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THEME
Geochemistry of the Groundwater of the Terminal Complex
Aquifer in the Wadi Righ Region

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ABSTRACT

Groundwater in the Algerian Sahara is an important source of water for various uses. Despite its abundance compared to surface water, it is still confronted with many problems in terms of overexploitation and quality. The excessive mineralization of this groundwater is a major issue in the Wadi Righ region in the northeastern Algerian Sahara. In this research, we attempt to examine the groundwater mineralization source of the Terminal Complex aquifer and analyze its spatiotemporal trends by combining tools from Geographic Information Systems (GIS) with hydrogeochemical analysis of results from 117 wells between a period of four years (1995, 2012, 2015 and 2017), and 613 groundwater measurements for six years (1998, 2005, 2010, 2013, 2015 and 2017). The results showed that the groundwater is mostly of SO₄-Cl-Mg-Ca and SO₄-Cl-Na water type. It also revealed a water/rock interaction as the main process affecting the mineralization of groundwater in the study area. The distribution of electrical conductivity (EC), the groundwater level and the saturation indices (SI) showed a gradual upward trend from south to north. Furthermore, an inverse relationship between the water level of the Terminal Complex aquifer and the mineralization in the Wadi Righ region was evidenced. According to statistical analyses, it has been determined that the TDS value of groundwater is mostly related to chloride, sulfate, magnesium, and sodium, and the correlation coefficients (R^2) between the variables generally show a moderate to high positive relationship. A temporal decrease in the groundwater level has been observed, and there has been no temporal variation in the conductivity and TDS values of groundwater.

Keywords: Wadi Righ, Terminal Complex aquifer, mineralization, hydrogeochemistry.

ملخص

المياه الجوفية في الصحراء الجزائرية هي مصدر مهم للمياه لمختلف الاستخدامات. وعلى الرغم من وفرتها مقارنة بالمياه السطحية، إلا أنها لا تزال تواجه العديد من المشاكل من حيث الإفراط في الاستغلال والجودة. ويمثل التمدن المفرط لهذه المياه الجوفية مشكلة رئيسية في منطقة وادي ريغ في شمال شرق الصحراء الجزائرية. في هذا البحث، نحاول فحص مصدر تمدن المياه الجوفية لخزان المياه الجوفية المركب النهائي وتحليل اتجاهاته المكانية والزمانية من خلال الجمع بين أدوات من نظم المعلومات الجغرافية (GIS) مع التحليل الهيدروجيوكيميائي لنتائج 117 بئرًا بين فترة أربع سنوات (1995 و 2012 و 2015 و 2017)، و 613 قياسًا للمياه الجوفية لمدة ست سنوات (1998 و 2005 و 2010 و 2013 و 2015 و 2017). أظهرت النتائج أن المياه الجوفية هي في الغالب من نوع $SO_4-Cl-Mg-Ca$ و $SO_4-Cl-Na$. كما كشف عن تفاعل الماء/الصخور كعملية رئيسية تؤثر على تمدن المياه الجوفية في منطقة الدراسة. أظهر توزيع الموصلية الكهربائية (EC) ومستوى المياه الجوفية ومؤشرات التشبع (SI) اتجاهًا تصاعديًا تدريجيًا من الجنوب إلى الشمال. علاوة على ذلك، تم إثبات وجود علاقة عكسية بين مستوى المياه في طبقة مياه المركب النهائي والتمدد في منطقة وادي ريغ. ووفقًا للتحليلات الإحصائية، فقد تم تحديد أن قيمة TDS للمياه الجوفية ترتبط في الغالب بالكلوريد والكبريتات والمغنيسيوم والصوديوم، وتظهر معاملات الارتباط (R^2) بين المتغيرات بشكل عام علاقة إيجابية متوسطة إلى عالية. وقد لوحظ انخفاض زمني في مستوى المياه الجوفية، ولم يكن هناك تباين زمني في قيم الموصلية و TDS للمياه الجوفية.

الكلمات المفتاحية: وادي ريغ، مجمع المياه الجوفية للمركب النهائي، التمدن، الكيمياء المائية.

Résumé

Les eaux souterraines du Sahara algérien constituent une ressource essentielle pour divers usages. Bien qu'elles soient plus abondantes que les eaux de surface, elles sont néanmoins confrontées à de nombreux problèmes, notamment liés à la surexploitation et à leur qualité. Une minéralisation excessive de ces eaux souterraines représente un enjeu majeur dans la région d'Oued Righ. Dans le cadre de cette recherche, nous avons cherché à identifier les sources de minéralisation des eaux souterraines de l'aquifère du Complexe Terminal, et à analyser leurs tendances spatio-temporelles en combinant des outils de Systèmes d'Information Géographique avec une analyse hydro-géochimique des résultats issus de 117 forages, sur une période de quatre années (1995, 2012, 2015 et 2017), ainsi que de 613 mesures d'eaux souterraines réparties sur six années (1998, 2005, 2010, 2013, 2015 et 2017). Les résultats ont montré que les eaux souterraines présentent principalement une signature chimique de type $\text{SO}_4\text{--Cl--Mg--Ca}$ et $\text{SO}_4\text{--Cl--Na}$. Ils ont également révélé que l'interaction eau/roche constitue le principal processus responsable de la minéralisation dans la zone d'étude. La distribution de la conductivité électrique, du niveau piézométrique, ainsi que des indices de saturation, a mis en évidence une tendance croissante du sud vers le nord. Par ailleurs, une relation inverse entre le niveau des eaux de l'aquifère du Complexe Terminal et leur minéralisation a été observée dans la région d'Oued Righ. D'après les analyses statistiques, il a été déterminé que la valeur de Total des Solides Dissous est principalement liée aux concentrations en chlorures, sulfates, magnésium et sodium. Les coefficients de corrélation (R^2) entre ces variables indiquent généralement une relation positive allant de modérée à forte. Une diminution temporelle du niveau des eaux souterraines a été observée, tandis qu'aucune variation temporelle significative n'a été constatée pour les valeurs de conductivité et de TDS.

Mots-clés : Oued Righ, aquifère du Complexe Terminal, minéralisation, hydro-géochimie.

Dedication

I dedicate this doctoral thesis to my beloved **parents**, whose unconditional love, endless sacrifices, patience, and unwavering support have been the foundation of all my achievements. Their encouragement and prayers have guided me throughout every stage of this journey.

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List of Symbols and Abbreviations

ABHS	Sahara Hydrographic Basin Agency
ADE	Algerian Water Company
AHP	Analytic Hierarchy Process
ANRH	National Agency for Water Resources
Bsa	Monthly Variation of Accumulated Water (mm)
Ca	Calcium
CaCO ₃ (Aragonite)	Aragonite (Calcium Carbonate)
CaCO ₃ (Calcite)	Calcite (Calcium Carbonate)
CaMg(CO ₃) ₂	Dolomite
CaSO ₄	Anhydrite
CaSO ₄ ·2H ₂ O	Gypsum
CI	Discontinuous Continent
Cl ⁻	Chloride
CT	Terminal Complex
EDTA	Ethylenediaminetetraacetic Acid
EC	Electrical Conductivity
ERESS	Study of Water Resources in the Northern Sahara
Eta	Actual Evapotranspiration
Etp	Potential Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
HAC	Hierarchical Ascending Classification
HCO ₃ ⁻	Bicarbonate
IWQI	Irrigation Water Quality Index
K	Potassium
KR	Kelly ratio
Mg	Magnesium
Na	Sodium
NaCl	Halite
ONM	National Meteorological Office
OSS	Observatory of the Sahara and Sahel
pH	Hydrogen Ion Concentration
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SASS	North Western Sahara Aquifer System
SO ₄ ²⁻	Sulfate
TDS	Total Dissolved Solids
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization
WQI	Water Quality Index
%MR	Magnesium Hazard
%Na	Sodium Ion Percentage
%PI	Permeability Index

1. INTRODUCTION

Water resources around the world are limited in quantity and are increasingly threatened by human activities such as population growth, urban expansion, and rising living standards (Liu et al., 2017). Climate change and shifts in natural conditions further exacerbate these pressures. Yet, water remains an essential element for both human life and ecosystems (Vasistha and Ganguly, 2020). Preserving the quality and quantity of water resources has therefore become a critical issue. In recent years, it appears that both the public and authorities have become more aware of the need for improved water management and protection. Groundwater plays an indispensable role in the Earth's hydrological cycle, owing to its intrinsic properties that make it suitable for a wide range of applications (Şener et al., 2017c). It also serves a pivotal function in sustaining ecosystems and meeting the growing water demands of living organisms.

Water quality is a critical environmental concern for domestic, agricultural, and industrial uses (Kumbur et al., 2008; Özlem and Sezer, 2017), as it directly impacts both environmental integrity and human health. Assessing water quality is essential prior to use, as regular monitoring ensures a reliable and safe water supply (Rowe and Wright, 1999; Şener et al., 2023). Such monitoring also plays a key role in protecting water sources from potential contamination, selecting appropriate treatment methods, and evaluating their effectiveness (Pesce and Wunderlin, 2000; Goher et al., 2014). The mismanagement of water resources through traditional agricultural practices, the discharge of untreated wastewater into natural environments, and inadequate treatment processes poses a serious threat to public health due to water contamination, as well as to ecological systems (Afroz et al., 2014; Olukulu, 2017).

The North Sahara Aquifer System covers a vast area (> 1 million km²) and includes two major groundwater bodies shared among Algeria, Tunisia, and Libya, known as Continental Intercalary (CI) and Terminal Complex (CT), composed of continental sediments (Edmunds et al., 2003). These geological reservoirs have long remained in excellent harmony with the Sahara ecosystem through natural discharge pathways (springs and foggaras) (Guendouz et al., 1998; Edmunds et al., 2003; Al-Gamal, 2011; Darling et al., 2018). The chemical characteristics of hydrological basin-based waters exhibit temporal and spatial variability, influenced by various factors. An increase in

water mineral density downstream is commonly observed with increased water/rock contact time. Spatial variability in aeration conditions of the water basin and lithological heterogeneity are other frequent sources causing spatial variability in aquifer hydrochemical properties (Guendouz and Michelot, 2006; Mamou et al., 2006). Additionally, understanding groundwater resources and identifying factors contributing to mineralization is crucial for effective management of water resources, especially in arid and semi-arid regions. Surface water scarcity and poor quality in these regions encourage intensive use of groundwater resources. However, potential sensitivities such as depletion due to overuse and surface pollution must also be considered. Salinization of water poses a significant threat to groundwater quality. Hence, hydrogeochemical assessment methods are widely used to understand water/rock interactions and the impacts of human activities on water resources. These processes, influenced by factors such as general geology, chemical alteration of different rock types, water renewal, and contributions from other sources, determine spatial and temporal variations in water chemistry that shape water quality evolution. In particular, evaporite mineral dissolution and evaporation are key factors in natural mineralization of groundwater in arid and semi-arid regions (Mamou et al., 2006).

The Wadi Righ region in southeastern Algeria is heavily affected by these issues. Previous studies indicate that groundwater in the region is associated with high total mineralization levels, which could lead to long-term health issues. Studies on groundwater in the area also reveal excessively hard water values that could result in degradation of agricultural lands, hydraulic structures, and the environment (Hacini, 2006; Benguergoura Laradj, 2014; Bouznad, 2017; Bettahar et al., 2017; Belksier et al., 2018; Kadri et al., 2022; Hammadi et al., 2023).

Our work aims to develop a comprehensive methodological approach for an exhaustive study of all aspects related to water geochemistry. This involves highlighting the relationship between water's hydrochemical characteristics and aquifer formations' lithological nature. To achieve the study's objective, the general chemical properties and hydrogeochemical processes of the waters forming the aquifer have been examined in detail from past to present. Additionally, the hydrogeochemical characteristics of groundwater have been identified, including the spatial distribution and temporal evolution of various chemical elements, as well as the hydrogeochemical

processes and their origins. Index methods, classification graphs, and statistical analyses have been utilized to determine the suitability of groundwater for drinking and irrigation purposes. The main headings of the thesis work and the studies conducted under each heading are presented in a flowchart shown in Figure 1.1.

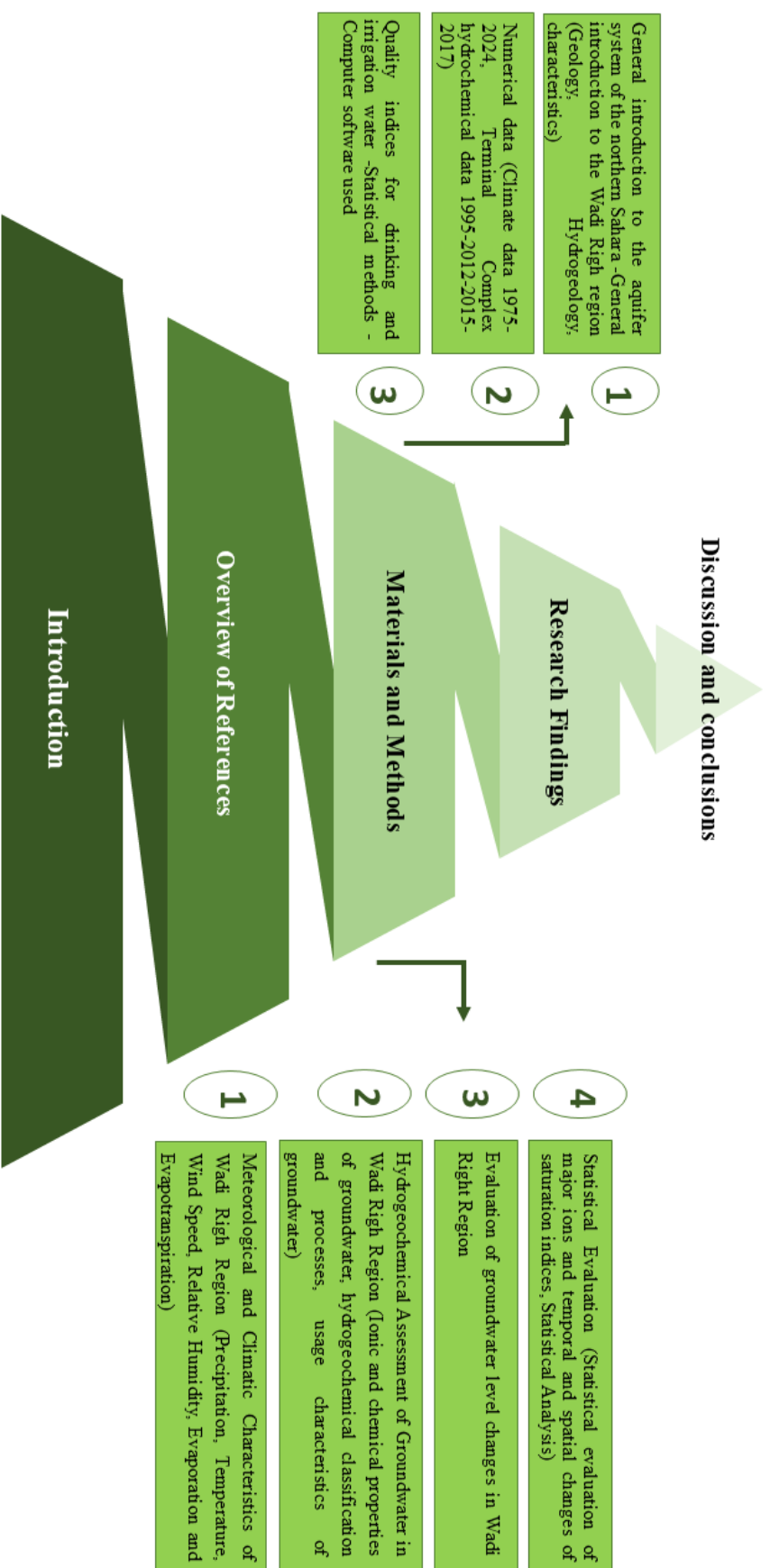


Figure 1.1 Flow chart of the study

2. OVERVIEW of REFERENCES

This section presents a comprehensive review of all studies conducted in the Terminal Complex Aquifer of Wadi Righ, designated as the study area, from past to present by various researchers.

Touati (1986) examined the climatic characteristics of the Wadi Righ region and their impact on agricultural activities were analyzed. According to the study, the regional climatic conditions have fostered the development of desert agriculture dominated by Phoenician farming practices, a phenomenon attributed to the presence of exceptional hydrological conditions. Wadi Righ, located in the Lower Algerian Desert, benefits from the utilization of groundwater, which supports crop growth. However, the excessive exploitation of this resource has led to the observation of low hydrostatic levels in the groundwater.

Mebrouk Oussedik (2001) identified severe water supply issues in Algeria's arid Sahara regions, which represent approximately two-thirds of the country's land area and receive an average annual rainfall of about 60 mm, face significant challenges in ensuring water supply for public, agricultural, and industrial use. The study highlights that a critical step in the development of the region where the city of Touggourt is located is the investigation of techniques to enhance potable water potential. The Albian aquifers have been considered an alternative water source to meet the drinking water needs of the Sahara region. However, the study notes that the water from these aquifers is both hot and saline, presenting challenges for use, and must undergo desalination to become suitable for consumption. The findings of the study reveal that water extracted from the Aïn-Sahara borehole has a temperature of 60°C, salinity of 2100 ppm, and a discharge rate of 130 l/s. Using an electrodialysis unit designed to treat brackish water with salinity levels below 2500 ppm, the groundwater quality was improved to meet the quality standards set by Algeria and the World Health Organization (WHO).

Guendouz et al. (2003) conducted investigations into groundwater mineralization in the Wadi Righ region. According to the study, mineral concentrations in groundwater increase along the flow path. The presence of evaporitic minerals such as halite, gypsum, and sylvite in the aquifer indicates that evaporation is the primary process

controlling groundwater chemistry. Additionally, due to the saturation of the water with carbonate minerals, the concentrations of HCO_3^- and Mg^{2+} remain relatively constant. Minor and trace elements (Br^- , Sr^{2+} , Li^+ , B^{3+} , F^- , I^- , and Rb^+) follow similar trends to major ions. Stable isotopes (^{18}O , ^2H , ^{13}C) and radiocarbon data align with hydrochemical interpretations of increasing water age and water-rock interactions. The presence of faults south of the city of Ouargla has caused the upward movement of ancient waters from the lower levels of the Continental Intercalaire (CI) aquifer. Radiocarbon dating identified two distinct ages: one ranging from 1,000 to 4,000 years before present (b.p.) and the other from 20,000 to 40,000 years b.p.

According to the study conducted by OSS (2003) in Algeria, the progressive aridification of the regional climate has led to a decline in groundwater potential within the aquifer system. Artesian discharges and spring flows observed in the past have almost entirely diminished. Since the late 19th century, when the first wells were drilled in the Tunisia-Algeria region, the aquifer system has experienced increasing decompression. During the 20th century, particularly since the 1980s, this decompression phenomenon has manifested in the drying up of the region's primary water sources and the weakening of artesian well flows. The study concludes that the relatively low, irregular, and intermittent rainfall in the region plays a minimal role in recharging the aquifer.

Helal and Ourihane (2004) described the Touggourt region's climate as extremely arid, characterized by high summer temperatures and very low annual rainfall. The recorded average maximum temperature is 33°C , the minimum is 10°C , and the annual average temperature is 21°C . The annual precipitation, measured at 62.73 mm, is both minimal and irregular, playing an insignificant role in directly recharging groundwater. Rainfall occasionally occurs as thunderstorms that generate runoff in border areas, with significant interannual variability. The study also analyzed the chemical properties of the groundwater. The findings indicate that the groundwater in the Touggourt region is highly mineralized and hard, with implications for its quality and drinkability. Due to these characteristics, caution is advised when using the water for irrigation, as preventative measures are needed to avoid soil alkalization. Furthermore, it is recommended that the water undergo treatment processes before being used as drinking water.

Bousaada (2007) detailed the Sahara region's climate, marked by low and irregular rainfall. This climate, which typically plays no significant role in replenishing water reserves, is marked by occasional intense thunderstorms. The average annual precipitation in the region ranges between 73 and 81 mm. Temperatures are notably high, with an annual average of 22°C and a maximum of 34°C, contributing to increased evaporation rates. The average annual relative humidity is 66% in December, decreasing to between 35% and 51% in July. The annual average evaporation rate is approximately 250 mm. The study's findings indicate that historical analysis of rainfall patterns reveals a direct correlation between groundwater level declines and periods of drought dominated by low rainfall. Additionally, the surface water quality in the region is significantly degraded due to anthropogenic factors, with elevated levels of chlorides and organic matter detected in the water.

Seraoui (2008) found that the groundwater used for drinking in the Touggourt region contains fluoride concentrations high enough to potentially cause fluorosis. The study aimed to determine the fluoride levels in the region's spring water and investigate methods to reduce the elevated fluoride concentrations. The Beni Yessoued spring water was selected to test the effectiveness of the sedimentation method. To optimize conditions for reducing fluoride levels, the study recommended the use of calcium treatment combined with coagulation-flocculation techniques.

Bouhekima et al. (2008) examined the potential role of brackish water as a freshwater source and the challenges of desalinating brackish water in southern Algeria were discussed. According to the study, providing freshwater to some remote desert regions in Algeria is extremely challenging, with water scarcity being one of the major constraints to the development of these areas. In certain locations, the presence of moderately saline water (2,000–3,000 mg/L) suggests that, with the adoption of an appropriate desalination plan, it is possible to achieve an economical and reliable freshwater supply. To illustrate the feasibility of desalinating brackish water compared to other water supply options, a case study was conducted using a reverse osmosis (RO) system.

Hacini et al. (2008) identified Chott Merouane in southeast Algeria as an ideal natural system for examining the effects of mineral dissolution and precipitation. In the study, the concentrations of major elements in the waters of Merouane Chott Lake were

measured weekly from January to June 2003. The analysis results were evaluated alongside estimates of lake volume and infiltration rates to calculate the temporal evolution of the total mass of major elements. The findings indicate that the rates of mineral precipitation in the lake waters systematically vary over time. The sequence of different phases, relative precipitation rates, and the data predicted from thermodynamic models of saline water evaporation were found to be broadly consistent. Furthermore, a general agreement was observed between the measured saturation indices of lake waters, the precipitation rates of halite, calcite, and gypsum determined in the field, and the rate equations established in laboratory studies.

The study conducted by Bouchahm and Achour (2008) identified that the varying aquifer levels observed in the regions of Ouargla, Touggourt, El Oued, and Biskra are associated with the two main aquifers of the northern Sahara: the Terminal Complex and the Continental Intercalaire. Increasing mineralization was observed in the sand and limestone aquifers with greater aquifer depth, and the water exceeded the permissible limits for drinkability. Regarding fluoride levels, the lowest concentrations were found in the Albian aquifer. According to the study, groundwater in the study area generally does not meet drinking water standards and is therefore unsuitable for potable use.

Zahi et al. (2011) linked geomorphology and insufficient drainage in Wadi Righ to recent flooding in upstream areas in recent years. This situation has led to water overflowing onto highways, the discharge of water into oases, obstruction of drainage, contamination of the phreatic aquifer by sewage, the emergence of waterborne diseases, and further increases in salinity levels.

Merabet and Righi (2011) described Wadi Righ's climate as extremely arid, with high summer temperatures and very low annual rainfall. The average maximum temperature is 29°C, the minimum is 16°C, and the annual average temperature is 22°C. Rainfall is minimal and irregular, measured at 66.09 mm per year, and plays an insignificant role in directly recharging groundwater. The study also determined the hydrodynamic properties of the aquifer using the Theis and Jacob methods.

Tabouche (2011) traced the evolution of brackish water in Wadi Righ, following the flow from recharge areas toward the surface. The study identified poorly mineralized

zones in the western and southwestern edges of the basin, corresponding to the recharge areas of Mزاب and Tademaït. In contrast, highly mineralized zones (with salinity exceeding 5 g/L) were observed in the northern part of Wadi Righ (between Meghaeir and Djamaa), in El Hadjira (between Ouargla and Touggourt), and along the line extending southward from Hassi Messaoud to the northern part of Chott Melghir. The increasing mineralization toward enclosed depressions (chotts and sebkhas) supports the proximity of these areas to the natural discharge points of groundwater flow from the CT aquifer. In Touggourt and Ouargla, shallower groundwater exhibits high fluoride content, indicating that the climate plays a role in influencing the salt content of groundwater in this region.

Debbakh (2012) used the Thornthwaite method to estimate evapotranspiration in Wadi Righ. The calculations revealed that between 1975 and 2009, the potential evapotranspiration in the region was 1,397.14 mm, while the actual evapotranspiration during the same period was 87.62 mm. Temperatures in the region are notably high, with an annual average temperature of 21.70°C and a maximum temperature reaching 33.34°C. The study also observed regular fluctuations in the piezometric levels in the area. A decrease in water levels was noted during the months of June and September due to the effects of evaporation, while slight increases in water levels were observed during rainy periods.

Bettahar (2013) found that Wadi Righ Terminal Complex groundwater is not suitable for human consumption, as it is highly mineralized and very hard. Using detailed and comprehensive methods, including diagrams, statistical tools (ACP), and simulations of saturation indices, the results indicated that the mineralization and salinity of the water are of geological origin. The hydrochemical characteristics of the water are directly related to the lithological composition of the layers forming the aquifers, and the excessive salinity in the water has been steadily increasing over time. The primary issue with Wadi Righ groundwater is its poor quality. The study suggests that solving this problem, improving the chemical quality of the water, and ensuring its drinkability according to international standards before reaching consumers requires strict rules and enforcement measures.

Medjani (2016) analyzed the physical and chemical quality of groundwater in Wadi Righ. The analysis results showed that the water has high conductivity and salinity

levels. Groundwater in the region is rich in mineral salts, particularly chlorides and sodium. According to the study, wetlands in the area are being degraded affected directly by human intervention and climate factors impacting water, soil, vegetation, and wildlife. In some cases, these wetlands face the threat of disappearing entirely.

Belksier (2017) examined the susceptibility of Wadi Righ aquifers to contamination. In the first phase, the hydrogeological, hydrodynamic, and hydrochemical characteristics of the Wadi Righ surface aquifer were defined. The second phase evaluated the sensitivity of the aquifer to anthropogenic pollution and agricultural activities. Using the GOD method, the results indicated that the surface aquifer in Wadi Righ exhibits moderate to high sensitivity to pollution in a spatial context. The study identified regions, such as agricultural lands, chotts, and urban areas, where aquifer sensitivity is most pronounced.

Guettaia et al. (2017) conducted a study using DRASTIC and GOD methods to assess aquifer vulnerability in Wadi Righ. The results for the Mio-Plio-Quaternary aquifer in the Wadi Righ region showed that the DRASTIC method better represented the distribution of sensitivity to pollution in the Mio-Plio-Quaternary aquifer compared to the GOD method.

Rahal and Belaid (2017) investigated the hydrochemical properties and origins of groundwater in the Wadi Righ region. According to their findings, the water in the Wadi Righ region is highly mineralized (3362 mg/L, electrical conductivity 3675 $\mu\text{S}/\text{cm}$), and the chemical analysis results exceed standard usage thresholds. The mineralization and salinity of the groundwater support the idea that these waters have a geological origin.

The study conducted by **Belkesier et al. (2018)** analyzed the hydrochemical properties of groundwater in the Wadi Righ region, revealing that salinity in the groundwater increases from south to north. Salinity is particularly dominant in the central part of Wadi Righ. The groundwater in the region was identified as predominantly major water types: Chloride-Sodium and Sulfate-Sodium.

Benhaddya (2020) conducted a hydrochemical study in the Wadi Righ region, revealing that groundwater exhibits high salinity due to the dissolution of geological formations, such as evaporites and carbonates. According to the study results, chemical

elements such as Cd, Cr, Cu, Mn, Ni, Pb, and Zn were detected in very low concentrations and found to be within acceptable limit values.

The study conducted by Hammadi et al. (2022) focuses on the quality and hydrogeochemistry of phreatic water, based on 30 samples collected in 2019 and 2020. Results show very high salinity levels and dominance of sodium-chloride and sulfate water types. Mineral equilibrium analysis indicates undersaturation with respect to evaporite minerals, while Gibbs diagrams highlight evaporation and crystallization as the main processes controlling salinity. Temporal variations in water chemistry are attributed to water/rock interactions and mixing processes.

According to Hammadi's et al. (2023) study, The Wadi Righ region is renowned for its date palm cultivation, supported by favorable climatic conditions, suitable soils, and abundant groundwater resources. This study aims to analyze the hydrodynamic behavior of the Terminal Complex aquifer using hydrodynamic parameters and piezometric data. Results derived from the Cooper-Jacob method indicate high transmissivity and permeability, reflecting significant aquifer productivity, with a maximum transmissivity of $2.36 \times 10^2 \text{ m}^2/\text{s}$ recorded in El Meghaier. Piezometric mapping further shows that groundwater flow is predominantly directed toward the chott.

Furthermore, national and international studies related to the subject of this thesis, particularly those focusing on groundwater chemistry, are examined and summarized below in chronological order.

Helena et al. (2000), in this study a dataset comprising quantitative analytical results from the sedimentary aquifer of the Pisuerga River, located in the northeast of Valladolid (Spain), was analyzed using multivariate statistical techniques to investigate the evolution of groundwater composition between the 1994 and 1995 surveys. Matrix analysis enabled the identification of strong correlations among several variables, including sulfate, chloride, bicarbonate, sodium, potassium, magnesium, calcium, and electrical conductivity, while revealing the absence of correlation among others, such as pH, nitrates, and trace metals. Principal Component Analysis (PCA) revealed up to five significant principal components, collectively accounting for 71.39% of the total variance. Two of these components were initially

attributed to "mineralization" processes, whereas the remaining components were associated with variables indicative of contamination. The findings suggest that mineralization can be further differentiated into two distinct components, one linked to natural mineralization (i.e., the dissolution of geological materials), and the other associated with salinization resulting from anthropogenic activities, particularly elevated levels of sodium and chloride.

Boyacioglu and Boyacioglu 2007, this study examined eleven variables to assess water quality across 17 riverine sites within the Büyük Menderes River basin and its tributaries in Turkey. Factor analysis was employed to elucidate the underlying relationships among observations through principal components, while cluster analysis was used to classify monitoring stations based on shared characteristics. The findings revealed that water quality was significantly influenced by agricultural activities, with marked differences observed between the main river course and its other segments.

Ji et al. (2016) assessed water quality degradation based on seven hydrochemical variables monitored bimonthly in 2010 at seventeen locations spanning rural, urban, and suburban sections of the Wen-Rui Tang River in eastern China. Seven distinct approaches were employed to evaluate water quality: the single-factor evaluation method, water quality classification, the comprehensive pollution index, the Nemerow pollution index, principal component analysis (PCA), fuzzy comprehensive assessment, and the comprehensive water quality identification index. The results indicated that the comprehensive water quality identification index was the most effective method, due to its superior ability to identify highly polluted waters characterized by multiple anomalies. Temporal variation in water quality was strongly influenced by precipitation, primarily due to dilution effects. Spatial variation was linked to anthropogenic influences, including urban, industrial, and agricultural activities as well as to flow direction, with downstream sections exhibiting cumulative impacts from upstream inputs.

Lu et al. (2017), This study focused on Huai'an to examine the water environmental carrying capacity from 2005 to 2014 using the Analytic Hierarchy Process (AHP) method. The research integrated regional socio-economic characteristics with the status of the water environment in the Huaihe River Basin. The findings indicated an overall upward trend in the water environmental carrying capacity. Social factors had

a significant impact on this capacity, with their fluctuations remaining relatively consistent. The total population, urbanization rate, and per capita domestic water use emerged as the primary constraints on the water environmental carrying capacity in Huai'an City.

Khashei-Siuki and Sharifan (2020) utilized ten decision-making parameters, applied sodium, calcium, magnesium, nitrates, total dissolved solids, sulfur oxide, electrical conductivity (EC), chloride (Cl), turbidity (S), and permeability index to evaluate water quality in the Birjand aquifer, Iran. The parameter values were calculated using both the Analytic Hierarchy Process (AHP) and the Fuzzy Analytic Hierarchy Process (FAHP), based on the influence of each parameter on raster layers. All raster layers were integrated within a Geographic Information System (GIS) to produce two final output layers. A comparative analysis revealed that the final layer generated using FAHP aligned more closely with actual field conditions than the one derived from the standard AHP method.

Veisi et al. (2022), This study applied the integrated Structure-Actor-Water (iSAW) framework and Analytical Hierarchy Process (AHP) to assess the sustainability of irrigation systems in Ardabil Province, Iran. Sixty stakeholders including farmers, experts, and NGO staff ranked nine indicators through a 42-item questionnaire. Results show a strong preference (69%) for pressurized irrigation systems (PISs), with employment, income, and productivity being the most influential indicators. The study highlights iSAW's effectiveness in integrating socio-economic factors into irrigation decision-making to promote sustainable agricultural practices.

