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Hydrogeological Evaluation of Fractured Volcanic Aquifer in Al-Sahoul Basin-IBB City-Yemen

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Abstract

The fractured Tertiary volcanic aquifer in the Al-Sahoul Basin near Ibb City, Yemen, was systematically investigated to assess groundwater quality and the impact of anthropogenic activities on this critical water resource. Sixteen groundwater samples were collected from 26 boreholes and analyzed for key physicochemical parameters, including electrical conductivity (EC), pH, total dissolved solids (TDS), total hardness, total alkalinity (TA), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), chloride (Cl^-), sulfate (SO_4^{2-}), fluoride (F^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). Advanced tools such as Geographical Information Systems (GIS) and Surfer software were employed to generate geological, hydrological, and topographical maps for data visualization and interpretation. The results revealed that wells located in the western part of the basin exhibited significant contamination, with chemical concentrations exceeding Yemeni and World Health Organization (WHO) drinking water standards. This contamination is attributed to the proximity of a landfill on the western side of the basin, likely releasing leachates that degrade the water quality and render it unsuitable for drinking. In contrast, wells in the southern and eastern parts of the basin demonstrated better water quality, meeting the required standards for drinking and agricultural use. The study highlights the vulnerability of groundwater in the Al-Sahoul Basin to anthropogenic influences, particularly improper waste disposal. It emphasizes the urgent need for effective landfill management, regular monitoring of groundwater quality, and the implementation of mitigation strategies to safeguard this vital aquifer system. The findings provide critical insights for decision-makers, encouraging the development of sustainable water resource management policies to ensure safe and reliable access to water for the region's population and agricultural needs. This research underscores the importance of proactive measures to prevent contamination and protect groundwater resources.

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1. Introduction

Yemen, one of the Arab countries with the highest population growth rates, is currently experiencing an acute water crisis. Freshwater resources are undergoing rapid depletion due to uncontrolled groundwater pumping, excessive extraction, and unregulated drilling, resulting in severe depletion of major aquifers. This unsustainable exploitation has created an increasing gap between natural recharge and withdrawals (Davison et al., 1994; Al-Sabahi et al., 2009; Khanbari, 2015; NWRA, 2020),(Fig.1). Climate change further exacerbates this scarcity, intensifying stress on the country's already fragile water resources (IPCC, 2021). According to Al-Khirbash et al. (1996), Yemen is divided into four major water basins: the Red Sea Basin, the Gulf of Aden Basin, the Arabian Sea Basin, and the Rub Al-Khali Basin (UNDP,2022). The present study focuses on the Al-Sahoul Basin, which forms part of the Red Sea Basin. The Ibb City catchment, where the study area is located, has two principal drainage systems: Wadi Maytam, which discharges into Wadi Tuban before reaching the Arabian Sea, and Wadi Al-Sahoul, which drains into Wadi Zabid and eventually flows into the Red Sea (Heikal et al., 2014; Abdulrahman et al., 2016) (Fig.1& 2). Groundwater is the most critical resource for urban development, domestic water supply, and agricultural activities in Ibb City (NWRA, 2010). Recent reports from the NWRA indicate that groundwater quality in the Al-Sahoul Basin is deteriorating, with alarming declines in the water table attributed to unregulated artesian and manually dug wells (NWRA, 2020). These practices have accelerated the depletion of groundwater reserves. Furthermore, the Environmental Protection Agency (EPA) has reported the establishment of a landfill in the study area, which poses a significant threat to groundwater quality. The landfill is a potential source of leachate contamination, directly or indirectly endangering the health of residents dependent on groundwater (Al-Oshari, 2012; El-Malt et al., 2013; Al-Sabahi et al., 2015; EPA, 2018).

Previous studies have examined the Ibb Basin more generally, focusing on geochemical assessments of its environmental impacts and its suitability for drinking and agricultural purposes. These studies have shown clear links between anthropogenic activities and groundwater degradation. Al-Sabahi et al. (2009) found that leachate from the Al-Sahool landfill infiltrated the aquifer, contaminating nearby wells with high TDS, Cl^-, NO_3^-, and NH_4^+ beyond drinking-water limits. Similarly, Al-Nozaily and Al-Sabahi (2012) confirmed elevated TDS, Cl^-, NO_2^-, NH_4^+, Ca^{2+}, Mg^{2+}, and total hardness in boreholes around the landfill, deeming the water unfit for domestic use. In the Maytam area, Mayas et al. (2015) reported unsafe levels of TDS, F^-, Cl^-, NO_2^-, and heavy metals, largely linked to wastewater effluent. More recently, El-Rayes et al. (2020) used GIS to map contamination sources, including landfill leachate, sewage discharge, and agrochemical runoff, highlighting multiple pollution hotspots within the basin. Elsewhere in Yemen, Al-Sakkaf (2013) demonstrated that rapid urbanization in the Sana'a Basin severely degraded groundwater quality through wastewater infiltration and unregulated land use, while Al-Amrani et al. (2024) investigated groundwater dynamics in relation to anthropogenic influences. Most recently, Alwathaf et al. (2025) employed scenario-based modeling in Yemen's Ibb sub-basins, estimating a groundwater recharge deficit of −10 Mm³ in 2021, potentially worsening to −44 Mm³ by 2040, with aquifer depletion projected by 2029 if interventions are not implemented. This analysis also delineated groundwater potential zones very high (26 %), high (51 %), moderate (13 %), poor (9 %), and very poor (1 %) that align with borehole distribution ($R^2 = 0.79$), providing a robust basis for strategic water-resource planning.

However, despite these contributions, there is still a lack of focused research on the Al-Sahoul Basin, particularly regarding its quantitative and qualitative groundwater characteristics and the direct impacts of the landfill on water quality. The extent to which this landfill affects drinking water quality, public health, and the surrounding environment has not been comprehensively evaluated. Based on an integrated evaluation of geochemical data and geological, hydrological, and spatial analyses using ArcGIS and Golden Surfer software, this study provides a detailed assessment of groundwater characteristics and quality within the fractured volcanic aquifer of the Al-Sahoul Basin. By combining advanced analytical methods with spatial visualization techniques, the research highlights the impacts of anthropogenic activities particularly landfill contamination and uncontrolled groundwater extraction on aquifer integrity. The findings contribute to a more comprehensive understanding of groundwater dynamics in the basin, offering critical insights to support evidence-based decision-making for sustainable water resource management and effective pollution mitigation.

2. Geological and Hydrogeological Settings

The Al-Sahoul area is geographically defined by high mountain ranges, which serve as the primary source of runoff during rainstorms for many valleys. Notably, the Ba'adan Mountains to the east and the Hobeish region to the west are the two highest points in the highlands, making them critical contributors to the hydrological recharge of the Al-Sahoul Basin (Awadh et al., 2021; Al-Mikhlafi, 2010). These topographic features are a direct result of tectonic activity that has significantly influenced the region's geological and hydrological characteristics(Fig.1). Historical tectonic movements, including uplift, volcanic eruptions, and the formation of fractures, faults, and dikes, have shaped the region's structural elements (Elkhirbash et al., 1996; Al-Oshari, 2020; Al-Sabahi et al., 2015). Among these, a prominent normal fault extends from the southeast to the northwest(Fig.2), forming the main component of Wadi Al-Sahoul. Numerous subsidiary faults intersect this primary fault at various angles, creating additional valleys. While some faults and fractures enhance groundwater availability by increasing aquifer permeability, others, such as volcanic dikes, act as barriers, leading to vertical and horizontal heterogeneity within the aquifer layers.

