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Integrated Hydrogeochemical and Water Quality Assessment of Groundwater in Eastern Benghazi, Libya

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ABSTRACT

Libya, located in the arid region of North Africa (Figure 1), faces severe water shortages due to low rainfall and high evaporation rates. The Benghazi coastal plain relies predominantly on groundwater supplies, which are mainly replenished by limited and highly variable rainfall. This study investigates the hydrochemical properties, assesses groundwater quality, and evaluates the potential uses of groundwater in the area situated to the east of Benghazi City in northeastern Libya. The chemical analyses were performed, and hydrogeochemical diagrams, such as Piper and Gibbs diagrams, were used to identify the origin, water type, and groundwater characteristics, thereby elucidating the interrelationships among various chemical variables for 17 groundwater samples collected from the study area. However, a bimodal salinity distribution is observed: approximately 50% of groundwater samples exhibit elevated total dissolved solids (TDS > 1000 mg/L), classifying them as saline, while the remaining samples maintain freshwater status (TDS < 1000 mg/L). This bimodal salinity distribution indicates the cumulative effects of seawater intrusion along the coastal margin, evaporative concentration under semi-arid climatic conditions, and intensive groundwater pumping, which together enhance salinization in the western sector of the study area. Pearson correlation analysis showed strong correlations between salinity indices and major ions, except for bicarbonate. The saturation index (SI) indicates that the groundwater is slightly saturated with respect to carbonate minerals and undersaturated with respect to evaporite minerals. Groundwater chemistry and quality are mainly controlled by natural processes, particularly water–rock interactions, evaporation effects, and the mixing or intrusion of seawater. The samples B1 and B2 are unsuitable for irrigation, while the other samples B3 to B17 range from "good to excellent," indicating their suitability for irrigating most crops, particularly in soils with medium to high permeability.

التقييم الهيدروجيوكيميائي المتكامل لجودة المياه الجوفية في شرق بنغازي، شمال شرق ليبيا

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تقع ليبيا ضمن النطاق شبه الجاف لشمال أفريقيا، وتعاني من ندرة ملحوظة في الموارد المائية. وفي شمال شرق ليبيا، يعتمد السهل الساحلي لمدينة بنغازي بشكل رئيسي على إمدادات المياه الجوفية، التي يتم تغذيتها أساسًا من خلال كميات محدودة ومتغيرة بدرجة كبيرة من مياه الأمطار. تهدف هذه الدراسة إلى دراسة الخصائص الهيدروكيميائية للمياه الجوفية، وتقييم جودتها، وتحديد إمكانات استخدامها في المنطقة الواقعة شرق مدينة بنغازي في شمال شرق ليبيا. أُجريت التحاليل الكيميائية لعينات المياه، كما استُخدمت المخططات الهيدروكيميائية، مثل مخططي بايبر (Piper) وجيبس(Gibbs) ، لتحديد أصل المياه ونوعها وخصائصها، مما أسهم في توضيح العلاقات المتبادلة بين المتغيرات الكيميائية المختلفة لعدد 17 عينة من المياه الجوفية جُمعت من منطقة الدراسة. أظهرت النتائج وجود توزيع ثنائي الملوحة؛ إذ تبين أن نحو 50% من عينات المياه الجوفية تحتوي على تركيزات مرتفعة من المواد الصلبة الذائبة الكلية (TDS > 1000 ملغم/لتر)، مما يصنفها كمياه مالحة، في حين حافظت العينات المتبقية على صفة المياه العذبة (TDS <

1000ملغم/لتر). ويعكس هذا التوزيع الثنائي للملوحة التأثيرات التراكمية لتداخل مياه البحر على طول الحافة الساحلية، إضافة إلى تأثيرات التركيز بالتبخر في ظل الظروف المناخية شبه الجافة، إلى جانب الضخ المكثف للمياه الجوفية، وهي عوامل مجتمعة تسهم في زيادة ملوحة المياه، خاصة في الجزء الغربي من منطقة الدراسة. أظهر تحليل الارتباط باستخدام معامل بيرسون (Pearson) وجود علاقات ارتباط قوية بين مؤشرات الملوحة والأيونات الرئيسة، باستثناء أيون البيكربونات. كما يشير مؤشر التشبع إلى أن المياه الجوفية في حالة تشبع طفيف بالنسبة لمعادن الكربونات، وفي حالة عدم تشبع بالنسبة لمعادن المتبخرات. وتبين أن كيمياء المياه الجوفية وجودتها تخضع أساسًا لسيطرة العمليات الطبيعية، ولا سيما تفاعلات الماء والصخور، وتأثيرات التبخر، إضافة إلى عمليات اختلاط المياه أو تداخل مياه البحر. وتشير نتائج تقييم صلاحية المياه للري إلى أن العينتين B1و B2غير مناسبتين لأغراض الري، في حين تتراوح صلاحية بقية العينات B3إلى B17 بين "جيدة إلى ممتازة"، مما يدل على ملاءمتها لري معظم المحاصيل، خاصة في التربة ذات النفاذية المتوسطة إلى العالية.