Suliman and Ali (2022), This study assesses groundwater potential sites (GWPS) in the semi-arid region of Khyber Pakhtunkhwa, Pakistan, using integrated GIS and remote sensing techniques. Eight factors including elevation, slope, geology, and rainfall were combined through the Analytical Hierarchical Process (AHP) to map suitable groundwater zones. Validation with tube well data confirmed that the central area has high groundwater potential. The approach is shown to be reliable and effective, offering a valuable tool for groundwater resource evaluation in semi-arid regions.

Yan et al. (2022) reviewed water quality assessment models based on expert systems (ES) and machine learning (ML) techniques, along with various water quality indices. The study also discussed the current state and future prospects of water quality management. The findings indicated that assessment indices can be applied across three key dimensions of surface water quality evaluation: 1- Water Quality Indices (WQIs), which integrate multiple parameters and are commonly used for classifying surface water quality; 2- Trophic State Indices, calculated from nutrient concentrations required by algae and bacteria, used to assess eutrophication levels in lakes and reservoirs; and 3- Heavy Metal Indices, primarily employed to evaluate human health risks and analyze the correlation of heavy metal sources. The study developed ES- and ML-based assessment models to efficiently generate evaluation indices and predict water quality status using large datasets derived from emerging technologies, offering promising improvements in the accuracy and reliability of water quality assessments.

Uc Castillo et al. (2022), This study delineates Groundwater Potential Zones (GWPZs) in the semi-arid San Luis Potosi basin in Mexico using Remote Sensing, GIS, and the Analytic Hierarchy Process (AHP). Seven factors, including geology, rainfall, and slope, were integrated to produce a GWPZ map. Results show that 68.21% of the area has low groundwater potential, while 26.30% is moderate. Validation using water residence time and Receiver Operating Characteristics (ROC) analysis (AUC = 0.677) confirms acceptable accuracy. The findings support sustainable groundwater management and decision-making in semi-arid regions.

Khan et al. (2023), This study identifies aquifer recharge potential zones (ARPZ) in the arid Duba region of Saudi Arabia, where groundwater resources face stress due to over-pumping, seawater intrusion, and climate change. Using remote sensing, GIS, and the Analytical Hierarchical Process (AHP), the study evaluated factors like geology, rainfall, slope, and vegetation. Results show that 43% of the area mainly in the south, west, and north has high to very high recharge potential, while 41.8% has low potential. High potential zones align with lower levels of TDS, EC, and nitrates, making the method valuable for similar regions facing groundwater challenges.

Kassa et al. (2023), This study identifies groundwater recharge potential zones in the Shinile Watershed, Eastern Ethiopia, using the Analytical Hierarchy Process (AHP) and GIS. Factors such as topography, lithology, slope, rainfall, and land use were

weighted and integrated to map five recharge classes: very low to very high. Validation with borehole data confirmed the model's accuracy. The results support sustainable groundwater management and offer valuable input for national water policy and long-term resource planning in water-scarce regions.

Missaoui et al. (2023), This study evaluates groundwater quality for irrigation in the semi-arid Regueb Basin, Central Tunisia, using Principal Component Analysis (PCA), the Analytical Hierarchy Process (AHP), and GIS. Forty-eight groundwater samples were analyzed for ten physicochemical parameters, with TDS, Na^+ , SO_4^{2-} , and Cl^- being the most dominant. Six key criteria were used to develop a weighted irrigation water quality index (WQI). The resulting WQI map classified groundwater into five categories, with 43.75% rated as excellent and 6.25% as unsuitable. The study supports sustainable groundwater management in arid regions.

Ulanova et al. 2024, this study monitored data collected during the spring and autumn seasons from 2001 to 2023 across five water reservoirs with varying purposes and hydrological regimes located in the Republic of Kalmykia. The results revealed that the degree of mineralization in all reservoirs was higher than in the water sources that feed them. It was established that mineralization in reservoirs with induced surface runoff is not geographically determined. Among the reservoirs situated in desert regions, mineralization levels were found to be lower than those in steppe-region reservoirs with similar functional purposes. Seasonal variation in water mineralization exhibited a consistent pattern across all reservoirs, with higher values recorded during autumn compared to spring. The spatial variability in mineralization levels across different parts of the reservoirs is attributed to the influx of newly supplied water, which has a lower mineral content than the reservoir water itself. Differences in mineralization between various reservoir sections and across seasons were smaller than the magnitude of the lowest mineralization values observed within the reservoirs. For the purposes of drinking water supply and irrigation, the reservoirs were classified based on long-term average mineralization levels.

Shinde et al. (2024), This study evaluates groundwater potential zones (GWPZs) in a semi-arid region of India using two methods: the Analytical Hierarchy Process (AHP) and the Multiple Influence Factor (MIF) approach. Nine thematic layers including land use, soil, geology, and groundwater level were analyzed using remote sensing and GIS.

Both methods classified the area into four GWPZ classes: poor, moderate, good, and very good. Validation with water yield data and ROC analysis showed AUC values of 0.93 for AHP (excellent) and 0.80 for MIF (good), indicating AHP is more accurate. The study supports groundwater resource planning and sustainable irrigation management in basaltic and drought-prone regions.

Yazdi et al. (2024) introduced the Fuzzy Groundwater Quality Index (FGWQI), employing a fuzzy inference system model to evaluate the groundwater quality of the Houmand-Absard region in Iran. The FGWQI integrates five agriculture-oriented quality indicators: Sodium Adsorption Ratio (SAR), Sodium Percentage (Na%), Magnesium Hazard Ratio (MHR), Kelly's Index (KI), and Potential Salinity (PS). A comparative analysis was conducted between the FGWQI and the widely used MHR index, using water samples collected from twenty stations during the 2021 season. The FGWQI model outperformed traditional indices, particularly MHR by providing more realistic assessments. While the MHR classified 47% of the samples as unsuitable for use when the FGWQI exceeded 60, the FGWQI suggested acceptable quality levels (scores between 30 and 70), indicating that with appropriate groundwater management, more water resources could be allocated for agricultural purposes.

Mishra et al. (2024) investigated the physicochemical and microbiological characteristics of the Asan River in India by collecting water samples across seven sites and analyzing fourteen water quality parameters from October 2018 to March 2019. The study developed a Water Quality Index (WQI) and spatial water quality maps using ArcGIS version 10.7. Datasets obtained from the samples were used to generate a spatial WQI map based on the Analytic Hierarchy Process (AHP). The results indicated that the water was heavily polluted near the third station, primarily due to intensive human activities. Therefore, coordinated governmental and non-governmental interventions are urgently required to slow the degradation of the Asan River and restore it to its original, unpolluted state an essential step for preserving the ecological health of the region.

Terán-Gómez et al. (2025), This study introduces the Integral Index of Vulnerability to Diffuse Contamination (IIVDC), a spatial, multi-criteria tool that assesses surface water vulnerability to agricultural pollution, especially in developing regions with limited data. Combining GIS and the Analytical Hierarchy Process (AHP), the IIVDC

uses six indicators slope, soil erodibility, land use, runoff potential, hydrological connectivity, and water quality weighted by expert input. Applied to Colombia's Guachal River watershed, the index revealed that over one-third of the area is highly vulnerable due to steep slopes, sparse vegetation, and strong pollutant pathways from farmland. The IIVDC enables targeted land management and supports sustainable water resource planning, especially where conventional assessment methods fall short. Future improvements should include real-time water quality monitoring and testing across diverse climates.

Collins et al. (2025) present a comprehensive assessment of a large groundwater quality dataset collected from diverse environments across New Zealand. The study develops methodologies for identifying missing redox-sensitive variables in groundwater and characterizes the spatial variability and temporal stability of redox conditions in comparison with related hydrogeochemical properties across environmental settings. The extreme gradient boosting method outperformed linear regression in predictive accuracy. The analysis of groundwater redox conditions revealed substantial spatial heterogeneity, strongly influenced by subsurface geology (rock types) and soil characteristics across varying hydrogeological environments. Additionally, the results indicated a higher prevalence of oxidizing redox states in shallow groundwater, along with greater temporal stability of oxidizing conditions across the New Zealand landscape.

Mani et al. (2025), This study employed Analytic Hierarchy Process (AHP) techniques and Geographic Information Systems (GIS) to assess the River Risk Zone (RRZ) in the Himalayan rivers of India. The analysis was based on fifteen thematic layers, including Total Dissolved Solids (TDS), conductivity, pH, salinity, temperature, depth, drainage density, land use/land cover (LULC), elevation, slope, flow, width, soil type, geology, and aspect. These were derived from primary survey data, open-source Digital Elevation Models (DEMs), and satellite imagery. The RRZ map was classified into five risk categories: very high, high, moderate, low, and very low. The results revealed that approximately 56.38% of the river area falls within the high and very high risk zones.

3. MATERIALS and METHODS

3.1. Material

3.1.1. General Introduction to the North Sahara Aquifer System (Geological and Hydrogeological Characteristics)

The North Sahara Aquifer System (SASS) is a hydrological unit spanning over a million square kilometers in the western part of North Africa, covering approximately 700,000 km² in Algeria, 80,000 km² in Tunisia, and 250,000 km² in Libya (Figure 3.1). This area includes two main aquifer formations known as the "Intercalary Continental (CI)" and the "Terminal Complex (CT)". Geologically, the Intercalary Continental aquifer comprises units from the Jurassic and Lower Cretaceous periods, while the Terminal Complex includes units from the Miocene-Pliocene and Upper Cretaceous periods. In the SASS, there is a complex underground flow system manifesting as springs and foggaras, which are oases well-known in these three countries, formed a very long time ago. The SASS holds an enormous water reserve with a volume of 30,000 billion m³. However, not all of this water is accessible for use. The recharge of the groundwater reserve is approximately equivalent to one billion cubic meters of water, making it a very limited renewable natural resource for the region (ERESS, 1972).

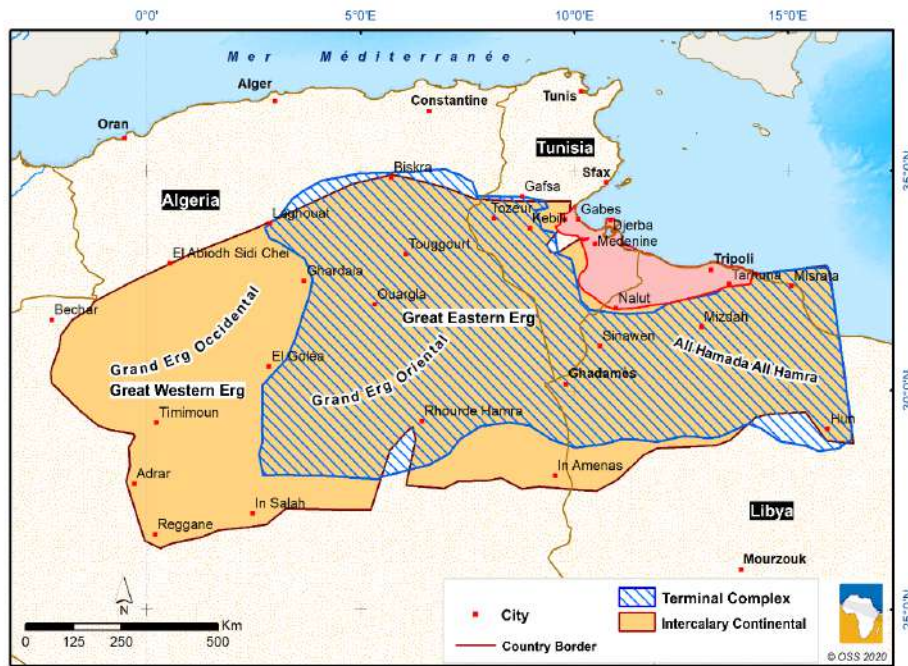


Figure 3. 1 The regional-scale extension of the formations constituting the North Saharan Aquifer System. (OSS, 2020)

The Intercalary Continental (CI) is a geological formation primarily composed of continental sandstone clay formations from the Lower Cretaceous, directly overlaid by Cenomanian clays. It extends in a continuous arc from El Golea to the southern boundary of Hamada El Hamra. This formation is defined as a continental unit formed between the Hercynian folds and the marine transgression of the Upper Cretaceous.

The term Continental Terminal refers to the continental, sandy, and clay formations of the Miocene-Pliocene. However, according to Bel and Demargne (1966), the Continental Terminal aquifer in the Miocene-Pliocene sands is related to the Eocene, Senonian, and Turonian aquifers. Therefore, throughout the Sahara desert, these different levels are considered to constitute the same "Continental Terminal" aquifer.

The concept of the Terminal Complex (CT) was first introduced by Bel and Cuche (1969) and is used to group several aquifers within different geological formations under the same term. While interactions between the Senonian, Eocene, and Miocene-Pliocene are clearly observable in the basin, the middle and upper Eocene levels are impermeable and thus excluded from the Chott region. The Turonian aquifer is classified separately due to the impermeable levels of the Senonian. However, in the

boundary region, it presents similarities with the Senonian or Miocene-Pliocene levels (Figure 3.2).

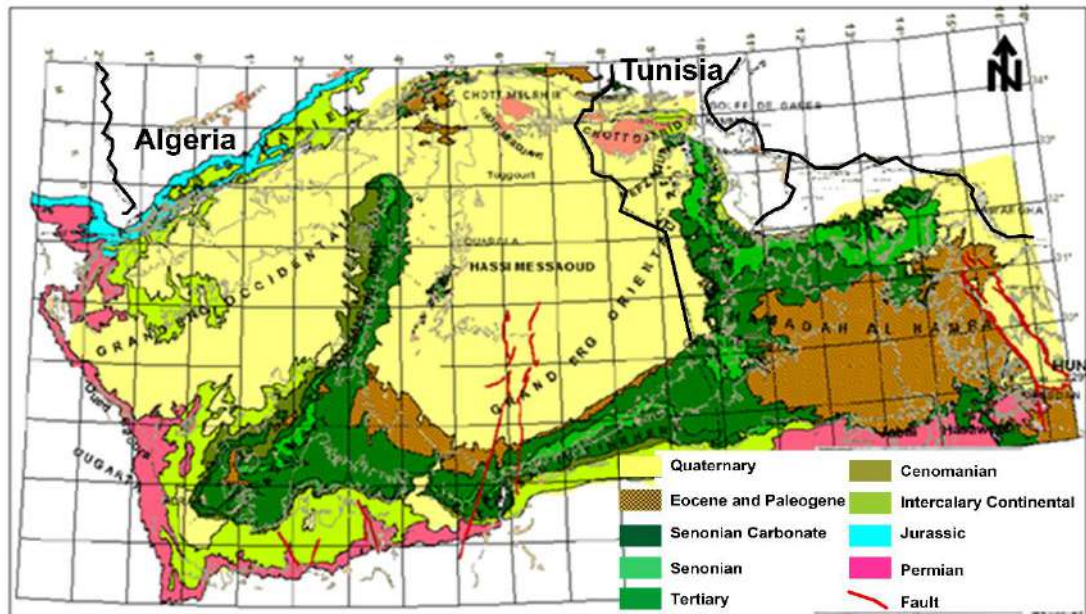


Figure 3. 2 Geological map of the Northern Sahara Aquifer System (OSS, 2003)

3.1.2. The North Sahara Aquifer System in Algeria

3.1.2.1. Geographical Location

The North Sahara Basin covers an area of approximately 872,373 km² (OSS, 2003). It encompasses a total of 96 municipalities within the wilayas of Ouargla, Touggourt, El Meghair, Ghardaïa, Biskra, El Oued, Adrar, Tamanrasset, Illizi, Laghouat, and Djelfa. The North Sahara Basin constitutes 38% of Algeria and is bounded by the Chott Melghir Basin to the north, the Hoggar and Tassili Basins to the south, the Tunisia-Libya border to the east, and the Saoura-Tindouf Basin to the west.

3.1.2.2. Hydrological and Climatic Characteristics of the Algerian Sahara

The Algerian Sahara stands as one of the driest and hottest regions globally, encompassing an expansive area of approximately 2 million square kilometers between 18° and 35° latitude north. The extreme aridity of this region is attributable to stable climatic conditions persisting for over four millennia. The climate plays a pivotal role in shaping vegetation and plant proliferation while imposing significant

constraints on agricultural activities. Low precipitation, high temperatures, and wind-driven evaporation severely limit agricultural development.

Precipitation:

Annual rainfall in the region is generally less than 50 mm and is highly irregular. In the northern parts, precipitation can reach up to 150 mm annually, whereas in southern areas, some years may record no rainfall at all. Rainfall occurs during a single season in the Sahel zone and two seasons in northern areas. For instance, the average annual rainfall in Biskra, located at the northernmost point, is 129 mm, while in Adrar, at the southernmost edge, it is only 12 mm.

Temperature:

The region experiences average winter temperatures ranging between 9°C and 13°C, which rise to approximately 40°C in the summer months. Across the area, average temperatures generally fall within the range of 11°C to 20°C. Frost occurrences are rare and, when present, are limited to brief periods in northern regions.

Winds:

Wind is another critical factor adversely affecting agricultural activities. Average wind speeds range between 2.4 and 6.6 meters per second, with sand transport and damaging sandstorms being common, particularly from March to August. In certain areas, wind speeds exceed 5 meters per second year-round. During spring months, these winds often result in severe sandstorms.

Humidity:

The annual average humidity levels are exceptionally low. For example, Ain Salah records a mere 32%, while El Oued reports 63%. On a monthly basis, humidity levels drop below 50% from February through October.

Solar Radiation:

The region enjoys exceptionally high annual sunshine duration, averaging around 3500 hours. Daily sunlight spans 8 to 12 hours on average, peaking in July and reaching its lowest levels in January.

Evaporation and Evapotranspiration:

Due to the arid climate, potential evaporation and evapotranspiration rates are extremely high in the region. In areas such as the Grand Erg Oriental and Gassi Touil, evaporation rates can reach up to 3500 mm annually. In the surrounding Atlas regions, potential evaporation is estimated at approximately 2000 mm annually, peaking during summer months.

3.1.2.3. Geomorphological Characteristics of the Basin

According to the ABHS report (2006), the primary geomorphological formations observed within the Algerian section of the North Sahara Aquifer System are regs, ergs, plains, and alluvial valleys. Regs are stony plateaus, the largest of which are the Tanezrouft in the south and the Tademaït in the center. The ergs are massive sand dune fields, with three particularly significant ones: Erg Chech, the Grand Erg Oriental, and the Grand Erg Occidental (Figure 3.3).

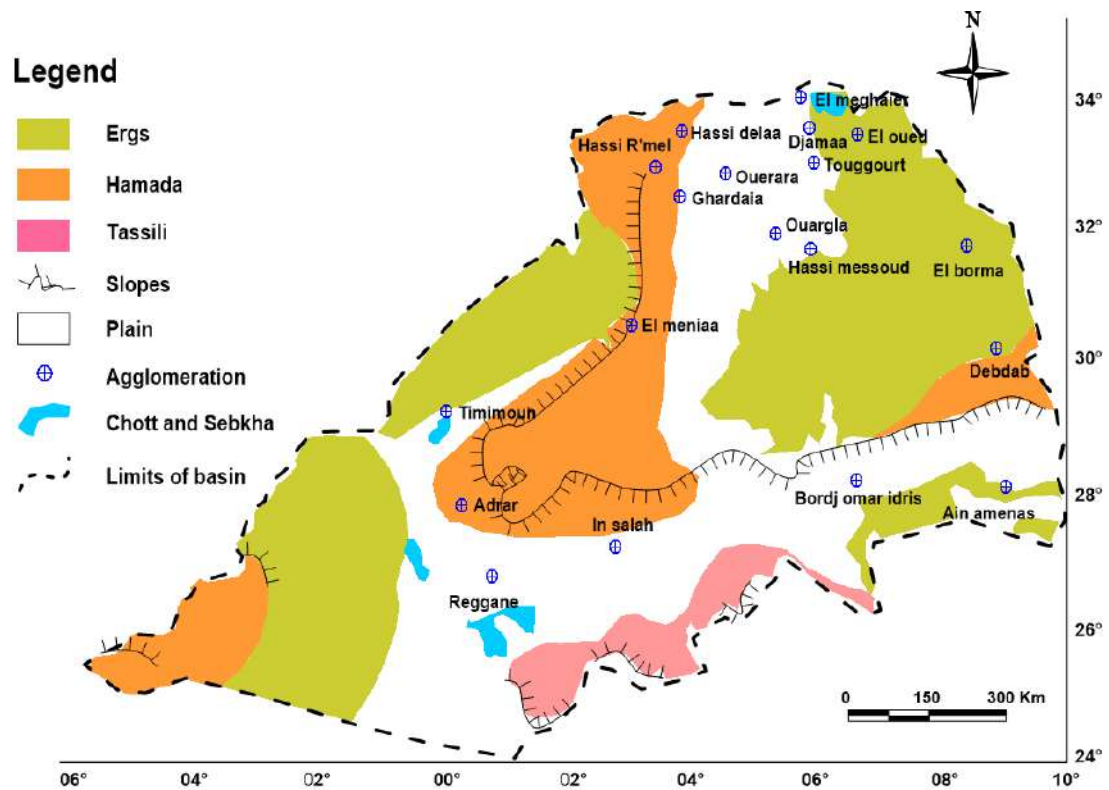


Figure 3. 3 Geomorphological map of the Basin (ABHS, 2006)

3.1.2.4. Geological Characteristics of the Basin

The section of the North Sahara Aquifer System within Algeria encompasses extensive flat areas with relatively low elevations (ranging from 200 to -30 meters) and includes vast regions where the summits rise in ergs (such as the Grand Erg Oriental) and allochthonous regs (such as Wadi Righ and Wadi Mya) (OSS, 2003). Depressions are concentrated in the lower parts of the chotts (e.g., Merouane, Safione).

The region's geology is characterized by an ancient geological formation distinguished by layered and eroded primordial sandstone strata, which form the hydrocarbon reservoir rocks. The upper portions consist of sandstone from the Intercalary Continental (CI) aquifer, also known as the Albian. Following the Cenomanian, marine layers from the Senonian and Eocene accumulate, culminating in the Miocene-Pliocene continental cover known as the Terminal Complex (CT) aquifer (Bied-Charreton, 2002). The central region is predominantly made up of hard sandstone and limestone plateaus and hills (Busson, 1970). A series of erosion-sculpted hills with steep cliffs extends to the Tademaït plateau (Figure 3.4).

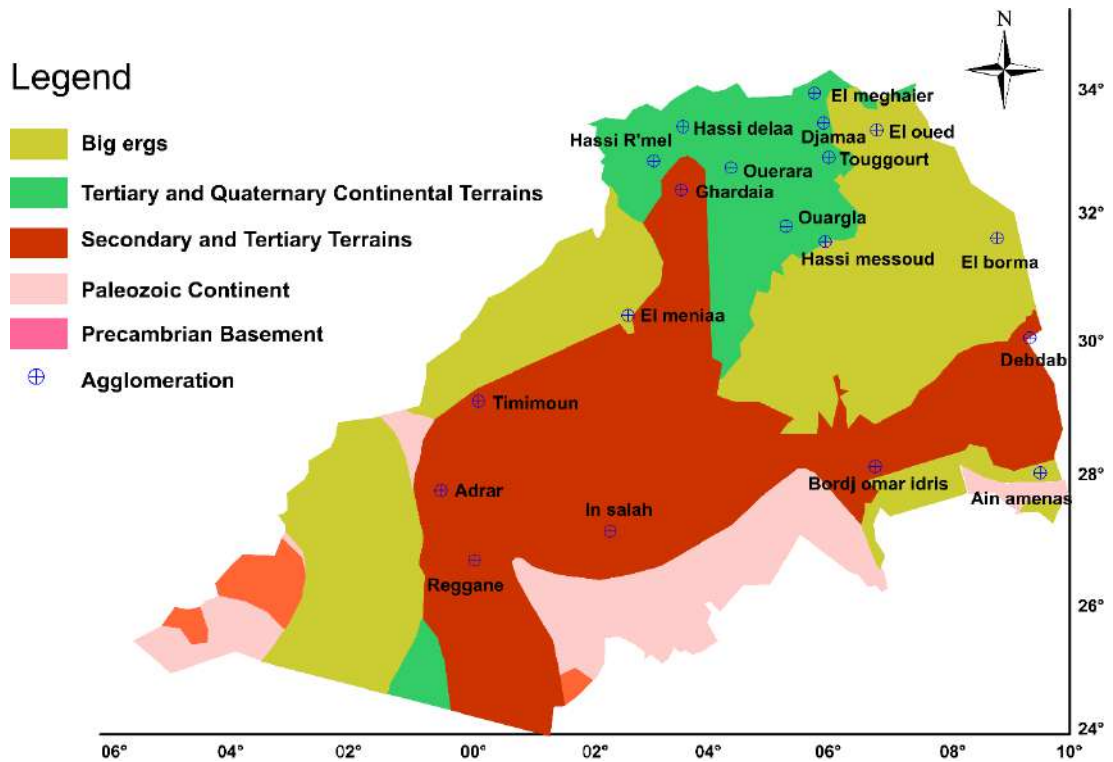


Figure 3. 4 Geological map of the Northern Sahara Aquifer System in Algeria (ABHS, 2006)

3.1.2.5. Hydrogeological Characteristics of the Basin

The North Sahara Aquifer System consists of two significant aquifers: the Intercalary Continental and the Terminal Complex aquifer (Figure 3.5). In certain areas of this region, particularly in Biskra, Ghardaïa, and El Oued, groundwater is extensively utilized for agricultural activities (OSS, 2003).

The Terminal Complex comprises a series of formations extending from the Upper Senonian to the Miocene-Pliocene, predominantly featuring carbonate and sandy lithological levels. The Intercalary Continental consists of a series of sedimentary deposits from a long continental interval situated between two marine cycles of the Paleozoic and Upper Cretaceous periods, forming a significant freshwater reservoir (Figure 3.5). Groundwater in the region is found within the sandy and clay-evaporitic levels of the Quaternary. At lower levels, the aquifer has a pelicular characteristic compared to the sand layer, which is constrained by a semi-permeable Miocene-Pliocene level.

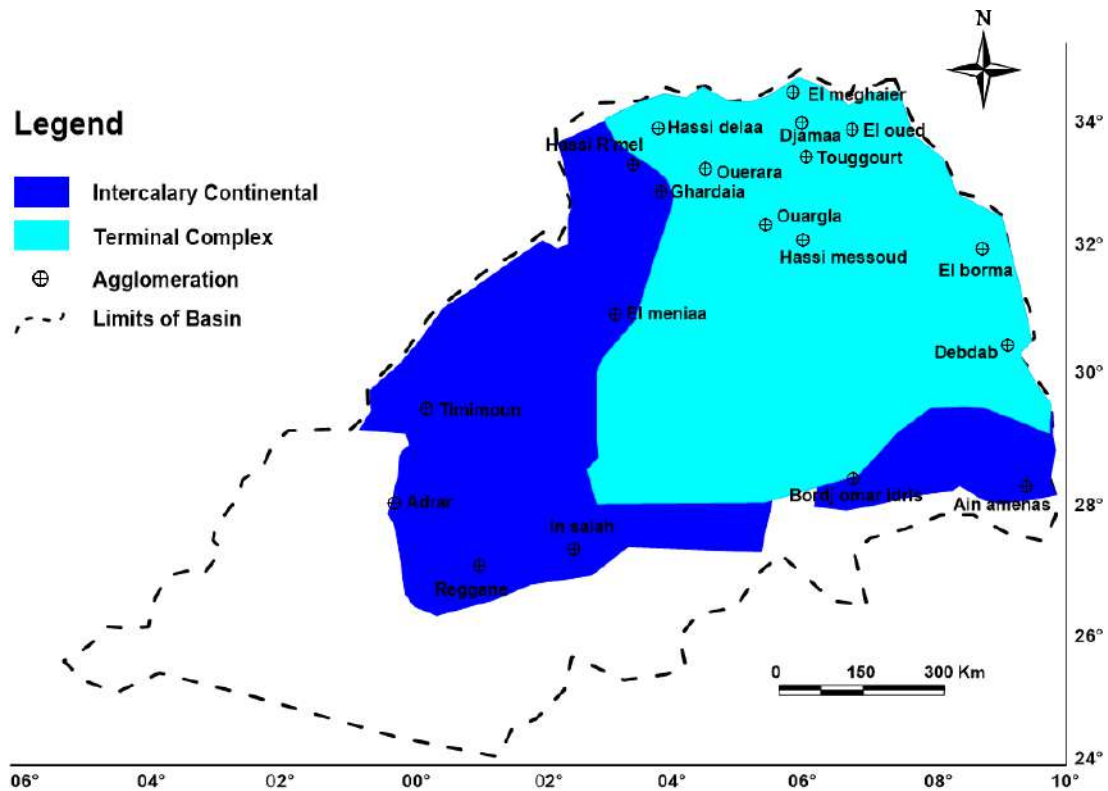


Figure 3. 5 Location of the Northern Sahara Aquifer System within Algerian borders (ABHS, 2006)

Intercalary Continental

Broadly defined, the term "Intercalary Continental" refers to all sedimentary deposits within the extensive continental crust situated between two marine cycles of the Paleozoic and Upper Cretaceous periods. This term favors the classic hydrogeological definition, which includes only true continental clastic (clay-sandstone) sediments with a relatively homogeneous reservoir, over the stratigraphic definition, which has the disadvantage of including lagoon sections. The deposits from the Lower Cretaceous period unconformably overlay units of different ages. The upper levels of the reservoir correspond to the clayey Cenomanian in the west and the clayey Albian in the east (Cornet, 1961; 1964). The Intercalary Continental forms the deep reservoir of the North Sahara. In the north, it spans more than 600,000 km² exclusively within Algerian and Tunisian territories, stretching from the southern Atlas to the rocky outcrops of Tidikelt and the southern edge of Tihert (Unesco, 1972). The average thickness of the aquifer exceeds 358 meters in some places (Baba Sy, 2005). Reservoir thicknesses reaching up to 1000 meters have been identified in the northwest (west of

Ghardaïa) and in the center (west of the main ridge of Amguid). The primary source of recharge for the aquifer is fossil water, which infiltrated during the pluvial periods of the Quaternary (Baba Sy, 2005). Groundwater flow direction in the aquifer environment is primarily north-south, flowing from the foothills of the Atlas Mountains towards the outcrop (and discharge) areas along the edges of the Tademaït plateau in the west. It also flows south-north, from the southern edge of the Tihert plateau towards the Grand Erg Oriental and from Hamada Al Hamra to the Nefusa Mountains. There is a west-east and northeast direction flow, where waters from the south (Dahar and Grand Erg Oriental) converge with waters coming from the north (Atlas) towards the Tunisian outlet. In the surface aquifer, the water table is unconfined, while beneath the Grand Erg Occidental, M'Zab, Tademaït, and Hamada Al Hamra, the aquifer is semi-confined or more generally confined. Artesian discharges are observed throughout the Wadi Righ – El Oued – Djerid – Grand Erg Oriental region (OSS, 2008).

To elucidate the geometry of the aquifer, data from approximately 800 boreholes (for water and hydrocarbons), geophysical data (petroleum drilling logs), and general seismic survey data have been evaluated (ABHS, 2006). In the Intercalary Continental, water quality tends to be poor in areas with high evaporation rates, resulting in saline water. In regions such as Ghardaïa, Ouargla, and El Oued, the water is relatively less saline (< 2.5 g/L). However, as one moves toward the center of the basin, salinity increases rapidly (e.g., $> 4 - 5$ g/L in Hassi Messaoud, in the Grand Erg Oriental, and approximately 10 g/L in El Borma) (OSS, 2003; ABHS, 2006).

Terminal Complex

The term "Terminal Complex" encompasses the most recent formations extending from the Upper Senonian to the Miocene-Pliocene, rather than the term "Continental Terminal," which is avoided due to the presence of numerous limestone formations not necessarily of continental origin. The term "complex" also reflects the grouping of several more or less related aquifers within the same reservoir. Major aquifers in the central parts of the basin include Senonian and carbonate Eocene (Lower Eocene) units and sandy Miocene-Pliocene formations. Miocene-Pliocene sands cover almost the entire region, except for the coastal areas where they are interrupted. The reservoir is subsequently represented by Senonian limestones, which are exposed at the surface by

Turonian dolomites. The units forming the Terminal Complex span the entire North Sahara (from the western Saoura to the eastern Graben de Hon, from the southern Atlantic to the Tademaït and Tinhert plateaus in Algeria, and the Gargaf plateau in Libya) (Unesco, 1972). Several distinct aquifer units are identified in the region, detailed below:

a) Western Region: Located west of the M'ZAB ridge, this area exhibits Turonian-Senonian series and is reduced to Neogene clastic layers (from Miocene-Pliocene to early Quaternary) directly overlying the Intercalary Continental. Dominated by red-colored clayey-sandy-sandstone layers, this aquifer is often referred to as the "Erg Formation" due to its coverage by the Grand Erg Occidental sand dunes south of the Atlas foothills. There is a pressure equilibrium between this Erg aquifer and the underlying Intercalary Continental aquifer (Cornet, 1961).

b) Central Region: East of the M'ZAB ridge, the Upper Cretaceous and Eocene carbonate series form a thick, complex aquifer (up to 2000 meters thick and thicker in the Chotts region). In the northern Chotts, two or three different sandy levels are identified in the Miocene-Pliocene, with distinct separation from the underlying Lower Eocene limestones by marl and evaporites (Eocene) of 100-250 meters. The water level in these deep limestones can reach up to 100 meters in places. In the southern region of Wadi Righ, three stacked aquifer units are distinguished: the upper sands of the Miocene-Pliocene, a more continuous and permeable lower sand unit, and a karstic aquifer composed of limestones (Bel and Demargne, 1966).

c) Eastern Region: In an area starting at Djebel Tebaga and extending to Dahar, there is no Miocene-Pliocene cover, and the Upper Cretaceous series presents a thinner structure. The carbonate Senonian in the El Borma region has been cut off by evaporites towards Libya, resulting in a low-potential aquifer.