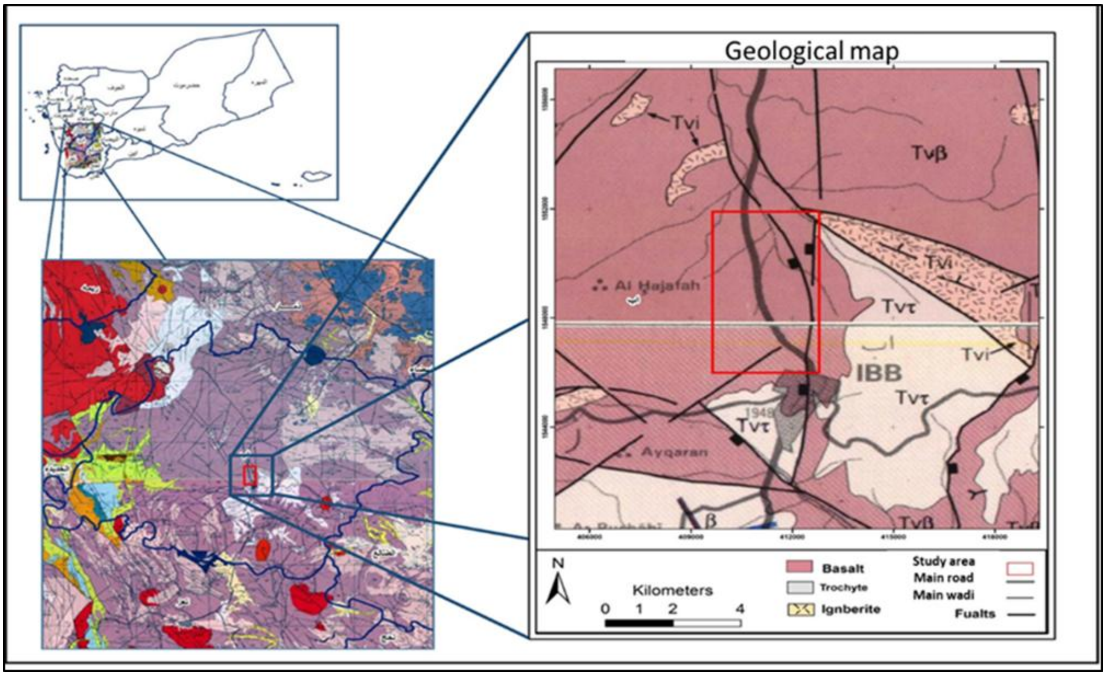

Fig. 1. General geological map of Ibb City with a zoomed-in View of the Al-Sahoul area, depicting the different lithological units. adapted from Nation Water Resources Authority (NWRA)

From a hydrological perspective, the Ibb City region, where Al-Sahoul is located, experiences similar water resource challenges as other areas in Yemen(Fig.3). However, Ibb benefits from relatively higher water availability due to substantial rainfall, numerous natural springs, and underground reserves (NWRA, 2005). The region lies within Yemen's southwestern highlands, characterized by a tropical climate where topographic features play a vital role in climatic variability. Rainfall, a critical factor for groundwater recharge, occurs in two distinct seasons: spring, driven by tropical winds from the Red Sea, and summer, influenced by equatorial currents from the Gulf of Aden and the Indian Ocean. Annual rainfall is estimated to be approximately 1,000 mm (Al-Ruwaih et al., 2007), although recent years have witnessed a significant decline in precipitation. Climatically, the region alternates between hot, rainy summers and cold, dry winters, with an average annual temperature of around 20°C.The soil and vegetation in Al-Sahoul further reflect the geological formations and prevailing climatic conditions. As noted by Elkhirbash et al. (1996), soils are primarily formed through weathering processes, and vegetation includes tropical plant species, such as trees, shrubs, and annual and perennial weeds. These are widely distributed across valleys, depressions, and agricultural fields, providing a natural ecological balance to the region.

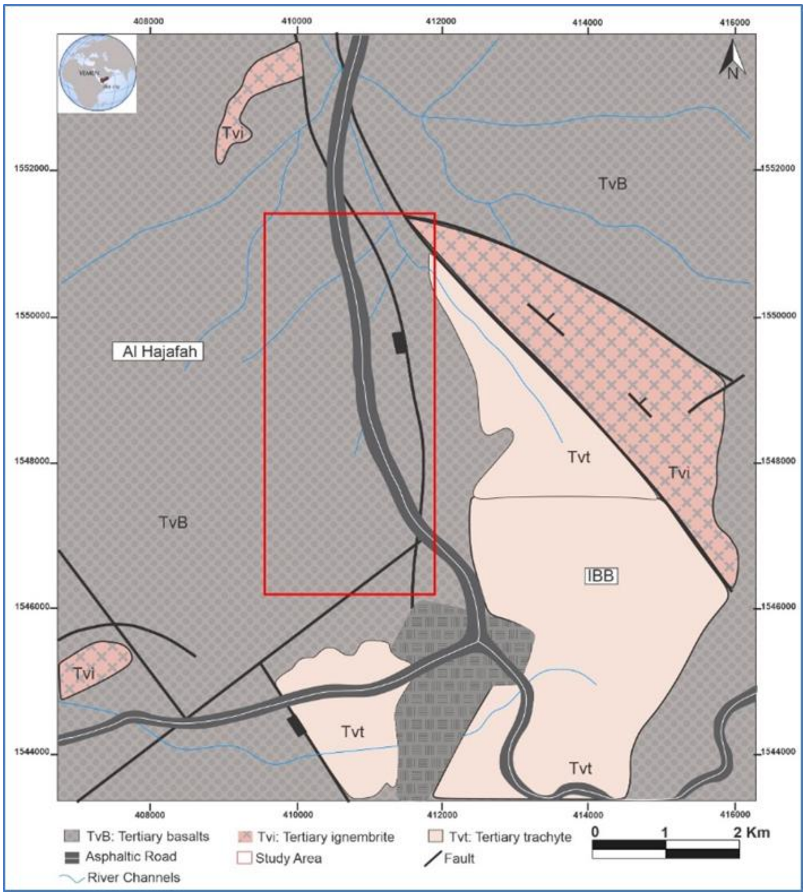

Fig. 2. Geological map of AL-Sahoul basin, modified after NWRA.

The subsurface lithological sequence in the Al-Sahoul Basin comprises two primary aquifers, each with distinct hydrogeological characteristics (Fig.3). The first is the unconfined shallow aquifer, which constitutes the uppermost aquifer and ranges in thickness from approximately 4 to 60 meters (Awadh et al., 2021). This aquifer is composed mainly of clay, gravel, and sand, with high permeability and renewable porosity. It is primarily recharged by surface water from rainfall, and the average water level in manual wells is approximately 30 meters. However, its productivity is low, ranging from 2–3 liters per second, and it is heavily depleted due to excessive water extraction and the drilling of deep boreholes (NWRA, 2005).

In contrast, the second aquifer, which is the focus of this study, is the fractured volcanic aquifer. This aquifer is composed of volcanic rocks from the Tertiary period, and its groundwater is largely confined to fracture zones, including cracks and joints (Al-Mikhlafi, 2010). It exhibits medium productivity, with yields of approximately 4–8 liters per second. The volcanic rocks primarily consist of weathered tuff, trachyte, and andesite, with a fractured bed filled with calcite veins and basalt (NWRA, 2005). The fractured nature of this aquifer, combined with its geological composition, makes it particularly dependent on structural features such as faults and fractures for water availability. Building on the foundational work of Al-Areeq et al. (2021), who emphasized the importance of integrating geochemical and spatial data in groundwater studies, and Al-Oshari et al. (2020), who highlighted the role of tectonic structures in aquifer dynamics, this study aims to comprehensively evaluate the groundwater characteristics of the Al-Sahoul Basin. Furthermore, Al-Amrani et al. (2024) explored the influence of anthropogenic activities, such as overextraction, on aquifer sustainability, providing a critical basis for addressing groundwater challenges in the region.

By synthesizing geochemical, geological, and hydrological data with advanced spatial analysis tools such as GIS and Golden Surfer, this research offers a detailed understanding of aquifer dynamics. Additionally, it assesses the vulnerability of the aquifer to both natural factors, such as tectonic structures, and anthropogenic pressures, including excessive groundwater pumping. This integrated approach aims to contribute to the development of sustainable groundwater management strategies for the Al-Sahoul Basin, ensuring the long-term viability of this vital water resource.

