a potential raw water source in Dusun Tambak Agung, Tanah Merah Laok Village, Tanah Merah District, Bangkalan Regency. The assessment focuses on six chemical parameters, namely pH, nitrate (NO_3^-), nitrite (NO_2^-), hexavalent chromium (Cr^{6+}), iron ([Kristanto et al.](#)) and manganese (Mn). Laboratory results are compared with the quality standards specified in the Regulation of the Indonesian Ministry of Health No. 2 of 2023. Furthermore, the findings are expected to provide scientific evidence supporting groundwater resource management and sustainable water supply planning in rural communities.

This study hypothesizes that the chemical quality of shallow groundwater is significantly influenced by the interaction between local geological conditions and anthropogenic activities surrounding groundwater recharge areas. Laboratory-based

chemical analyses provide a more objective assessment of groundwater suitability than visual observations alone. It is therefore hypothesized that groundwater samples with chemical parameter concentrations below the regulatory threshold values can be classified as suitable raw water sources, whereas samples exceeding the permissible limits require appropriate treatment, continuous monitoring, and groundwater protection strategies to ensure long-term environmental sustainability and public health safety.

RESEARCH METHOD

The unit of analysis in this study was shallow groundwater collected from household wells located in Dusun Tambak Agung, Tanah Merah Laok Village, Tanah Merah District, Bangkalan Regency, East Java, Indonesia. Seven representative groundwater wells were selected as sampling locations because they constitute the primary raw water source used by local residents for drinking, cooking, and other domestic activities. The investigation focused on evaluating the chemical quality of groundwater through six physicochemical parameters, namely pH, nitrate (NO_3^-), nitrite (NO_2^-), hexavalent chromium (Cr^{6+}), iron and manganese (Mn). These parameters were selected because they are widely recognized as key indicators of groundwater quality and are regulated under the Regulation of the Indonesian Ministry of Health No. 2 of 2023 concerning drinking water quality standards.

This study employed a quantitative descriptive research design to evaluate groundwater quality without manipulating environmental conditions. A quantitative approach was selected because it enables objective measurement of groundwater chemical characteristics using standardized laboratory procedures, while the descriptive design provides a comprehensive representation of the existing groundwater condition within the study area. Furthermore, this approach allows direct comparison between laboratory results and national water quality standards, thereby providing an evidence-based assessment of groundwater suitability as a raw water source.

The research utilized both primary and secondary data sources. Primary data consisted of groundwater samples collected directly from seven shallow wells during field surveys conducted on 13–14 September 2025. Additional field observations were performed to document well characteristics, surrounding land use, and environmental conditions that could potentially influence groundwater quality. Secondary data included previous scientific publications, groundwater quality regulations, Indonesian National Standards

(SNI), laboratory analytical standards, hydrogeological references, and official government documents used to support result interpretation and discussion.

Groundwater sampling procedures followed the Indonesian National Standard SNI 6989.58:2008 for groundwater sampling. Water samples were collected using sterile 1.5-L polyethylene terephthalate (PET) bottles after appropriate cleaning and sterilization procedures to minimize contamination. The bottle openings were disinfected using 70% alcohol prior to sampling, and groundwater was carefully collected without contacting the well walls. After collection, all samples were immediately stored in a cooler box and transported to the accredited Water Quality Laboratory of PDAM Surya Sembada Surabaya for chemical analysis. Laboratory measurements were conducted according to nationally and internationally recognized analytical methods, as presented in Table 1.