The primary recharge and main source of groundwater in the reservoir is precipitation in the region (Baba Sy, 2005). Groundwater flow occurs southward from open areas towards the southern boundary of the Grand Erg and the outcrop area of the Intercalary Continental in the western basin. In the far western regions, groundwater flow is directed towards Saoura (OSS, 2008). From the M'ZAB mountains, all surface and groundwater flow moves towards the Chotts region.

The initial natural springs of the aquifer, particularly in the Wadi Righ region and around the Chotts in Tunisia, have largely dried up over time. The total flow of springs fed by the Terminal Complex aquifer in Tunisia is approximately 5 m³/s. Many low-flow springs are found along the western (Saoura valley) and northern (Zibans) borders (ERESS, 1972). Artesian wells, manually drilled using older techniques, are present in the Wadi Righ and Ouargla basins. Their discharge increased from 3.5 m³/s in the early 1900s to approximately 28 m³/s by 1997. Today, only a few localized sectors in Algeria (west-southwest Djamaa, northeast El Oued) still have artesian wells (ERESS, 1972).

According to the hydrochemical characteristics of the North Sahara Basin's groundwater, calcium, magnesium, and sodium are the dominant cations, while sulfates and chlorides are the dominant anions. Limestone and dolomites are the main sources of calcium and magnesium, while clays and marls are the sources of sulfates (ABHS, 2006).

3.1.3. Wadi Righ Area

3.1.3.1. Site Identification

Wadi Righ is one of the three major regions of the Sahara, alongside Ziban and Souf. It is a key area where sands, salts, and artesian waters fed by the Terminal Complex aquifers are concentrated. The regional capital is the city of Touggourt, with other significant municipalities including El Oued, Meghair, and Ouargla. The region is notably homogeneous, extending approximately 150 km from north to south. The Biskra-Ouargla highway intersects with a railway line that runs nearly parallel to it (Figure 3.6). Date palm cultivation has long been the primary livelihood in this area. There are over two million date palms irrigated by dug wells and boreholes, mostly tapping into the Miocene-Pliocene aquifers.

In 1925, the Wadi Righ channel measuring 150 km in length and 10 m in width, was excavated by the local population using traditional methods. The locals constructed this channel to drain excess irrigation water and to discharge wastewater. The channel serves as the primary collector of the water it directs into Chott Merouane. The topography of the Wadi Righ region is characterized by a very flat, north-south oriented depression stretching between El Goug (32° 54' N) and Oum El Thiour (34°

9') over 150 km (Dubost, 1992). The main feature of this depression is its slope towards the north and the large chotts. The elevation exceeds 100 meters at El Goug and drops to a minimum of 27 meters in the middle of Chott Merouane (with elevations of +70 m at Touggourt, +30 m at Djamaa, and 0 m at El Meghier). This gradient allows excess water to flow northward (Dubost, 1992).

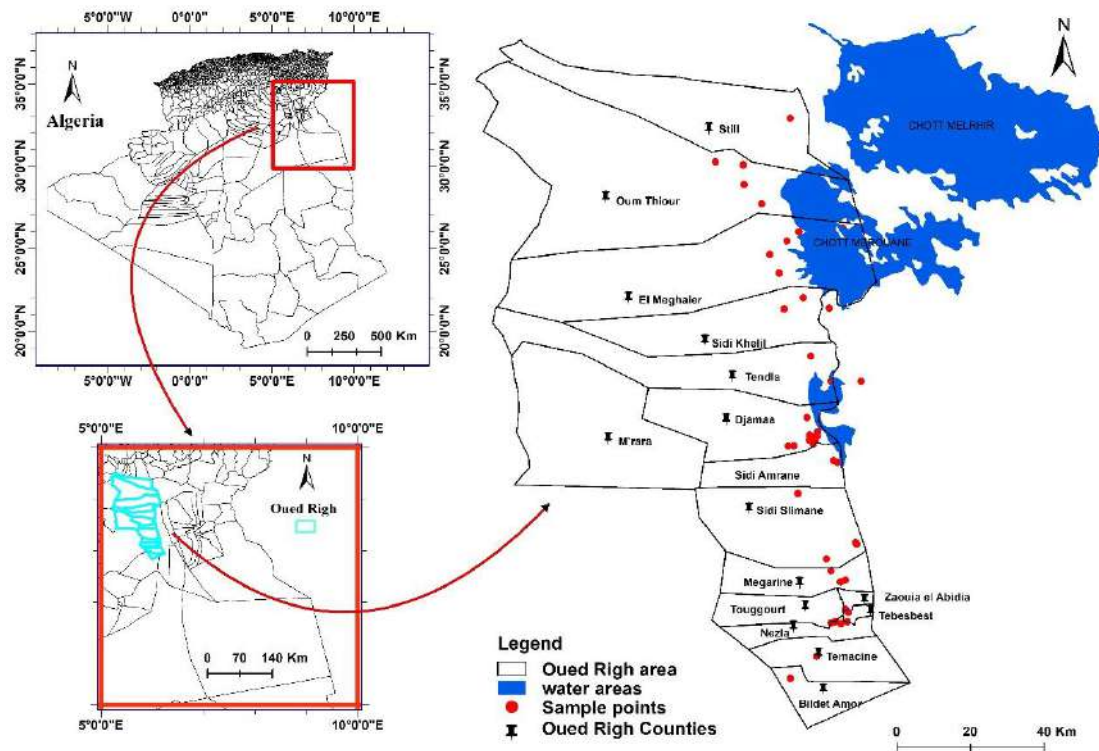


Figure 3. 6 Location of the Wadi Righ region

3.1.3.2. Geological and Hydrogeological Characteristics of the Wadi Righ Region

The geological formations of the Wadi Righ have been described by many authors (Paix 1956; Cornet 1964; Bel and Demargne 1966; Bel and Cuche 1970; Bel et al. 1970; UNESCO 1972; Faber et al. 1976; Guendouz et al. 2003; Melouah and Pham 2021).

From the oldest to the most recent (Figure 3.7), the following geological formations may be distinguished (Cornet 1964; Faber et al. 1976):

- The Albian is presented as a very thick (# 450 m) series composed of an alternation of sandy layers with passages of shale clay.
- The Vraconian consists in an irregular alternation of clay and dolomitic levels, sandy clays and more rarely passages of sandstone with limestone cement.
- The Cenomanian has a considerable thickness that gradually decreases towards the north. It outcrops in the atlasic zone. It is composed essentially of marly lagoonal deposits where layers of anhydrite and sometimes even salt predominate.
- The Turonian is represented by a marine, calcareous-marly deposit, and its thickness remains fairly constant.
- The Senonian is essentially made up of white limestone with an alternation of marly limestone and layers of gypsum. It is formed of two very different sets from a lithological point of view: the lagoonal Senonian, at the base, and the carbonate Senonian, above.
- The Eocene is composed of two distinct lithologic sets: a lower carbonate set and an upper evaporite set. The lower Eocene carbonate level has characteristics that make it difficult to distinguish from the Senonian. The presence or absence of nummulites is the main difference. Limestones are generally more frequent than dolomites and evaporites are much rarer or completely absent compared to the Senonian. The flint limestones encountered at the top of the Senonian carbonate continue into the Eocene. The thickness of this formation varies between 100 and 500 meters. The middle level of the Eocene evaporite is composed of an alternation of limestone, anhydrite and marls, and its thickness reaches about 100 meters under the Chotts (Bel and Cuche 1969). In the Wadi Righ, the limestone formation seems to be located in a carbonate level belonging to the Eocene evaporite.
- The lenticular deposits of the Mio-pliocene are divided into four levels according to Bel and Demargne (1966). Level 1 is composed of thin clay layers, found only in the central zone of the Eastern Sahara, forming a poorly permeable barrier between the Senonian and Eocene carbonat  aquifers and the sands of level 2. Level 2 is a thick and consistent gravelly-sandy layer, sometimes containing gravel at the base and clay at the top, reaching 400 meters in thickness in the South of Gassi Touil. It is the main aquifer horizon

of the Mio-Pliocene. Level 03 is a poorly defined clay-sandy formation, impermeable and present only in certain areas, particularly in the region of the chotts. Level 04 is a sandy layer, sometimes continuing from level 02, containing a crust of gravel-limestone at the top and 300 meters in thickness.

- The Quaternary deposits are mainly sandy, located beneath semi-permeable clay and evaporite layers. These Quaternary formations are the source of the phreatic aquifer, which is mainly fed by the infiltration of water from wadis and especially by the percolation of excess water during irrigation periods.

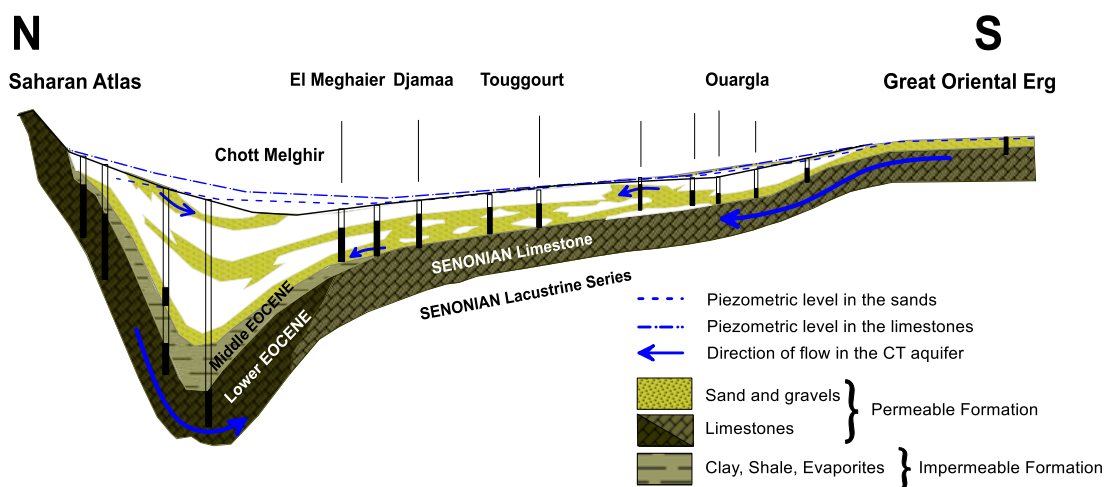


Figure 3. 7 Hydrogeological cross section of the Terminal Complex aquifer of the northern Sahara in Algeria (after Guendouz et al. 2003)

3.1.3.3. Demographics of the Wadi Righ Region

With a population of approximately 325,000, the Wadi Righ region ranks third in importance in the Sahara, following Ziban and Souf (Figure 3.8). The Touggourt agglomeration currently has more than 100,000 inhabitants. Two other significant urban centers are El Meghair in the north, with a population of 41,000, and Djamaa, with 35,000 inhabitants. Since 1987, the entire region has experienced increasing demographic growth; however, it does not rank among the highest in the Sahara (9th out of 15).

Overall, there is a steady trend toward urban concentration, with some smaller towns experiencing negative net migration: Sidi Slimane (-2.2%), Djamaa (-1.8%), and Balidat Ameur (-1.4%) (Kouzmine, 2012).

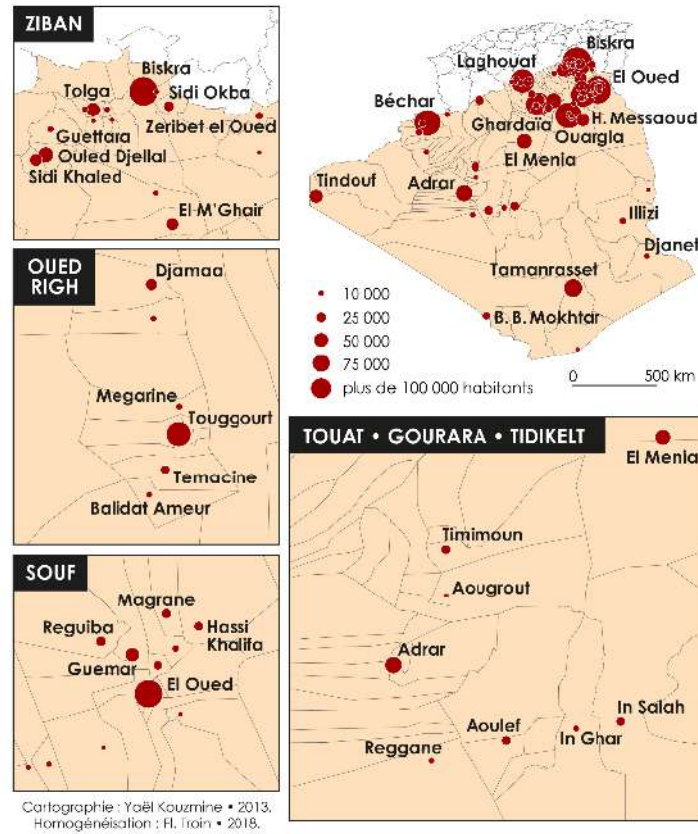


Figure 3. 8 Urbanization in the Algerian Sahara in 2008 (Kouzmine and Fontaine, 2018)

3.2. Methods

3.2.1. Acquisition of Numerical Data

In the valley of Wadi Righ, the aquifer of the Terminal Complex underwent sampling by the Algerian Water (ADE) and the National Agency for Water Resources (ANRH) in 1995, 2012, 2015, and 2017 (Figure 3.9). A total of 117 wells were included in these sampling efforts. The collected samples were analysed at the ADE and ANRH laboratories, following standard techniques. The measurements and analysis involved the use of various methodologies and instruments. Flame spectrophotometry (Corning 410) was utilized to analyze Calcium, Sodium, and Potassium levels. Sulphates, Nitrates, and Chlorides were quantified using the HACH DR2000 spectrophotometer.

Magnesium levels were determined through complexometric titration using ethylenediaminetetraacetic acid (EDTA) as the titrant, with the equation $Mg^{2+} = TH - Ca^{2+}$, while electrical conductivity (EC) and pH were measured in situ.

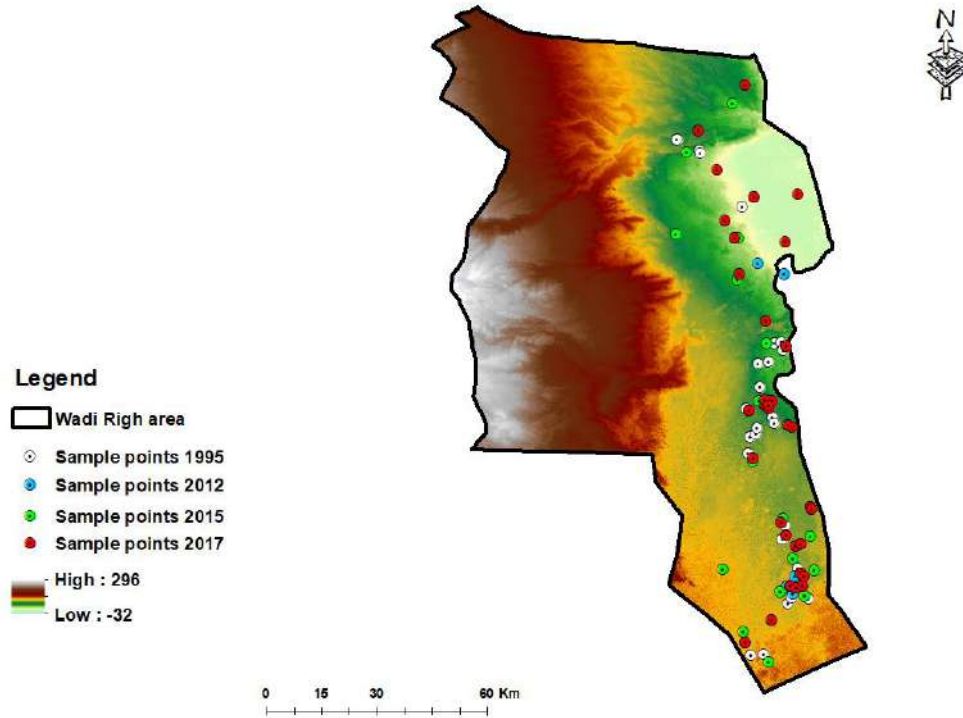


Figure 3. 9 Spatial distribution of groundwater sampling sites

To map the distribution of static groundwater levels, 613 groundwater samples distributed over 6 years (1998, 2005, 2010, 2013, 2015, and 2017) were used, to ensure an even distribution and a significant periodical coverage to facilitates a clearer, accurate or more precise results (Figure 3.10).

To gain an accurate understanding of the climatic characteristics of the study area, data on monthly precipitation, temperature, relative humidity, and wind speed (both minimum-maximum and average) for the period from 1975 to 2024 were obtained from the Touggourt meteorological station (Latitude: 33° 11' N; Longitude: 06° 13' E; Elevation: 85 m). This data was sourced from the National Meteorological Office (ONM).

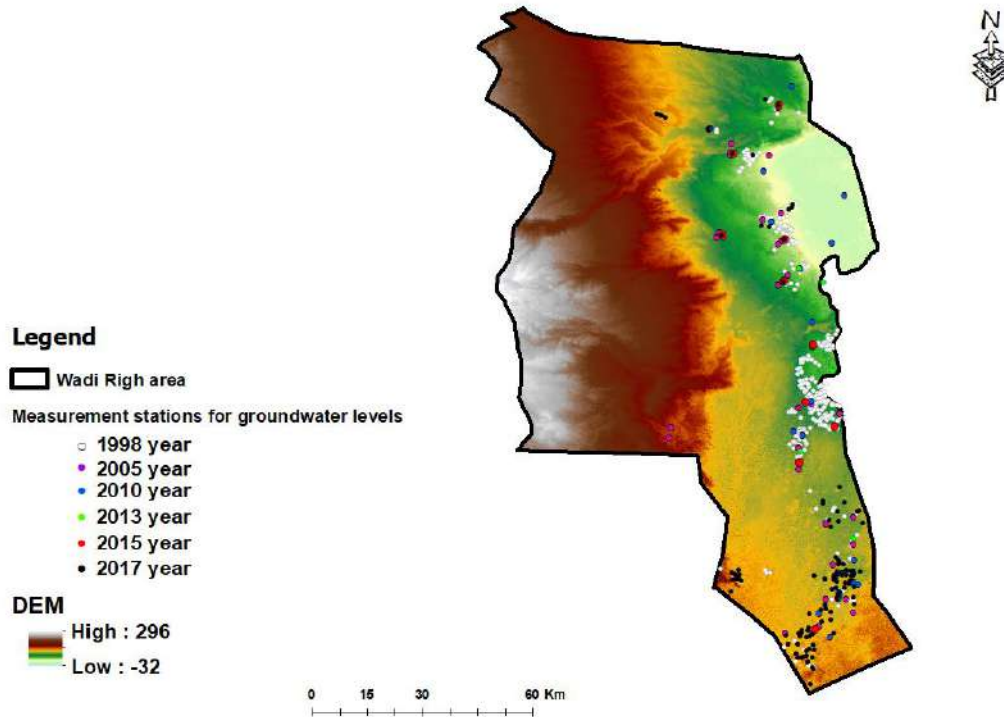


Figure 3. 10 Measurement stations of groundwater level samples in Wadi Righ

3.2.2. Water Quality Indices for Drinking and Irrigation use

3.2.2.1. Water Quality Index (WQI)

The Water Quality Index (WQI) is used to assess the suitability of water for consumption and other various uses. Developed by Horton in 1965, WQI is an effective method for protecting human health and the environment by providing an overview of water quality in a specific area and assisting in management decisions aimed at improving water quality (Brown et al., 1970 ; Tyagi et al., 2013 ; Uddin et al., 2021 ; Patel et al., 2023).

The variation in the formula used to calculate the Water Quality Index (WQI) depends on local water quality standards, which take into account physical, chemical, and biological parameters such as dissolved oxygen, conductivity, pH, bacteria, turbidity, temperature, and major ions.

Weights are assigned to each water quality parameter based on its relative importance for a specific use. These weighted scores are then integrated into a single index value.

The resulting value provides an overall assessment of water quality, where higher values indicate poorer quality and lower values reflect better quality (Table 3.1).

In the calculations, the relative weight (W_i) is first determined using the following equation :

$$W_i = w_i / \sum_{i=1}^n w_i$$

Where W_i is the relative weight, w_i is the weight of each parameter, and n is the number of parameters.

In the next step, the concentration of each parameter in the water sample is divided by the standard values specified by the World Health Organization (WHO 2017). Each parameter is then assigned a quality rating scale (q_i), and the result is multiplied by 100 :

$$q_i = (C_i/S_i) \times 100$$

Where q_i is the quality rating, C_i is the concentration of the parameter (mg/l), and S_i is the standard value for the parameter (mg/l).

To calculate the WQI, the SI value for each chemical parameter is first determined using the following equation. The sum of the SI_i values provides the WQI for the water sample :

$$SI_i = W_i \times q_i$$

$$WQI = \sum SI_i$$

Where q_i is the rating based on the concentration of the i parameter, SI_i is the sub-index for the i parameter, , and n is the number of parameters. The classification according to the WQI method is presented in Table 3.1.

3.2.2.2. THE CCME WQI (the Canadian Council of Ministers of the Environment's Water Quality Index method)

The Water Quality Index (WQI) developed by the Canadian Council of Ministers of the Environment (CCME) takes into account three key factors in its calculation: scope

(F1), frequency (F2), and amplitude (F3). This index serves as a tool for evaluating the status of water quality at various sampling locations within a water body, as outlined in CCME (2001). The CCME WQI classifies water quality into five categories: Excellent, Good, Fair, Marginal, and Poor (Table 3.1).

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \right)$$

The calculation of these three factors is as follows;

Scope (F1) quantifies the degree to which water quality guidelines have not been met during the specified time frame.

$$F1 = \frac{\text{Number of failed variables}}{\text{Total number of variable}} \times 100$$

Frequency (F2) measures the proportion of individual tests that fail to meet the specified established water quality objectives.

$$F2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100$$

An asymptotic function is used in the calculation of the amplitude factor (F3), which reflects the extent to which failed test results deviate from their respective water quality objectives. This function transforms the sum of standard deviations from the objectives (nse) into a scale ranging from 0 to 100.

The concept of excursion has been thoroughly addressed in studies such as CCME (2001); Lumb et al. (2006); Tyagi et al. (2013); Wag et al. (2017); Bilgein (2018); and Van den Dool et al. (2023). It is defined as any instance in which an individual concentration exceeds the specified water quality objective.

$$F3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01} \right)$$

$$\text{excursion}_i = \left(\frac{\text{Failed test value } i}{\text{Objective } i} \right) - 1$$

$$\text{nse} = \frac{\sum_{i=1}^n \text{excursion } i}{\text{Number of test}}$$

3.2.2.3. Sodium Adsorption Ratio (SAR)

The impacts of elevated sodium concentrations in irrigation water include the deterioration of soil structure, dispersion, and compaction, as it negatively affects the soil's physical properties. Therefore, it is recommended that the Sodium Adsorption Ratio (SAR) in irrigation water does not exceed 10 (mmol/L)^{-0.5} in order to preserve soil quality (Richards, 1954; Ghazaryan et al., 2020; Aravinthasamy et al., 2020; Chapman, 2021).

Soil quality and physical structure tend to deteriorate when water with a high Sodium Adsorption Ratio (SAR) is used for irrigation. The SAR is calculated using the following equation, and irrigation water is classified into four distinct categories based on SAR values, as detailed in Table 3.1.

$$\text{SAR \%} = \frac{\text{Na}}{\sqrt{\frac{(\text{Ca} + \text{Mg})}{2}}}$$

3.2.2.4. Sodium Ion Percentage (Na%)

Under saline or alkaline conditions, the accumulation of sodium in the soil inhibits plant growth (Todd, 1980; Acharya et al., 2018; Meireles et al., 2010). When sodium concentrations in water are high, calcium and magnesium ions on clay particles are replaced through ion exchange reactions. This process reduces the soil's ability to facilitate water movement, limiting the free circulation of both air and water. As a result, such soils tend to harden upon drying, negatively affecting agricultural productivity (Collins and Jenkins, 1996; Saleh et al., 1999). Wilcox (1948) introduced the Sodium Percentage (Na%) as a parameter to assess the suitability of water for irrigation purposes. This percentage is calculated using the following formula, and irrigation water is classified based on Na% as presented in Table 3.1.

$$\text{Na\%} = \frac{\text{Na}}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}} \times 100$$

3.2.2.5. Permeability Index (PI)

Based on his research on the physical properties of irrigated soils, Doneen (1966) developed the Permeability Index (PI) equation. The value of the Permeability Index is determined by the concentrations of bicarbonate (HCO_3^-), total salinity and sodium

(Na⁺) of the irrigation water, and it is computed using the following equation. Irrigation water quality is categorized into three groups based on the PI (Table 3.1).

$$PI = \left[\frac{Na + \sqrt{HCO_3}}{Ca + Mg + Na} \times 100 \right]$$

3.2.2.6. Residual Sodium Carbonate (RSC)

As a result of high sodium concentrations, the Residual Sodium Carbonate (RSC) index measures the potential of irrigation water to induce soil alkalinity (Pareek and Yadav, 2011; Murtaza et al., 2021). A high RSC value indicates a strong likelihood that the irrigation water will lead to soil alkalinity and degradation. The RSC is calculated using the following equation (Gupta, 1983), and Table 3.1 illustrates irrigation water quality based on RSC values.

$$RSC = (HCO_3 + CO_3) - (Ca + Mg)$$

3.2.2.7. Magnesium Hazard (MH%)

High concentrations of magnesium in irrigation water influence soil alkalinity and, consequently, negatively affect plant productivity (Raghunath, 1987). Therefore, it is preferable for the Magnesium Hazard (MH) value of irrigation water to remain below 50% (Szabolcs, 1964). This value is calculated using the following equation, and the classification based on MH is presented in Table 3.1.

$$MH = \frac{Mg}{(Ca + Mg)} \times 100$$

3.2.2.8. Kelly Index (KR)

The Kelley's Ratio index (KR) was proposed by Kelley in 1940 to assess the suitability of water for irrigation. It is calculated by taking into account the concentrations of calcium, sodium, and magnesium ions (Sundaray et al., 2009; Shil et al., 2019; Pivic et al., 2023). The following equation is used to determine the KR value, and the water quality classification based on this index is presented in Table 3.1.

$$KR = \frac{Na}{Ca + Mg}$$

3.2.2.9. Irrigation water quality index (IWQI)

In this study, we developed the criteria and cutoff values for evaluating irrigation water quality based on Ayers and Westcot (1985) recommendations. The chemical analysis data were examined according to the appropriate cutoff values in the corresponding guideline. Individual weights (coefficients), ranged from 1 (lowest suitability) to 4 (highest suitability), for the indicators TDS, SAR, EC, B, Cl, HCO₃, NO₃, and pH, were determined based on the factors affecting irrigation water quality (specific ion toxicity (SIT) and infiltration and permeability hazard (IPH) were given weights in decreasing order of importance). The IWQI was calculated as follows:

$$IWQI = \sum_{i=1}^n q_i w_i$$

In this context, “n” denotes the total number of parameters under consideration. To compute the IWQI, values “q_i” from Table 3.2 were multiplied by the respective weight “w_i” assigned to each parameter, as documented in Table 3.2

Table 3. 1 The classification of groundwater quality according to different indices

Indices	Range	Water class
WQI	< 50	Good
	50–100.1	Acceptable
	100–200.1	Poor
	200–300.1	Very poor
	> 300	Unfit for drinking
CCME WQI	95-100	Excellent
	80-94	Good
	65-79	Fair
	45-64	Marginal
	0-44	Poor
SAR	0 – 10	Excellent
	10 – 18	Good
	18 – 26	Moderate
	> 26	Poor
Na%	< 20%	Excellent
	20- 40%	Good
	40- 60%	Permissible
	60- 80%	Suspect
	> 80%	Unsuitable
PI	> 75 %	Suitable
	25–75 %	Good
	< 25 %	Unsuitable
	< 1.25	Good
RSC	1.25 – 2.5	Moderate
	> 2.5	Unsuitable
MH	< 50%	Suitable
	> 50%	Unsuitable
KR	< 1	Suitable
	> 1	Unsuitable
IWQI	85-100	Excellent
	70-85	Good
	50-70	Permissible
	40-55	Doubtful
	0-40	Severe

Table 3. 2 Irrigation water quality criteria classification and assigned weights of all criteria (Ayers and Westcot 1985)

	Weight	Criteria	Weight	Criteria	Subcriteria	Weight
Hazard Salinity	4					
		EC	3			
					< 700	4
					700-2000	3
					2000-3000	2
					>3000	1
		TDS	3			
					< 450	3
					450-2000	2
					>2000	1
Permeability	3					
		SAR: 0-3	3	and EC	> 700	3
					700-200	1
		SAR: 3-6	2		> 1200	3
					1200-300	1
		SAR: 6-12	1		> 1900	3
					1900-500	1
Specific ion toxicity	2					
		Sodium	3			
					< 3	3
					3 - 9	2
					> 9	1
		Chloride	2			
					< 140	3
					140-350	2
					> 350	1
		Boron	1			
					< 0.7	3
					0.7-3	1
Miscellaneous effects	1					
		Nitrate–nitrogen	3			
					< 5	3
					5 - 30	2
					>30	1
		Bicarbonate	2			
					90-500	3
					> 500	1
		pH	1			
					7 - 8	3
					< 6.5 and > 8.5	1

3.2.3. Statistical Methods

3.2.3.1. Hierarchical Ascending Classification (HAC)

Cluster Analysis encompasses a range of statistical techniques used to identify natural statistical groups or structures within data. Hierarchical ascending classification is a method that involves creating a distance matrix between observations and variables. This method is carried out by a program that classifies ppp variables and nnn observations. Subsequently, a rule is defined to calculate the distances between discrete groups of variables or observations. The two closest groups (according to this criterion) are merged, and the process is repeated until the classification of clusters is complete (Saporta, 1990 ; Vega et al., 1998 ; Singh et al., 2004).

3.2.3.2. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), developed in the 1970s by mathematician Thomas L. Saaty (Saaty, 1977), is a decision-making method based on mathematical principles that incorporates multiple criteria. It involves breaking down a complex, multi-criteria decision problem into a hierarchical structure, also known as decision modeling to improve organization, comprehension, and analysis.

After reclassifying all thematic layers, appropriate weights are determined using the AHP method. At this stage, criteria are evaluated, compared, and prioritized within a pairwise comparison matrix, reflecting the decision-makers' judgments of each criterion's relative importance (Table 3.3). Saaty's fundamental scale is applied to quantify these judgments, and relative weights are calculated through the eigenvalue technique. Because these judgments are inherently subjective, their consistency must be verified. For this purpose, Saaty introduced the consistency ratio (CR), which measures the degree of consistency in the comparisons and ensures the reliability of the results.

$$CR = \frac{CI}{RI} \quad (06)$$

Here, RI denotes the Random Index and CI represents the Consistency Index. A Consistency Ratio (CR) value of ≤ 0.10 is generally considered acceptable, whereas a CR value of 0 indicates perfect consistency (Saaty, 1990; Saaty, 2008).

Table 3. 3 The comparison scale in AHP (Saaty 1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

3.2.4. Computer Software Used

3.2.4.1. Aquifer Test Software

The analytical data used in this study were validated using the Aquifer Test (Aq.QA computer program Demo version 1.1) (RockWare, Inc., Golden, Colorado, USA). Aq.QA is a hydraulic modeling software developed by RockWare. It is used for designing, analyzing, and interpreting hydraulic tests for both surface and groundwater resources. Aq.QA facilitates the accurate processing of hydraulic test data, aiding in

the precise determination of hydraulic properties. The software is also employed to visualize water quality data, perform statistical analyses, and conduct quality control (Al Bassam and Khalil, 2012; Ghobadi et al., 2018; Sreedhar Reddy and Al Dawery, 2018; Radulescu et al., 2019; Aher and Deshmukh, 2021).

3.2.4.2. Diagramme v2 Software

The Diagramme software, developed by Roland Simler from the Avignon Hydrogeology Laboratory, is a free hydrochemical software designed to facilitate the use of water analyses. This software performs various hydrochemical diagram analyses, including Piper, Stiff, Schoeller-Berkalov, and Korjinski diagrams, as well as calculations for ionic balance, cation content, hardness, anion content, and saturation indices (calcite, dolomite).