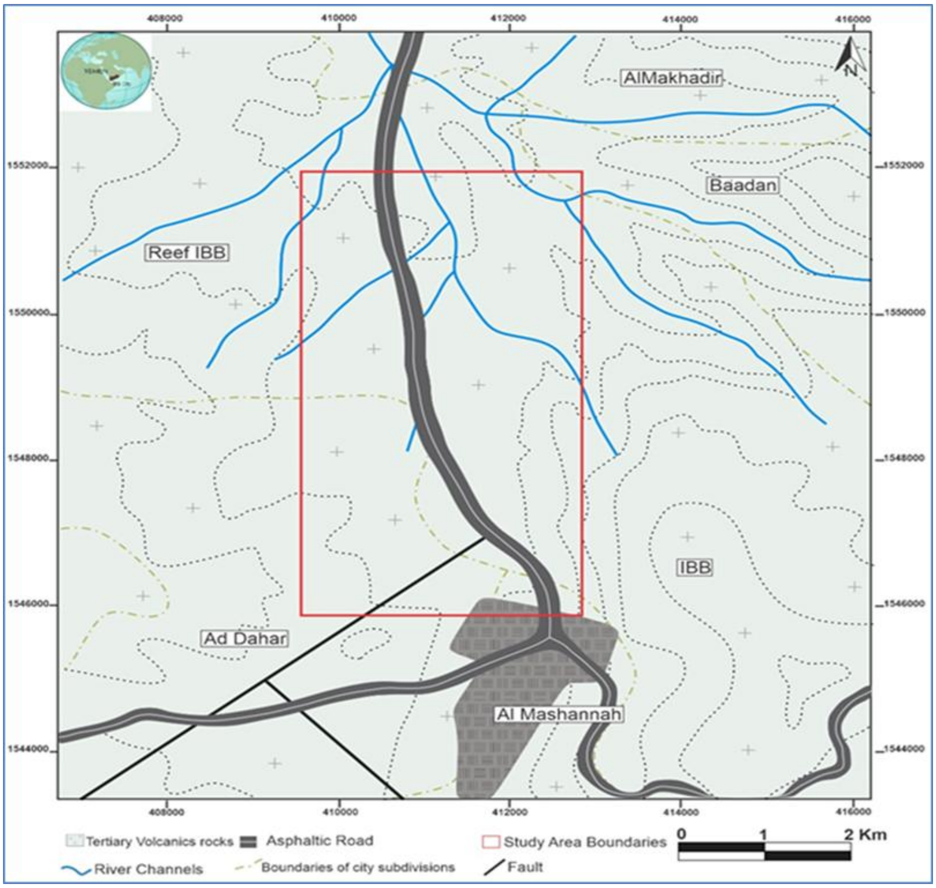

Fig. 3. Hydrological map of the study area, modified after (NWRA 2009).

3. Methodology

In November 2022, groundwater samples were collected from 16 boreholes in the Al-Sahoul area following a standardized process to ensure reliability (Fig.4). Pumping was conducted for 5 minutes to remove drilling debris, and sterilized polyethylene bottles were used for sample collection, which were labeled and refrigerated until analysis. Physical parameters, including pH and electrical conductivity (EC), were measured in the field using Multi-350i equipment, while total dissolved solids (TDS) and turbidity were analyzed using a portable Hack case. Chemical analyses for key elements such as calcium (Ca), magnesium (Mg), chloride (Cl), fluoride (F), iron (Fe), and nitrate (NO_3) were conducted using a spectrophotometer 7500 (Palintest), and sodium (Na) and potassium (K) concentrations were determined using a flame photometer. Carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and alkalinity levels were measured with a digital burette, and biological analyses were performed using an incubator to detect microbial contamination.

Laboratory procedures included cleaning, heating, sterilizing, and drying of equipment using autoclaves, oven binders, and SN 510 tools, all facilitated by the National Water Resources Authority (NWRA), Ibb branch. To visualize and interpret the data, geological, hydrological, and topographical maps, as well as contour maps of chemical parameters, were produced using Surfer, ArcGIS, and Excel. This comprehensive methodology ensured accurate and reliable data for evaluating groundwater quality in the fractured volcanic aquifer of the Al-Sahoul Basin.

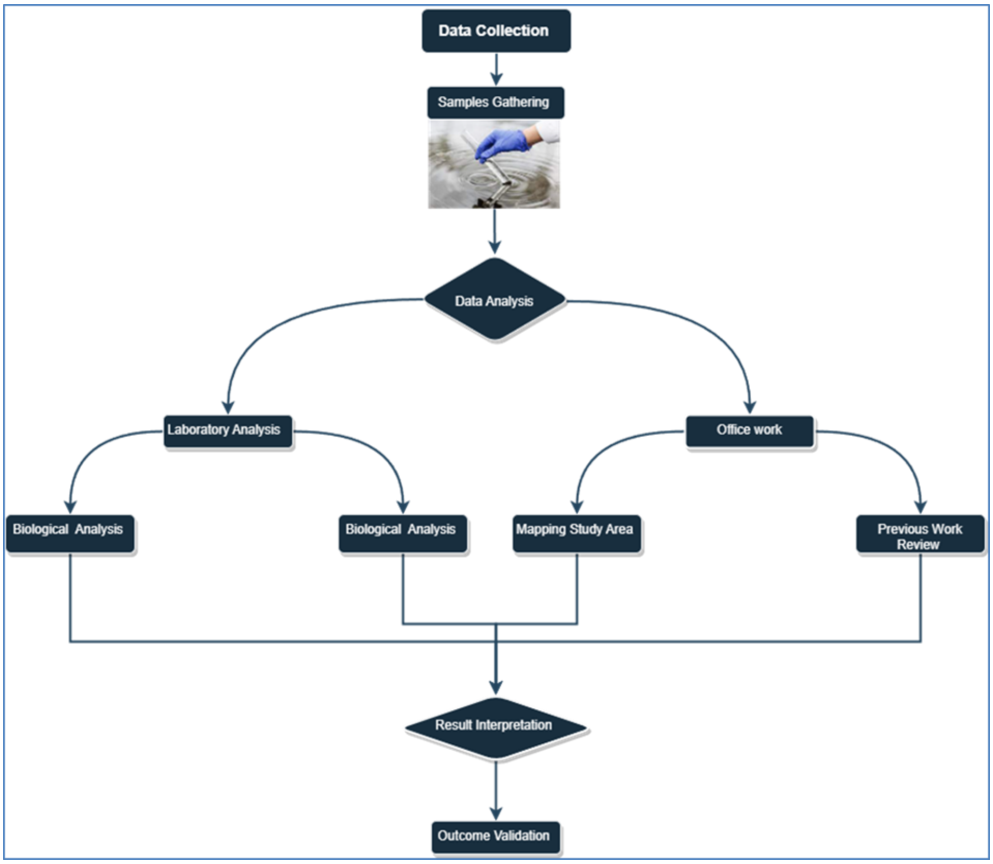

Fig. 4. The adopted methodology workflow of the conducted.

4. Results and Discussion

The results of the chemical analysis of groundwater samples collected from the selected wells revealed spatial variations in groundwater chemical composition (Supplementary Table 1) and (Figs 5 to 8). The pH of the samples ranged from 6.9 to 8.8, with an average value of 7.5, indicating mostly neutral water. Electrical conductivity (EC), which varies with salt concentration, ranged between 576 and 5620 µs/cm, with a mean value of 1302 µs/cm. The lowest EC was recorded in WT13, while the highest was observed in WT4. Most groundwater samples showed high total dissolved solids (TDS) levels, ranging from 650 mg/L to 1000 mg/L, along with elevated ion concentrations. Total hardness values varied significantly, ranging from 284 to 3653 mg/L, with an average of 843 mg/L. Similar to EC, the lowest and highest hardness values were detected in WT13 and WT4, respectively, reflecting the interactions between groundwater and the underground rock formations. The concentrations of major cations showed no systematic variation with depth, but elevated chloride (Cl) levels, ranging from 20 to 1672 mg/L, suggested potential contamination sources or natural contributions from geological formations (Al-Ruwaih et al., 2007; Yehya & Al-Asbahi, 2021; De Boer et al., 2021). High nitrate (NO_3) concentrations, ranging from 1.32 to 101.69 mg/L, were observed, raising concerns about groundwater contamination. In addition, major inorganic groundwater quality issues included elevated levels of fluoride, iron, sulfate, and manganese. Fluoride concentrations ranged from 0.03 to 1.77 mg/L, with the lowest level found in WT8 and the highest in WT13. Iron and manganese concentrations were notably high, ranging from 8 to 278 mg/L, further highlighting the spatial variability of groundwater quality across the study area. These findings underscore the influence of geological formations and potential contamination sources on groundwater chemistry.