INTRODUCTION

Groundwater is a crucial freshwater resource in semi-arid regions of North Africa, where limited rainfall restricts surface water availability. It is generally less affected by external influences than surface water, making it increasingly important in the context of global climate change and the rising frequency of droughts and floods (Mishra, 2023). Intensive groundwater abstraction has increased pressure on aquifers, raising concerns about salinization and seawater intrusion in the coastal plain of Benghazi. However, rapid economic growth and unplanned human activities put considerable pressure on groundwater supplies (van der Gun, 2021; Stigter et al., 2023). Recently, groundwater resources in the Mediterranean region have become increasingly important for drinking water and economic development. Groundwater in these areas may be contaminated by the accumulation of major and trace elements resulting from farming operations and associated anthropogenic activities (Alexakis et al., 2021). Libya, situated in a dry region of northern Africa (Figure 1), faces significant water shortages primarily due to low rainfall and high evaporation rates. This highlights the urgent need to locate and safeguard groundwater sources, which serve as a crucial alternative to surface water. Continuous monitoring of water used for drinking and irrigation is crucial, as it may contain pollutants that pose a risk to human health (Salem et al., 2022). Additionally, overexploitation and pollution further threaten the limited groundwater supplies. The chemical parameters of groundwater are crucial for evaluating water quality and determining its suitability for consumption and irrigation purposes under current environmental conditions (Zurqani, 2025). The main aquifer system in the Benghazi area of northeastern Libya is under intense human pressure from extensive groundwater extraction to meet increasing domestic, agricultural, and industrial demands, particularly since current withdrawal rates exceed natural recharge, which primarily comes from limited and irregular rainfall (Telahigue et al., 2020). Furthermore, geochemical analyses provide important information on possible variations in groundwater quality as development progresses. The appropriateness of groundwater for domestic and irrigation purposes is largely determined by its chemical composition (Jalali et al., 2024). Techniques such as correlation analysis, ionic ratio examination, and saturation index assessment are effective tools for exploring the hydrogeochemical evolution of groundwater (Sunkari et al., 2021). Several studies have investigated groundwater chemistry in Libya and the Mediterranean region, with a particular focus on processes such as seawater intrusion, evaporation, and rock–water interaction. For example, Shaltami et al. (2021) and El Fallah et al. (2025) reported significant salinization in southeastern Benghazi, where total dissolved solids (TDS) levels fluctuated between 1,000 and 6,800 mg/L. In contrast, Imneisi (2024) observed a dominance of calcium bicarbonate in the Sidi Faraj area, with TDS values remaining within the FAO irrigation standards. Despite several studies addressing groundwater chemistry in the Benghazi region, a comprehensive understanding of the combined effects of seawater intrusion, evaporation, and water–rock interaction remains limited. In particular, integrated hydrogeochemical assessments incorporating statistical analyses and water quality indices, such as the Water Quality Index (WQI) and saturation index (SI), are still scarce for the eastern Benghazi coastal aquifer. Despite several studies addressing groundwater chemistry in the Benghazi region, a comprehensive understanding of the combined effects of seawater intrusion, evaporation, and water–rock interaction remains limited, particularly in terms of integrated multi-method approaches. This study presents a comprehensive and integrated hydrogeochemical assessment of groundwater in eastern Benghazi, combining hydrochemical analysis, statistical methods, geochemical modeling (saturation indices), and water quality indices to offer a more robust framework for interpreting groundwater evolution. Accordingly, this study aims to assess groundwater quality and identify the key hydrogeochemical processes controlling its composition in northeastern Benghazi, thereby supporting sustainable groundwater management in the region.

Study area

1.1. LOCATION AND CLIMATE CONDITIONS OF THE STUDY AREA

The study area is located east of Benghazi city, in northeastern Libya, between 20° 05′ 00″ and 20° 50′ 00″ E and 31° 50′ 00″ and 32° 30′ 00″ N (Figure 1). It is bordered to the north by the Mediterranean Sea, to the east by Al Jabal al Akhdar, to the south by the Soluq

Depression, and to the west by Benghazi city. This region features a semi-arid Mediterranean climate, characterized by hot and dry summers and cool, wet winters (Elfadli et al., 2024). During the summer (June–September), temperatures average between 25–32°C, occasionally reaching 40°C during hot Ghibli winds from the south, which are accompanied by low humidity. The winter season (December–February) is mild, with temperatures ranging from 12 °C to 18°C, and most of the annual rainfall (~270 mm/year) occurs during this period (Carlucci et al., 2023). The spring and autumn are short transitional periods with moderate temperatures and occasional sandstorms. Coastal breezes moderate the climate; however, the dry, dusty Ghibli winds can cause sudden temperature spikes and reduced visibility (Alrteimei et al., 2023).

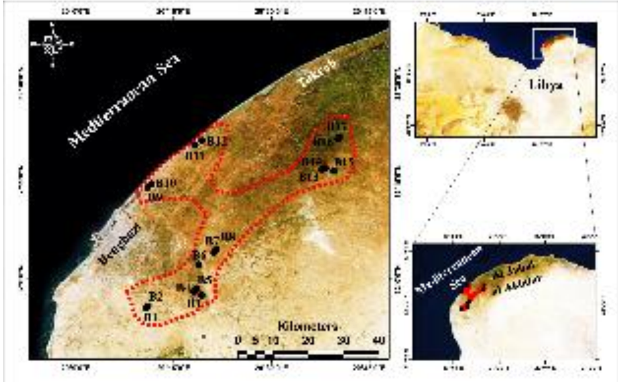

Fig. (1): Satellite images showing the location of the studied groundwater wells.