Diagrams produced using this software simplify the comparison and classification of the chemical properties of water (Karmegam et al., 2011; Ravikumar et al., 2015; Tomodiatounga et al., 2016; Ketchemen-Tandia et al., 2017; Ouarekh et al., 2021; Jalees et al., 2021; Madhav et al., 2021).

3.2.4.3. Statistica v6.1

Statistica is a data analysis and visualization software that provides a wide range of fundamental and advanced procedures for scientific research, data mining, and various industrial and commercial applications (Hilbe, 2007; De Sá, 2007; Jascaniene et al., 2013; Shulaeva et al., 2018). The software includes a specific Principal Component Analysis (PCA) module and supports numerous statistical techniques. It is designed to facilitate comprehensive data analysis and interpretation.

3.2.4.4. ArcGIS 10.8

ArcGIS is a Geographic Information System (GIS) software developed by ESRI. It is widely used globally for mapping and data analysis across various fields. ArcGIS supports the visualization, analysis, and sharing of geographic data, as well as the creation and management of geographic information. It includes tools for analyzing spatial problems and opportunities, and is utilized in planning and decision-making

processes. The software suite includes various components such as ArcGIS Desktop, ArcGIS Online, ArcGIS Pro, ArcGIS Enterprise, and ArcGIS Developer.

ArcGIS is employed by governments, organizations, researchers, and many other sectors. Its applications span agriculture, environmental management, energy, transportation, health, tourism, and numerous other areas (MacMillan et al., 2004; Aaron et al., 2007; Scott and Janikas, 2010; Fu and Zhou, 2015; Lhmod, 2015; Sanjeevi and Shahabudeen, 2016; Amaguaya and Hernández, 2020; Jordan et al., 2021; Akay et al., 2022; Seisia et al., 2022; Bux et al., 2022; Bao et al., 2023).

The data maps were generated using the Spatial Analyst extension in ArcGIS version 10.6.1. Our study employed the Inverse Distance Weighted (IDW) interpolation method as the primary technique, due to its suitability for estimating values at unsampled locations based on the spatial proximity and influence of surrounding data points. Essentially, this method assumes that values at unknown locations can be estimated using nearby sample points, with these points being weighted inversely in proportion to their distance from the target location.

There were two key reasons for choosing the IDW method. First, IDW is well-suited for interpolating spatially correlated data, a common feature in groundwater datasets where nearby samples are likely to share similar characteristics. Second, the IDW algorithm is straightforward and easy to implement, making it an accessible and time-efficient choice that aligns well with the objectives of our research. In summary, the IDW interpolation technique was applied using ArcGIS 10.6.1 based on the characteristics of our groundwater dataset and the aims of the study.

4. RESEARCH FINDINGS

4.1. Meteorological and Climatic Features of the Wadi Righ Region

The study area, the Wadi Righ region, is located in the northern Sahara and has a climate characterized by high evaporation, low rainfall, and generally intense storms, which define the arid Sahara. This section of the study aims to examine regional climate parameters (such as precipitation, temperature, etc.) that play a significant role in groundwater recharge. These climatic parameters also play a critical role in the development of soil types, vegetation, and agricultural activities in the study area.

4.1.1. Precipitation analysis

Precipitation is a crucial component of global climate systems and plays a vital role in areas such as water resources, agriculture, forestry, energy production, and industry. However, in recent years, the amount, intensity, duration, and distribution of precipitation have been significantly affected by climate change.

Climate change arises from the increased emissions of greenhouse gases in the atmosphere, leading to global temperature increases and causing imbalances in climate systems. A decrease in precipitation and/or extreme rainfall events far exceeding the average in a short period are examples of these imbalances (O'Neill et al., 2010; Hansen et al., 2013; IPCC, 2014; Trenberth et al., 2014; Frölicher et al., 2015; Schleussner et al., 2016; Forster et al., 2020; UNEP, 2022). In many regions, changes such as increases or decreases in rainfall, shifts in precipitation intensity, delays in rainy seasons, or early rains have been observed. These changes create significant economic challenges and difficulties in agriculture and water resources management (IPCC, 2013; Schubert et al., 2016; Mishra and Shah, 2018; Kundzewicz et al., 2019). Furthermore, the impact of precipitation anomalies on water resources is substantial, as changes in precipitation regimes affect both surface water and groundwater resources, creating challenges for water resource management. Sahara rainfall is known for its low amounts, and stormy rains are rare. Annual precipitation varies greatly from year to year. Wadi Righ is a desert region characterized by the rarity and irregularity of rainfall. According to 50 years of rainfall data measured at the

Touggourt meteorological station, the region's precipitation values vary between an annual average of 11.5 mm (1989) and 161.8 mm (2004) (Figure 4.1; Table 4.1).

Table 4. 1 Annual average precipitation recorded at Touggourt meteorological station (1975–2024)

Year	Annual precipitation (mm)	Year	Annual precipitation (mm)
1975	118.10	2000	58.60
1976	107.00	2001	141.20
1977	44.70	2002	96.90
1978	44.90	2003	69.20
1979	51.90	2004	161.80
1980	153.00	2005	25.70
1981	43.40	2006	78.00
1982	72.40	2007	77.10
1983	31.60	2008	55.70
1984	30.90	2009	155.90
1985	33.70	2010	31.20
1986	79.40	2011	21.30
1987	41.70	2012	18.20
1988	54.50	2013	55.70
1989	11.50	2014	24.70
1990	148.40	2015	66.30
1991	42.80	2016	37.50
1992	132.20	2017	96.80
1993	55.20	2018	31.60
1994	48.70	2019	73.72
1995	61.40	2020	56.27
1996	88.50	2021	40.43
1997	64.20	2022	38.02
1998	46.40	2023	25.57
1999	118.10	2024	66.67

According to the monthly rainfall measurement records (Figure 4.2 and Table 4.2), the highest average monthly precipitation occurs in January at approximately 13.1 mm, while the lowest value is recorded in July at approximately 0.7 mm. Based on these data, the summer months are typically rainfall-free.

Table 4. 2 Monthly average precipitation measured at Touggourt meteorological station (1975–2024)

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Pr (mm)	6.5	4.8	8.0	5.0	13.1	5.3	8.8	7.9	3.8	1.2	0.7	2.4

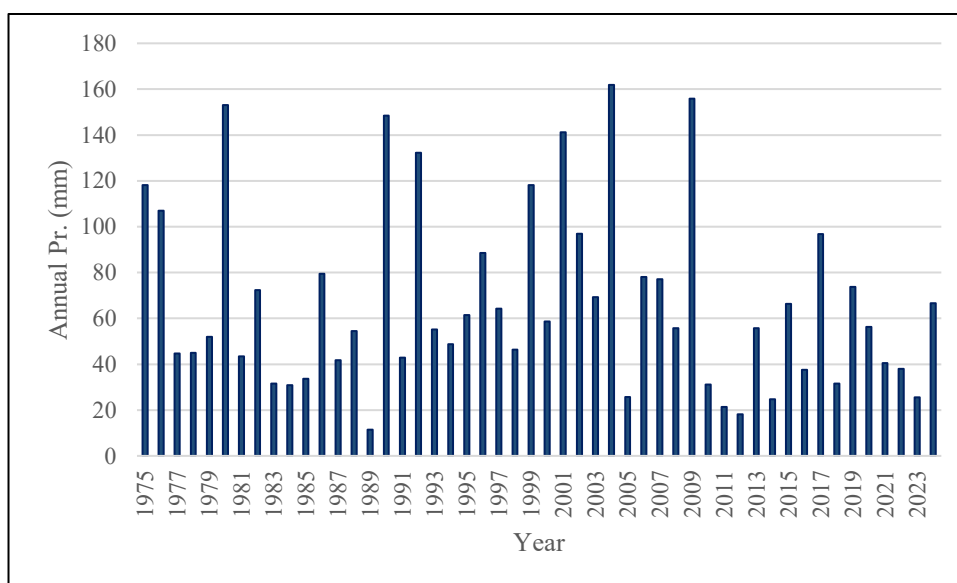


Figure 4. 1 Annual Distribution of Precipitation Based on Data from the Touggourt Meteorological Station (1975–2024)

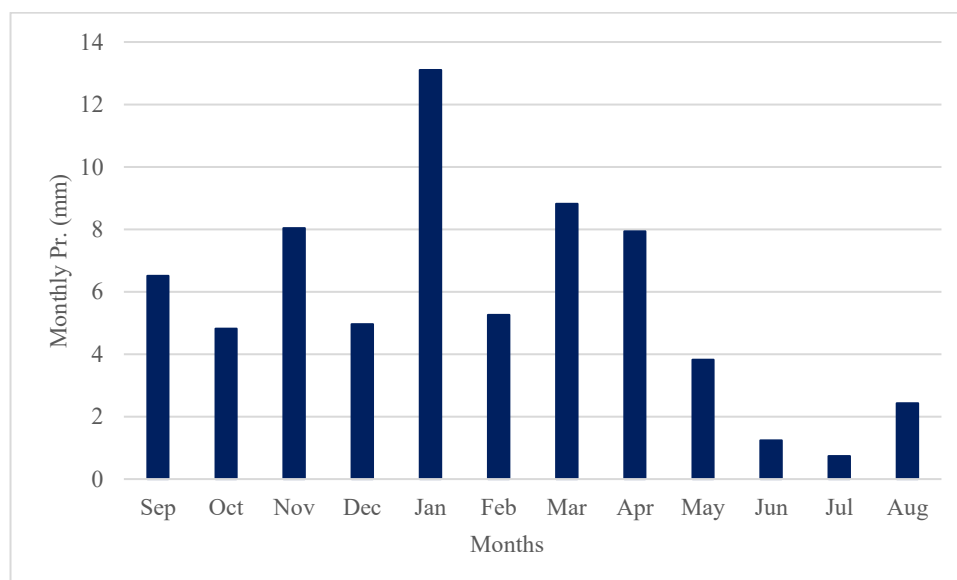


Figure 4. 2 Monthly Distribution of Precipitation Based on Data from the Touggourt Meteorological Station (1975–2024)

4.1.2. Temperature analysis

Air temperature is a measure of the movement of air molecules in the atmosphere, and these movements regulate the temperature. Higher potential movements correspond to higher temperatures. Air temperature is generally expressed in units like Celsius (°C) or Fahrenheit (°F) and is influenced by various factors. These include the angle at which sunlight strikes the Earth's surface, the region's geographical location, ocean and air currents, local surface features (such as forests, deserts, seas, mountain areas, etc.), cloud cover, and other environmental factors. Air temperature plays a significant role in meteorological forecasts and in various sectors such as agriculture, construction, transportation, and tourism. It also has a major impact on human health. High temperatures can cause health issues like heat stroke, dehydration, and sunburn, while low temperatures can lead to frostbite, hypothermia, and other cold-related illnesses.

Air temperature is also closely related to climate change. Climate change is a long-term alteration caused by a range of human-driven factors, leading to an increase in global temperatures. Climate temperature refers to the average temperature values measured over a long period in a particular region, and it serves as an indicator of the overall climate structure of that area. This temperature can be calculated as the average value of data collected over a specific period, such as monthly or yearly. Climate temperature is an important data point used to determine the general climatic features of a region, all of which vegetation, water resources, soil quality, and other natural factors are influenced by temperature (Kiehl and Trenberth, 1997; Meehl et al., 2010; Sherwood and Huber, 2010; Knutti et al., 2002; Hansen et al., 2006; Solomon et al., 2007; IPCC 2013; Mansouri et al., 2019; Hansson et al., 2023; Radha et al., 2023).

In the study area, the temperature difference between day and night during the spring season averages around 15°C. During this period, afternoon temperatures rise rapidly, and occasional rains and storms are observed in March and April. In the Sahara during the summer, daytime temperatures can reach a maximum of 43°C, sometimes rising as high as 55°C (Benhaddya, 2014). At night, temperatures rarely drop below 25°C. In the autumn season, maximum temperatures fall to around 25°C. During the winter months, average temperatures are recorded below 20°C, and humidity levels are quite

low. Nights are very cold, and frost can be observed in December and January (Guettiche and Ben Abdasadok, 2006).

According to the monthly average temperature values measured at the Touggourt meteorological station, provided in Table 4.3, the hottest months are July and August, with average temperatures recorded at 31.6°C and 31.01°C, respectively. The coldest months are December (11.48°C) and January (10.81°C). The monthly distribution of minimum, maximum, and average temperatures according to the Touggourt meteorological station data is shown in Figure 4.3. Generally, temperatures are very high during the summer months, and low during the winter months. The annual average temperature over the study period from 1975 to 2024 was calculated to be 20.99°C.

Table 4. 3 Monthly average temperature recorded at Touggourt meteorological station (1975–2024)

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug
T(°C)	27.09	21.54	15.36	11.47	10.80	12.92	16.31	20.10	24.55	29.15	31.60	31.01

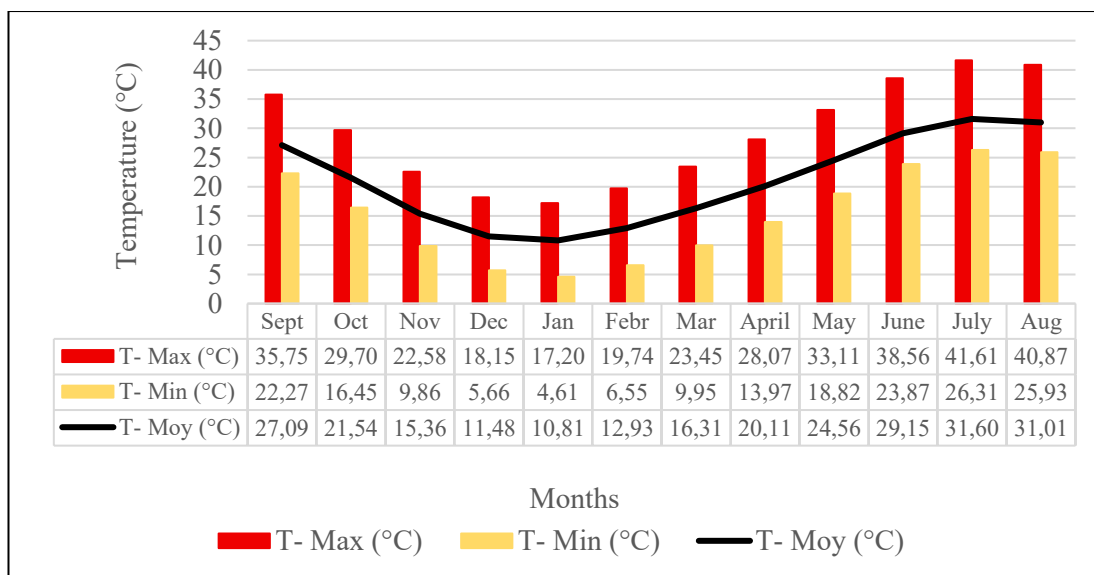


Figure 4. 3 Monthly Distribution of Minimum, Maximum, and Average Temperatures Based on Data from the Touggourt Meteorological Station (1975–2024)

4.1.3. Wind speed

Wind is a climatic parameter determined by its speed and direction. In the study area, the strongest winds are observed from March to June, with the maximum wind speed recorded in May at 5.321 m/s. During the other months of the year, wind speeds are recorded at lower levels. In December, the minimum wind speed is measured at 3.42 m/s, and the annual average wind speed is 4.33 m/s (Figure 4.4 and Table 4.4).

The wind direction in the study area is generally recorded from the South-North and Southwest-Northeast directions. However, winds from the South and Southwest are dominant only in January (Benhaddya, 2006).

Table 4. 4 Monthly average wind speed recorded at Touggourt meteorological station (1975–2024)

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Wind Speed (m/s)	4.13	3.75	3.72	3.42	3.75	4.17	4.79	5.32	5.32	4.95	4.43	4.25

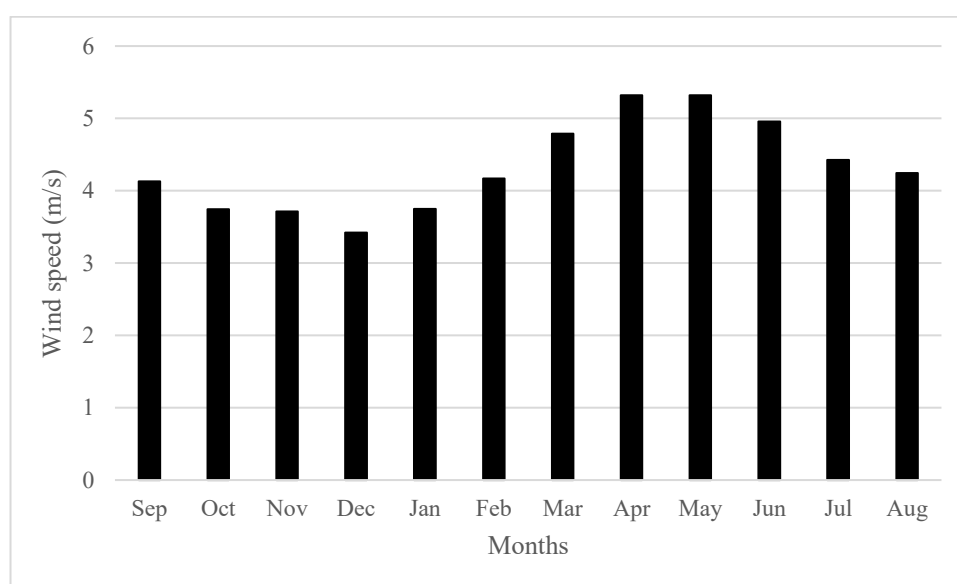


Figure 4. 4 Monthly Distribution of Average Wind Speed Based on Data from the Touggourt Meteorological Station (1975–2024)

4.1.4. Relative Humidity

According to the monthly average humidity values measured at the Touggourt meteorological station, the maximum average humidity in the region is approximately 64.15% in December, while the minimum average humidity is 31.01% in July (Figure 4.5 and Table 4.5). October, November, December, January, February, and March are characterized as humid months (Average Humidity > 46.44%), while the other months (Average Humidity < 46.44%) are considered dry months.

Table 4. 5 Monthly average relative humidity (%) measured at the Touggourt meteorological station (1975–2024)

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
H (%)	42.81	49.68	58.56	64.14	62.41	52.55	47.59	43.03	38.87	33.44	31.01	33.16

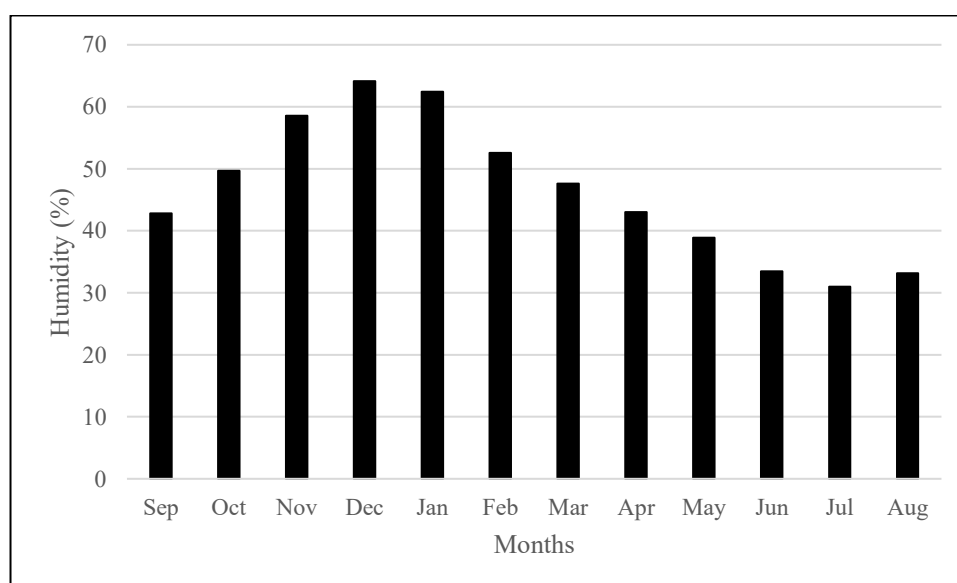


Figure 4. 5 Monthly Distribution of Average Relative Humidity (%) Based on Data from the Touggourt Meteorological Station (1975–2024)

4.1.5. Evaporation (Evaporation)

Evaporation is a crucial climate factor that cannot be ignored, especially in arid regions such as Wadi Righ. Evaporation is the process in which liquid water transforms into water vapor (Azlak, 2015). The commonly used term "evaporation" refers to the evaporation from non-vegetated soil surfaces, not covered by plant life, and from free

water surfaces. In evaporation from a free water surface, meteorological factors such as, humidity, wind speed, air temperature, total solar radiation and wind direction, as well as factors like the size and shape of the water surface, topography, and surrounding vegetation, play a significant role (Bayazit, 2013).

Other important factors affecting evaporation include dissolved substances in the water. Additionally, the chemical properties of the soil play an important role in evaporation from exposed soil surfaces. Besides meteorological factors, other factors affecting evaporation include groundwater depth and soil type (Şaylan, 2011). Transpiration by plants is the process in which liquid water from plant tissues evaporates into the atmosphere. Plants absorb water through their roots, and most of this water is lost through their pores. Key factors influencing transpiration include atmospheric vapor pressure, temperature, wind, light intensity, and characteristics of the plant's root and leaf system (Subramanya, 1994; Allen et al., 2006). While the factors affecting transpiration and evaporation from free water surfaces are the same, transpiration is limited to daytime hours and is dependent on the plant's growth period. In contrast, evaporation occurs both during the day and night, with varying evaporation rates during the day and night (Subramanya, 1994; Bayazit, 2013).

According to the monthly average evaporation values measured at the Touggourt meteorological station, the monthly average evaporation in the region varies between 100.55 mm and 388.67 mm (Table 4.6 and Figure 4.6). High evaporation amounts above 300 mm were recorded in June, July, and August. The maximum average evaporation amount of 388.67 mm occurred in July, while the minimum average evaporation amount of 100.55 mm was recorded in December.

Table 4. 6 Monthly average evaporation values (mm) measured at Touggourt meteorological station (1975–2024)

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug
ET (mm)	261.8	190.7	124.3	100.5	110.7	128.4	194.4	244.9	303.9	359.5	388.6	356.6

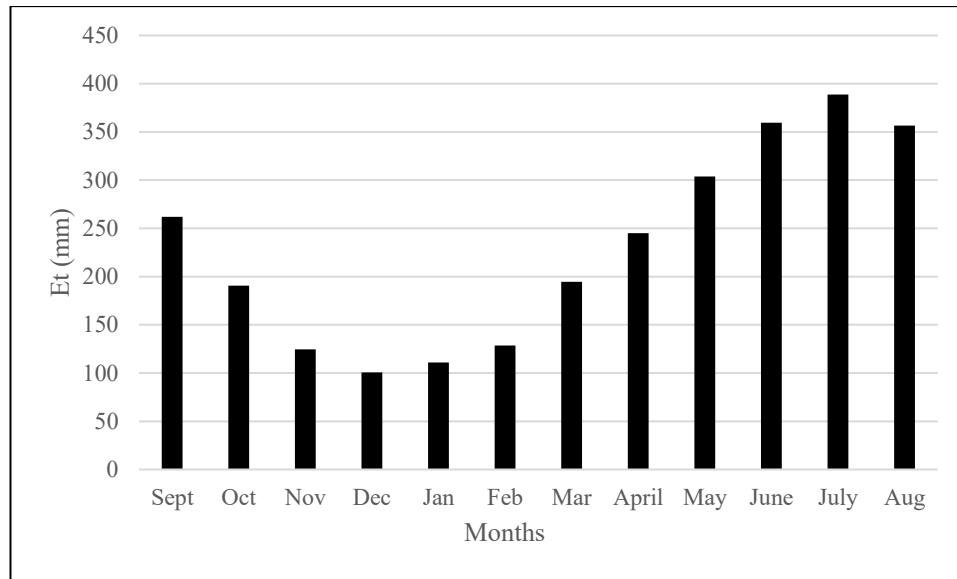


Figure 4. 6 Monthly distribution of average evaporation (mm) based on data from the Touggourt meteorological station (1975–2024)

4.1.5.1. Evapotranspiration

The total amount of water lost through evaporation from soil, water, and snow surfaces, as well as transpiration from plants, is referred to as evapotranspiration (Bayazit, 2013). Evapotranspiration is an important factor for the water and energy cycles and is a crucial variable in fields such as hydrology, climatology, agriculture, forestry, and ecology. Globally, approximately 64% of precipitation on land returns to the atmosphere through evapotranspiration (Rivas and Caselles, 2004). In some regions, about 90% of precipitation can return to the atmosphere through evapotranspiration. In the hydrological system, since large amounts of water are transmitted to the atmosphere through evaporation and transpiration, accurately predicting evapotranspiration is of great importance for hydrological budget calculations (Rivas and Caselles, 2004; Varni et al., 1999).

When evaluating evapotranspiration losses, it is necessary to distinguish between potential and actual evapotranspiration values. Potential evapotranspiration (ET_p) is defined as the amount of water transferred to the atmosphere under conditions where there are no limiting factors in the soil moisture source (Federer et al., 1996; Kay et al., 2013). Actual evapotranspiration (ET_a) refers to the amount of water vapor transferred to the atmosphere from a plant-covered surface per unit area and time.

Additionally, water evaporated through dew and interception from plant surfaces is included in actual evapotranspiration. In this process, the necessary energy is provided not only by solar radiation but also through advection. Actual evapotranspiration is a definition that takes into account atmospheric parameters as well as soil and plant factors. Since it depends on the amount of moisture in the soil, actual evapotranspiration can be less than potential evapotranspiration. Moreover, in the absence of precipitation, evapotranspiration ceases once the soil reaches the point of dryness (Şaylan, 2011; Bayazıt, 2013).

4.1.5.2. Calculation of Water Balance in Wadi Righ Region Using C.W.

Thornthwaite Formula

The Thornthwaite method, primarily used for climate classification, also has a wide range of applications in areas such as agricultural hydrology and water resources development, where direct evapotranspiration calculations are not possible. Using this method, climate types can be determined by preparing water budget tables (Thornthwaite and Mather, 1955; Willmott and Matsuura, 1995; Yeşilnacar et al., 1998). Many researchers have used climate classification methods based on water budget tables to study water deficits and climate types (Bacanlı and Saf, 2005; Chen et al., 2005; Chen et al., 2017; Xu et al., 2020; Xu et al., 2021).

The Thornthwaite climate classification method is based on the creation of a water balance table to determine the climate of an area. This table is prepared using monthly average temperature and monthly average precipitation data. It includes information on accumulated water in the soil, monthly changes in accumulation, excess or deficit water in the soil, etc. By using this data, factors such as rainfall efficiency, temperature regime, temperature efficiency, and rainfall regime are calculated. As a result of these calculations, the climate type of the area is determined. The water balance is calculated using various formulas. The monthly average precipitation and temperature data from the Touggourt meteorological station were used to calculate the potential evapotranspiration (ET_p) and actual evapotranspiration (ET_a) values, which are presented in Table 4.7. Additionally, the monthly water deficit and surplus amounts have been calculated.

According to the Thornthwaite-based water balance, the total average annual precipitation is 67.68 mm, the potential evapotranspiration (ET_p) value is 1083.97 mm, and the actual evapotranspiration (ET_a) value is 67.7 mm. Based on the data obtained, a significant difference between ET_p (Potential evapotranspiration) and ET_a (Actual evapotranspiration) was observed. Particularly, from May to September, the potential evapotranspiration and temperature values are high, while precipitation is low. In this period, the average precipitation in July decreases to as low as 0.74 mm. The measured evaporation amounts to 2765.06 mm, whereas the estimated annual potential evapotranspiration (ET_p) is 1083.97 mm. This reveals a very significant discrepancy, with evaporation being more than 2.5 times higher than the estimated ET_p. Under normal conditions, potential evapotranspiration, especially when estimated using empirical methods, should be of the same order of magnitude as evaporation, or at least not drastically lower in hyperarid environments such as the Sahara Desert. This difference suggests that the Thornthwaite method likely underestimates ET_p in this context. The reason lies in the method's dependence primarily on temperature, without adequately accounting for key climatic factors such as solar radiation, wind speed and low relative humidity. These factors are particularly intense in arid regions and significantly enhance evaporation rates. Therefore, the Thornthwaite relationship appears not well adapted to this environment. It is generally more suitable for humid to temperate climates, and its application in desert conditions leads to systematic underestimation of evapotranspiration.

Table 4. 7 Thornthwaite adjusted water balance for the Touggourt meteorological station in the Wadi Righ Region

	T(°C)	ET _p	P (mm)	Bsa	ET _a	Water deficit	Excess water (mm)
Sep	27.09	126.10	6.51	00	6.5	119.59	00
Oct	21.54	70.62	4.82	00	4.8	65.80	00
Nov	15.36	29.10	8.04	00	8.0	21.06	00
Dec	11.48	14.15	4.96	00	5.0	9.19	00
Jan	10.81	13.27	13.11	00	13.1	0.16	00
Feb	12.93	19.46	5.26	00	5.3	14.20	00
Mar	16.31	39.93	8.82	00	8.8	31.11	00
Apr	20.11	68.49	7.93	00	7.9	60.56	00
May	24.56	118.57	3.82	00	3.8	114.75	00
June	29.15	176.33	1.24	00	1.2	175.09	00
Jul	31.60	215.16	0.74	00	0.7	214.42	00
Aug	31.01	192.78	2.43	00	2.4	190.35	00
Annual	21.00	1083.97	67.68	00	67.7	1016.29	00

Therefore, with the exception of January, the amount of precipitation is lower than the potential evapotranspiration throughout the year, resulting in a significant water deficit in the region. In January, the precipitation amount exceeds both the potential and actual evapotranspiration, with temperatures recorded below 10.81°C. Although there is a water deficit (0.16 mm) in this month, no water surplus is observed either (Figure 4.7). This is due to the fact that the soil moisture has already been utilized due to the high temperatures observed in other months. On the other hand, the actual evapotranspiration values are largely consistent with the precipitation amounts. This explains the absence of water surplus throughout the year.

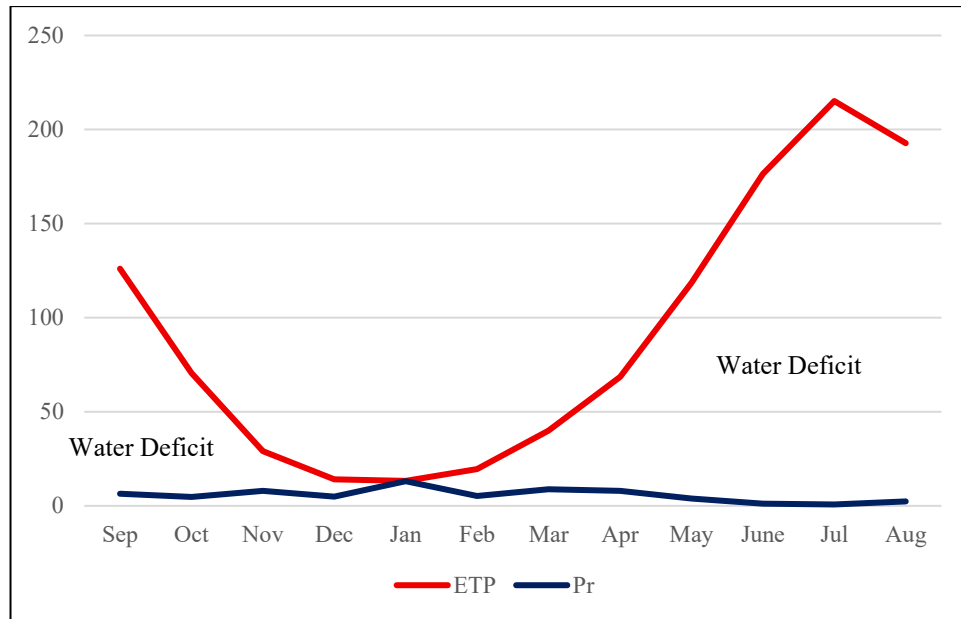


Figure 4. 7 Monthly variation graph of precipitation and potential evapotranspiration (Etp) based on the Thornthwaite method (Touggourt Meteorological Station)

4.2. Hydrogeochemical Assessment of Groundwater in the Wadi Righ Region

Only 3% of the world's water resources consist of freshwater, and merely 30% of that freshwater is stored as groundwater. As a limited and vital resource, groundwater serves as a primary source for drinking water, as well as agricultural and industrial water supply across many regions worldwide (Çelik and Yıldırım, 2006; Gallardo and Tase, 2007; Partey et al., 2010; Hosseiniard and Mirzaei, 2015; Mirzavand and Ghazavi, 2015; Carreira et al., 2018; Carrard et al., 2019). Investigating groundwater resources and identifying the factors influencing water chemistry are of paramount importance for the effective management of water supplies, particularly in arid and semi-arid regions. The scarcity and poor quality of surface water in these regions often lead to the extensive exploitation of groundwater resources. However, excessive groundwater abstraction and pollution have become major threats to its sustainability. Another critical phenomenon posing a significant risk to groundwater quality is saltwater intrusion and salinization (Polemio et al., 2009; Farid et al., 2013; Hamed et al., 2014; Bahir et al., 2018; Foster et al., 2018; Lyazidi et al., 2019; Arani et al., 2023). Recent studies suggest that groundwater salinity may be a crucial limiting factor for

its use in domestic consumption and food production, especially in arid and semi-arid environments. This issue is increasingly emerging as a global concern for water security (Edmunds, 2012; Thorslund and van Vliet, 2020; Ashik and Gain, 2023).