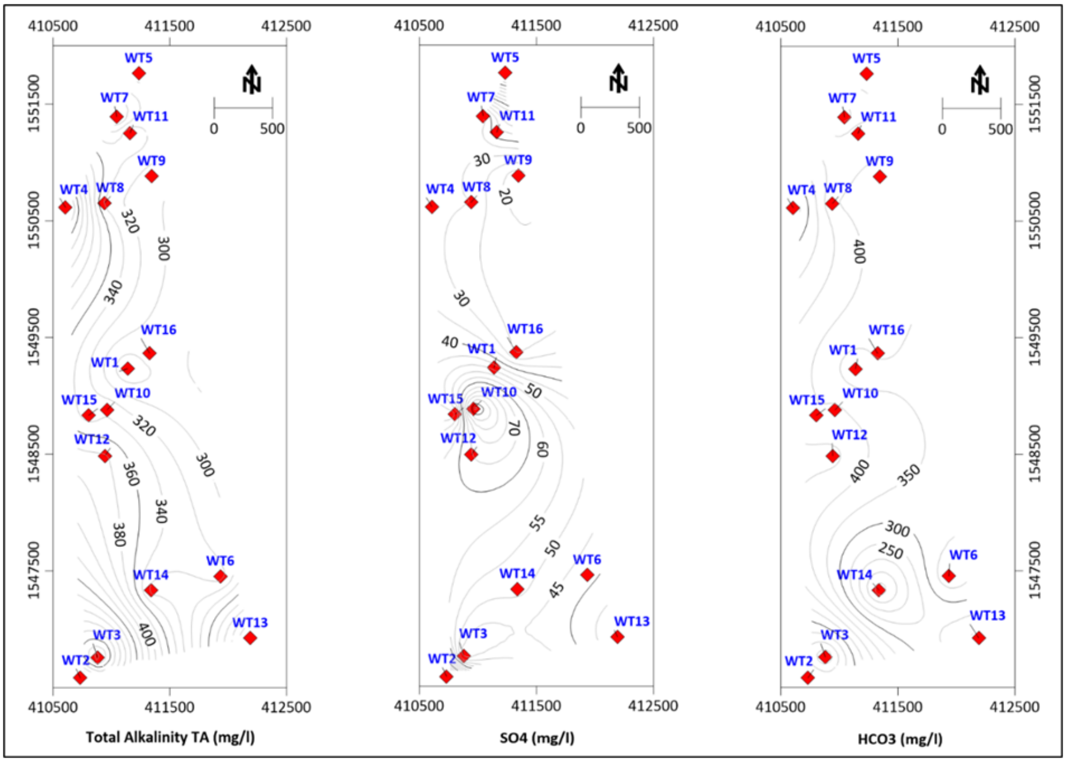

Fig. 5. Contour maps showing the spatial variation of the TA, SO_4 and HCO_3 in the study area

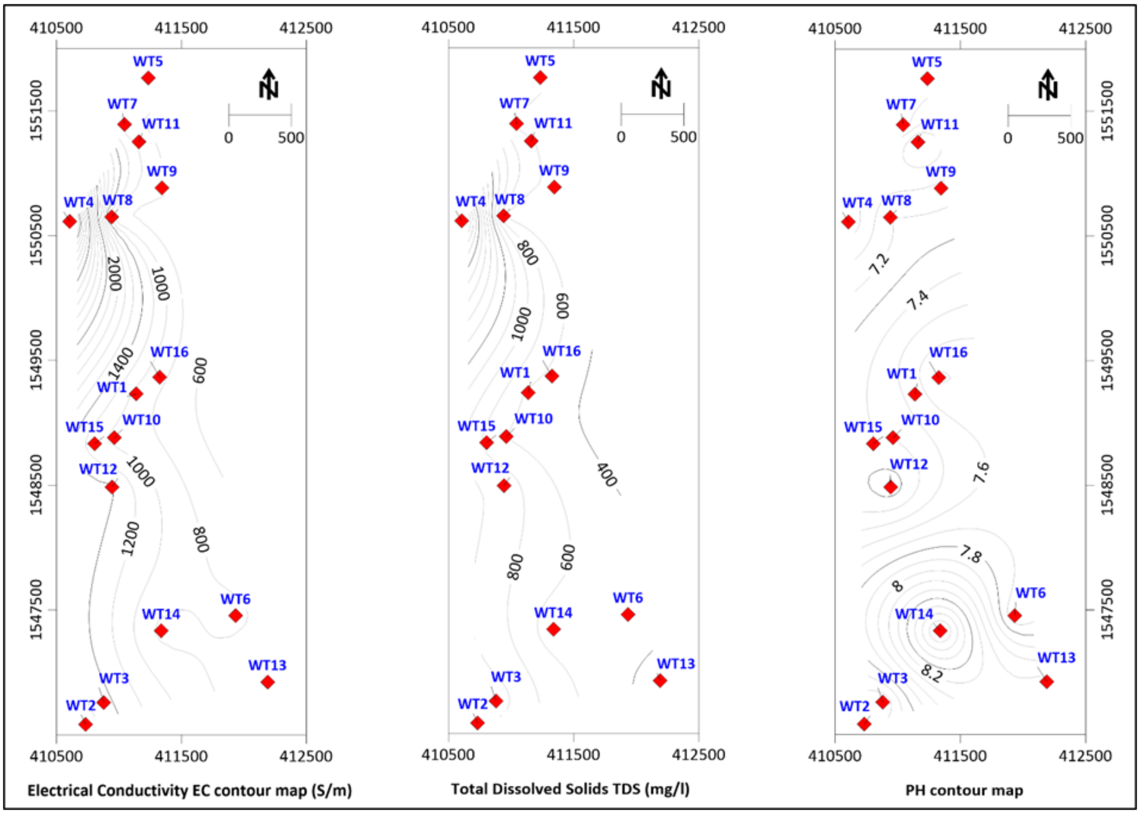

Fig. 6. Contour maps showing the spatial variation of EC, TDS and PH in the study area.

4.1 PH values interpretation

The observed pH values of groundwater in the study area (Fig.6) ranged from 6.87 to 8.76, generally falling within the acceptable range for irrigation water, which is between 6.5 and 8.4 (WHO, 2017; FAO, 2008). Most groundwater samples were neutral, indicating favorable conditions for general usage. However, exceptions were noted, such as the highest pH value of 8.76, recorded on the southern side of WT14. This slightly alkaline condition could be attributed to the dissolution of carbonate rocks or the presence of alkaline minerals within the aquifer system (Hem, 1985). On the other hand, the lowest pH value of 6.87 was recorded on the northern side of WT11, reflecting slightly acidic conditions likely caused by factors such as organic matter decay, leaching of acidic compounds, or agricultural runoff (Appelo & Postma, 2005). The neutral pH range across most samples suggests an absence of significant acidification or alkalinization processes in the aquifer, pointing to stable geochemical conditions overall (USEPA, 2018). However, the localized deviations at WT14 and WT11 highlight the influence of site-specific geochemical interactions between groundwater and surrounding geological formations or external inputs. These findings emphasize the importance of site-specific monitoring to better understand the spatial variability in groundwater pH and its implications for both human and agricultural uses (Todd & Mays, 2005).

Although pH is not directly harmful to human health, extreme values can affect the solubility and mobility of chemical constituents in groundwater, such as heavy metals or nutrients, potentially leading to secondary water quality issues (WHO, 2017). For agricultural purposes, irrigation water with pH values outside the standard range can impact soil chemistry and crop health (FAO, 2008). Therefore, regular monitoring and appropriate management strategies are essential to mitigate potential imbalances in water quality and ensure sustainable groundwater use for domestic and agricultural purposes.

Table 1. Result of the chemical parameters ranges compared with WHO and Yemeni Standards.

Chemical Parameters(mg/l)	Maximum	Minimum	WHO Standard	Yemeni standard
EC	5620	576	400-1500	400-1500
pH	8.76	6.87	6.5-8.5	6.5-8.5
TDS	3653	284	1000	650-1000
TH	2323	63	100-500	100-500
TA	617	147		
HCO_3	752	65	150-500	150-500
CO_3^-	155.1	0		
Cl	1627	20	250	200-600
SO_4	130	16	25-400	200-400
F^-	1.77	0	0.5-1.5	0.5-1.5
Ca	472	23	75-200	75-200
Mg	278	8	30-50	30-150
Na	234	34	20-175	200-400
K	6	1	8--12	8--12
NO_3	101.69	1.32	25-50	10--50
Fe	0.01	13	0.3-1	0.3-1

4.2 Salinity (TDS)

Total dissolved solids (TDS), comprising inorganic salts and organic matter, are a critical indicator of groundwater quality, influenced by factors such as water-rock interactions, lithology, and residence time (Hem, 1985; Appelo & Postma, 2005). In this study, TDS (Fig.6)levels in the Yemen Highlands ranged from 228 mg/L to 3120 mg/L, with an average of 720 mg/L, showing significant spatial variability. Notably, two wells in the western study area (WT3 and WT4) recorded TDS levels exceeding 1000 mg/L, surpassing both Yemeni and international water quality standards (WHO, 2017; NWRA, 2005). These elevated levels reflect prolonged water-rock interactions, limited groundwater movement, and prolonged residence times. The variability in TDS suggests additional factors, including the influence of geological formations and differences in local hydrological conditions. Anthropogenic activities exacerbate TDS levels, particularly through unregulated groundwater extraction and contamination from landfill leachates in the western region

(Al-Sabahi et al., 2015; Al-Mikhlafi, 2010). These factors increase salinity, reduce groundwater flow, and contribute to the accumulation of dissolved solids. Elevated TDS poses risks to public health, including renal diseases in vulnerable populations such as children, and impacts agricultural productivity through soil salinization, reducing soil fertility and crop yields (FAO, 2008; WHO, 2017). These findings emphasize the urgent need for sustainable groundwater management, including improved landfill practices, regulated water extraction, and regular monitoring to mitigate both natural and human-induced impacts on groundwater quality.