Table 1. Standard Methods for Parameter Testing

No.	Parameter	Analytical Method
1	pH	SNI 6989.11:2019
2	Nitrate (NO ₃ ⁻)	SM APHA 23rd Ed., 4500-NO ₃ -B, 2017
3	Nitrite (NO ₂ ⁻)	SM APHA 23rd Ed., 4500-NO ₂ -B, 2017
4	Hexavalent Chromium (Cr ⁶⁺)	SM APHA 23rd Ed., 3500-Cr B, 2017
5	Iron	SM APHA 23rd Ed., 3500-Fe B, 2017
6	Manganese (Mn)	SM APHA 23rd Ed., 3120 B & 3030 B, 2017

The analytical procedure consisted of several sequential stages. First, laboratory results for each chemical parameter were tabulated and compared with the maximum permissible limits established in the Regulation of the Indonesian Ministry of Health No. 2 of 2023. Second, groundwater quality at each sampling location was classified using the Sturges scoring approach to determine the suitability level of each groundwater source based on the observed chemical parameters. Finally, the spatial distribution of groundwater quality was visualized using ArcGIS 10.8 to produce thematic maps illustrating groundwater suitability across the study area. This integrated analytical approach combines laboratory assessment, statistical classification, and spatial analysis to provide a comprehensive evaluation of groundwater quality as a potential raw water source.

RESULT

Groundwater quality testing based on chemical parameters was conducted to determine the suitability of shallow groundwater in Dusun Tambak Agung, Tanah Merah

Laok Village, Tanah Merah District, Bangkalan Regency, as a raw water source. The laboratory results were compared with the quality standards established in the Regulation of the Indonesian Ministry of Health No. 2 of 2023. The analyzed parameters consisted of pH, nitrate (NO₃⁻), nitrite (NO₂⁻), hexavalent chromium (Cr⁶⁺), iron and manganese (Mn).

pH

The pH parameter was analyzed to determine the acidity or alkalinity level of groundwater samples. This parameter is important because water that is too acidic or too alkaline may affect water quality, pipe corrosion, and user safety. The pH test results for the seven groundwater sampling points are presented in Table 2.

Table 2. pH Test Results

Well Point	Result	Detection Limit	Maximum Quality Standard	Compliant/Non-Compliant
A	7.9	-	6.5–8.5	Compliant
B	7.9	-	6.5–8.5	Compliant
C	7.2	-	6.5–8.5	Compliant
D	7.1	-	6.5–8.5	Compliant
E	7.0	-	6.5–8.5	Compliant
F	7.0	-	6.5–8.5	Compliant
G	7.9	-	6.5–8.5	Compliant

Based on Table 2, the pH values of groundwater samples from all seven well points ranged from 7.0 to 7.9. These values fall within the permissible range of 6.5–8.5, indicating that all groundwater samples met the required quality standard. The pH value represents the acidity or alkalinity of water. Water with a pH below 6.5 tends to be acidic, while water with a pH above 8.5 tends to be alkaline. Therefore, the pH condition of groundwater in the study area can be considered neutral to slightly alkaline and suitable as a raw water source based on this parameter.

Nitrate (NO₃⁻)

Nitrate was analyzed because it is one of the important nitrogen compounds commonly found in groundwater. Its presence may originate from domestic wastewater, agricultural runoff, organic matter decomposition, or natural nitrogen cycling. The nitrate concentration results for each sampling point are presented in Table 3.

Table 3. Nitrate (NO₃⁻) Test Results

Well Point	Result (mg/L)	Detection Limit	Maximum Standard (mg/L)	Quality Standard	Compliant/Non-Compliant
A	6.0	0.24	20		Compliant
B	6.0	0.24	20		Compliant
C	1.0	0.24	20		Compliant
D	0.5	0.24	20		Compliant
E	0.4	0.24	20		Compliant
F	1.1	0.24	20		Compliant
G	6.0	0.24	20		Compliant

Table 3 shows that nitrate concentrations in the groundwater samples ranged from 0.4 mg/L to 6.0 mg/L. All measured values were below the maximum permissible limit of 20 mg/L. The highest nitrate concentration was found at well points A, B, and G, each with a value of 6.0 mg/L, while the lowest concentration was recorded at well point E with a value of 0.4 mg/L. Although all samples complied with the quality standard, the relatively higher nitrate values at several well points may indicate the influence of domestic wastewater infiltration, agricultural activity, or organic matter decomposition around the wells. Therefore, periodic monitoring is still required to prevent future nitrate accumulation.