Due to the escalating challenges in water security, hydrogeochemical research has gained significant importance, particularly in Mediterranean regions (Voutsis et al., 2015; Mongelli et al., 2019). Globally, numerous researchers employ hydrogeochemical techniques to conduct detailed investigations into water chemistry and quality (De Montety et al., 2008; Prasanna et al., 2010; Gaofeng et al., 2010; Zhu and Schwartz, 2011; Alexakis, 2011; Ryzhenko and Cherkasova, 2012; Ahmed et al., 2013; Voutsis et al., 2015; Zhang et al., 2015; Nair et al., 2015; Nematollahi et al., 2016; Walter et al., 2017; Barzegar et al., 2017; Sánchez et al., 2017; Madhav et al., 2018; Wang et al., 2022; Dhaoui et al., 2023). Geochemical assessments play a crucial role in understanding rock-water interactions and anthropogenic influences on water resources. These processes account for the temporal and spatial variations in water chemistry are influenced by factors such as the degree of chemical weathering of different rock types and regional geology, groundwater recharge, and contamination. The interplay of these factors governs the evolution of water quality. In arid and semi-arid regions, the primary natural drivers of groundwater mineralization include the dissolution of evaporite minerals, evaporation, and seawater intrusion (Galego Fernandes et al., 2005; Singhal et al., 2020; Lal et al., 2023; Vetrimurugan et al., 2023; Alqarawy, 2023; Vespasiano et al., 2023). Meanwhile, agricultural and industrial activities are among the most influential anthropogenic contributors to groundwater salinization (mineralization) (Aghazadeh et al., 2017; M'nassri et al., 2019).

This section of the study is based on a dataset collected from Fifty two (52) groundwater wells during the year 2017. The selected wells are spatially distributed across the study area to ensure a representative assessment of groundwater conditions. The dataset includes physicochemical parameters that were systematically measured and recorded to evaluate the hydrochemical characteristics and overall water quality. These data provide a reliable basis for subsequent analyses, including the identification of dominant geochemical processes, spatial variability, and the assessment of groundwater suitability for various uses.

4.2.1. Hydrochemistry and Physicochemical Characteristics

4.2.1.1. Potential of Hydrogen (pH)

pH is a parameter that represents the abbreviation for hydrogen ion concentration and is used to determine whether a given medium is acidic or basic. Solutions with a pH below 7 are classified as acidic, while those with a pH above 7 are considered basic. The pH values of groundwater samples from the Terminal Complex aquifer range between 6.77 and 8.7. Based on these values, the groundwater in this aquifer generally exhibits a basic water character (Figure 4.8).

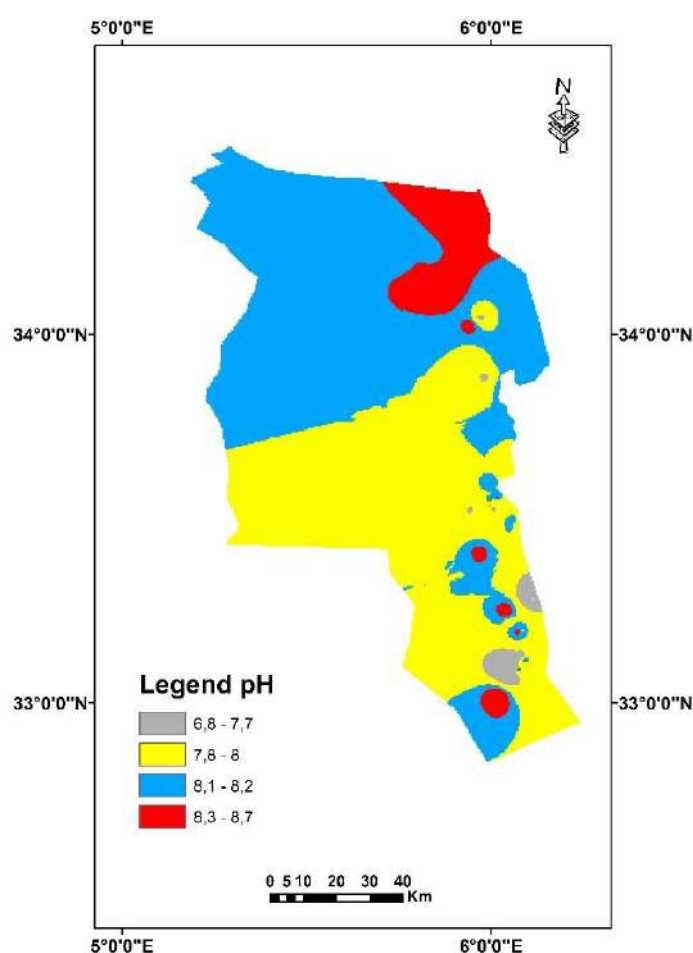


Figure 4. 8 pH distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.2. Electrical Conductivity (EC)

The distribution map of groundwater EC values is presented in Figure 4.9. Upon examining the distribution map, it is observed that groundwater EC values range between 2,000 $\mu\text{S}/\text{cm}$ and 10,000 $\mu\text{S}/\text{cm}$, with the most frequently observed class interval being 4,000–6,000 $\mu\text{S}/\text{cm}$. The collected groundwater samples from the central and southern regions of the study area exhibit high electrical conductivity values, ranging between 8,000 and 10,000 $\mu\text{S}/\text{cm}$. The high EC values of these groundwater samples indicate an elevated ion content, which is primarily attributed to intense salinization processes.

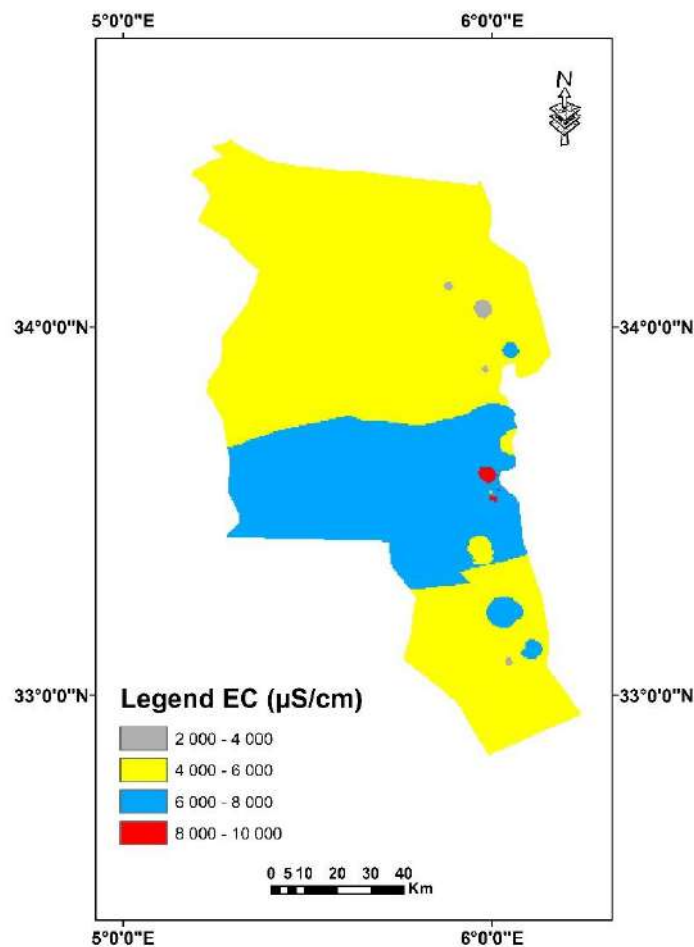


Figure 4. 9 EC ($\mu\text{S}/\text{cm}$) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.3.Total Dissolved Solids (TDS)

The Total Dissolved Solids (TDS) concentrations in groundwater range from 1,934 to 8,318 mg/L. According to the TDS distribution map presented in Figure 4.10, most groundwater samples exhibit TDS values within the range of 4,500–6,000 mg/L. A significant increase in TDS values is observed in the northern and central regions of the Wadi Righ, where measurements range between 4,500 and 9,000 mg/L. The variation in TDS concentrations is closely associated with the abundance of ions present in the groundwater.

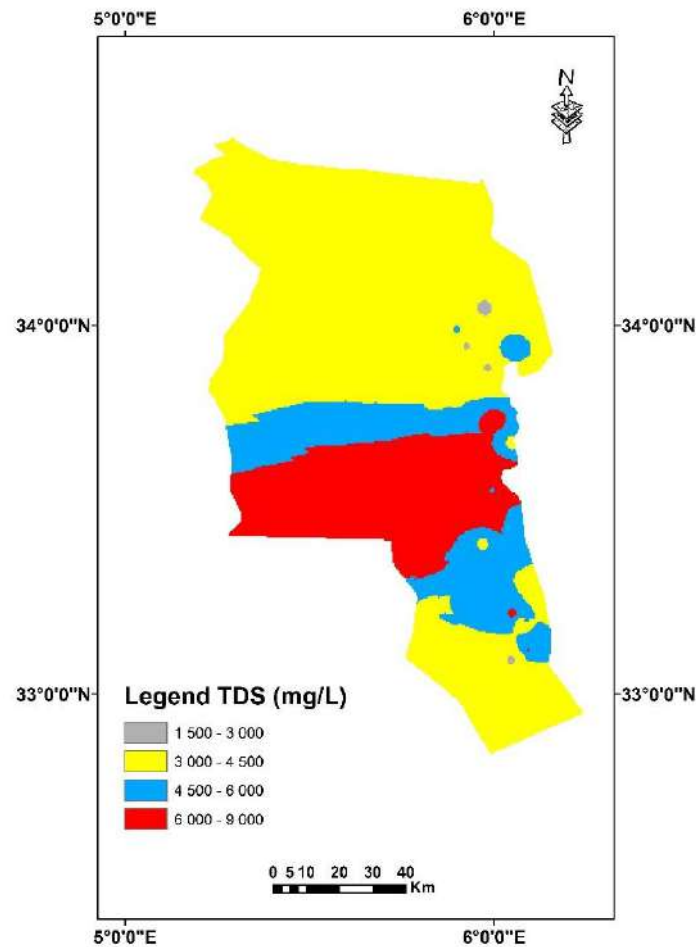


Figure 4. 10 TDS distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.4. Calcium (Ca^{2+})

The calcium values exceed the permissible limits (200 mg/L) in most water points. As illustrated in the distribution maps in Figure 4.11, it is evident that the Ca content in groundwater samples collected from the central and southern of the Wadi Righ area ranges between 400 and 600 mg/L.

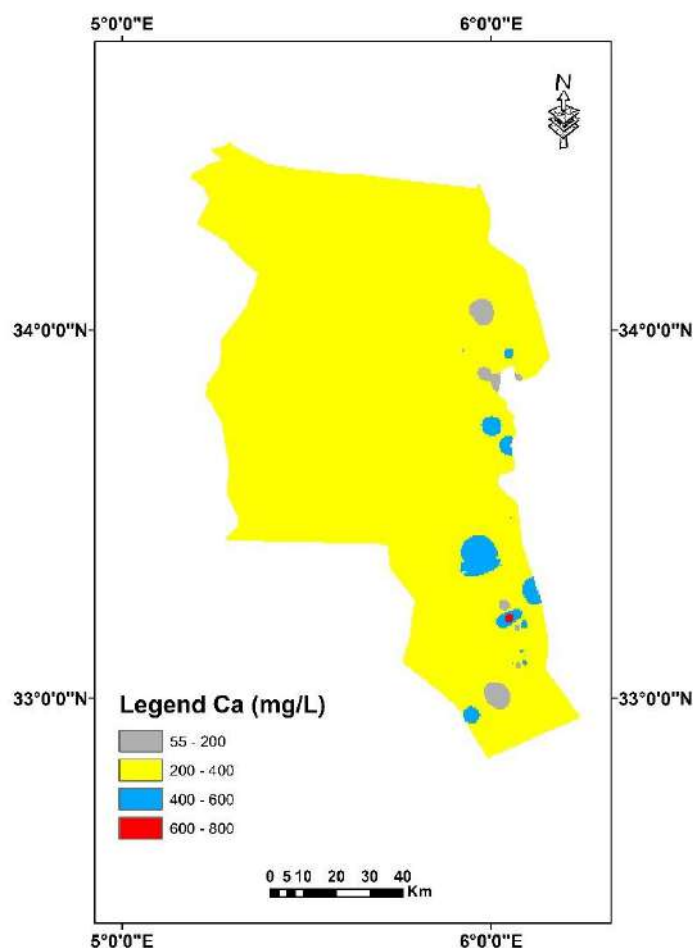


Figure 4. 11 Calcium (Ca) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.5. Sodium (Na^+)

Groundwater sodium (Na^+) concentrations range between 168.83 mg/L and 1513 mg/L. According to the sodium distribution map (Figure 4.12), Na concentrations in groundwater are significantly high, decreasing from north to south. The highest

sodium levels are correlated with water salinization. In general, sodium concentrations across the study area are observed within the range of 400–1600 mg/L.

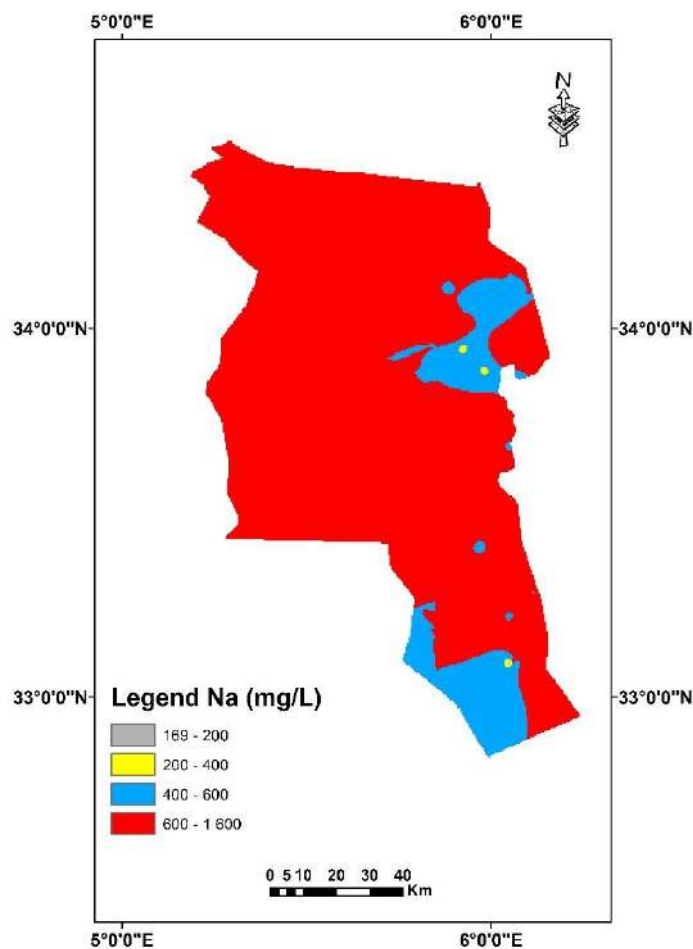


Figure 4. 12 Sodium (Na) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.6. Magnesium (Mg^{2+})

Groundwater magnesium (Mg^{2+}) concentrations range between 85.06 mg/L and 802 mg/L. According to the magnesium distribution map (Figure 4.13), the elevated Mg values (450–750 mg/L) were identified in the areas of Sidi Amrane and Djamaa, located in the central part of the study area.

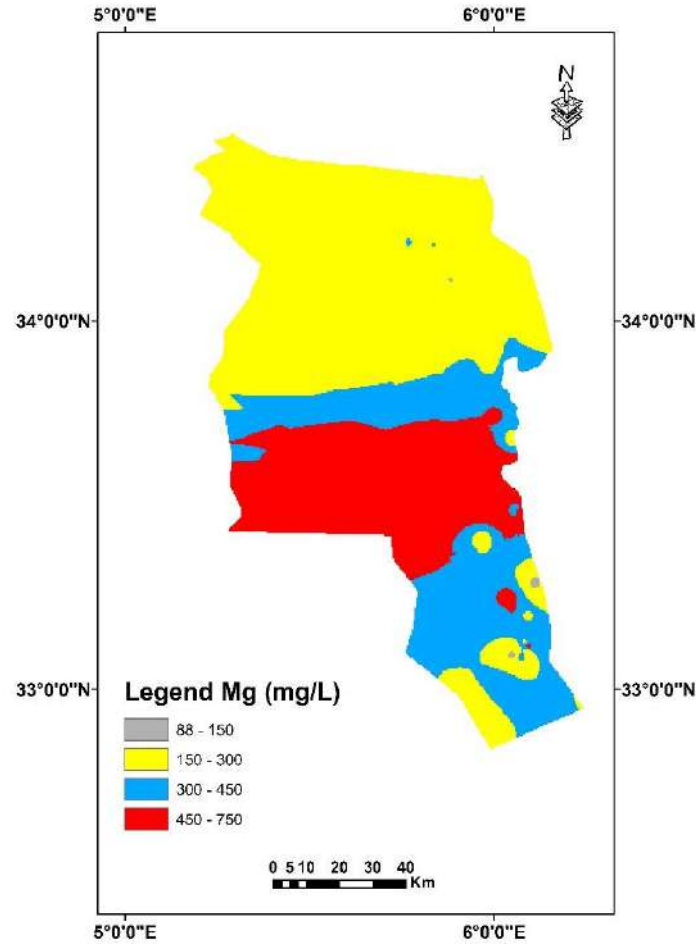


Figure 4. 13 Magnesium (Mg) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.7. Potassium (K^+)

Groundwater potassium (K^+) concentrations range between 10 mg/L and 40.5 mg/L. According to the potassium distribution map (Figure 4.14), groundwater potassium concentrations generally vary between 20 mg/L and 30 mg/L across the study area. The highest potassium levels (>30 mg/L) have been recorded in water points collected from the southern regions of Wadi Righ area.

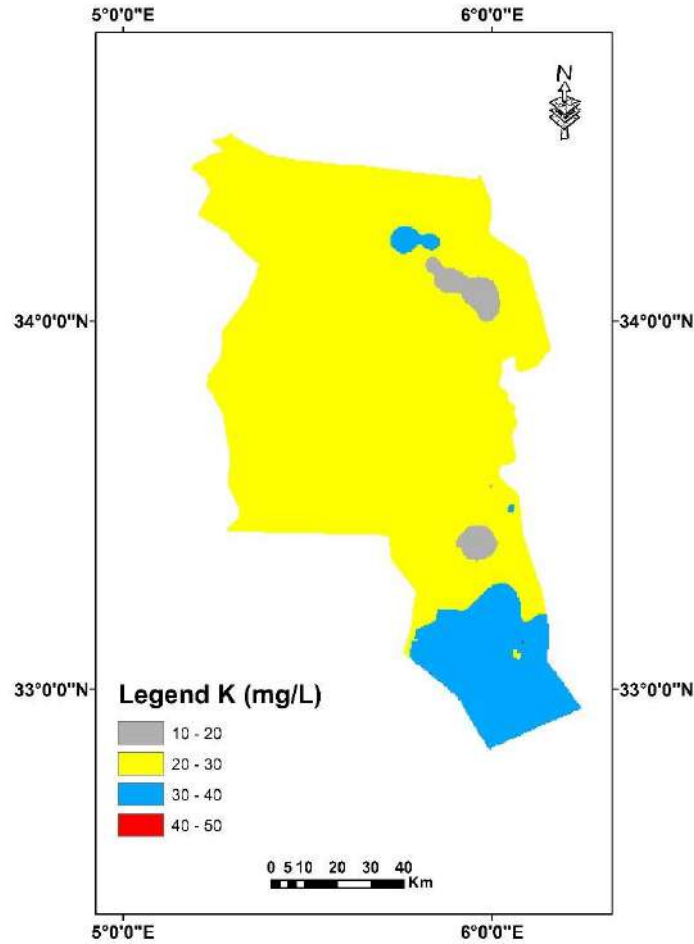


Figure 4. 14 Potassium (K) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.8. Chloride (Cl^-)

Groundwater chloride (Cl^-) concentrations range from 444.69 mg/L to 2912 mg/L. According to the chloride distribution map (Figure 4.15), groundwater samples collected from boreholes in the central and southern parts of the study area contain significantly high chloride levels. Chloride concentrations exhibit a decreasing trend toward the north. The maximum recorded chloride concentration in groundwater is 3000 mg/L. Overall, groundwater in Wadi Righ exhibits elevated chloride values due to salinization effects.

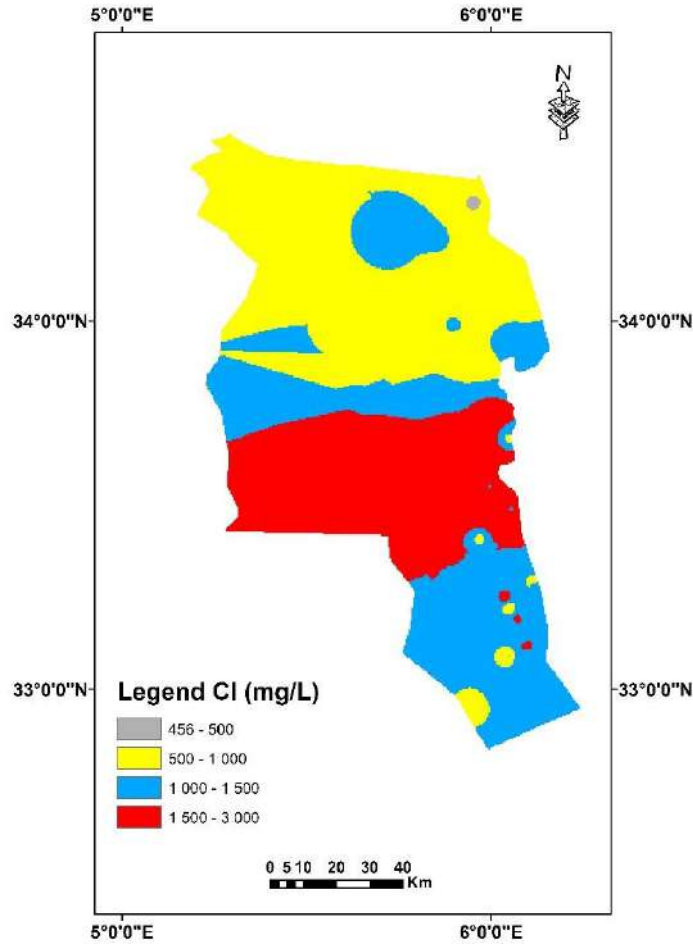


Figure 4. 15 Chloride (Cl) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.9. Sulfate (SO_4^{2-})

Groundwater sulfate (SO_4^{2-}) concentrations range from 776 mg/L to 4150 mg/L. According to the sulfate distribution map (Figure 4.16), sulfate levels in groundwater are significantly high. Groundwater samples collected from the northern regions showed relatively lower sulfate concentrations, whereas those obtained from the southern regions recorded levels exceeding 2400 mg/L.

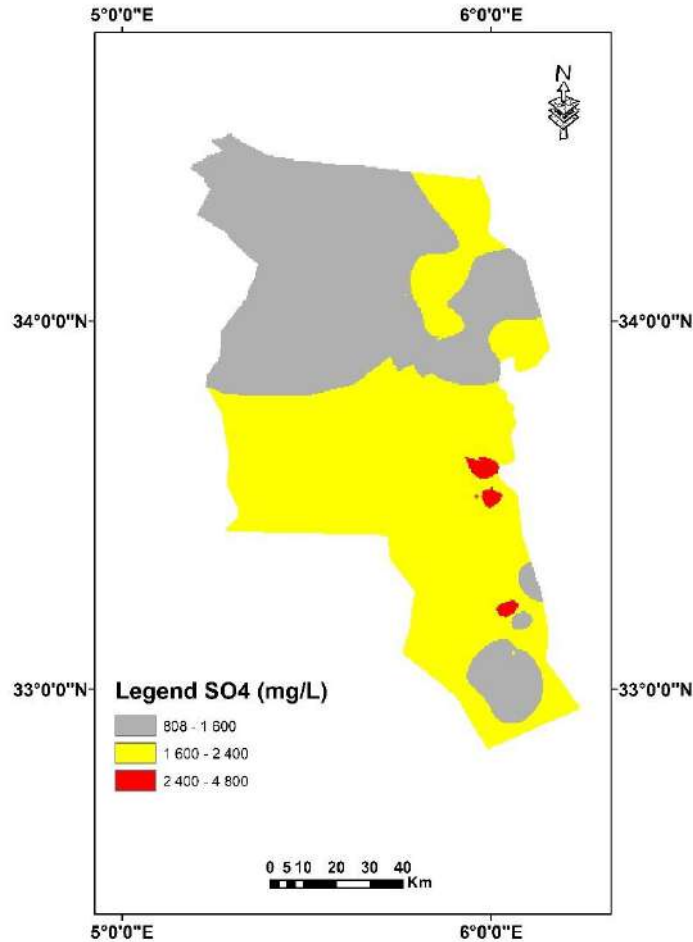


Figure 4. 16 Sulfate (SO_4) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.1.10. Bicarbonate (HCO_3^-)

Bicarbonate, along with sodium, magnesium, and calcium, is one of the natural components of water. Its concentration varies depending on the type of soil through which water infiltrates (percolation) or the surfaces over which it flows (runoff). In the study area, groundwater HCO_3^- concentrations range from 88 to 231.15 mg/L. According to the bicarbonate distribution map (Figure 4.17), bicarbonate levels in the region are generally low, with higher concentrations predominantly concentrated in the northern part. Groundwater samples collected from the northern region contain bicarbonate levels exceeding 150 mg/L.

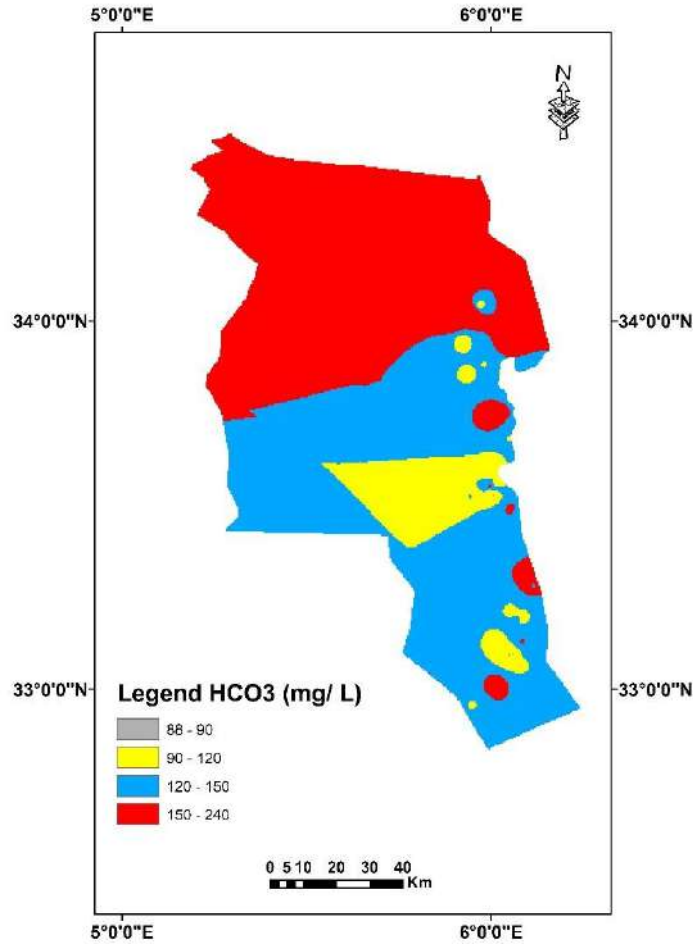


Figure 4. 17 Bicarbonate (HCO_3^-) distribution map of groundwater in the Terminal Complex aquifer (2017)

4.2.2. Hydrogeochemical Facies and Water Type

4.2.2.1. Piper Diagram

Graphical representation of analysis results is a useful method for accurately defining hydrogeochemical facies and understanding the qualitative characteristics of groundwater. In this study, a Piper diagram was used to determine the hydrogeochemical facies and classify the water types of groundwater in the study area. The Piper diagram represents anions and cations in two triangular fields, where each ion's proportional content is plotted relative to the total ions (Piper, 1944). To characterize water types, the triangular fields are divided into nine subfields, each representing specific water types as defined by Piper (1944) (Figure 4.18):

1. Alkaline earth elements (Ca+Mg) exceed alkali metals (Na+K).
2. Alkali metals (Na+K) exceed alkaline earth elements (Ca+Mg).
3. Weak acids (CO_3+HCO_3) dominate over strong acids (SO_4+Cl).
4. Strong acids dominate over weak acids.
5. Carbonate hardness (secondary alkalinity) exceeds 50%.
6. Non-carbonate hardness (secondary salinity) exceeds 50%.
7. Non-carbonate alkali metals (primary salinity) exceed 50%.
8. Carbonate alkali metals (primary alkalinity) exceed 50%.
9. No single cation-anion pair exceeds 50%.

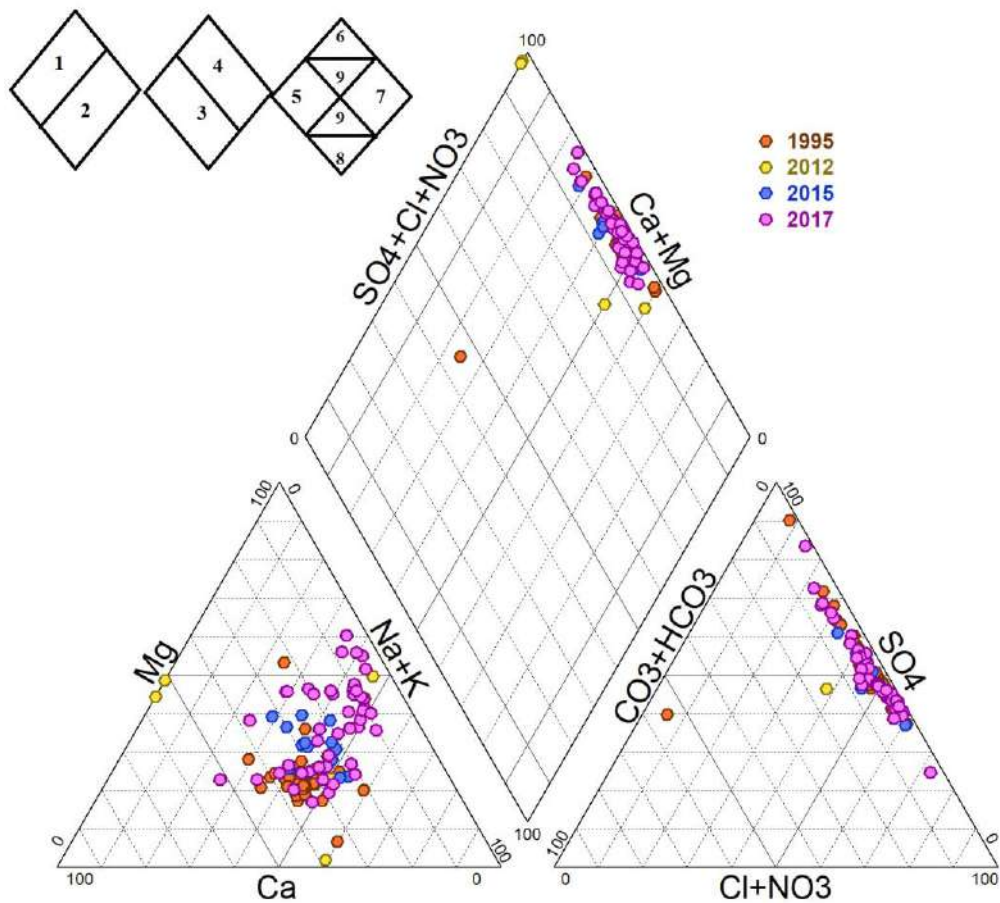


Figure 4. 18 Piper diagram of Terminal Complex groundwater samples (1995-2012-2015 and 2017)

This diagram is particularly suitable for examining the evolution of water facies as mineralization increases in water samples. It is used to compare samples in groups and determine the dominant cation and anion types. Most of the groundwater samples collected from the Terminal Complex aquifer (1995, 2012, 2015, and 2017) are located in Region 4 of the Piper diagram (Figure 4.18). Water samples falling into this region are characterized by a water type in which strong acids ($\text{SO}_4^{2-} + \text{Cl}^-$) are more prevalent than weak acids (HCO_3^-). Additionally, water samples in Region 6 exhibit carbonate hardness exceeding 50%, while those in Region 7 are characterized by a water type where non-carbonate alkali hardness exceeds 50%. Based on the classification derived from the Piper diagram by evaluating different cations and anions, groundwater in the study area is categorized as belonging to the Ca-Mg-Cl- SO_4 and Na-Cl- SO_4 water types. The presence of Ca and Mg ions is attributed to rock-water interactions, primarily influenced by the dissolution of limestone and calcareous rocks within the study area. Meanwhile, the increase in Na, Cl, and SO_4 concentrations is linked to the dissolution of gypsum, anhydrite, and evaporitic formations.