1.2. GEOLOGICAL FRAMEWORK AND HYDROGEOLOGICAL CONDITIONS

The Benghazi Plain in northeastern Libya is capped mainly by Tertiary carbonate rocks (limestones, dolostones) with intermittent clay, gypsum, and marl sequences (Faraj et al., 2016). Stratigraphically, the exposed rocks are mainly attributed to the Benghazi Formation, which is dominated by fossiliferous limestones with subordinate green clays, as they extensively crop out in the southern and eastern parts of the Benghazi area. This formation occurs unconformably and is overlain by the Wadi Al-Qattarah Formation. The Benghazi Formation mainly consists of fossiliferous algal limestone and dolomitic carbonate rocks that are highly susceptible to dissolution and karstification, which enhances secondary porosity and groundwater flow within the aquifer system. The Upper Miocene Wadi Qattara Formation consists of siliceous oolite limestones with a granular texture, with thick, irregular gypsum bodies in its upper part (Klen, 1974; El Hawat and Pawellek, 2005; Muftah et al., 2015; 2025). The Quaternary deposits, including littoral marine sands, lagoonal (sebkha) evaporites, and alluvial sediments, unconformably cover the underlying rock units. The karstification phenomenon is a key hydrogeological feature influencing groundwater flow within the Benghazi Formation (Abdelmalik et al., 2007). The development of karst conduits and caverns, indicated by features such as brackish-water doline lakes on the coastal plain (e.g., Budzaira lakes), promotes significant groundwater flow toward the Mediterranean coast. However, this increased permeability also provides efficient pathways for salinization, resulting in a clear groundwater salinity gradient toward the coast. (Abdelmalik et al., 2007). This imbalance has resulted in a continuous and significant decline in groundwater levels over the past few decades. The decrease in the freshwater potentiometric surface mainly leads to seawater intrusion, which advances inland through preferred pathways such as the karst network, contaminating large portions of the coastal aquifer and endangering its long-term sustainability (Telahigue et al., 2020). These carbonate formations play a significant role in controlling groundwater chemistry through dissolution processes, which is reflected in the dominance of Ca^{+2}–HCO$_3^-$ facies observed in inland wells.

MATERIALS AND METHODS

Seventeen groundwater samples, labeled B1 through B17, were analysed in the General Water Authority laboratory in Benghazi. The levels of major cations and anions, as well as total hardness (TH) and alkalinity, were measured using titrimetric analytical methods. Other anions were measured via spectrophotometry. Total dissolved solids (TDS) were estimated gravimetrically. A statistical evaluation of all chemical parameters was conducted, with minimum, maximum, average, and standard deviation values calculated. The ionic balance error for all samples was within ±5%, indicating acceptable analytical accuracy. The results were evaluated against the standards set by the World Health Organization (WHO, 2022) guidelines and Libyan National Standards (LNS, 2020). A Piper diagram, created using RockWorks 17 software, was applied to evaluate the water origin and its hydrochemical facies. A Gibbs diagram was generated in Microsoft Excel software to identify the dominant processes influencing groundwater chemistry. Additionally, SPSS software (SPSS, 2013) was used to perform a bivariate correlation analysis (Pearson correlation) to examine relationships between variables. In addition, the saturation index (SI) was computed with the PHREEQC interactive program based on the following equation (1) (Parkhurst and Appelo, 2013):

$$\mathbf{SI = \log [\, IAP / KT \,]} \qquad \mathbf{(1)}$$

Where: KT is the equilibrium constant at temperature T, and IAP is the ion activity product

The Wilcox's, U.S. Salinity Laboratory diagrams were used to assess the suitability of groundwater for irrigation purposes. The sodium absorption ratio (SAR) represents the degree to which soil water undergoes cationic interaction. SAR is also used to classify irrigation water based on EC (Richards, 1954; USSL Staff, 1954). SAR is calculated by applying the following equation (2):

$$\mathbf{SAR = Na/\sqrt{0.5\,(Ca + Mg)}} \quad \mathbf{meq/L} \qquad \mathbf{(2)}$$

The Water Quality Index (WQI) was determined using the weighted arithmetic approach based on major physicochemical parameters and WHO (2022) drinking water standards. Measured concentrations were normalized, weighted, and then summed to compute WQI values for classifying groundwater suitability for drinking (Abolli et al., 2024).

RESULTS

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1. Statistical analyses

1.1. Descriptive statistics

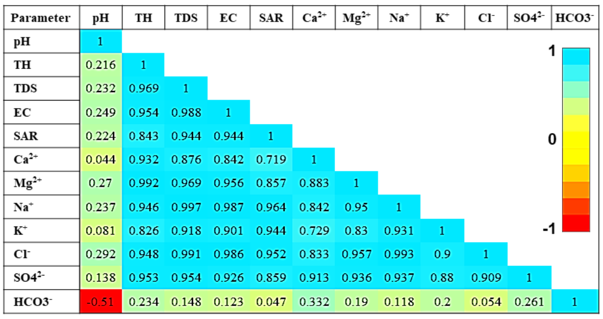
The chemical composition of the analysed samples (Table 1) reveals that the concentrations of total dissolved salts, magnesium, sodium, chloride, and sulphate exceed the permissible limits, while calcium, potassium, and bicarbonates are within the limits set by the World Health Organization (WHO) and Libyan standards. In the eastern sector of the study area, total dissolved solids (TDS) concentrations are less than 1000 mg/L, indicating freshwater, whereas values exceeding 1000 mg/L in the western parts suggest saline water.

Table 1: Descriptive statistical analysis of the groundwater samples, compared with the standard values of WHO (2022) and LNS (2020), (all Element concentrations and TDS are in mg/L, except EC is in µS/cm).