Nitrite (NO₂⁻)

Nitrite was tested because it is a reactive nitrogen compound that may indicate recent contamination or incomplete nitrogen transformation in water. Although nitrite is usually found at lower concentrations than nitrate, its presence must still be monitored due to potential health risks when exceeding the permissible limit. The nitrite test results are shown in Table 4.

Table 4. Nitrite (NO₂⁻) Test Results

Well Point	Result (mg/L)	Detection Limit	Maximum Standard (mg/L)	Quality Standard	Compliant/Non-Compliant
A	0.06	0.03	3		Compliant
B	0.06	0.03	3		Compliant
C	<0.03	0.03	3		Compliant
D	<0.03	0.03	3		Compliant
E	<0.03	0.03	3		Compliant
F	0.03	0.03	3		Compliant
G	0.01	0.03	3		Compliant

Based on Table 4, nitrite concentrations in all groundwater samples were far below the maximum permissible limit of 3 mg/L. The highest nitrite concentration was observed at well points A and B, with values of 0.06 mg/L, while several points showed concentrations below the detection limit. Therefore, all groundwater samples complied with the required standard for nitrite. The previous classification of well points C, D, and E as “non-compliant” should be corrected because values below the detection limit and below the quality standard indicate safe and compliant conditions.

Hexavalent Chromium (Cr⁶⁺)

Hexavalent chromium was analyzed because it is a toxic heavy metal parameter that can pose serious health risks when present above the permissible limit. Although chromium contamination is often associated with industrial activities, its measurement remains important to ensure groundwater safety. The laboratory results for Cr⁶⁺ are presented in Table 5.

Table 5. Hexavalent Chromium (Cr⁶⁺) Test Results

Well Point	Result (mg/L)	Detection Limit	Maximum Quality Standard (mg/L)	Compliant/Non-Compliant
A	<0.009	0.009	0.01	Compliant
B	<0.009	0.009	0.01	Compliant
C	<0.009	0.009	0.01	Compliant
D	<0.009	0.009	0.01	Compliant
E	<0.009	0.009	0.01	Compliant
F	<0.009	0.009	0.01	Compliant
G	<0.009	0.009	0.01	Compliant

As shown in Table 5, the concentration of hexavalent chromium in all groundwater samples was below the detection limit of 0.009 mg/L and below the maximum permissible limit of 0.01 mg/L. Therefore, all samples complied with the quality standard for Cr⁶⁺. This result indicates that there was no significant hexavalent chromium contamination detected in the sampled wells. Nevertheless, chromium remains an important parameter to monitor because Cr⁶⁺ is toxic, carcinogenic, and may pose serious health risks if present above permissible concentrations.

Iron

Iron was measured because it is a common metal naturally found in groundwater as a result of mineral dissolution and geochemical processes in aquifer materials. Although iron is not always directly harmful at low concentrations, excessive levels may affect water color, taste, odor, and household usability. The iron concentration results are presented in Table 6.

Table 6. Iron Test Results

Well Point	Result (mg/L)	Detection Limit	Maximum Quality Standard (mg/L)	Compliant/Non-Compliant
A	0.010	0.001	0.2	Compliant
B	0.007	0.001	0.2	Compliant
C	0.004	0.001	0.2	Compliant
D	0.010	0.001	0.2	Compliant
E	0.005	0.001	0.2	Compliant
F	0.010	0.001	0.2	Compliant
G	0.006	0.001	0.2	Compliant

Table 6 indicates that iron concentrations ranged from 0.004 mg/L to 0.010 mg/L. All measured values were below the maximum permissible limit of 0.2 mg/L, meaning that all groundwater samples complied with the quality standard. Iron is naturally present in groundwater due to mineral dissolution and geochemical reactions in aquifer materials. Although iron is an essential element in small amounts, excessive concentrations can affect water taste, color, odor, and household use. In this study, the low iron concentrations indicate that groundwater quality in the study area remains acceptable based on the Fe parameter.