4.2.2.2. Chadha diagram

To classify the hydrogeochemical characteristics of groundwater in the study area and interpret the major geochemical processes, a Chadha diagram was prepared and presented in Figure 4.19 (Chadha, 1999; Fu et al., 2018; Yang et al., 2019). The Chadha diagram, used to define the chemical properties of groundwater, is structured as a quadrilateral and divided into eight sub-regions. This diagram provides a clearer representation of the evolution of hydrochemical processes. To determine the primary water type, the rectangular area of the diagram is divided into eight sub-regions, each characterizing a specific hydrogeochemical water type:

Region 1: Alkaline earth elements exceed alkali elements.

Region 2: Alkali elements exceed alkaline earth elements.

Region 3: Weak acidic anions exceed strong acidic anions.

Region 4: Strong acidic anions exceed weak acidic anions.

Region 5: Alkaline earth elements and weak acidic anions exceed alkali metals and strong acidic anions, respectively. This type of water exhibits temporary hardness. The

data points in this region of the diagram represent $\text{Ca}^{2+}\text{--Mg}^{2+}\text{--HCO}_3^-$ type, $\text{Ca}^{2+}\text{--Mg}^{2+}$ dominant HCO_3^- type, or HCO_3^- dominant $\text{Ca}^{2+}\text{--Mg}^{2+}$ type waters.

Region 6: Alkaline earth elements exceed alkali metals, and strong acidic anions exceed weak acidic anions. This type of water exhibits permanent hardness and does not accumulate residual sodium carbonate when used for irrigation. The data points in this region represent $\text{Ca}^{2+}\text{--Mg}^{2+}\text{--Cl}^-$ type, $\text{Ca}^{2+}\text{--Mg}^{2+}$ dominant Cl^- type, or Cl^- dominant $\text{Ca}^{2+}\text{--Mg}^{2+}$ type waters.

Region 7: Alkali metals exceed alkaline earth elements, and strong acidic anions exceed weak acidic anions. This type of water generally causes salinity issues in irrigation and drinking water usage. The data points in this region represent $\text{Na}^+\text{--Cl}^-$ type, Na_2SO_4 type, Na^+ dominant Cl^- type, or Cl^- dominant Na^+ type waters.

Region 8: Alkali metals exceed alkaline earth elements, and weak acidic anions exceed strong acidic anions. This type of water accumulates residual sodium carbonate when used for irrigation and causes foaming issues. The data points in this region represent $\text{Na}^+\text{--HCO}_3^-$ type, Na^+ dominant HCO_3^- type, or HCO_3^- dominant Na^+ type waters (Chadha, 1999).

According to the Chadha diagram classification, the majority of the groundwater samples analyzed from 1995, 2012, 2015, and 2017 fall into Regions 1, 4, and 6. This indicates that the hydrogeochemical composition of the groundwater is dominated by alkaline earth elements exceeding alkali metals, and strong acidic anions exceeding weak acidic anions. While alkaline earth elements (Ca^{2+} , Mg^{2+}) are more abundant than alkali metals (Na^+ , K^+), strong acidic anions (Cl^- , SO_4^{2-}) dominate over weak acidic anions (HCO_3^- , CO_3^{2-}). The positioning of data points in the Chadha diagram confirms that the Ca-Mg-Cl- SO_4 water type is the dominant hydrochemical facies in the study area across the four different years.

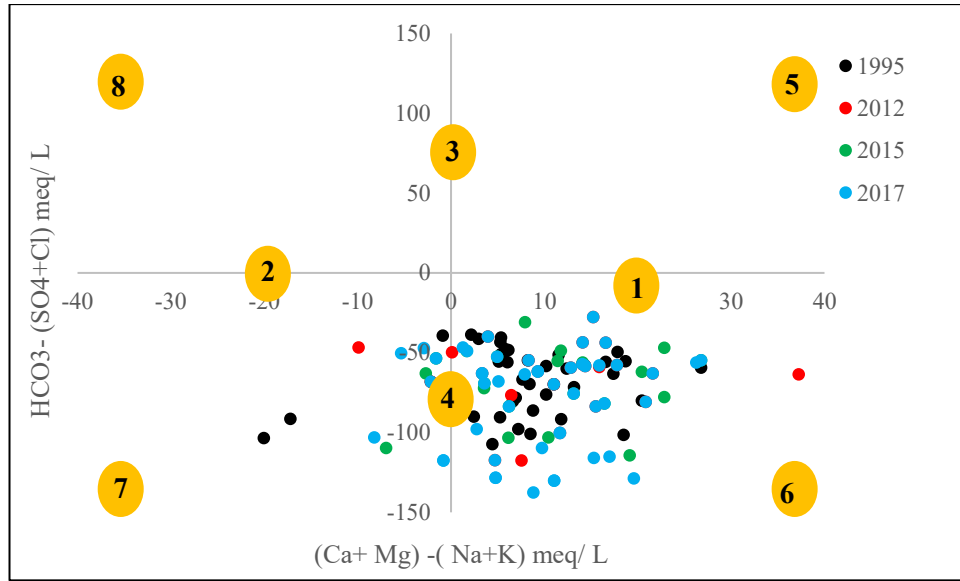


Figure 4. 19 Classification of Terminal Complex groundwater based on the Chadha diagram (1995, 2012, 2015, and 2017)

4.2.3. Hydrogeochemical Processes of Groundwater

4.2.3.1. Gibbs diagram

The interaction between groundwater and the rocks within the aquifer environment plays a critical role in determining groundwater quality and provides insight into the evolution of water chemistry. The Gibbs diagram is widely employed to identify the relationship between water composition and the lithological characteristics of the subsurface reservoir (Gibbs, 1970; Annapoorna and Janardhana, 2015; Hamidi et al., 2023). Furthermore, it is considered an important tool in hydrogeochemical analyses for explaining the impact of geochemical processes.

The Gibbs ratios are calculated using the following equations (4.1 and 4.2):

$$\text{Gibbs Ratio 1 (for anions)} = \frac{\text{Cl}}{(\text{Cl} + \text{HCO}_3)} \quad (4.1)$$

$$\text{Gibbs Ratio 2 (for cations)} = \frac{\text{Na}}{(\text{Na} + \text{Ca})} \quad (4.2)$$

Cl = Chloride, HCO_3^- = Bicarbonate, Na = Sodium, Ca^{2+} = Calcium

Figure 4.20 presents the Gibbs diagram constructed using the TDS values of the groundwater samples in relation to the cation ratio $\text{Na} / (\text{Na} + \text{Ca})$ and the anion ratio $\text{Cl} / (\text{Cl} + \text{HCO}_3^-)$. The analysis reveals that the distribution of cations in the groundwater is predominantly $\text{Na}^+ > \text{Ca}^{2+}$, indicating a stronger interaction between groundwater and sodium-rich lithological units. In the majority of the samples, the Na/Ca ratio exceeds 0.5, reflecting a notable increase in the $\text{Na} / (\text{Na} + \text{Ca})$ ratio, which signifies the occurrence of ion exchange processes.

The diagram further illustrates that most of the major cations and anions in groundwater cluster within the rock-dominant field, suggesting that the chemical characteristics of the groundwater are primarily governed by interactions between groundwater and the lithological units. The dissolution of ions as a result of this interaction contributes significantly to the chemical evolution of groundwater in the study area.

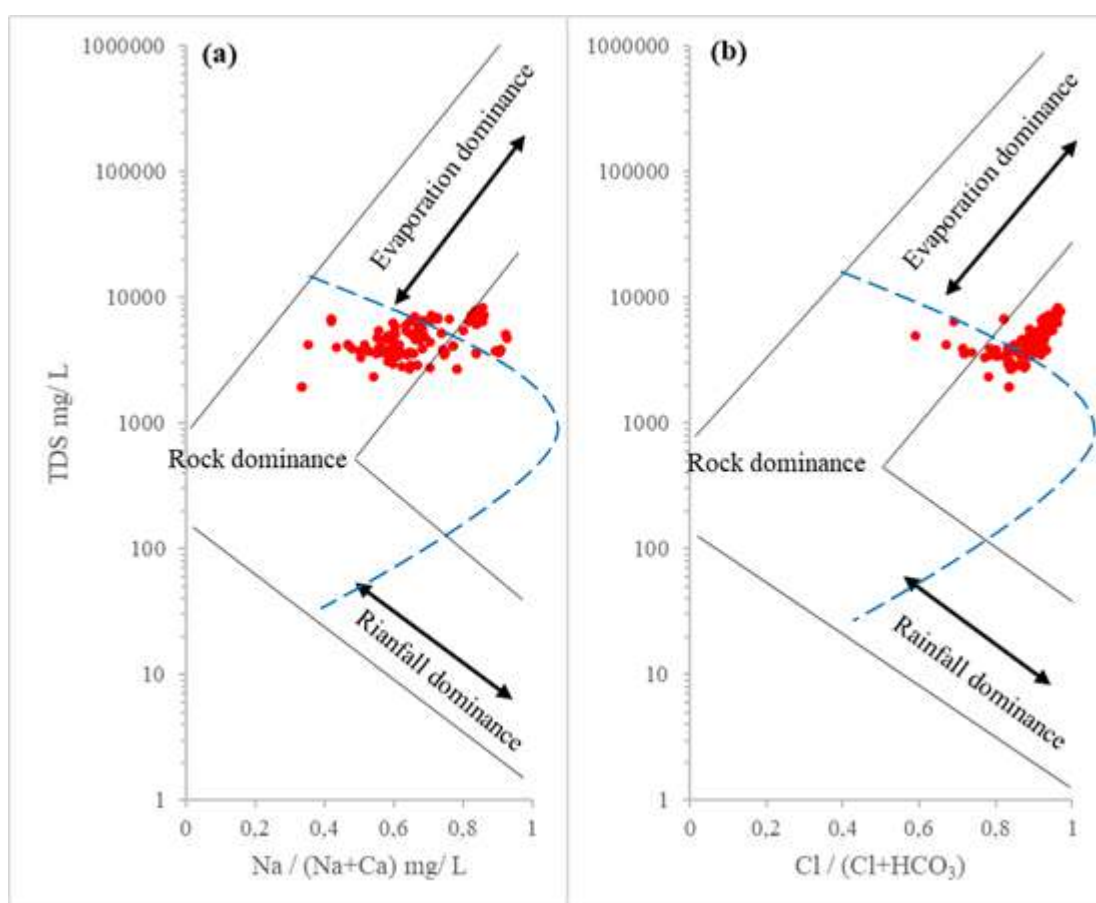


Figure 4. 20 Classification of Terminal Complex groundwater samples according to the Gibbs diagram (1995, 2012, 2015, and 2017)

4.2.3.2. Origin of groundwater mineralization

Ca/Mg - Cl/SO₄

According to Figure 4.21, when the SO₄/Cl ratio shows values greater than 1, it indicates an enrichment in sulfate ions. If the ratio is less than 1, it indicates an enrichment in chloride ions. The Ca/Mg ratio, showing values greater than 1, indicates an enrichment in calcium, while value less than 1, indicates an enrichment in magnesium. The dominant facies found in 1995 is the calcium chloride and sulfate (31 samples out of 33). Most of the observations had the magnesium chloride and sulfate facies in the years 2012, 2015, and 2017, while calcium and magnesium chloride for other water samples. The variations of the chemical facies probably reflects the heterogeneous geological formations containing the Terminal Complex aquifer (Guendouz et al. 2003; Bettahar et al. 2017b; Houari et al. 2019).

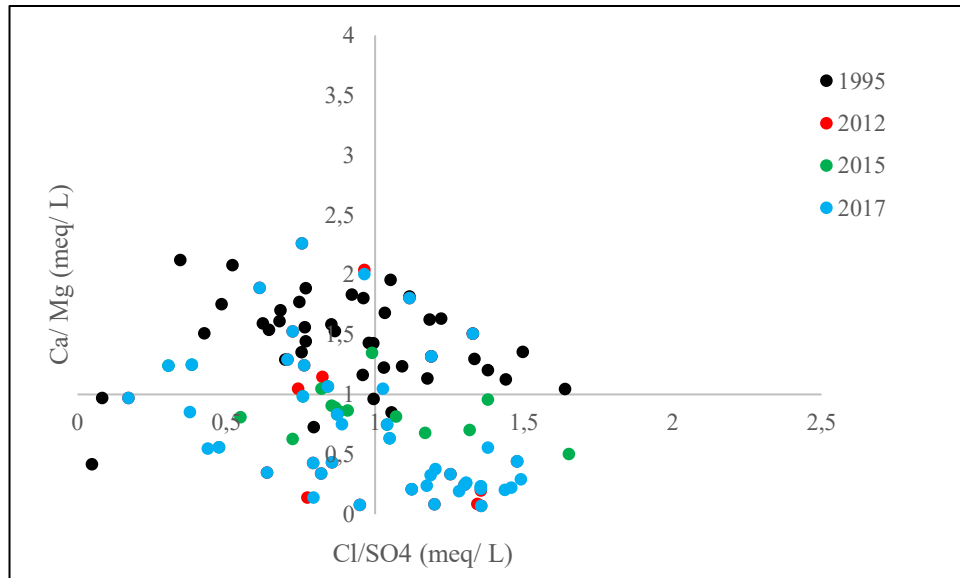


Figure 4. 21 Relationships between major elements Ca/Mg vs. Cl/SO₄ in the analyzed groundwater samples (1995, 2012, 2015 and 2017)

Na - Cl

The relationship between sodium (Na⁺) and chloride (Cl⁻) is frequently employed to identify mineralization mechanisms in arid and semi-arid regions (Dixon and Chiswell, 1992; Guo et al., 2019; Bahir et al., 2021).

According to Figure 4.22, a strong correlation ($R^2= 0.85$ in 1995, 0.78 in 2012, 0.74 in 2015 and 0.87 in 2017) is observed between Na^+ and Cl^- concentrations in groundwater, suggesting a likely dissolution of halite (NaCl) within the study area. The negative values of the halite saturation index (Halite-SI) in the groundwater further indicate that both Na and Cl ions are being enriched from a common source. This finding implies that halite dissolution represents one of the dominant hydrogeochemical processes occurring in the study area (Yang et al., 2019; Ouarani et al., 2020).

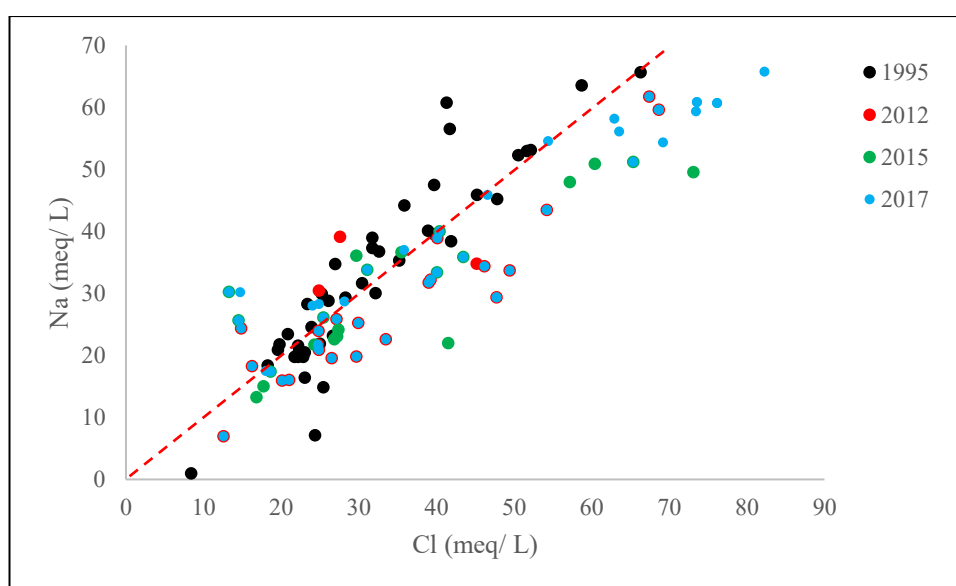


Figure 4. 22 Correlation Diagram (Na vs. Cl) in the analyzed groundwater samples (1995, 2012, 2015 and 2017)

Water samples collected between 2012 and 2015 from wells characterized by a chloride-sodium facies within the study area exhibited exceptionally high sodium concentrations. Most of these groundwater sources are located in the Chott Merouane region, suggesting that the elevated sodium levels are primarily controlled by water–rock interactions and the dissolution of evaporitic minerals. In this context, sodium enrichment in groundwater is likely associated with processes such as halite dissolution and cation exchange mechanisms rather than external saline inputs. Unlike chloride, sodium may also be influenced by ion exchange processes, which can enhance its concentration independently of direct mineral dissolution. (Houari, 2020).

In cases where Cl^- concentrations exceed those of Na^+ , this is generally attributed to cation exchange processes. During this process, Na^+ is adsorbed onto mineral surfaces while Ca^{2+} and Mg^{2+} concentrations increase (Hem, 1985; Ouarani et al., 2020). The $\text{Na}^+ - \text{Cl}^-$ hydrochemical facies observed in the study area also suggests the possible dissolution of salt minerals such as halite. This phenomenon is commonly encountered in aquifers composed of sedimentary sequences containing evaporitic layers (e.g., halite, sylvinite) (Klimchouk, 2000; Zakaria et al., 2015). The geological structure of the study area supports the occurrence of this hydrogeochemical process.

Ca - Mg

Figure 4.23 illustrates shows a weak correlation between Ca^{2+} and Mg^{2+} ions in the groundwater samples $R^2 = 0.24$ (2017), $R^2 = 0.17$ (2012), $R^2 = 0.6$ (2015) and $R^2 = 0.08$ (2017), indicating that these elements do not systematically originate from a common source. This suggests the influence of multiple and independent geochemical processes controlling their distribution.

The source of magnesium in groundwater may include dolomite, magmatic rock minerals, and evaporites. In the study area, the widespread presence of evaporitic formations is considered a primary contributor to magnesium content in the water. In contrast, the presence of calcium is more likely associated with the dissolution of limestone and calcareous rocks.

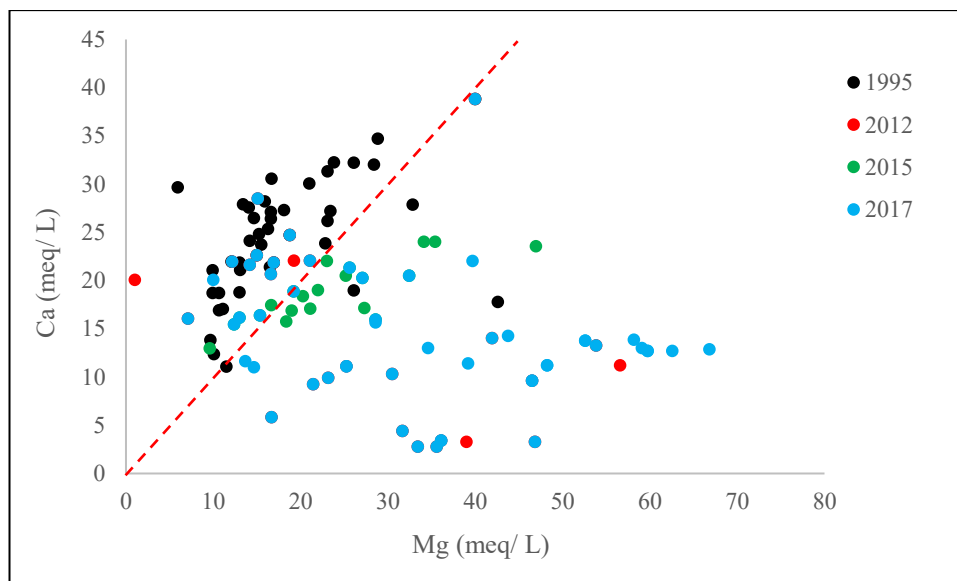


Figure 4. 23 Correlation Diagram (Ca vs. Mg) in the analyzed groundwater samples (1995, 2012, 2015 and 2017)

Ca - SO₄

The Ca versus SO₄ correlation diagram (Figure 4.24) shows that the majority of samples are located below the gypsum and/or anhydrite dissolution line ($R^2 = 0.68$ in 1995, 0.22 in 2012, 0.63 in 2015 and 0.13 in 2017), reflecting an excess of SO₄ over Ca. The depletion of Ca content in comparison to SO₄ concentration can be attributed to various processes. These processes include: a) cation exchange reactions, wherein calcium ions are adsorbed into clay minerals while sodium ions are simultaneously released, and b) incongruent dissolution of dolomite and gypsum, accompanied by the simultaneous precipitation of calcite (Bischoff et al. 1994; Appelo and Postma 2005; Jacobson et al. 2010), and/or c) precipitation of carbonates due to CO₂ degassing. (Zakaria et al. 2015; Pisciotta, 2019; Ouarani et al. 2020; Bahir et al. 2021).

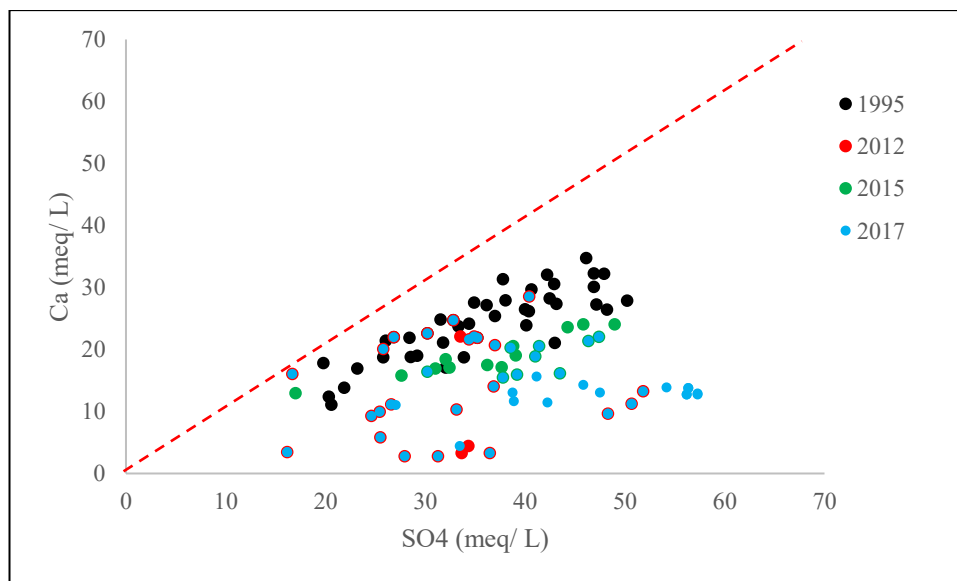


Figure 4. 24 Correlation Diagram (Ca vs. SO₄) in the analyzed groundwater samples (1995, 2012, 2015 and 2017)

Ca - HCO₃

The representation of the relationship between Ca and HCO₃ using a regression line of slope equal to 1 (Figure 4.25) shows that the groundwater sample points are above the line, thus indicating that the origin of Ca may come from the dissolution of calcite and/or cation exchange reactions (Clark and Fritz 1997; Jin et al. 2010; Bahir et al. 2021). Regarding bicarbonates, they do not influence the chemistry of the studied waters ($R^2 = 0.01$ in 1995, 0.02 in 2012, 0.01 in 2015 and 0.008 in 2017), the sources generating HCO₃ are very low or the bicarbonate salts are oversaturated and are in the solid phase (Figure 4.31) (Houari 2020).

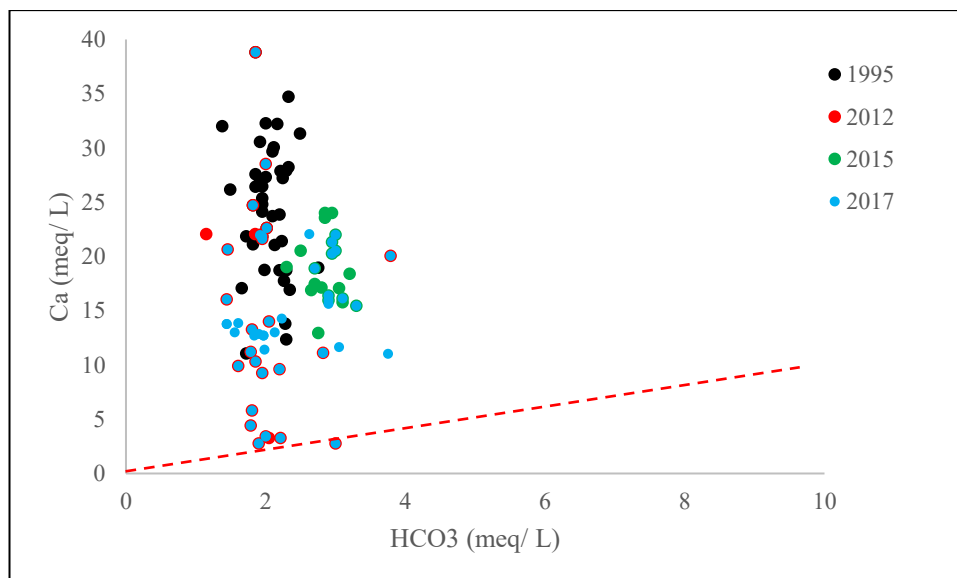


Figure 4. 25 Correlation Diagram (Ca vs. HCO₃) in the analyzed groundwater samples (1995, 2012, 2015 and 2017)

4.2.4. Spatial and temporal evolution of groundwater mineralization

The internal distribution of cation concentrations in groundwater samples is presented in Figure 4.26 and Table 4.8. According to the statistical analysis, the correlation coefficient determined for calcium is 0.2571, indicating a negative relationship between calcium concentrations and time.

For magnesium, minimum values ranged from 71 mg/L (1995) to 115.2 mg/L (2015), while average concentrations increased from 216.29 mg/L in 1995 to 390.71 mg/L in 2017 (Figure 4.26). The correlation coefficient calculated for Mg²⁺ (0.1459) indicates a weak positive relationship over time, suggesting that magnesium concentrations exhibit only a slight increasing trend with significant variability and limited temporal control.

In the case of sodium, minimum concentrations varied between 193 mg/L (1995) and 160 mg/L (2017), while average concentrations slightly increased from 736.48 mg/L in 1995 to 836.55 mg/L in 2017, as shown in Figure 4.26. The correlation coefficient for Na⁺ (0.0066) indicates an almost negligible relationship with time, suggesting that sodium concentrations remain essentially stable over the studied period with no significant temporal trend.

Regarding potassium, average concentrations were recorded as 24.18 mg/L in 1995, 29.0 mg/L in 2012, 32.49 mg/L in 2015, and 26.42 mg/L in 2017 (Figure 4.26). The very low correlation coefficient for potassium (0.0283) indicates an absence of a significant temporal relationship, suggesting that potassium concentrations do not exhibit a systematic trend over time.

Table 4. 8 Minimum, Maximum, and Average values of the chemical parameters of groundwater

Year	Statistic	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	HCO ₃ (mg/L)	EC (μS/cm)	TDS (mg/L)
1995	Min	221	71	193	13	252	950	84	4300	2711
	Max	776	511	1525	42.5	2325	4150	166.3	11200	7011
	Mean	488.52	216.29	736.48	24.18	1172.12	1764.57	126.23	6936.59	4578.74
2012	Min	55	12	160	10	444.69	776	88	2760	1934
	Max	776	679	1420	80	2431	4150	680	11200	7346
	Mean	292.59	326.89	672.12	29.00	1192.51	1665.37	144.62	5448.52	4278.67
2015	Min	258.8	115.2	305	13.5	470	815	140.3	2440	2310
	Max	480	563.2	1177.5	71.3	2588	2350	201.3	7560	7130
	Mean	374.70	281.47	718.93	32.49	1230.29	1819.95	175.75	5157.14	4633.62
2017	Min	55	85.06	160	10	444.69	776	88	2800	1934
	Max	776	802	1513	40.5	2912	4150	231.15	9030	8318
	Mean	290.01	390.71	836.55	26.42	1468.71	1893.22	137.20	5984.42	5049.33

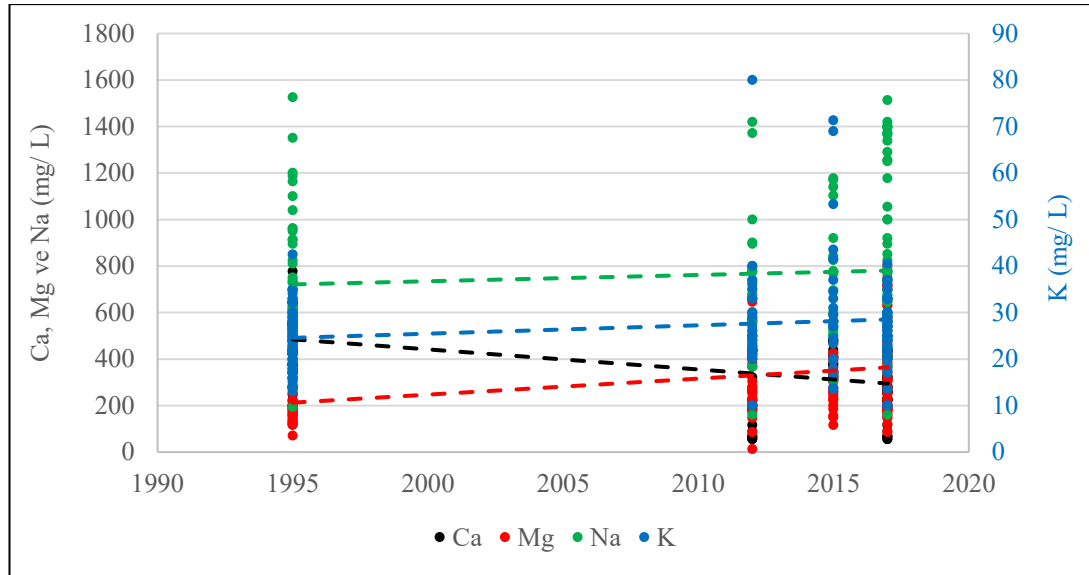


Figure 4. 26 Temporal variation of cation concentrations in the groundwater of the Wadi Righ region

For chloride ions, minimum values ranged from 252 mg/L (1995) to 444.69 mg/L (2017), while average values increased from 1172.12 mg/L in 1995 to 1468.71 mg/L in 2017. The internal distribution of anion concentrations in the groundwater is presented in Figure 4.27. For sulfate ions, minimum values ranged between 950 mg/L (1995), 815 mg/L (2015), and 776 mg/L (2017). The average concentration increased from 1764.57 mg/L in 1995 to 1893.22 mg/L in 2017 (Figure 4.27). As for bicarbonate concentrations, the average values were recorded as 126.23 mg/L in 1995, 144.62 mg/L in 2012, 175.75 mg/L in 2015, and 137.20 mg/L in 2017 (Figure 4.27). The correlation coefficient for chloride (0.0237) indicates an extremely weak and negligible relationship with time, suggesting the absence of any significant temporal trend. Similarly, sulfate exhibits a near-zero correlation (0.0044), confirming that its concentration remains essentially stable over time with no discernible trend. The correlation coefficient for bicarbonate (0.0265) also reflects a negligible relationship with time, indicating that bicarbonate concentrations do not show any systematic temporal evolution.