Parameters	Min	Max	Average	St. Dev	LNS (2020)	WHO (2022)
EC	740	6780	2152	1595	–	–
T H	258	1125	484	248	–	–
SAR	1	14.01	4.88	3.93	–	–
pH	6.66	8.37	7.18	0.44	6.5 – 8.5	6.5 – 8.5
TDS	354	4072	1256	1091	500	500
Ca^{2+}	68	160	91.6	25.15	150	200
Mg^{2+}	21	176	61.4	44.74	50	50
Na^{+}	37	1081	285	313.6	100	200
K^{+}	3	35	11	10.4	50	50
Cl^{-}	103	1826	513	520.6	150	250
SO_4^{2-}	23	653	178	191	200	250
HCO_3^{-}	165	311	233	52.6	400	500

1.2. Pearson correlation

Pearson correlation (r) measures the linear relationship between two variables. It indicates the strength and direction of a linear connection, ranging from -1 to +1. In this study, the Pearson correlation analysis showed strong positive correlations among salinity indicators and major ions. Total dissolved solids (TDS) almost perfectly correlated with electrical conductivity (EC, r = 0.988), sodium (Na^+, r = 0.997), and chloride (Cl^-, r = 0.991) (Figure 2). Simultaneously, Na^+ and Cl^- exhibited a nearly perfect correlation (r = 0.993). Total hardness was also highly associated with TDS (r = 0.969), magnesium (Mg^{2+}, r = 0.992), and calcium (Ca^{2+}, r = 0.932). The sodium adsorption ratio (SAR) increased along with TDS (r = 0.944), Na^+ (r = 0.964), and potassium (K^+, r = 0.944). Strong positive correlations existed between Mg^{2+} and Cl^- (r = 0.957), between Mg^{2+} and sulfate (SO_4^{2-}, r = 0.936), and between K^+ and Na^+ (r = 0.931) and K^+ and Cl^- (r = 0.900). In contrast, bicarbonate (HCO_3^-) showed minimal correlations with most parameters but had a moderate negative correlation with pH (r = –0.505), suggesting its relatively independent behavior within the system.



Parameter	pH	TH	TDS	EC	SAR	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	$SO4^{2-}$	$HCO3^{-}$
pH	1											
TH	0.216	1										
TDS	0.232	0.969	1									
EC	0.249	0.954	0.988	1								
SAR	0.224	0.843	0.944	0.944	1							
Ca^{2+}	0.044	0.932	0.876	0.842	0.719	1						
Mg^{2+}	0.27	0.992	0.969	0.956	0.857	0.883	1					
Na^{+}	0.237	0.946	0.997	0.987	0.964	0.842	0.95	1				
K^{+}	0.081	0.826	0.918	0.901	0.944	0.729	0.83	0.931	1			
Cl^{-}	0.292	0.948	0.991	0.986	0.952	0.833	0.957	0.993	0.9	1		
$SO4^{2-}$	0.138	0.953	0.954	0.926	0.859	0.913	0.936	0.937	0.88	0.909	1	
$HCO3^{-}$	-0.51	0.234	0.148	0.123	0.047	0.332	0.19	0.118	0.2	0.054	0.261	1

Fig. (2): Heat map of Pearson correlations among the different chemical variables.

1.3. Hydrochemistry of the groundwater

1.3.1. Piper's trilinear diagram

Piper's diagram (Piper, 1944) is widely applied to evaluate the chemical relationships among water samples and to identify the dominant geochemical processes occurring within aquifers. It is constructed using the equivalent proportions of alkali metals and alkaline earth elements relative to strong and weak acidic anions, providing a graphical interpretation of hydrogeochemical facies and the evolution of water types. In this study, most water samples are in the mixed water type, indicating that no cation-anion pair exceeds 50%. The alkaline earths (Ca^{2+} + Mg^{2+}) surpass alkalis (Na^+ + K^+), and strong acids exceed weak acids (Figure 3). However, there are two samples B1 and B2 in the calcium chloride type (Ca^{+2}–Cl^-) and three samples B3, B4, and B5 in the sodium chloride type (Na^+–Cl^-), which indicates that the water is high in calcium, chlorides, and sodium salts, resulting from seawater intrusion into the coastal aquifers due to the proximity of the study area to the shoreline.

1.3.2. Gibbs's diagram

Gibbs's diagram serves as a useful tool for determining the origin of dissolved ions in groundwater and for understanding the processes that control its chemical composition (Gibbs, 1970). These diagrams help distinguish the dominant geochemical processes influencing water composition, such as mineral dissolution or evaporation. In Gibbs's diagram, there are two diagrams: one shows the relative concentrations of Cl^- and HCO_3^- on the x-axis and TDS on the y-axis with a logarithmic scale, and the second diagram shows the ratio of Na^+–$Cl^-$and HCO_3^- on the x-axis and TDS on the y-axis with a logarithmic scale. It includes three distinct zones: evaporation and mineral crystallization, rock weathering, and rainfall.