4.3 Electrical Conductivity (EC)

Electrical conductivity (EC) is a critical parameter for classifying water quality, as it indicates the concentration of dissolved ions and, consequently (Fig. 6), the salinity of water. It is commonly used to assess the suitability of water for both drinking and irrigation purposes. In this study, EC values ranged from 576 to 5620 µS/cm, with the highest levels observed in the western part of the study area, specifically at wells WT2 and WT4 (Figure 6). These values significantly exceed the maximum permissible limit of 1500 µS/cm set by both the World Health Organization (WHO, 2017) and Yemeni standards, indicating that water from these wells is not suitable for drinking due to its high salinity. The elevated EC levels in WT2 and WT4 are attributed to the influence of a nearby landfill, which likely contributes to the leaching of dissolved ions into the groundwater.

The high salinity associated with these wells suggests prolonged water-rock interactions, combined with contamination from anthropogenic sources such as landfill leachates. Elevated EC levels in water not only affect its potability but also pose challenges for agricultural use, as high salinity can lead to soil degradation, reduced crop yields, and long-term impacts on soil structure and fertility. These findings highlight the need for regular monitoring of EC levels and the implementation of effective waste management practices to prevent further contamination. Proper regulation of landfill sites and the introduction of protective measures, such as leachate barriers, are crucial to safeguarding groundwater quality in the region.

4.4 Alkalinity (TA)

The alkalinity of groundwater, determined by the concentration of carbonates, bicarbonates, and hydroxides, plays a critical role in the water's ability to neutralize acids and maintain a stable pH. In neutral water, alkalinity is closely related to bicarbonate concentrations (Fig. 5), which are primarily sourced from the weathering of carbonate rocks (Hem, 1985; Appelo & Postma, 2005). In this study, alkalinity levels in groundwater samples ranged from 146 mg/L to 617 mg/L, with significant spatial variation. According to the World Health Organization (WHO, 2011) standards, the recommended limit for alkalinity in drinking water is 200 mg/L, indicating that most of the analyzed samples exceed the permissible limit (Table 1). The lowest alkalinity value of 147 mg/L was recorded in well WT13, located in the southwestern part of the study area, reflecting minimal carbonate weathering in this region. Conversely, alkalinity was moderately high in the northeastern part of the study area, with values ranging from 265 mg/L in WT7 to 617 mg/L in WT3 and 525 mg/L in WT4. These elevated values suggest a higher degree of carbonate dissolution due to prolonged water-rock interactions in this area. High alkalinity levels in groundwater are not typically harmful to human health; however, they can influence water taste and its suitability for domestic use. Additionally, excessive alkalinity can impact irrigation by altering soil pH and nutrient availability, potentially reducing crop productivity. These findings highlight the importance of understanding the spatial distribution of alkalinity and its sources. Effective management strategies, including regular monitoring and assessment of carbonate weathering processes, are essential for maintaining water quality and ensuring its suitability for drinking and agricultural purposes.

4.5 Major ions distribution

The distribution of major ions in groundwater provides critical insights into the quality and suitability of water for drinking and agricultural purposes. This study analyzed key parameters, including sulfate (SO_4^{2-}), chloride (Cl^-), nitrate (NO_3^-), fluoride (F^-), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na^+), and potassium (K^+), revealing significant spatial variability across the Al-Sahoul Basin. The findings highlight the combined influence of natural geological processes and anthropogenic activities on groundwater quality.

Sulfate Analysis ($SO4^{-2}$)

Sulfate is a minor component of the Earth's crust but is often present in groundwater due to the dissolution of sulfate-bearing minerals, such as gypsum or anhydrite, and evaporite deposits (Hem, 1985; Appelo & Postma, 2005). In this study, sulfate concentrations (Fig.5), ranged from 16 mg/L (WT9 in the northeast) to 130 mg/L (WT2 in the southeast), with a median value of 52 mg/L. These values fall within the Yemeni and WHO-recommended limits (25–400 mg/L), indicating that sulfate concentrations in the groundwater do not pose health risks under current conditions. However, elevated sulfate levels can cause a bitter taste in drinking water and contribute to scaling in pipelines and appliances (Todd & Mays, 2005). The moderate concentrations observed in this study area reflect contributions from natural geological formations, specifically the weathering of sulfate-rich minerals.

Chloride (Cl^-)

Chloride in groundwater originates from multiple sources, including the weathering of chloride-rich minerals, leaching from salt-bearing formations (Figs 7, 8, and 9), and anthropogenic sources such as landfill leachates and agricultural runoff (Appelo & Postma, 2005). In this study, chloride concentrations ranged from 20 mg/L (WT13 in the southeast) to 1627 mg/L (WT4 in the west near the landfill), with an average of 200 mg/L. The WHO and Yemeni standards recommend a maximum chloride concentration of 250 mg/L for drinking water, a limit exceeded in wells near the landfill.

Elevated chloride levels in WT4 highlight the influence of landfill leachate infiltration, which introduces salts into the aquifer. High chloride concentrations are associated with health risks for individuals with kidney and heart conditions and contribute to soil salinization, negatively affecting agricultural productivity (WHO, 2017)

Nitrate (NO_3^-)

Nitrate concentrations ranged from 73 mg/L to 101 mg/L in five wells (WT2, WT6, WT10, WT12, and WT15), exceeding the WHO and Yemeni permissible limit of 50 mg/L. Elevated nitrate levels are primarily attributed to agricultural runoff, excessive use of fertilizers(Figs 7, 8, and 9), , and waste disposal near these wells. High nitrate concentrations in groundwater can lead to oxygen depletion and contribute to methemoglobinemia ("Blue Baby Syndrome") in infants, posing a serious health risk (WHO, 2017; Al Sabahi et al., 2015). Elevated nitrate levels also indicate pollution from human activities and require immediate mitigation measures, such as the implementation of sustainable agricultural practices and enhanced waste management.

Fluoride (F^-)

Fluoride levels in the study area(Figs 7, 8, and 10), were generally within the recommended limits of WHO and Yemeni standards ($\leq$1.5 mg/L), except for WT13, where the concentration reached 1.77 mg/L, exceeding the permissible limit. Elevated fluoride levels are often linked to the dissolution of fluoridebearing minerals, such as fluorite, and volcanic activity in the region (Mukhopadhyay et al., 2022). While low fluoride concentrations benefit dental health, excessive levels can lead to dental fluorosis, particularly in children. This highlights the need for localized defluoridation measures in wells with higher fluoride concentrations.

Iron (Fe), Calcium (Ca^{2+}), and Magnesium (Mg^{2+})

Iron concentrations (Fig.10) ranged from 0.01 mg/L (WT8) to 13 mg/L (WT4), with values in WT4 exceeding the WHO limit of 0.3 mg/L. Elevated iron levels are likely due to landfill contamination and the corrosion of borehole components. Excessive iron in water affects taste, stains fixtures, and promotes bacterial growth (Hem, 1985). However, the calcium concentrations varied from 23 mg/L to 472 mg/L, with a median value of 242 mg/L, exceeding Yemeni standards (75–200 mg/L) in some wells. High calcium levels contribute to water hardness, leading to scaling in pipelines and reducing appliance efficiency.

These findings are consistent with the dissolution of carbonate minerals (Fig. 10), which is common in calcium-enriched aquifers (Appelo & Postma, 2005). Additionally, the magnesium concentrations ranged from 8 mg/L (WT14) to 278 mg/L (WT4), with a median value of 134 mg/L, exceeding the recommended range of 30–150 mg/L. Elevated magnesium concentrations are linked to both natural geochemical processes and anthropogenic influences (Fig.10). High magnesium levels can increase the risk of cardiovascular diseases, as suggested by Rosanoff (2013).