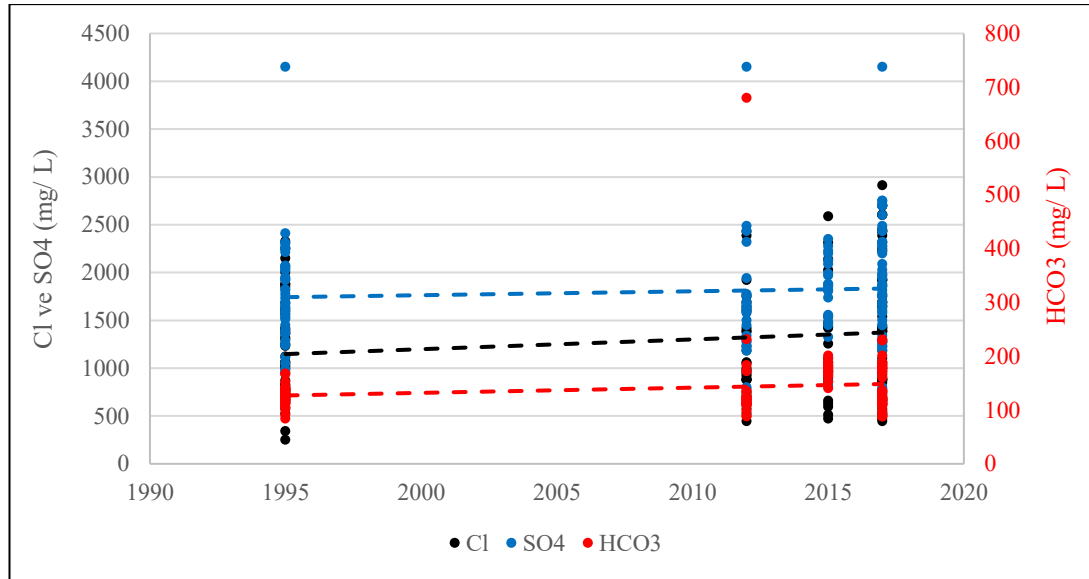


Figure 4. 27 Temporal variation of anion concentrations in the groundwater of the Wadi Righ region

Upon analyzing the relationship between chemical elements and total mineralization (TDS) (Figure 4.28), it becomes evident that the variability of the latter (TDS) is primarily influenced by chloride, sulfate, magnesium, and sodium, with correlation coefficients (R^2) of 0.59, 0.54, 0.88, and 0.8 for chloride, 0.7, 0.74, 0.86, and 0.88 for sodium, 0.39, 0.54, 0.62, and 0.76 for magnesium, and 0.53, 0.6, 0.67, and 0.68 for sulfate. These elements are pivotal factors contributing to the mineralization of water in the samples under investigation (Zakaria et al., 2015).

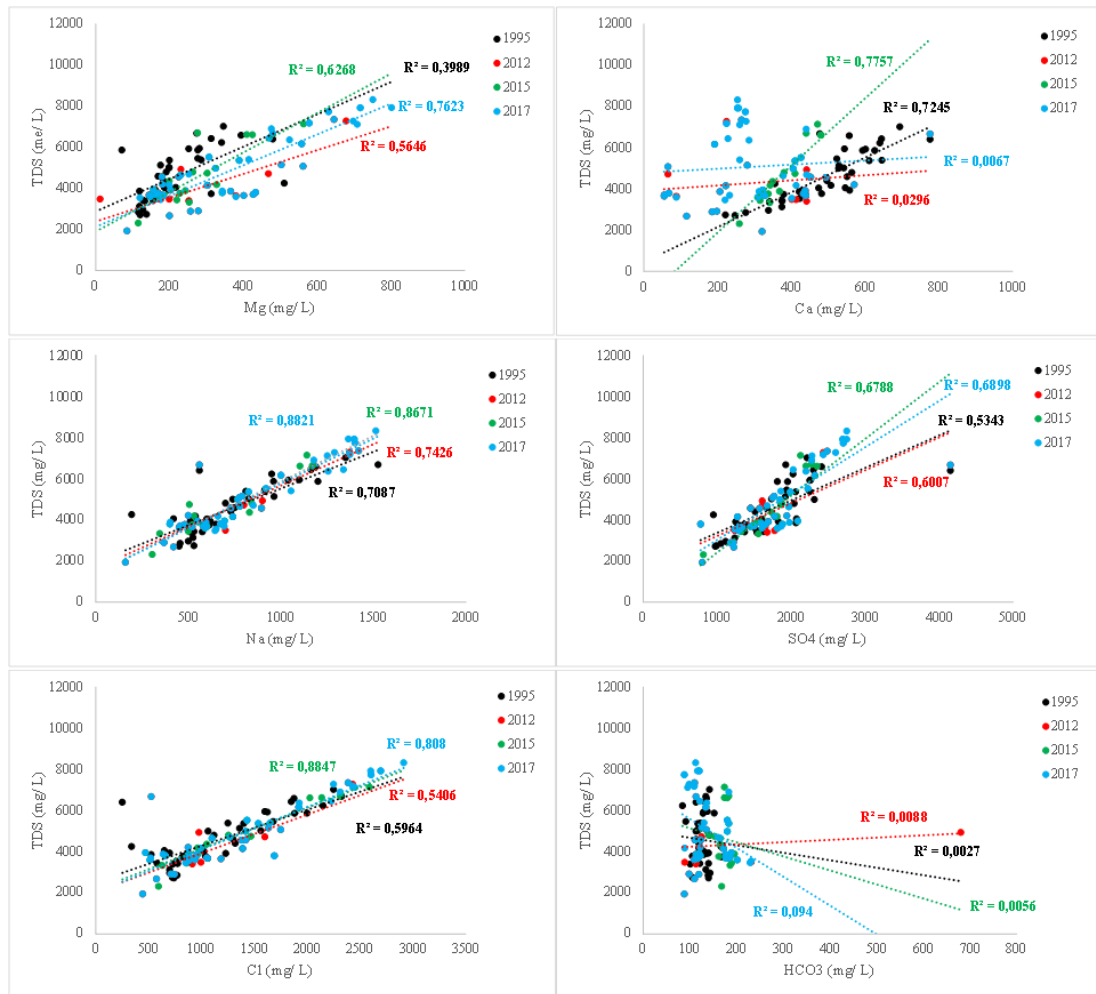


Figure 4. 28 Relationship between major chemical elements and total mineralization (TDS) (mg/L)

The Total Dissolved Solids (TDS) value is a useful indicator of the mineralization degree of water. Since electrical current is transported by ions in the solution, conductivity increases as the ion concentration increases (Hiscock and Bense 2014). The average TDS values of groundwater in the Terminal Complex (Table 4.9) range from 4303.59 to 5052.17 mg/L. Approximately, 90.47%, 81.47%, 95.23%, and 94.23% (1995, 2012, 2015, and 2017, respectively) of the samples are highly mineralized (>3000 mg/L). It is generally observed that the electrical conductivity values exceeded potability standards (>1000 $\mu\text{S}/\text{cm}$ for highly mineralized) (Gurmessa et al. 2022; Al Haj et al. 2023). The conductivity values ranges from 4300 to 11200 $\mu\text{S}/\text{cm}$ for the year 1995, from 2760 to 11200 $\mu\text{S}/\text{cm}$ for the 2012 campaign, from 2440 to 7560 $\mu\text{S}/\text{cm}$ for 2015, and from 2800 to 9030 $\mu\text{S}/\text{cm}$ for the year 2017 (Table 4.9). The

electrical conductivity and TDS values generally change along the flow direction (from South to North) (Figure 4.29) and they also increase in palm tree areas (Bettahar et al. 2017b).

Table 4. 9 Elementary statistics of Electrical Conductivity ($\mu\text{s}/\text{cm}$) and TDS (mg/L) of groundwater in the Terminal Complex aquifer (1995, 2012, 2015, and 2017)

		EC ($\mu\text{s}/\text{cm}$)	TDS (mg/L)
1995	Min	4300	2711
	Max	11200	7011
	Moy	6974.42	4591.57
2012	Min	2760	1934
	Max	11200	7346
	Moy	5554.14	4303.59
2015	Min	2440	2310
	Max	7560	7130
	Moy	5143.48	4641.13
2017	Min	2800	1934
	Max	9030	8318
	Moy	5981.85	5052.17

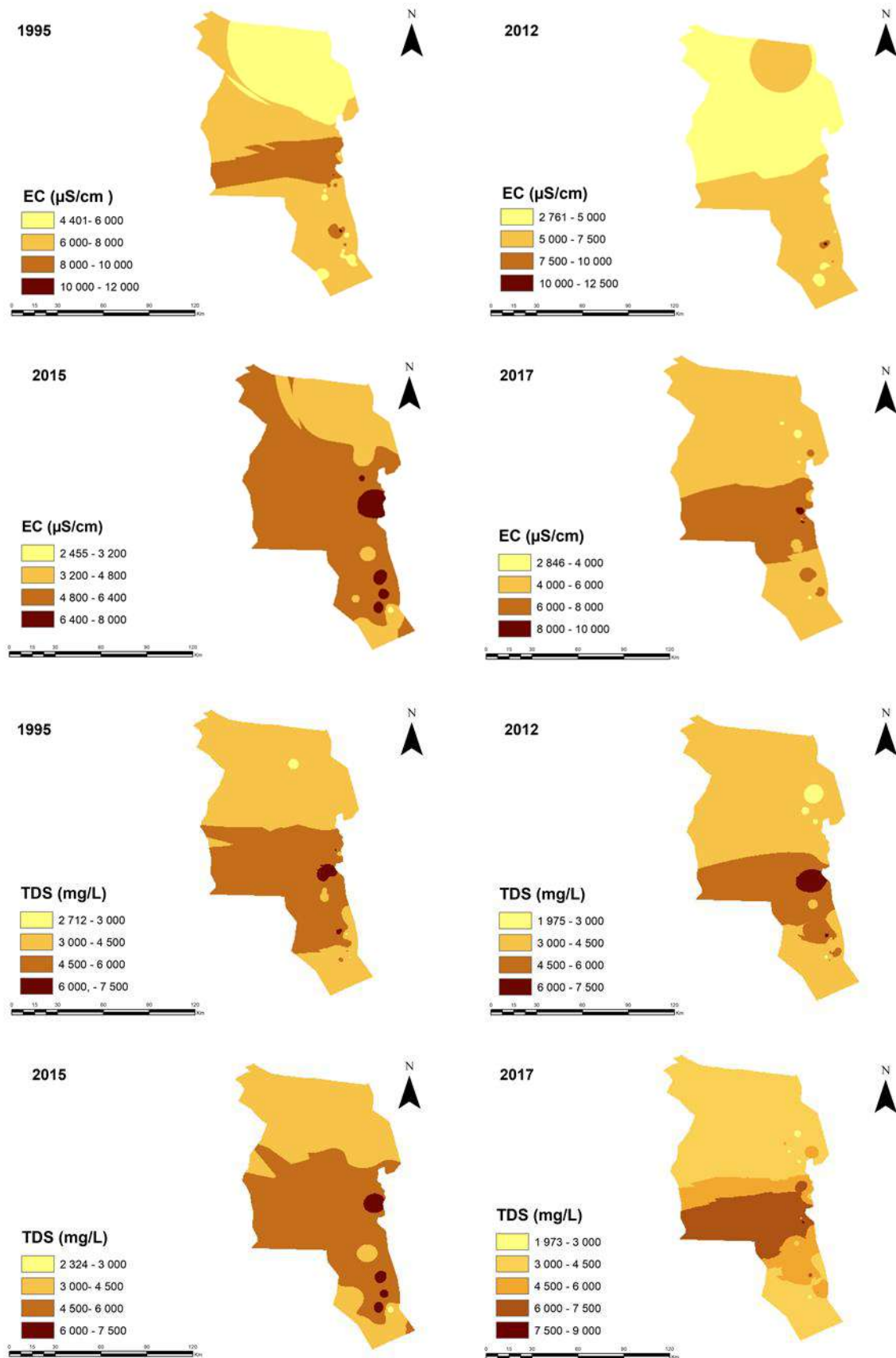


Figure 4. 29 Spatial distribution of electrical conductivity and TDS in the Terminal Complex aquifer of the Wadi Righ (1995, 2012, 2015, and 2017)

Figure 4.30 represents the evolution of the saturation indices of the waters of the Terminal Complex aquifer over time (from 1995 to 2017); these indices are Anhydrite (CaSO_4), Aragonite (CaCO_3), Calcite (CaCO_3), Dolomite ($\text{CaMg}(\text{CO}_3)_2$), Halite (NaCl), and Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). These dissolved mineral saturation indices show the sensitivity of carbonate minerals (dolomite, calcite, and aragonite) to precipitation.

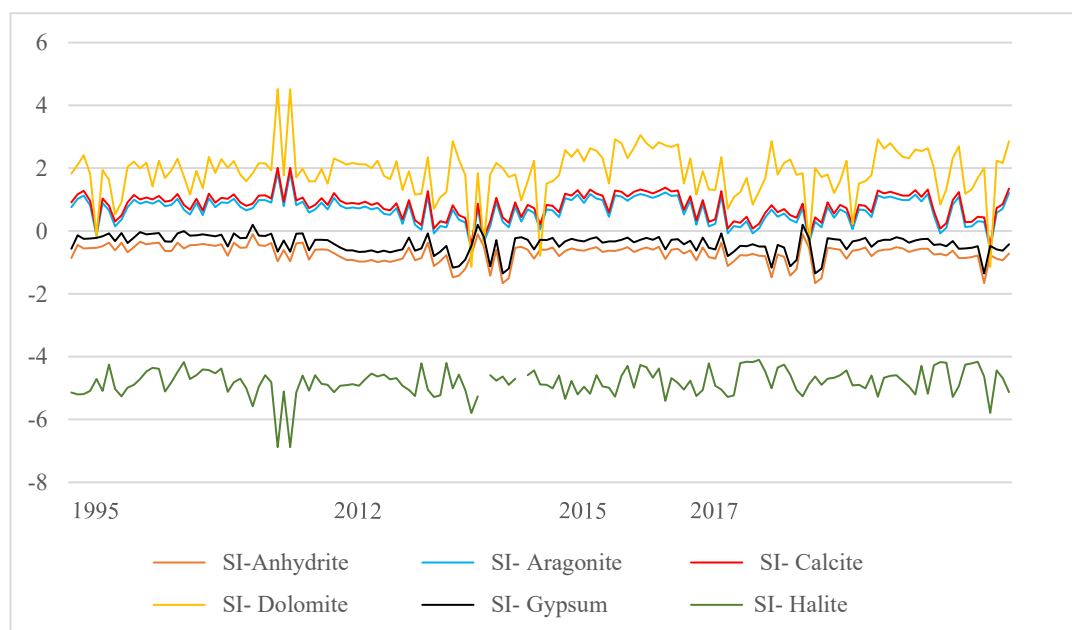


Figure 4. 30 Saturation indices of minerals related to interactions with water samples

This is also the case for evaporite minerals, namely gypsum and anhydrite. Carbonate minerals have different saturation indices, calcite varies from -0.44 to 2.01, followed by aragonite, which ranges from -0.59 to 1.86, and finally dolomite, which ranges from -1.14 to 4.52 (Figure 4.31). It can be said that the three elements have reached their supersaturation state in most of the analyzed waters.

The evaporative minerals, specifically gypsites, undergo precipitation after the less soluble carbonates. The gypsum and anhydrite from evaporative minerals show saturation indices with negative values that range from -1.35 to 0.2 and -1.66 to -0.1 respectively (Figure 4.31), reflecting the contribution of the dissolution of gypsum and anhydrite to the mineralization of groundwater (Bahir et al. 2021). Despite the dominance of the chemical components (Na and Cl) in concentration in some samples, halite, whose saturation indices vary from -6.88 to -4.1, remains undersaturated (Idder et al. 2016).

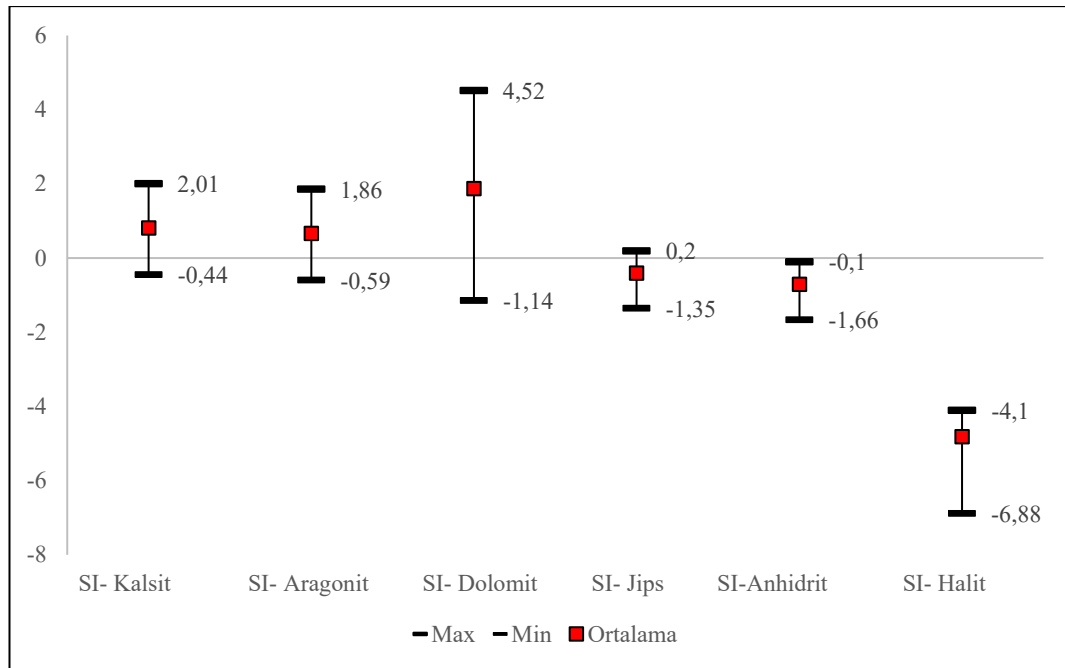


Figure 4. 31 Min-Max and Mean values of saturation indices from Terminal Complex aquifer

According to the spatial distribution figures of indices in the Wadi Righ region (Figures 4.32, 4.33 and 4.34), the average values of saturation indices (SI-Calcite, SI-Aragonite, and SI-Dolomite) have decreased over the years. Although they are still in a state of oversaturation, their values range from 0.98 (1995) to 0.66 (2017) for SI-Calcite, 0.84 (1995) to 0.51 (2017) for SI-Aragonite, and 1.92 (1995) to 1.76 (2017) for SI-Dolomite. The Gypsum and Anhydrite indices decreased with very low percentages, ranging from -0.21 (1995) to -0.49 (2017) for SI-Gypsum and -0.52 (1995) to -0.79 (2017) for SI-Anhydrite, while the values of SI-halite gradually increased from -4.91 (1995) to -4.72 (2017).

The precipitation of carbonate minerals (calcite, aragonite, and dolomite) and the dissolution of evaporite minerals (gypsum, anhydrite and halite) increases from north to south, and this as a result of the slow movement of water flow in the south of the Wadi Righ region in general; this means that the residence time of groundwater in aquifers results in a longer time for water/rock interactions to occur and for minerals to equilibrate between groundwater and host rocks (Edmunds et al. 2003, Gurmessa et al. 2022).

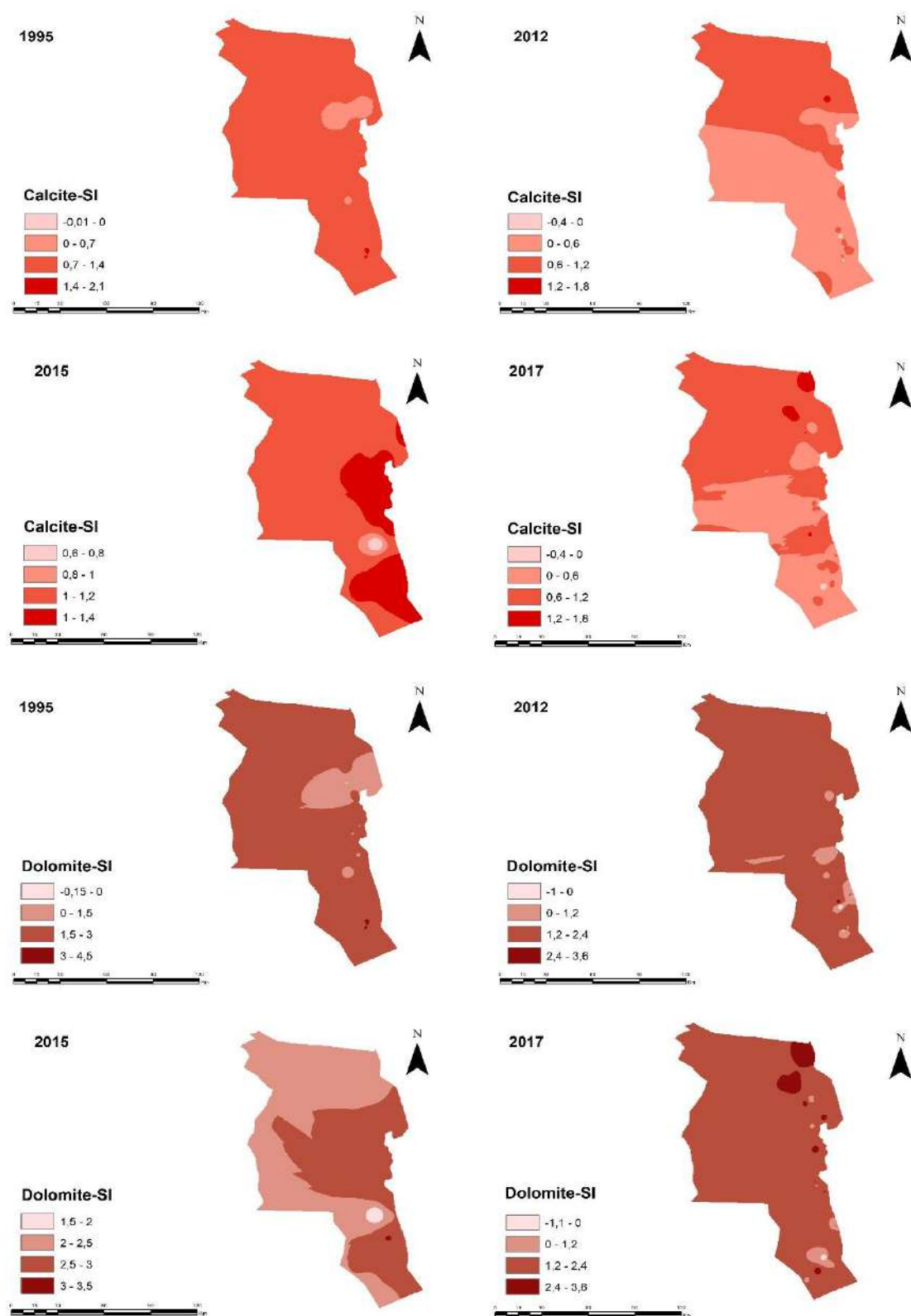


Figure 4.32 Spatial distribution of saturation indices (1995, 2012, 2015 and 2017); SI- Calcite and SI-Dolomite

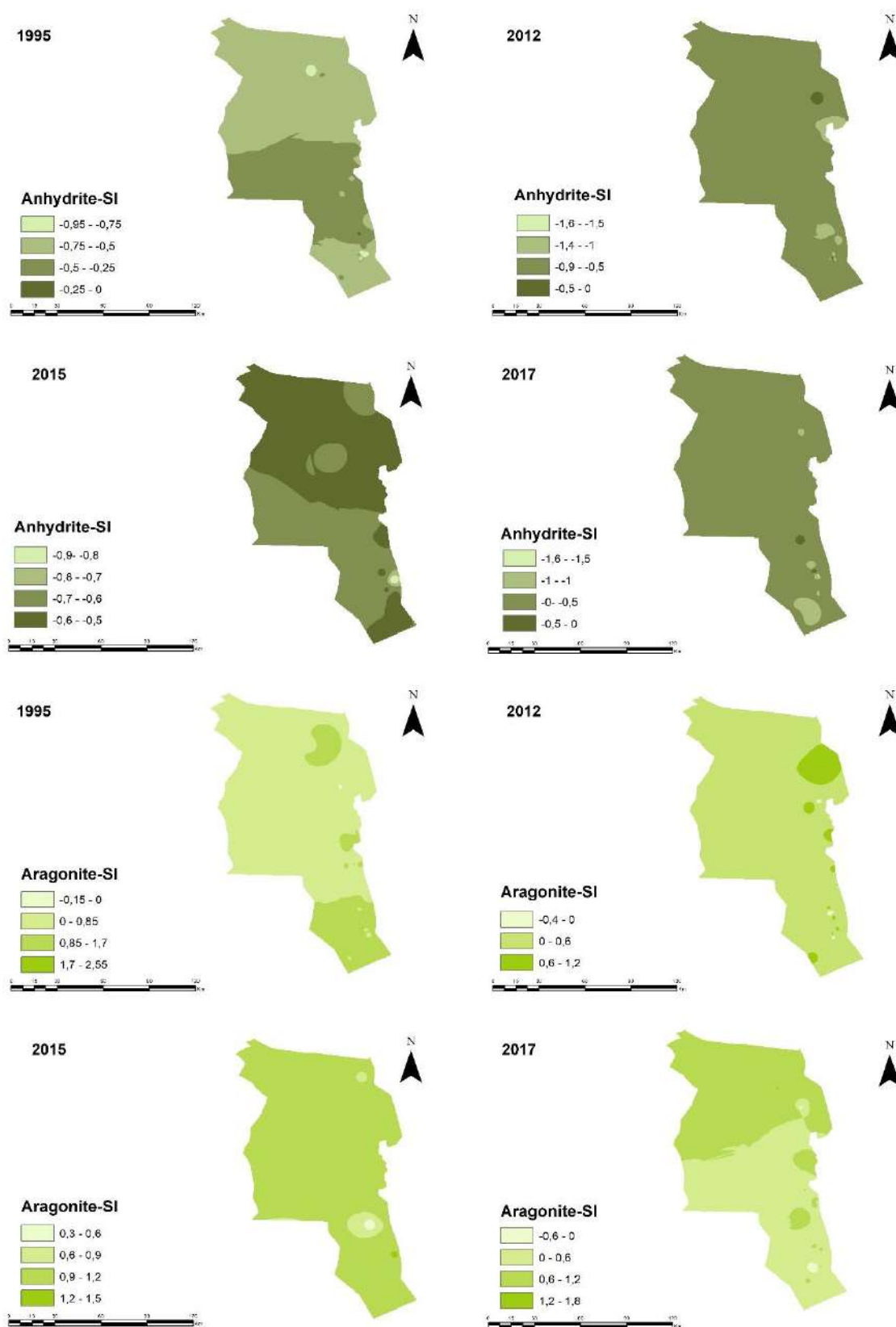


Figure 4. 33 Spatial distribution of saturation indices (1995, 2012, 2015 and 2017); SI-Anhydrite and SI-Aragonite

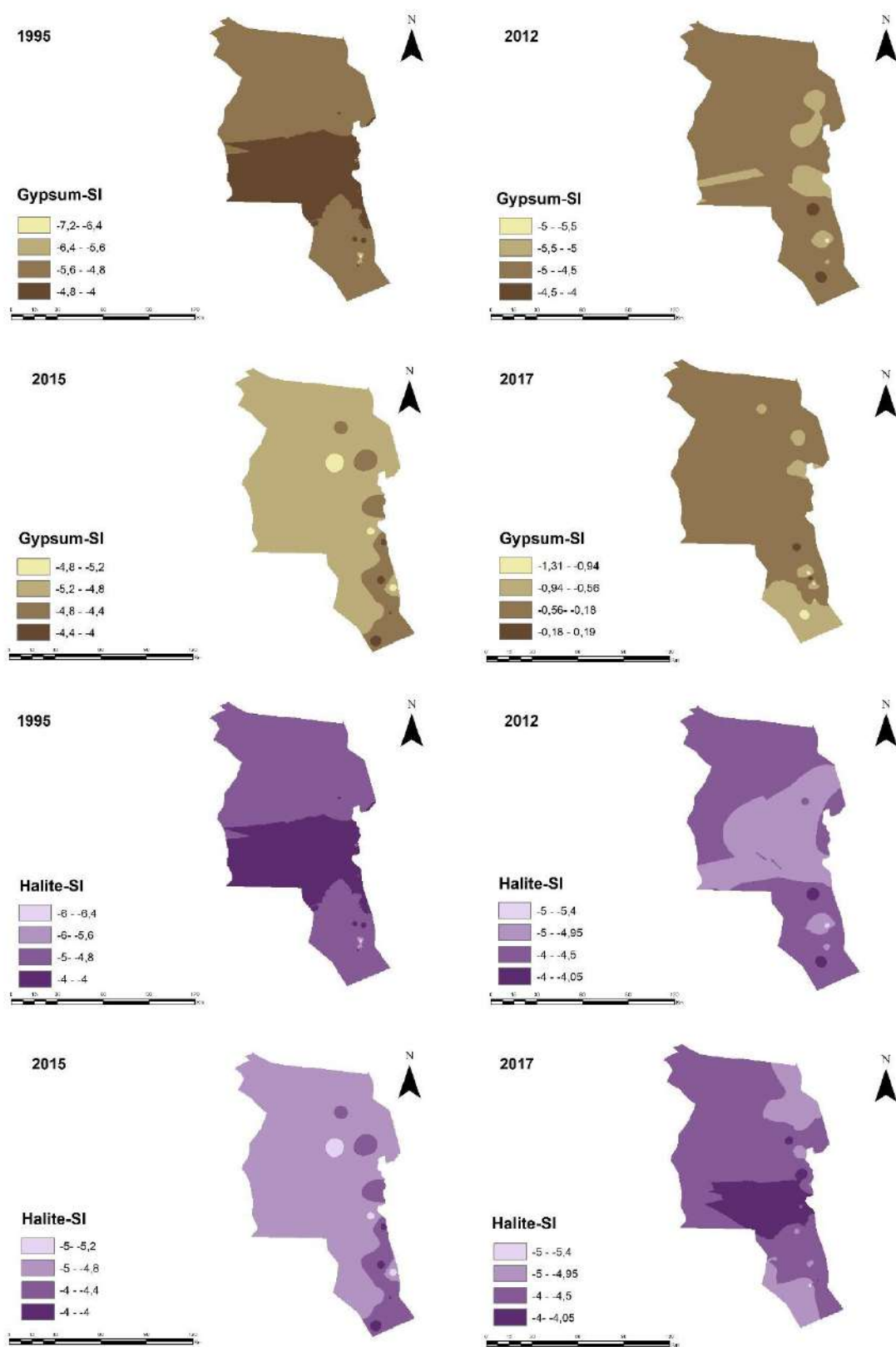


Figure 4. 34 Spatial distribution of saturation indices (1995, 2012, 2015 and 2017); SI-Gypsum and SI-halite

4.2.5. Spatial and temporal evolution of the groundwater levels of groundwater in the Terminal Complex aquifer

In the study area, static groundwater levels ranged between 0 m and 35.5 m in 1998, between 0 m and 48.35 m in 2005, between 10.9 m and 45.4 m in 2010, between 13.85 m and 45.5 m in 2013, between 12 m and 44.9 m in 2015, and between 1.6 m and 50.3 m in 2017.

The spatial evolution of the static groundwater level (Figure 4.35) shows a flow direction following the topographic model of the region. The general direction begins from the south to the north (where the natural outlet are located “Chott Merouane”), or towards areas of overexploitation, indicating the main palm groves and the urban areas. In recent years (2010-2013-2015-2017), there has been a noticeable rise in water levels in the southern and central areas (palm grove zones) of the region. This rise may be accelerated by the infiltration of irrigation water and waste water at the irrigation network level into the aquifer (Zahi et al. 2011).