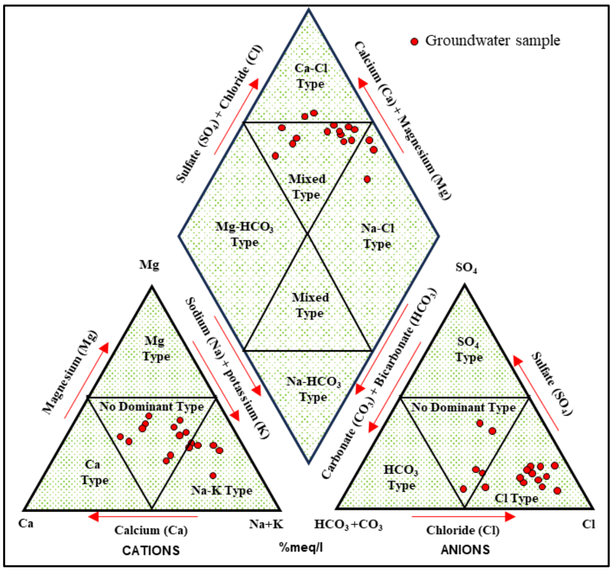


Fig. (3): Piper's diagram showing the hydrogeochemical facies of the studied groundwater samples.

These graphical representations facilitate the interpretation of groundwater evolution and the identification of natural versus anthropogenic influences on water quality. The analysed groundwater samples do not show a clear dominance of any ions (Figure 4a, b); their position within the Gibbs classification zones of rock weathering and evaporative crystallization indicates that the interaction of water with aquifer rocks and evaporative processes is the main natural mechanism controlling groundwater chemistry of the study area. This reflects the overlapping influence of multiple hydrogeochemical processes rather than a single dominant mechanism.

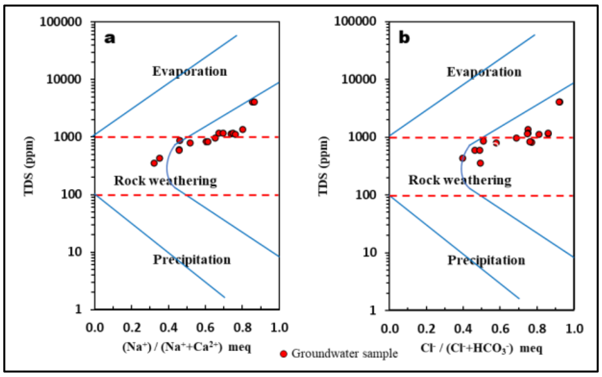


Fig. (4): Illustrates Gibbs's diagram depicting the hydrogeochemical processes influencing groundwater chemistry based on a) major cations and b) major anions.

1.3.3. *Saturation Indices of the Water*

The evolution of water chemistry along the groundwater flow was examined through a simulation performed with the PHREEQC interactive program, applying Equation (1) (Parkhurst and Appelo, 2013). This simulation was employed to determine the saturation indices (SI) of dissolved minerals in water and to identify the types of these minerals. The saturation index (SI) is defined as the logarithm of the ratio of ionic activity products (IAP) to the solubility product (Ksp) at a given temperature. The ability of groundwater to dissolve or precipitate minerals could be studied using the saturation indices (Redwan et al., 2016). Additionally, integrating statistical and hydrogeochemical tools facilitates the development of groundwater management plans (Taheri et al., 2020; Abu Salem et al., 2021, 2022). In general, equilibrium between water and rock is attained at an SI of 0. When SI is negative, the water is undersaturated, and mineral dissolution occurs to restore equilibrium; a positive SI indicates supersaturation, leading to mineral precipitation (Wen et al., 2024). The saturation index analysis reveals that the majority of the groundwater samples are undersaturated with respect to evaporite minerals, including anhydrite, gypsum, halite, and sylvite. At the same time, they range from slightly saturated to saturated for carbonate minerals, including aragonite, calcite, and dolomite (Figure 5). This pattern is attributed to the interactions between groundwater and the minerals present in the surrounding aquifer rocks, which are primarily composed of limestone and dolomite.

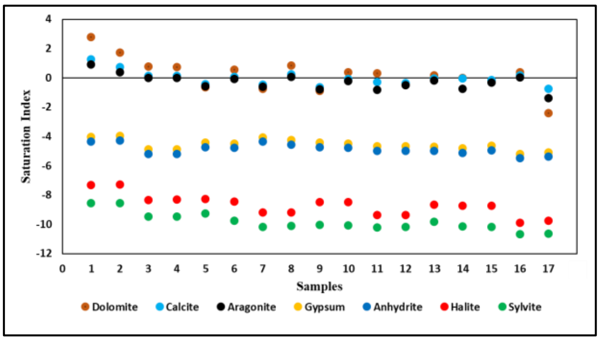


Fig. (5): Saturation indices of the studied groundwater samples.

1.3.4. *Ionic relations*

The distribution of samples along the 1:1 line on the SO_4^{2-} + HCO_3^- versus Ca^{2+} + Mg^{2+} biplot (Figure 6a) indicates the influence of carbonate weathering. Most groundwater samples plot close to the 1:1 line, suggesting that calcium and magnesium are largely balanced by bicarbonate and sulfate ions. This relationship reflects the dominant role of carbonate mineral dissolution, particularly that of calcite and dolomite, in controlling the hydrochemical composition of groundwater. Minor deviations from the line may indicate the influence of ion exchange during water–rock interaction. The Ca^{2+} + Mg^{2+} versus Mg^{2+} diagram (Figure 6b) illustrates the processes governing magnesium in groundwater. Most samples occur above the 1:1 line, indicating that magnesium mainly originates from the dissolution of dolomite rather than calcite. This pattern suggests that dolomite weathering is the principal source of Mg^{2+} in the aquifer system, with only a minor contribution from reverse ion exchange processes. The relationship between Ca^{2+} and SO_4^{2-} in the biplot (Figure 6c) reflects the effect of gypsum dissolution. Most samples trend toward the 1:1 line, indicating that increases in calcium are associated with corresponding increases in sulfate. This trend highlights the contribution of gypsum dissolution to the groundwater chemistry, although slight deviations from the ideal line may reflect additional geochemical processes. The Na^+ versus Cl^- relationship (Figure 6d) indicates that most samples cluster near the 1:1 line, suggesting that halite dissolution is the primary source of sodium and chloride in the groundwater. This pattern demonstrates the important role of evaporite mineral dissolution in the hydrochemical evolution of the aquifer.