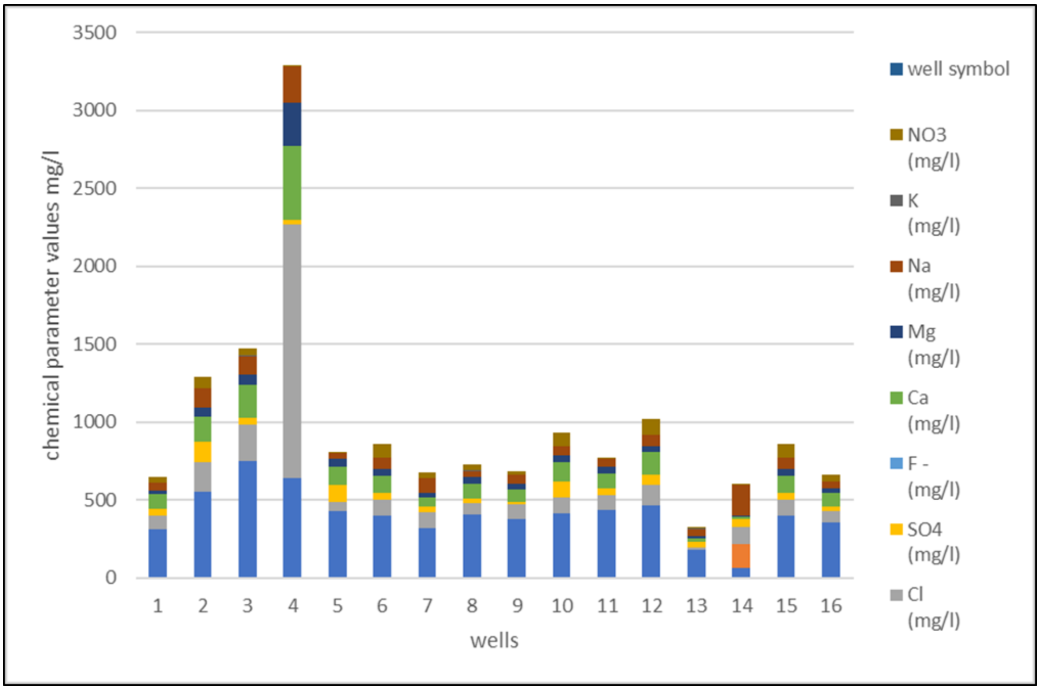

Fig. 7. Graph illustrating the distribution of principal ions in groundwater from the examined wells.

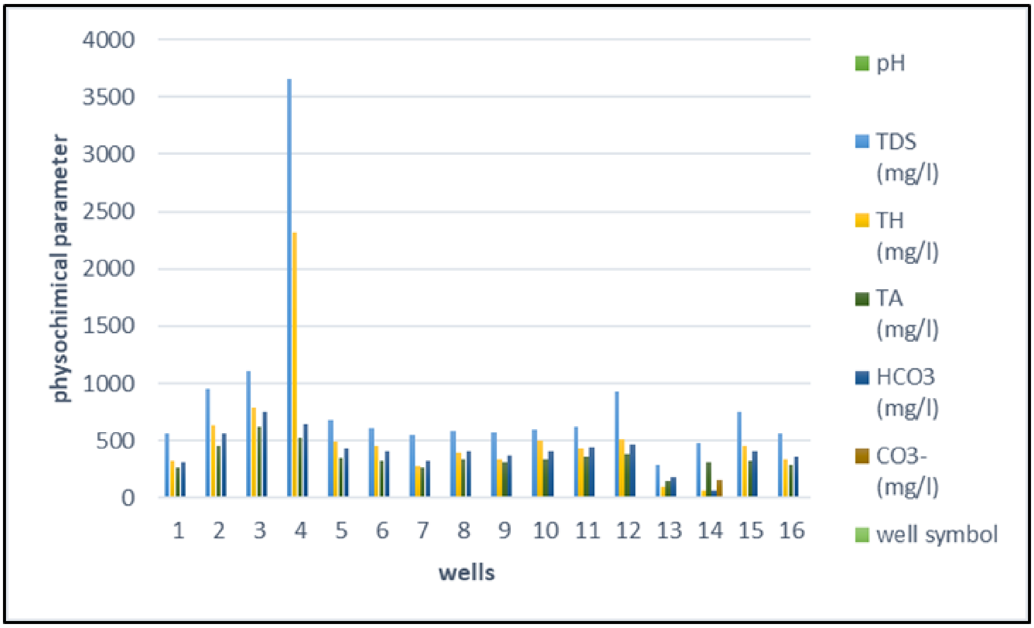

Fig. 8. Graph illustrating the distribution of principal ions (HCO_3, CO_3^-) and physiochemical parameters (e.g., pH, EC, TDS, TA, and TH) in groundwater samples collected from the examined wells within the Al-Sahoul Basin.

Sodium Na^+ and Potassium K^+

Sodium concentrations in the study area (Fig. 11)ranged from 34 mg/L (WT5) to 234 mg/L (WT4), with a median value of 134 mg/L. Although sodium does not have a strict health guideline for drinking water, concentrations above 135 mg/L can impact water taste and may indicate contamination from anthropogenic activities, such as wastewater infiltration or agricultural runoff (Hem, 1985; Appelo & Postma, 2005). Elevated sodium levels, particularly in WT4, suggest potential leaching from nearby waste or interaction with saline geological formations, warranting further investigation into the contamination sources and potential health implications. In contrast, potassium concentrations ranged from 0.6 mg/L (WT11) to 5.6 mg/L (WT3), with a median value of 3.1 mg/L, which falls within permissible limits for drinking water. The relatively low potassium concentrations observed across the study area indicate minimal anthropogenic influence on this ion in the aquifer system. Potassium is a naturally occurring ion in groundwater, often derived from the weathering of potassium-rich minerals(Fig.10), such as feldspars and micas, and does not generally pose health risks at these levels. These findings highlight the need for targeted groundwater quality monitoring to address specific contamination risks while ensuring the sustainable use of water resources in the region.

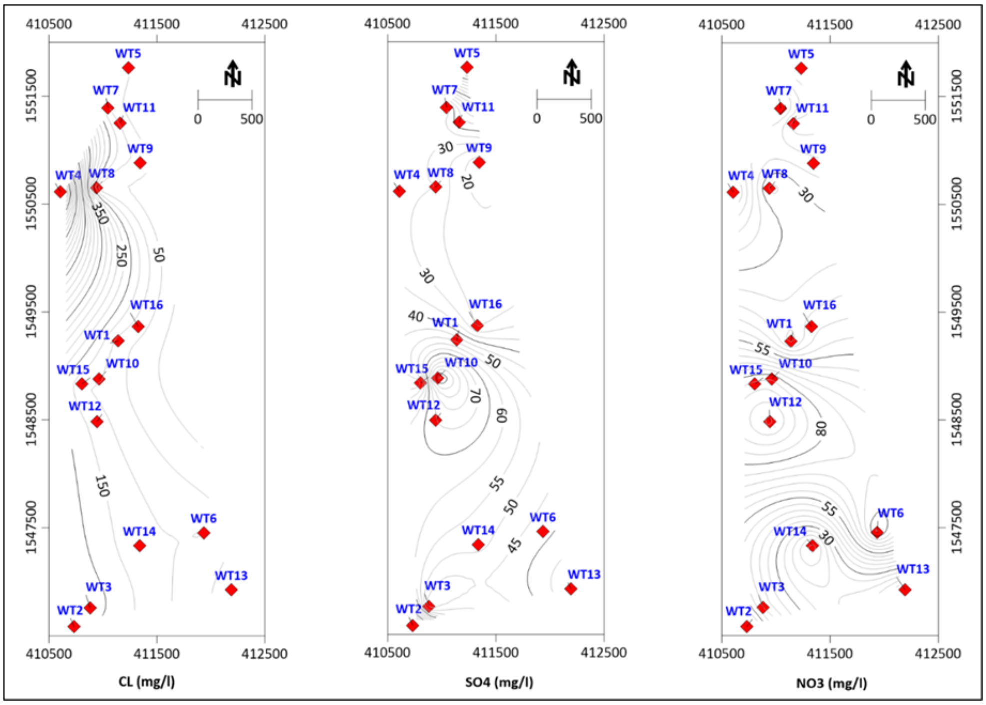

Fig. 9. Contour maps illustrating the spatial distribution of major ions, including chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-), across the study area.