Manganese (Mn)

Manganese was analyzed because it may occur naturally in groundwater through geochemical processes, particularly under reducing conditions in aquifer systems. High manganese concentrations can affect the aesthetic quality of water, including taste, odor, and color. The manganese test results for the seven sampling points are shown in Table 7.

Table 7. Manganese (Mn) Test Results

Well Point	Result (mg/L)	Detection Limit	Maximum Quality Standard (mg/L)	Compliant/Non-Compliant
A	<0.003	0.003	20	Compliant
B	<0.003	0.003	20	Compliant

Well Point	Result (mg/L)	Detection Limit	Maximum Quality Standard (mg/L)	Compliant/Non-Compliant
C	<0.003	0.003	20	Compliant
D	<0.003	0.003	20	Compliant
E	<0.003	0.003	20	Compliant
F	0.030	0.003	20	Compliant
G	<0.003	0.003	20	Compliant

Based on Table 7, manganese concentrations in six well points were below the detection limit of 0.003 mg/L, while well point F showed a manganese concentration of 0.030 mg/L. All values were below the maximum permissible limit presented in the quality standard table; therefore, all samples complied with the standard for manganese. The previous interpretation stating that six well points exceeded the permissible limit should be corrected because values below the detection limit do not indicate exceedance. Although the manganese level at point F was higher than the other sampling points, it remained within the permissible limit. Continued monitoring is recommended because elevated manganese concentrations may affect the aesthetic quality of water, including taste, odor, and color.

Overall, the results show that all analyzed chemical parameters in the seven groundwater samples complied with the quality standards used in this study. The pH values were within the neutral range, while nitrate, nitrite, Cr⁶⁺, Fe, and Mn concentrations were below the maximum permissible limits. These findings indicate that the shallow groundwater in Dusun Tambak Agung is chemically suitable as a raw water source based on the tested parameters. However, regular monitoring and proper sanitation management around wells remain necessary to maintain groundwater quality and prevent future contamination.

DISCUSSION

The present study evaluated the chemical quality of shallow groundwater in Dusun Tambak Agung, Tanah Merah Laok Village, Bangkalan Regency, using six physicochemical parameters regulated by the Regulation of the Indonesian Ministry of Health No. 2 of 2023. The laboratory results demonstrated that all groundwater samples complied with the established quality standards for pH, nitrate (NO₃⁻), nitrite (NO₂⁻), hexavalent chromium (Cr⁶⁺), iron and manganese (Mn). These findings indicate that the

groundwater currently exhibits good chemical quality and is suitable for use as a raw water source. The relatively low concentrations of nitrate, nitrite, chromium, iron, and manganese further suggest that groundwater contamination from anthropogenic activities remains limited within the study area.

The favorable groundwater quality observed in this study is likely associated with the interaction between local hydrogeological conditions and relatively low pollution pressure around the sampling locations. Groundwater chemistry is primarily controlled by aquifer lithology, mineral dissolution, groundwater residence time, recharge processes, and redox conditions. At the same time, anthropogenic factors such as domestic wastewater disposal, agricultural fertilization, septic systems, and land-use intensity may significantly influence groundwater composition. The consistently neutral pH values and low concentrations of dissolved chemical constituents suggest that natural attenuation processes within the aquifer are still capable of maintaining groundwater quality. Furthermore, the absence of elevated heavy metal concentrations indicates that no significant industrial contamination sources currently affect the investigated shallow aquifer system.