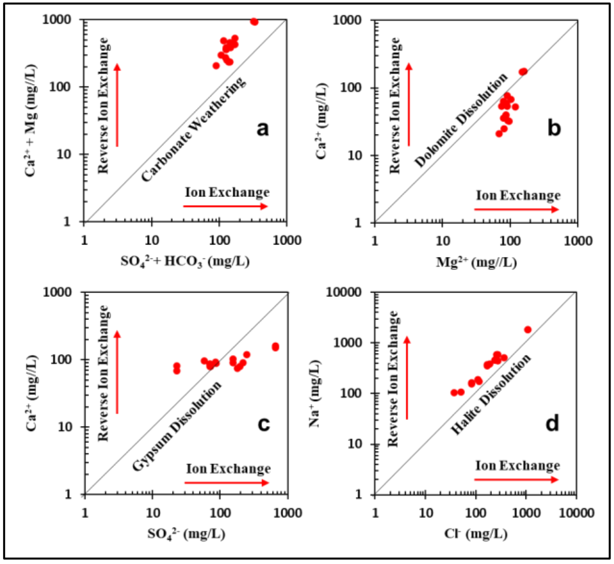


Fig. (6): Bivariate plot of various hydrogeochemical parameters showing ion exchange reaction and /or mineral dissolution.

1.4. Water quality assessment

1.4.1. Suitability for drinking and household use

The evaluation of water suitability for drinking and domestic purposes is based on the total dissolved solids (TDS) and the concentrations of major ions. According to the standard limits for drinking given by WHO (2022) and LNS (2020), (Table 1): The TDS value of studied groundwater samples in the eastern part of the study area are suitable for drinking where it is within the WHO (2022) and LNS (2020) permissible limits, conversely, groundwater samples collected from the western region surpass the allowable limits, rendering them unfit for drinking and household use. Additionally, all groundwater sample pH values fall within the safe range. The Water Quality Index (WQI) assessment highlights clear spatial variability in groundwater quality across eastern Benghazi (Table 2, Figure 7). Coastal western wells (B1 and B2) recorded extremely high WQI values (>300), classifying them as unsuitable for drinking due to excessive salinity and sodium–chloride enrichment. In contrast, the inland eastern wells (B11, B12, B16, B17) exhibited very low WQI values (<50), indicating excellent water quality suitable for both drinking and irrigation purposes. Intermediate samples (B3–B10, B13–B15) ranged between good and poor categories, reflecting localized exceedances of sodium and chloride but retaining potential for use after minor treatment or controlled irrigation. These findings suggest that the quality of groundwater in the study area is strongly influenced by natural hydrogeochemical processes, including water–rock interactions, evaporation, and seawater intrusion, as well as anthropogenic factors such as overextraction.

Table 2: Classification of Water Quality Index (WQI)

Sample	WQI	Classification
B1	312.4	Unsuitable
B2	305.7	Unsuitable
B3	98.6	Good
B4	95.2	Good
B5	145.8	Poor
B6	88.4	Good
B7	72.1	Good
B8	69.7	Good
B9	110.3	Poor
B10	107.5	Poor
B11	42.6	Excellent
B12	41.9	Excellent
B13	85.7	Good
B14	78.3	Good
B15	76.9	Good
B16	28.4	Excellent
B17	33.1	Excellent

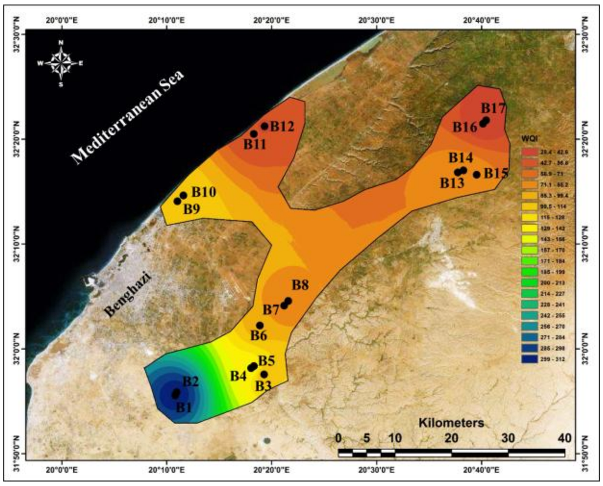


Fig. (7): Distribution of the WQI of groundwater in the study area.

1.4.2. Suitability for irrigation purposes

The suitability of water for irrigation can be assessed using specific calculation ratios:

1.4.2.1. Wilcox's diagram

Wilcox's diagram (Wilcox, 1955) illustrates the relationship between electric conductivity (EC) on the X-axis and sodium percentage (Na%) on the Y-axis, which clearly visualizes the suitability of water for agricultural irrigation. It provides a quick and effective visual tool for assessing potential hazards related to salinity and sodium content in irrigation water, aiding in agricultural planning and sustainable water management. The Sodium percentage (Na%) was determined using the following equation (3):

$$\mathbf{Na\% = (Na^{+} + K^{+}) / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})} \qquad \mathbf{(3)}$$

Where all concentrations are in meq/L.