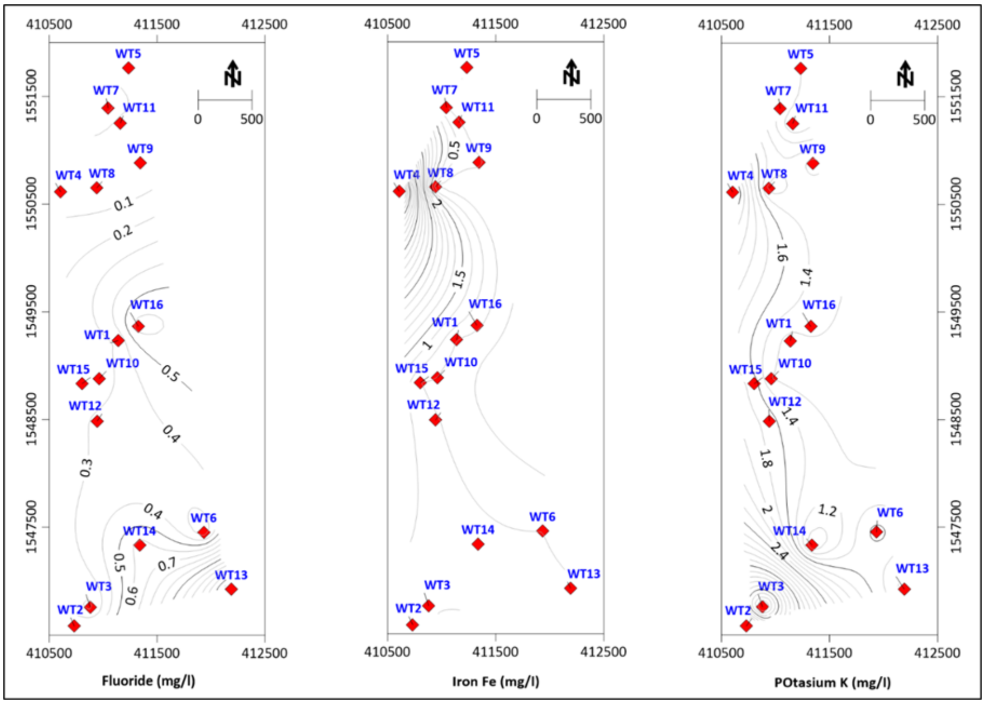

Fig. 10. Spatial distribution maps of fluoride (F^-), iron (Fe), and potassium (K^+) concentrations across the study area.

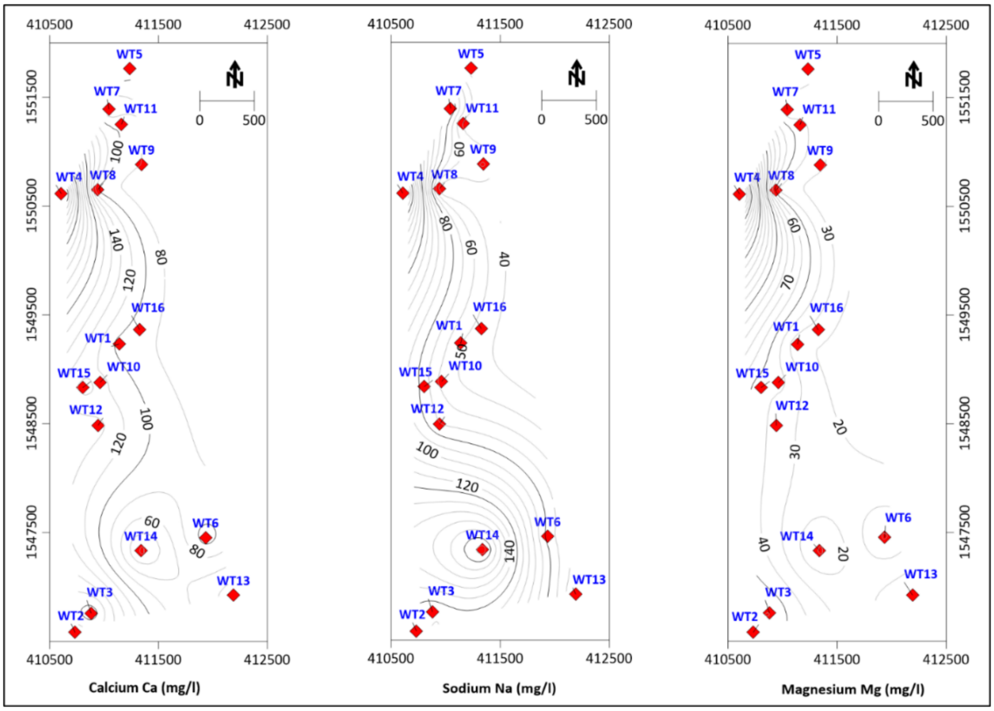

Fig. 11. Contour maps showing the spatial distribution of major ions, including calcium (Ca^{2+}), sodium (Na^{+}), and magnesium (Mg^{2+}), in the Al-Sahoul Basin.

5. Conclusion

This study offers a detailed quantitative and qualitative evaluation of groundwater quality in the fractured basalt aquifer of the Al-Sahoul region. Chemical analyses were conducted on 16 groundwater samples collected from 26 wells to assess variations in water quality parameters. The results were presented using advanced visualization tools such as Surfer, ArcGIS, and Microsoft Excel, which generated contour maps and hydrological and geological models. The analysis identified elevated concentrations of key water quality parameters, including TDS, EC, pH, bicarbonates, carbonates, chloride, sulfate, fluoride, calcium, magnesium, sodium, potassium, nitrate, iron, and total alkalinity, in several wells situated in the western part of the study area near the landfill (e.g., WT3 and WT4). These elevated levels, combined with biological contamination detected in wells such as WT2, WT3, WT4, WT11, and WT12, render the water unsuitable for drinking but still viable for agricultural purposes. Contamination is strongly linked to proximity to the landfill, and its impact diminishes with increasing distance, particularly toward the northern and southern sections of the basin. In contrast, groundwater from wells in the southern and northern parts of the basin (e.g., WT5, WT6, WT7, WT8, WT9, WT10, WT13, WT14, WT15, and WT16) met established drinking water standards, reflecting good water quality. These findings underscore the spatial variability of groundwater contamination and highlight the significant influence of anthropogenic activities, particularly landfill leachate, on water quality in the region. This study emphasizes the critical need for sustainable groundwater management and mitigation strategies to safeguard water resources for both domestic and agricultural use in the Al-Sahoul Basin.

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References

Abdullah, E. A. N., Al-Areeq, N. M., Al, A., & Al-Masgari, S.(2022). Petrophysical evaluation of the Upper Qishn Clastic Reservoir in Sharyoof Oilfield, Sayun-Masilah Basin, Yemen. ResearchGate. Retrieved from https://www.researchgate.net/publication/358987697.

Al Aizari, H., Lebkiri, A., Fadli, M., & Albaseer, S. S (2018). Quality assessment of groundwater in Dhamar City, Yemen. International Journal of Environment, Vol. 6(4), pp. 56–71. https://doi.org/10.3126/ije.v6i4.18910.Al-Sabahi, E. A., Rahim, S. A., Wan Zuhairi, W. Y., Al-Nozaily, F. A., & Alshaebi, F. (2009). The characteristics of leachate and groundwater pollution at municipal solid waste landfill of Ibb City, Yemen. *American Journal of Environmental Sciences, 5*(3), 256–266. https://doi.org/10.3844/ajessp.2009.256.266

Al-Nozaily, F. A., & Al-Sabahi, E. A. (2012). Ecological study on ground water pollution around Ibb landfill using physico-chemical analysis. *Journal of Science and Technology, 17*(2), 45–54. Retrieved from https://journals.ust.edu/index.php/JST/article/view/94

Mayas, A., Al-Sabahi, E. A., & Abdullhafez, S. (2015). Groundwater quality at Maytam area in the city of Ibb, Yemen, by using physico-chemical analysis. *International Journal of Emerging Technology and Advanced Engineering, 5*(11), 318–325. Retrieved from https://www.academia.edu/83495715

El-Rayes, A. E., Arnous, M. O., & Al-Oshari, F. (2020). Integrated groundwater contamination assessment of tertiary volcanic aquifer, Ibb Basin, Yemen. In *Proceedings of the Saudi Society for Geosciences Conference (SSG 2020)* (pp. 1–14). ResearchGate. https://www.researchgate.net/publication/342551748

Al-Areeq, N. M., Quriaa, H. A., AL-Areeq, A. M., & Al-Sabri, A. M.(2021). Evaluation of groundwater quality variations using Geographical Information System (GIS) and multivariate statistical techniques: A case study from Qa'Jahran Basin, Dhamar, Yemen. Advances in Science, Technology and Innovation, Springer Nature, pp. 131–145. https://doi.org/10.1007/978-3-030-67028-3_11.