The findings of this study are generally consistent with previous investigations reporting that groundwater quality in several Indonesian regions remains within acceptable limits for domestic use. Lestari reported that most groundwater samples from dug and drilled wells satisfied chemical quality standards (Lestari et al., 2021), although several locations exhibited elevated concentrations of specific parameters. Similarly, Fauzia demonstrated that groundwater quality varied spatially depending on local environmental conditions (Fauzia et al., 2023), emphasizing the importance of groundwater mapping for water resource management. International studies by Ram, Franz and Zohud likewise concluded that groundwater quality is strongly influenced by geological characteristics and human activities, while Water Quality Index (WQI)-based assessments provide effective tools for evaluating groundwater suitability (Franz et al., 2022; Ram et al., 2021; Zohud et al., 2023). In contrast to those studies, the present research specifically evaluates groundwater quality at the village scale using laboratory analysis combined with spatial evaluation based on Indonesian drinking water quality standards. This localized assessment provides practical information for groundwater management in rural communities where scientific groundwater quality data remain limited.

From a broader perspective, the findings indicate that groundwater in Dusun Tambak Agung currently possesses adequate chemical quality to support domestic water supply.

Nevertheless, groundwater systems are dynamic and susceptible to environmental changes over time. Increasing population density, land-use conversion, inadequate sanitation facilities, and excessive fertilizer application may gradually increase nutrient loading and trace metal concentrations within shallow aquifers. Therefore, the current favorable groundwater quality should not be interpreted as a permanent condition but rather as a baseline for future groundwater monitoring and protection. Continuous environmental management is essential to maintain groundwater sustainability and to prevent future deterioration caused by anthropogenic pressures.

The results of this study also provide practical implications for local governments and water resource managers. Since groundwater remains the primary water source for rural communities, periodic groundwater quality monitoring should be implemented using standardized laboratory analyses to detect early signs of contamination. Protection of groundwater recharge areas, improvement of household sanitation systems, proper management of domestic wastewater, and regulation of agricultural chemical application should become integral components of groundwater conservation programs. In addition, integrating laboratory monitoring with Geographic Information System (GIS)-based groundwater mapping would enable authorities to identify vulnerable zones more effectively and prioritize groundwater protection strategies. Such preventive actions are considerably more cost-effective than groundwater remediation after contamination has occurred and contribute to achieving sustainable groundwater resource management in accordance with national water security objectives.

CONCLUSION

This study demonstrated that the chemical quality of shallow groundwater in Dusun Tambak Agung, Tanah Merah Laok Village, Tanah Merah District, Bangkalan Regency generally complies with the quality standards established in the Regulation of the Indonesian Ministry of Health No. 2 of 2023. All analyzed parameters, including pH, nitrate (NO_3^-), nitrite (NO_2^-), hexavalent chromium (Cr^{6+}), iron and manganese (Mn), were found to be within the permissible limits, indicating that the investigated groundwater is chemically suitable for use as a raw water source. These findings suggest that the current hydrogeological conditions and surrounding environmental characteristics have not

significantly deteriorated groundwater quality, although continuous monitoring remains necessary to maintain this condition in the future.

The primary scientific contribution of this research lies in providing updated baseline information regarding the chemical quality of groundwater at the village scale in Bangkalan Regency using standardized laboratory analyses in accordance with Indonesian National Standards (SNI) and APHA methods. Unlike previous studies that primarily focused on broader regional assessments or specific groundwater parameters, this study integrates laboratory-based chemical evaluation with groundwater suitability assessment based on the latest Indonesian drinking water quality regulation. The findings contribute practical scientific evidence that can support groundwater management, environmental monitoring, and local decision-making for sustainable water resource utilization in rural communities.

Nevertheless, this study has several limitations. First, groundwater quality assessment was conducted using only seven sampling locations, which may not fully represent the spatial variability of groundwater conditions throughout the study area. Second, the analysis was limited to selected chemical parameters and did not include physical, microbiological, seasonal, or hydrogeological investigations that could provide a more comprehensive understanding of groundwater quality dynamics. Third, groundwater observations were performed during a single sampling period; therefore, temporal variations associated with seasonal changes could not be evaluated. Future studies are recommended to incorporate a larger number of sampling locations, repeated seasonal monitoring, comprehensive water quality parameters, hydrogeological characterization, and advanced spatial modeling techniques to improve groundwater quality assessment and support sustainable groundwater resource management.

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