The diagram (Figure 8) reveals a clear variation in the studied groundwater quality; samples B1 and B2 fall within the "unsuitable for irrigation" category due to their high salinity and sodium levels, which significantly limit their suitability for irrigation. In contrast, samples B3 to B17 range from "good to excellent," indicating their suitability for irrigating most crops, particularly in soils with medium to high permeability, considering both soil type and crop sensitivity.

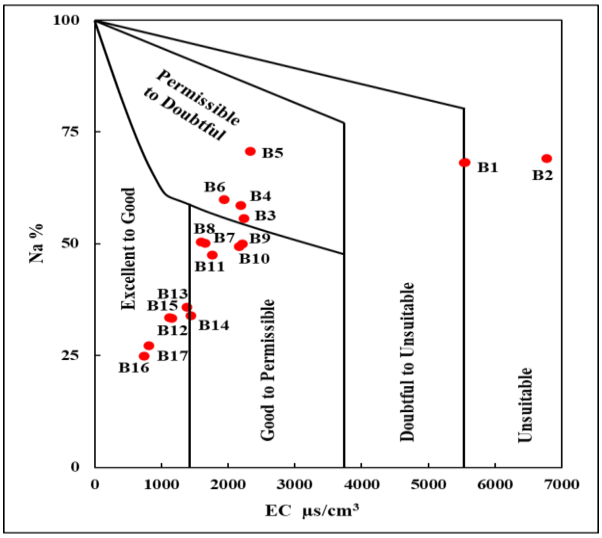


Fig. (8): Wilcox's diagram representing the analysed groundwater samples.

1.4.2.2. *Salinity index*

The United States Salinity Laboratory diagram (USSL Staff, 1954) classifies groundwater based on salinity, EC on the X-axis, and sodium hazards, indicated by SAR, on the Y-axis. The chart categorizes water into zones: C1-C4 for salinity risk, ranging from low to very high, and S1-S4 for sodium risk, also categorized from low to very high. These zones enable farmers to select the optimal water for their crops, thereby improving productivity and reducing soil damage. The graph was improved by Shahid and Mahmoudi (2014), who expanded the water salinity range to 30,000 µS/cm to reflect better the high salinity conditions found in arid and semi-arid regions. The plotted groundwater samples on the US salinity diagram (Figure 9) reveal that most groundwater samples fall in zones C4S1 and C4S2, indicating very high salinity with low to moderate sodium hazard. Such water demands proper irrigation planning, including the use of salt-tolerant crops and efficient soil drainage. A small number appear in zones C4S3 and C4S4, suggesting high sodium levels that could pose risks to soil structure if not managed with treatment or soil amendments.

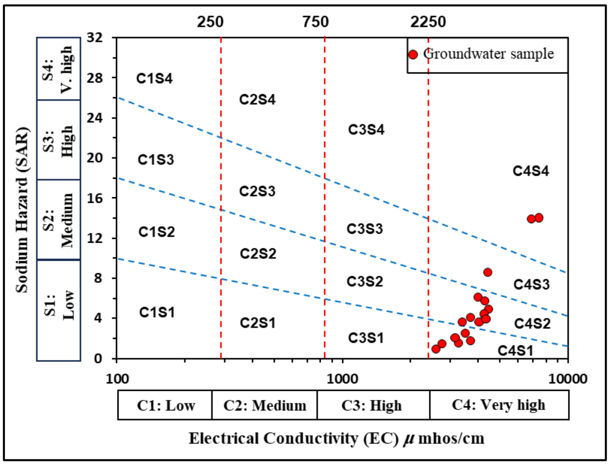


Fig. (9): Illustrates the US Salinity Laboratory (USSL) diagram of the analysed groundwater samples.

1.4.3. *Sodium Adsorption Ratio (SAR)*

The sodium adsorption ratio (SAR) is a crucial parameter for evaluating the potential risks associated with irrigation water, which can lead to soil structure degradation and indicate sodium hazard levels (Qadir et al., 2021). The sodium adsorption ratio (SAR) was determined using Equation (2), where SAR values ranged from 1.0 to 14.01, showing significant variation in sodium hazard. Samples B1 and B2 have the highest SAR (14.01) (Figure 10), suggesting that their use in irrigation may raise the risk of reduced soil permeability unless treated. Conversely, samples B16 and B17 have low SAR values (≤1.3), indicating minimal sodium hazard. The water from certain regions may need improvement to protect soil structure and promote long-term agricultural sustainability.

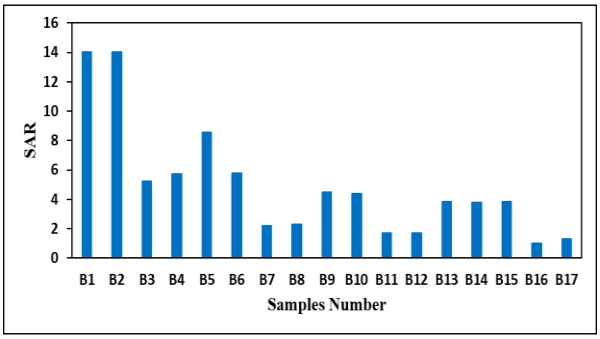


Fig. (10): Sodium Adsorption Ratio (SAR) distribution.