Al-Hmani, A., Ben Jamaa, N., Kharroubi, A., & Agoubi, B (2022). Assessment of groundwater in Sana'a Basin aquifers, Yemen, using hydrogeochemical modeling and multivariate statistical analysis. Arabian Journal of Geosciences, Vol. 15(8). https://doi.org/10.1007/s12517-022-09979-3.

Aljawzi, A. A., Fang, H., Abbas, A. A., & Khailah, E. Y (2022). Assessment of water resources in Sana'a region, Yemen Republic (Case Study). *Water (Switzerland)*, Vol. 14(7). https://doi.org/10.3390/w14071039.

Al-Kharabsheh, Atef, and Mohamad Alatoum. "Effect of agricultural activities on water quality deterioration of Mujib basin, Jordan." *Current World Environment* 8, no. 3 (2013): 341.

Al-Kharbash, S. A., & Al-Anbaawi, M. I. (1996). *Geology of Yemen* (1st ed.). Sana'a, Yemen: Abadi Center for Studies and Publishing.

Al Khateeb, Y., Matraf, A. M. B., & Mohamed, F. A. (2016). Management of water Issues in Taiz basin, Yemen. *Thamar University Journal of Natural & Applied Sciences*, *6*(1), 121-141.

Allam, M., et al (2020). Geo-statistical assessment of groundwater quality in Dhamar Basin, Yemen. Applied Ecology and Environmental Research, Vol. 18(1), pp. 625–644. https://doi.org/10.15666/aeer/1801_625644.

Al-Mikhlafi, A. S. (2010). Groundwater quality of Yemen volcanic terrain and their geological and geochemical controls. Arabian Journal of Geosciences, Vol. 3(2), pp. 193–205. https://doi.org/10.1007/s12517-009-0068-7.

Al-Amrani, W. A., Mohammed, A. H. A., Al-Mammary, H., Al-Hanshali, S., Al-Wajeeh, T., Soileh, M., ... & Al-Dakah, B. Evaluation of Water Quality and Health Risks for Groundwater in the Selected Areas from An-Nadirah District for Drinking and Irrigation, Ibb Governorate, Republic of Yemen. *Ibb Governorate, Republic of Yemen*.

AL-OSHARI, F. A. A. (2012). *SUSTAINABLE MANAGEMENT OF GROUNDWATER IN IBB BASIN–YEMEN* (Doctoral dissertation, Suez Canal University).

Al-Qubatee, W., Al Hasan, F., Ritzema, H., Nasher, G., & Hellegers, P. (2022). Natural and human-induced drivers of groundwater depletion in Wadi Zabid, Tihama coastal plain, Yemen. Journal of Environmental Planning and Management, Vol. 65(14), pp. 2609–2630. https://doi.org/10.1080/09640568.2021.1975104.

Al-Ruwaih, F. M., Talebi, L. A., & Almedeij, J.(2007). Palaeohydrogeology and water quality control of the tertiary aquifer, Kuwait. Water International, Vol. 32(2), pp. 325–338. https://doi.org/10.1080/02508060708692210.

Al Sabahi, E., Al Nozaily, F. A., & Abdullhafez, S. (2015). Evaluation of Groundwater Quality for Drinking Water by Using Physico-chemical Analysis in the City of Ibb, Yemen. *British Journal of Applied Science & Technology, 5*(5), 425.

Al-Sakkaf, R. A. M. (2013). *Environmental Management in Sana'a Basin: Urbanization and degradation of groundwater quality.* (Report).

Appelo, C. A. J., & Postma, D. (2005). Geochemistry, groundwater, and pollution. CRC Press.

Arnous, M. O., El-Rayes, A. E., Geriesh, M. H., Ghodeif, K. O., & Al-Oshari, F. A.(2020). Groundwater potentiality mapping of tertiary volcanic aquifer in IBB basin, Yemen, by using remote sensing and GIS tools. Journal of Coastal Conservation, Vol. 24(3). https://doi.org/10.1007/s11852-020-00744-w.

Alwathaf, Y., Al-Areeq, N., Al-Areeq, A. M., & Aksever, F. (2025). Assessing and addressing groundwater depletion in yemen's Ibb sub-basins: an original study on challenges and sustainable management strategies. *All Earth*, *37*(1), 1-17.

Awadh, S. M., Al-Mimar, H., & Yaseen, Z. M. (2021). Groundwater availability and water demand sustainability over the upper mega aquifers of the Arabian Peninsula and western Iraq. Environment, Development, and Sustainability, Vol. 23(1). https://doi.org/10.1007/s10668-019-00578-z.

Baba, A., AL Karem, R., & Yazdani, H (2021). Groundwater resources and quality in Syria. Groundwater for Sustainable Development*, Vol. 14. https://doi.org/10.1016/j.gsd.2021.100617.

Davison, I. A. N., Al-Kadasi, M., Al-Khirbash, S., Al-Subbary, A. K., Baker, J., Blakey, S., ... & Yelland, A. (1994). Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen. Geological Society of America Bulletin, 106(11), 1474-1493.

De Boer, T., Paltan, H., Sternberg, T., & Wheeler, K (2021). Evaluating vulnerability of central Asian water resources under uncertain climate and development conditions: The case of the Ili-Balkhash Basin. Water (Switzerland), Vol. 13(5). https://doi.org/10.3390/w13050615.

El-Malt, L. M., Abdel Hameed, K. G., & Mohammed, A. S. (2013). Microbiological evaluation of yoghurt products in Qena city, Egypt. *Veterinary World*, *6*(7), 400-404.

FAO. (2008). Water quality for agriculture. Irrigation and Drainage Paper 29 Rev. 1, Food and Agriculture Organization, Rome.

Heikal, M. T. S., Al-Khirbash, S. A., Hassan, A. M., Al-Kotbah, A. M., & Al-Selwi, K. M. (2014). Lithostratigraphy, deformation history, and tectonic evolution of the basement rocks, Republic of Yemen: an overview. *Arabian Journal of Geosciences*, *7*(5), 2007-2018.

Hem, J. D. (1985). Study and interpretation of the chemical characteristics of natural water. US Geological Survey, Vol. 2254.

Kheireldin, K. (2008). Republic of Yemen Ministry of Water and Environment: Sana'a Basin water management project (IDA Credit 3774-YEM). Draft Final Report, Sub-Component 3(d), Hydro-geological and water resources monitoring and investigations.

Khanbari, K. (2015). Structural Analysis and Tertiary Tectonic Evolution of Yemen. Faculty of Science Bulletin, 27, 75-87.

Mukhopadhyay, A., Duttagupta, S., & Mukherjee, A (2022). Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes, and remediation. Journal of Environmental Chemical Engineering, Vol. 10(3), Article 107560.

Nation Water Resources Authority (NWRA) (1998). Water strategy. NWRA, pp. 1–2.

Nation Water Resources Authority (NWRA). (2005). Water status in IBB City. NWRA, pp. 14–20.

Rosanoff, A., Costello, R. B., & Johnson, G. H (2021). Effectively prescribing oral magnesium therapy for hypertension: A categorized systematic review of 49 clinical trials. Nutrients, Vol. 13(1), p. 195.

Sabahi, A., & Mayas, A.(2015). Groundwater pollution assessment in Yemen.

Todd, D. K., & Mays, L. W. (2005). Groundwater hydrology. John Wiley & Sons.

USEPA. (2018). National Primary Drinking Water Regulations. U.S. Environmental Protection Agency.

Water Availability in Yemen. (2021). Literature review of the current and future water resources and water demand in Yemen. Final Report.

World Health Organization (WHO). (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. World Health Organization.

Yaacob, W. Z., & Al-Nozaily, F.(2021). A study of surface water and groundwater pollution in Ibb City, Yemen. ResearchGate. Retrieved from https://www.researchgate.net/publication/266276984.

Yehya, Q., & Al-Asbahi, A. M.(2021). Water resources information in Yemen. Water International, pp. 1–14.