DISCUSSION

The spatial variability of groundwater chemistry in the eastern Benghazi coastal aquifer reflects the combined influence of several hydrogeochemical processes operating under semi-arid climatic conditions. Elevated concentrations of total dissolved solids (TDS), Na^+, Cl^-, Mg^{2+}, and SO_4^{2-} in the western coastal sector indicate progressive salinization associated with seawater intrusion and evaporative concentration. Strong correlations exist among salinity indicators, particularly between TDS and EC, as well as Na^+ and Cl^-, suggesting a common origin of dissolved salts and highlighting the significant influence of marine water mixing and evaporation on groundwater composition near the coastline. Similar hydrochemical behavior has been reported in Mediterranean coastal aquifers affected by seawater intrusion and intensive groundwater abstraction (Telahigue et al., 2020). Hydrochemical facies identified from the Piper diagram show that most groundwater samples belong to mixed water types, while several coastal wells are characterized by Na^+–Cl^- and Ca^{2+}–Cl^- facies. This transition from Ca^{2+}–HCO_3-dominated water in inland areas to Na^+–Cl^- type water near the coast reflects progressive mixing between fresh groundwater and saline water. Such hydrochemical evolution is commonly observed in coastal aquifers where excessive groundwater withdrawal and limited natural recharge facilitate seawater intrusion and groundwater salinization (Stigter et al., 2023; Jalali et al., 2024). The Gibbs diagrams further indicate that groundwater chemistry is mainly controlled by rock–water interaction and evaporation processes (Gibbs, 1970). The distribution of samples within the rock weathering and evaporation dominance fields suggests that mineral dissolution from carbonate formations, particularly calcite and dolomite within the Benghazi Formation, plays a key role in regulating calcium, magnesium, and bicarbonate concentrations. This interpretation is supported by saturation index results, which show slight saturation with respect to carbonate minerals and undersaturation with respect to evaporite minerals, such as gypsum and halite, indicating ongoing mineral dissolution (Parkhurst and Appelo, 2013; Redwan et al., 2016). Ionic relationships also underscore the significance of mineral dissolution and seawater mixing in regulating groundwater chemistry. The close relationship between Na^+ and Cl^- indicates that halite dissolution and marine influence contribute significantly to groundwater salinity. In contrast, the relationships between Ca^{2+}, Mg^{2+}, and bicarbonate reflect carbonate weathering processes within the aquifer system. The Water Quality Index (WQI) results further demonstrate clear spatial variability, where coastal wells show poor water quality due to salinization, while inland wells generally exhibit good to excellent water quality. Similar groundwater quality patterns have been reported in other semi-arid regions where hydrogeochemical processes and human activities jointly influence groundwater composition (Salem et al., 2022; Hossain et al., 2024). Overall, groundwater evolution in the eastern Benghazi coastal aquifer is controlled by the combined effects of seawater intrusion, evaporation, and water–rock interaction within carbonate formations. These processes collectively regulate groundwater salinity and highlight the need for continuous monitoring and sustainable groundwater management to prevent further salinization of this important coastal aquifer. The quantitative results, particularly the high WQI (>300) and SAR (~14) in coastal wells, along with the strong correlation between TDS, Na^+, and Cl^-, indicate that groundwater deterioration is mainly driven by seawater intrusion and evaporation. These findings provide a scientific basis for management strategies, including desalination, regulation of groundwater abstraction, and controlled irrigation practices to ensure long-term sustainability.

CONCLUSION

This study provides a comprehensive hydrogeochemical characterization and an assessment of groundwater quality in the eastern Benghazi area, northeastern Libya. The results indicate considerable spatial heterogeneity in groundwater quality, primarily influenced by water–rock interactions, evaporation under arid climatic conditions, and seawater intrusion along the coast. Groundwater in the eastern sector generally meets the WHO (2022) drinking standards, whereas the western part is characterized by elevated salinity and TDS levels, making it unsuitable for potable use. hydrogeochemical facies analysis reveals mixed water types, predominantly characterized by Na^+–Cl^- and Ca^{2+}–Mg^{2+}–HCO_3^-, with seawater intrusion contributing to increased salinity in coastal wells. Saturation index values indicate a slight equilibrium with carbonate minerals but undersaturation with evaporite minerals, confirming the presence of active geochemical processes. Irrigation assessments show that most groundwater is suitable for agricultural use, although wells B1 and B2 pose risks due to high salinity and sodium hazards. Overall, while the eastern groundwater remains largely ideal for drinking and irrigation, western sectors face critical salinization challenges that demand sustainable management. These findings provide a scientific basis for developing regional water policies that prioritize regulated pumping, desalination of highly saline wells, and implementing comprehensive management strategies to protect groundwater resources in the long term, amid increasing human and climate-related pressures.

RECOMMENDATIONS

Based on the quantitative hydrogeochemical results, the following recommendations are proposed:

1. Wells B1 and B2 (TDS >1000 mg/L, WQI >300, SAR ~14) are unsuitable for use and require desalination or blending before application.
2. Low-WQI groundwater (<100), particularly in eastern wells (e.g., B11, B12, B16, B17), is suitable for use but requires periodic monitoring.
3. High-salinity water (C4) with moderate–high SAR should be used cautiously for irrigation, with salt-tolerant crops and efficient irrigation methods.

4. The Na^+–Cl^- dominance and strong TDS correlation indicate seawater intrusion; therefore, groundwater abstraction should be regulated in coastal zones.
5. A long-term monitoring program focusing on TDS, SAR, WQI, and major ions is essential for sustainable groundwater management.

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