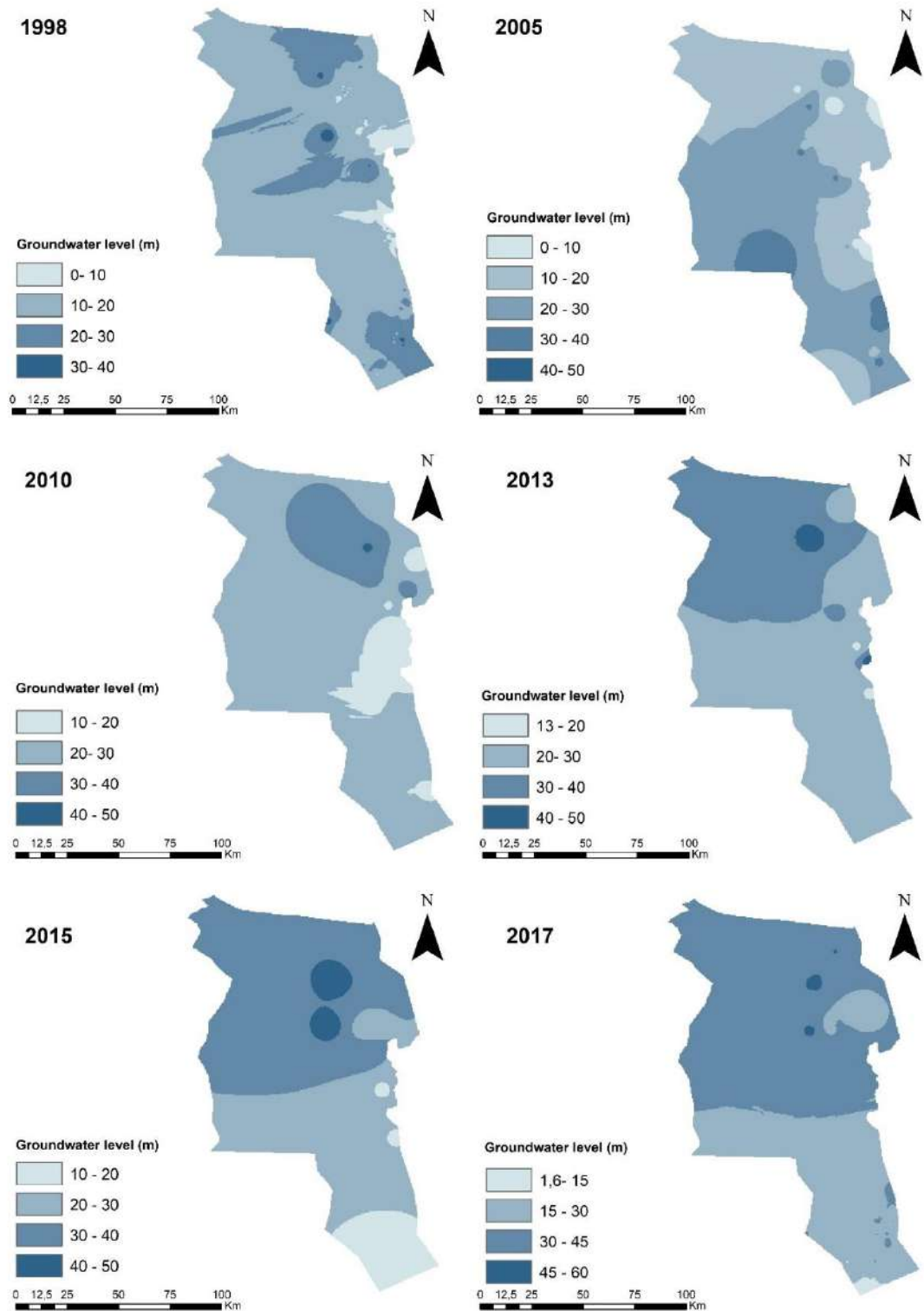


Figure 4. 35 Evolution of groundwater levels map of the Terminal Complex in the Wadi Righ (1998, 2005, 2010, 2013, 2015 and 2017)

The groundwater level of the Terminal Complex decreased by approximately 14.7 meters (Figure 4.36) between the years 1998 and 2017 ($L_{\max} = 35.6$ m in 1998 compared to $L_{\max} = 50.3$ m in 2017). This is consistent with the results of the (OSS, 2003) report, which predicted, through simulation, a decrease in the groundwater level of the Terminal Complex aquifer by about 30 meters by the year of 2050. This decrease can be explained by the intensive exploitation of the aquifer (Barrez et al. 2004; Jamaa et al. 2017) and by a supply deficit being a result of the successive drought years, and the noticeable climate changes that the world and the Wadi Righ region in particular are experiencing (MacDonald et al. 2012; Bettahar and Şener 2022).

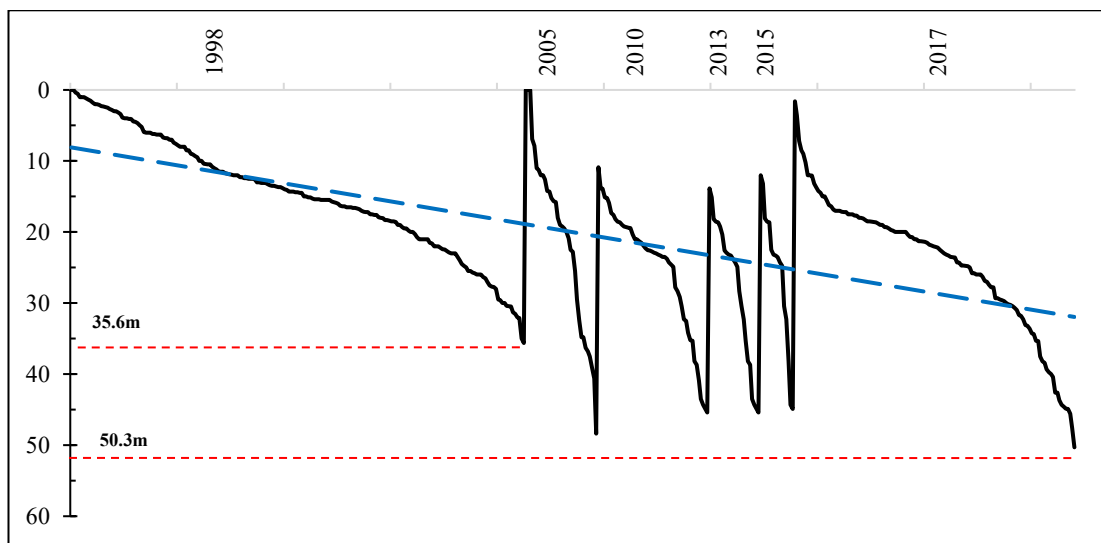


Figure 4. 36 Evolution of groundwater levels of the Terminal Complex in the Wadi Righ (1998, 2005, 2010, 2013, 2015 and 2017)

The decrease in the groundwater level of the aquifer (Figure 4.37) is accompanied by a slight decrease in conductivity and mineralization over time. This is due to a clear inverse correlation between groundwater recharge and conductivity (Gurmessa et al. 2022). It's important to note that the evolution of the water table level can be influenced by many factors, such as precipitation, irrigation, water resource exploitation, and human activities (Ouarani et al., 2020). Anthropogenic impact, such as unplanned pumping in the region, can have a significant effect on groundwater levels by increasing the volume of water leaving the aquifer and decreasing its recharge. Regions with low to very low recharge in North Africa are generally characterized by variable

salinities with more frequent salty groundwater wells (high mineralization) (Bettahar et al. 2017b; Houari 2020; Gurmessa et al. 2022; Al Haj et al. 2023).

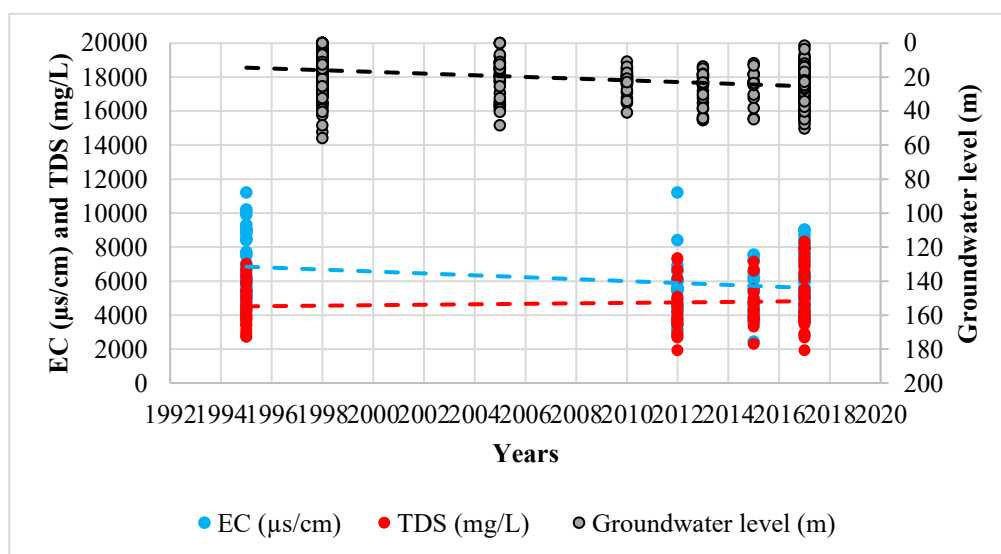


Figure 4. 37 Correlation between groundwater level, Electrical Conductivity and Total Dissolved Solids (TDS) of the Terminal Complex aquifer

4.2.6. Evaluation of Terminal Complex Groundwater Quality

4.2.6.1. Assessing the suitability of drinking water

The potability and chemical quality of water depend on the concentration of dissolved chemical ions. To manage a water source or determine its suitability for specific uses according to user-defined standards, it is essential to monitor its quality. In assessing the suitability of groundwater for drinking purposes, the Algerian drinking water standards (Official Journal of the Algerian Republic N° 18, 2011) and World Health Organization (WHO, 2017) have been considered as reference limit values (Table 4.10).

Table 4. 10 Comparison of Algerian and World Health Organization drinking water standards

Parameters	Algerian Standards (Official Journal of the Algerian Republic N° 18, 2011)	World Health Organization (WHO, 2017)
pH	6.5 – 8.5	6.5 – 8.5
Electrical Conductivity (µS/cm)	2800	2800
Calcium (mg/l)	200	200
Magnesium (µg/l)	150	150
Sodium (mg/l)	200	200
Potassium (mg/l)	12	/
Sulfate (mg/l)	400	250
Chloride (mg/l)	500	250
Alkalinity	500	/

Upon examining the graphs presented in Figures 4.38, 4.39 and 4.40, it is evident that the analyzed groundwater samples generally exhibit ion concentrations exceeding the permissible limits established by international (WHO) and Algerian drinking water standards.

The calcium concentrations in the Terminal Complex groundwater, typically exceed the limit of 200 mg/L. Sodium concentrations are generally above 800 mg/L and are characterized by maximum values surpassing 1500 mg/L (Figure 4.38).

The majority of the analyzed groundwater samples contain magnesium concentrations exceeding the standard limit with values reaching up to 750 mg/L (Figure 4.38). Potassium concentrations were found to slightly exceed the permissible limit of 20 mg/L.

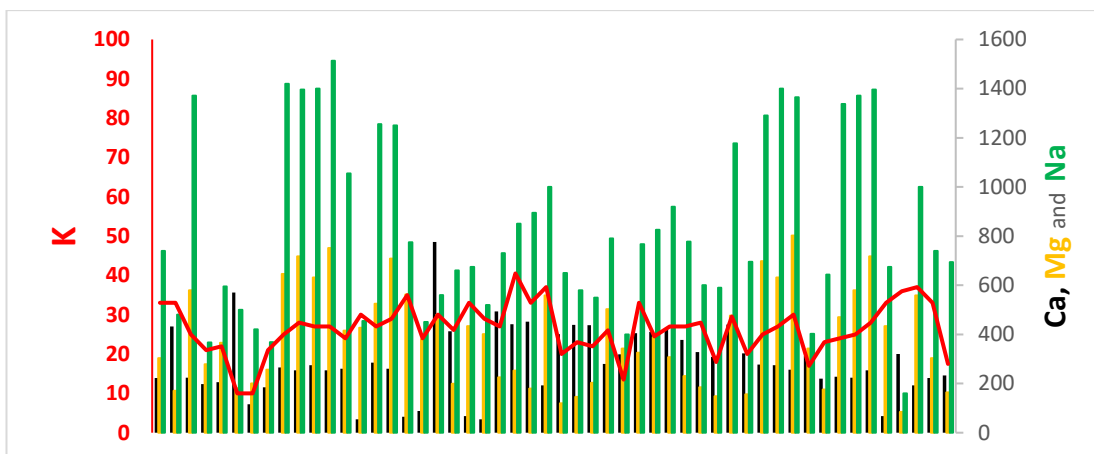


Figure 4. 38 The Ca, Mg, Na, and K ion concentrations in the Terminal Complex groundwater (2017)

Chloride concentrations in the groundwater significantly exceed the standard limit of 500 mg/L, with recorded values surpassing 2500 mg/L (Figure 4.39). Similarly, sulfate concentrations were found to be substantially higher than the limit of 400 mg/L, with values exceeding 4000 mg/L (Figure 4.39). However, bicarbonate concentrations range between 100 and 250 mg/L (Figure 4.39).

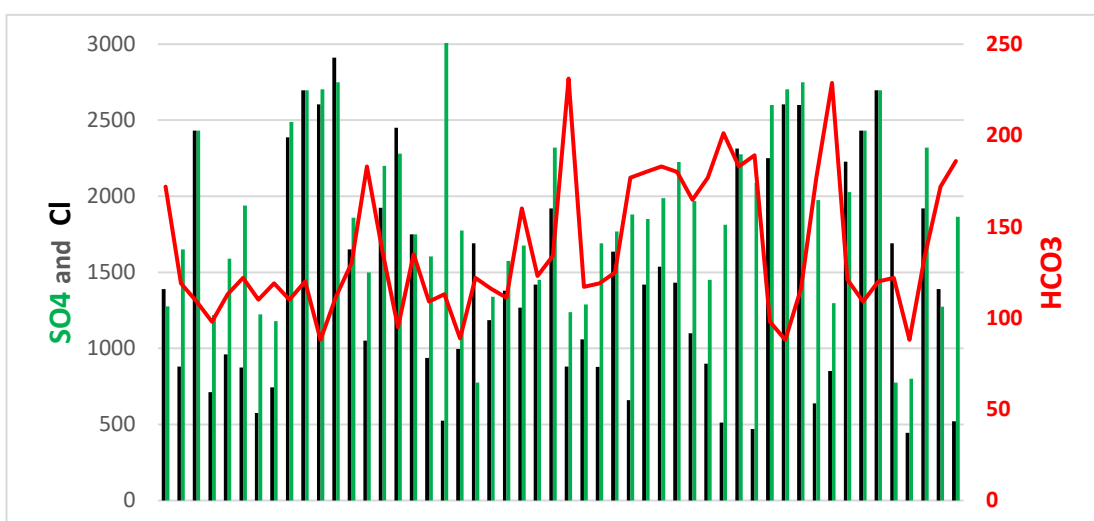


Figure 4. 39 The SO₄, Cl and HCO₃ ion concentrations in the Terminal Complex groundwater (2017)

The measured pH values in the groundwater range from 6 to 8.5, which are within acceptable limits for drinking water use (Figure 4.40). On the other hand, electrical

conductivity values significantly exceed the standard limit of 2800 $\mu\text{S}/\text{cm}$, with groundwater samples exhibiting conductivity values ranging from 2800 to 9030 $\mu\text{S}/\text{cm}$ (Figure 4.40).

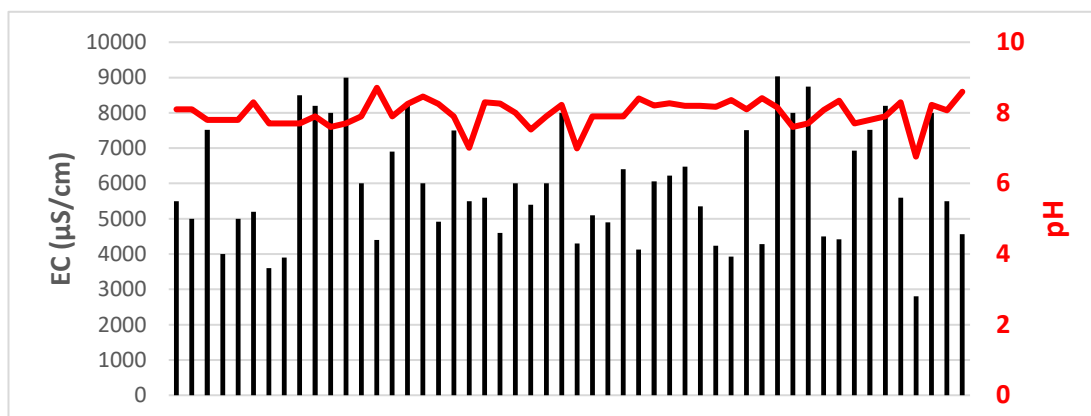


Figure 4. 40 The Electrical Conductivity and pH values in the Terminal Complex groundwater (2017)

Water quality index (WQI and CCME WQI)

To assess the drinking water quality of the groundwater, Water Quality Index values were calculated, the groundwater in the Terminal Complex aquifer of the Wadi Righ region falls into the categories of poor (101–200), very poor (201–300), and extremely poor (301–500) water quality. Figure 4.41 represented the spatial distribution of WQI values. It was observed that water samples collected from the central and southern parts of the study area exhibit higher WQI values compared to other regions, indicating lower water quality. The lowest recorded WQI values were observed in only a few samples, ranging between 100 and 200, which also fall under the poor water quality category. Based on the overall assessment, the groundwater in the study area is deemed unsuitable for drinking purposes, both in terms of regulatory limit values and WQI classifications.

As shown in Table 4.11, for all the collected samples, the CCME WQI values vary between 13.75 and 51.81 indicating poor and marginal water quality that is unsuitable for consumption.

4.2.6.2. Assessing the suitability of water for irrigation

The Sodium Adsorption Ratio (SAR) values ranged between 1.57 and 10.45 (Table 4.11). Based on these values, the groundwater quality is generally considered excellent to good for irrigation use, suggesting moderate to low sodium hazard (Figure 4.41). The Sodium Percentage (Na%) falls within the "good" (20–40%) and "permissible" (40–80%) ranges. According to the spatial distribution map (Figure 7), the highest Na% values exceeding 40% are mainly concentrated in the northern and southeastern parts of the study area.

Permeability Index values are mostly within the "unsuitable" (<25%) and "good" (25–75%) categories. The areas showing the lowest PI values, indicating reduced suitability for irrigation, are also located in the southeastern and northern zones of Wadi Righ (Figure 4.41). Residual Sodium Carbonate (RSC) values for groundwater in this region vary from -77.78 to -20.66 (Table 4.11), and these negative values indicate that the water is generally appropriate for irrigation purposes, classifying it as good irrigation water (Figure 4.41).

The Magnesium Hazard (MH) values, represented spatially in Figure 4.41, show that most samples from the Wadi Righ basin exceed the 50% threshold, rendering them unsuitable for irrigation. The Kelly Index (KR) values lie between 0.3 and 1.19 (Table 4.11), with the majority of samples exhibiting KR values below 1, indicating acceptable quality for agricultural use (Figure 4.41). The Irrigation Water Quality Index (IWQI) values in Wadi Righ range from 64 to 97 (Table 4.11), suggesting that most groundwater in the area falls under the category of excellent irrigation water.

Overall, the findings of our study are consistent with those reported in previous research (Koull et al., 2013; Kadri et al., 2022), which classified the majority of groundwater in the region as suitable for irrigation. The water generally falls into the "good" or "permissible" categories based on several irrigation suitability indices, including Sodium Percentage (Na%), Permeability Index (PI), Residual Sodium Carbonate (RSC), Sodium Adsorption Ratio (SAR), Irrigation Water Quality Index (IWQI), Magnesium Hazard (%MH), and Kelley's Ratio (KR).

Table 4. 11 The outcome of descriptive statistical analysis for hydrochemical characteristics in Wadi Righ (2017)

	Average	Minimum	Maximum	Standard deviation
Na%	43.614	24.351	55.22	7.017
RSC	-44.811	-77.782	-20.663	16.005
KR	0.77	0.301	1.193	0.205
MH	66.332	30.658	93.511	18.381
SAR	6.472	1.572	10.451	2.197
PI	38.414	10.95	66.743	15.045
WQI	351.103	132.761	577.822	117.526
IWQI	74.654	64	97	6.709
CCME WQI	20,562	13.752	51.811	7.084

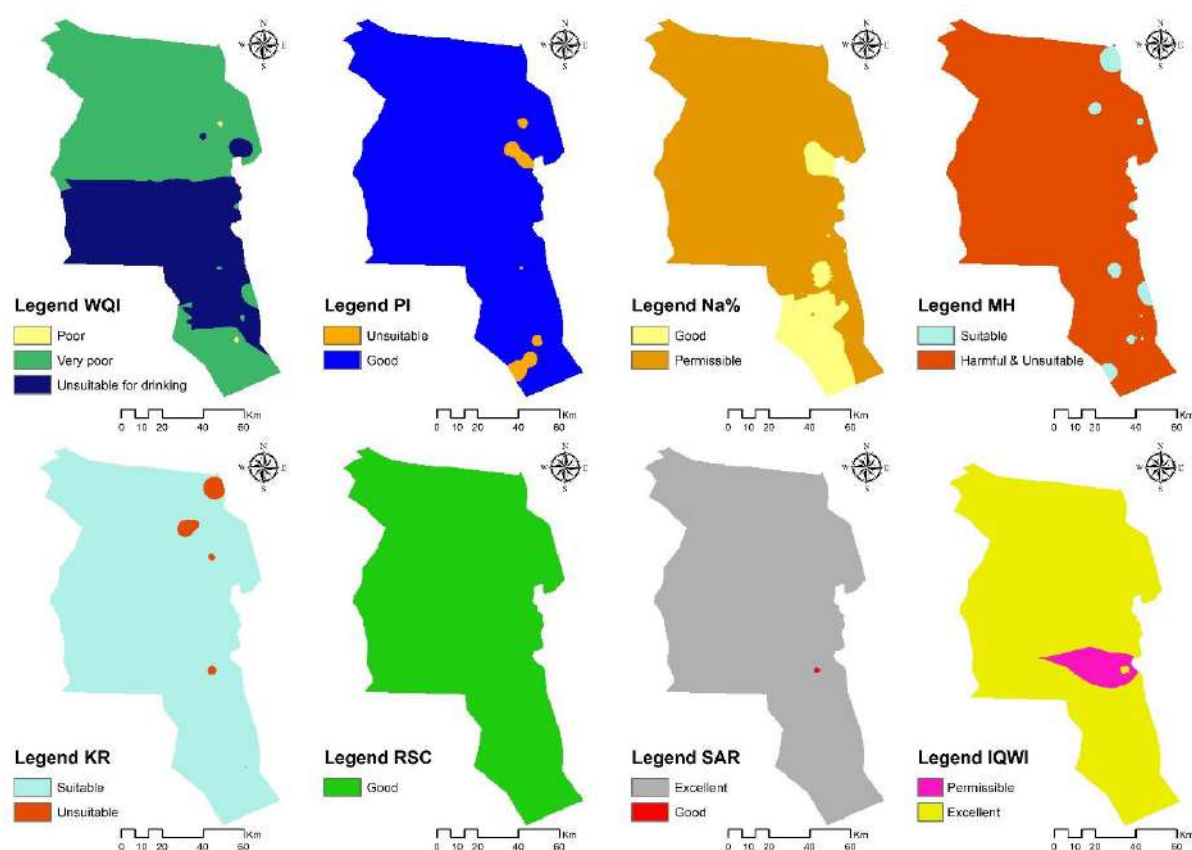


Figure 4. 41 Spatial distribution maps of water suitability indices in Wadi Righ (2017)

4.2.7. Pearson Correlation

The Pearson correlation results of calculated groundwater indexes values indicate a number of important correlations. Correlations have been observed with EC, TDS and Water Quality Index. TSD, PI, SAR and RSC. In addition, Mg is correlated with the Magnesium Hazard (MH) index, Na and SAR, KR and Na%, and also HCO₃ and RSC. Finally, the IWQI value correlated with EC, TDS, Na, Ca, KR, SAR, PI and WQI (Figure 4.42). These correlations provide valuable insights into the interrelationships between water quality indices and the variability of chemical constituents in the Wadi Righ region. The strong associations observed among sulfate, calcium, and magnesium ions reflect the geochemical composition of the groundwater, indicating the influence of gypsum and carbonate mineral dissolution within the aquifer system. Typically, the association of sodium with chloride can be explained by the dissolution of halite, which lies in the geological formations underneath the Wadi Righ area (Sajil Kumar and James, 2016; Rahimi Shahid et al., 2023). The detection of sodium, even in the absence of a strong correlation with other elements, could reflect the impact of increased agricultural and industrial operations in the area. This presence is likely influenced, at least in part, by human-induced pollution sources such as the use of agrochemicals and the release of industrial effluents (Houari, 2020; Samtio et al., 2023). The strong positive correlations among the irrigation water suitability indices can be attributed to the use of similar input parameters in their calculation. Furthermore, all variables that exhibit a positive relationship with the water quality index values play a role in influencing the quality of groundwater. Overall, most of these relationships can be explained by the region's hydrogeochemical characteristics (Helena et al., 1999).

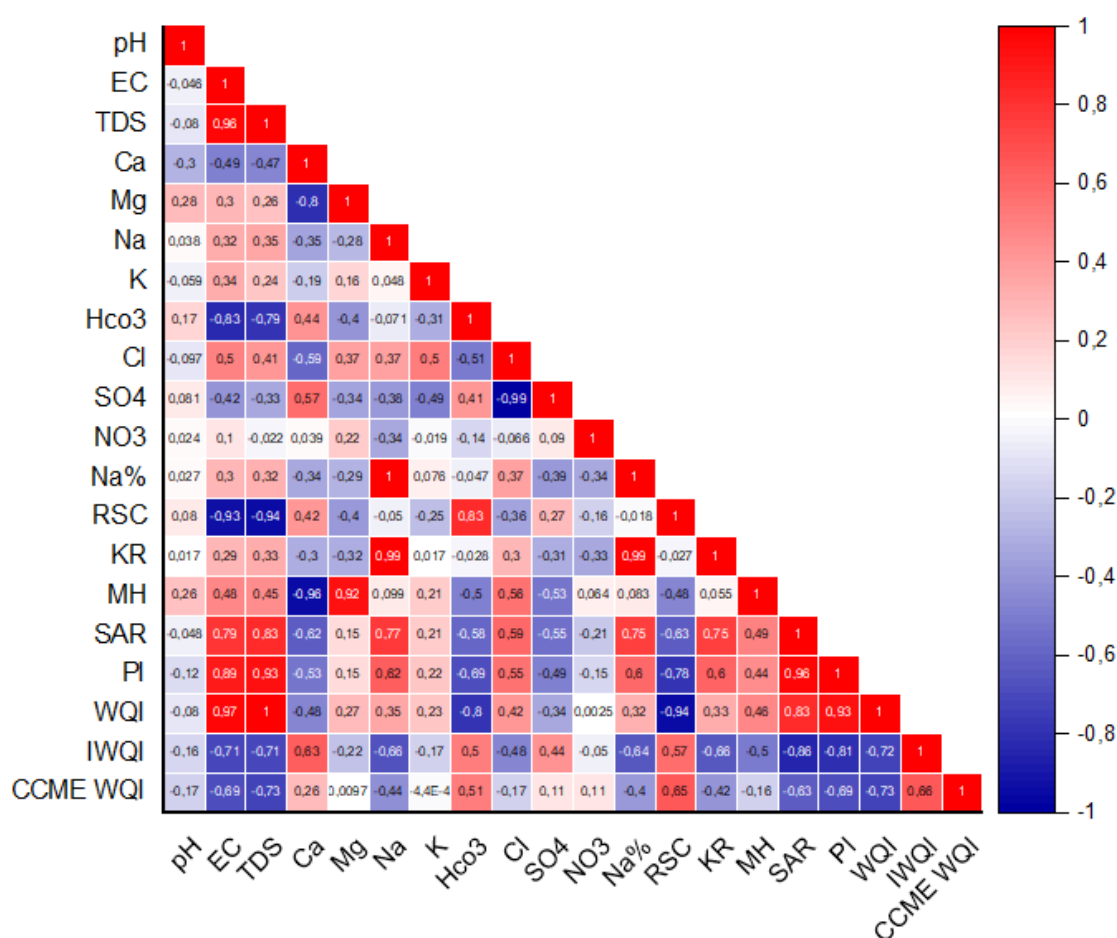


Figure 4. 42 Lower triangular matrix plot among 20 groundwater variables in Wadi Righ ($p > 0.05$)

4.2.8. Hierarchical cluster statistical analysis (HCA)

Based on the HCA classification (Figure 4.43), The first group encompasses subsection 1.1, which delves into bicarbonates and potassium. It elucidates that bicarbonate has the potential to vie with potassium for sorption sites on minerals in the subsurface. This competitive interaction could result in the liberation of potassium into the groundwater as concentrations of bicarbonate escalate.

On the other hand, branch 1.2 comprises chloride, sodium, and magnesium, which constitute the chemical facies of the water obtained earlier and connects with halite, attributing the source of chloride and sodium in the water to it. The correlation of this group with Total Dissolved Solids (TDS) arises from the fact that these elements are the fundamental contributors to the mineralization of water in the studied samples.

The second group is divided into two sections. The correlation between SO_4^{2-} and Ca^{2+} with electrical conductivity signifies the impact of evaporated rocks on the salinity of water in this region. Gypsum and anhydrite are associated with calcium in group 2.1, which, in turn, connects to section 2.2. This linkage is because calcium (Ca) is a major component present in three minerals: aragonite (CaCO_3), calcite (CaCO_3), and dolomite ($\text{CaMg}(\text{CO}_3)_2$).

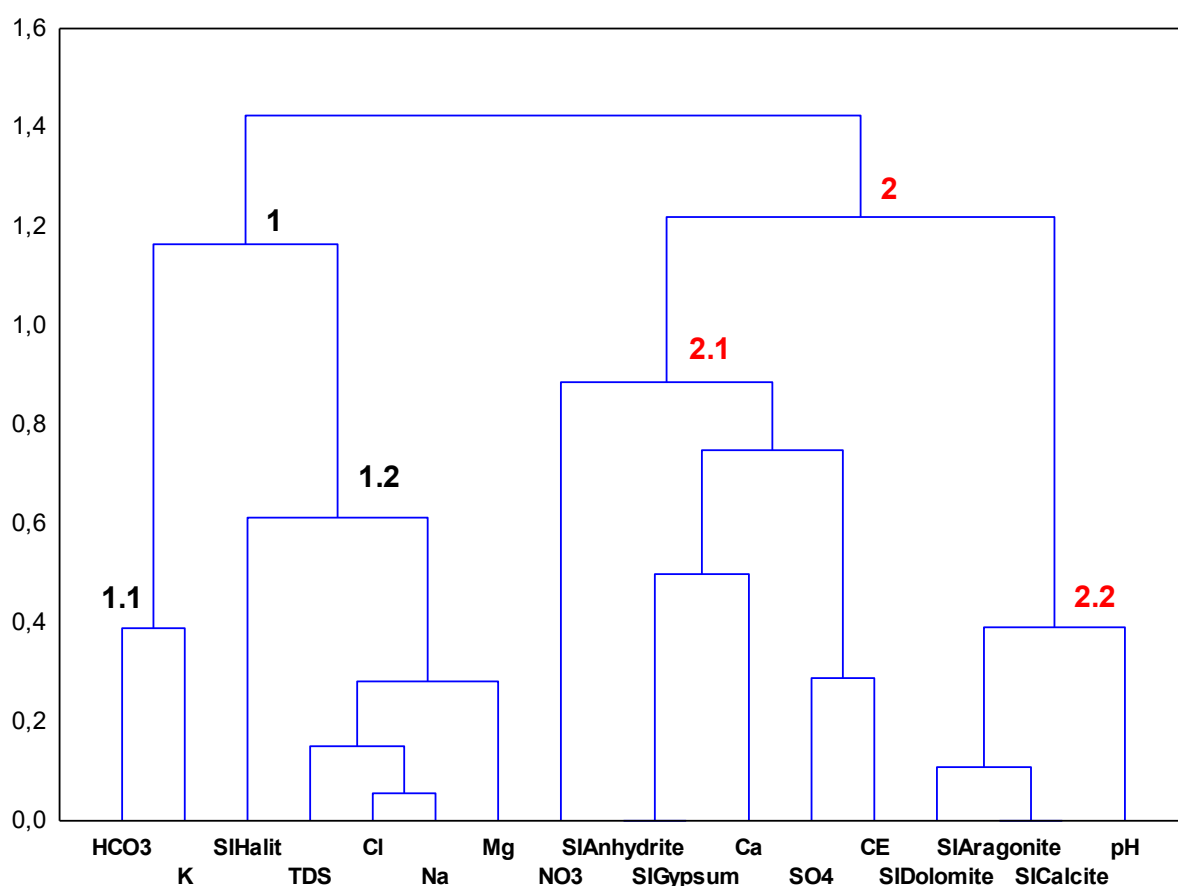


Figure 4. 43 Cluster analysis results of physicochemical variables of the Complex Terminal groundwater in the Wadi Righ area

4.2.9. Utilizing GIS and Multi-Criteria Decision Analysis via AHP for Assessing Groundwater Irrigation Suitability

The integration of Geographic Information Systems (GIS) and Remote Sensing facilitates access to diverse spatial datasets, particularly for areas that are difficult to reach. While parts of the study area were accessible, remote sites located in rugged desert regions could not be surveyed directly. In these cases, data collection relied on

remote sensing sources such as the U.S. Geological Survey and NASA databases, historical records, and interpolated values from nearby accessible points. Spatial analyses were carried out using geoprocessing tools in ArcGIS. Groundwater depth data (2017) were obtained through field surveys in collaboration with the Algerian Water Company (ADE), whereas Land Use/Land Cover (LULC) was derived from supervised classification of Landsat 8 imagery provided by the USGS.

A comprehensive spatial geodatabase was constructed from these datasets. Thematic layers were generated for each factor, converted into raster format, and reclassified into five categories according to their relevance for irrigation suitability, with scores assigned as shown in Table 4.12. A multi-criteria decision analysis (MCDA) was then implemented using the Weighted Overlay tool in ArcGIS in combination with the Analytic Hierarchy Process (AHP). This process integrated multiple classified thematic layers (e.g., TDS, SAR, PI, RSC, water depth, NDSI, LULC), each weighted by its relative importance. The weighted overlay produced the final irrigation suitability map, synthesizing the spatial alignment and assigned scores of all factors.

Table 4. 12 Classification of Water Quality Index (WQI) categories

Water Quality Parameter	Very good	Good	Permissible	Doubtful	Un-suitable
MH	< 10	10–20	20–35	35–50	> 50
KR	< 1	1–2	2–3.5	3.5–5	> 5
PI	< 10	10–25	25–40	40–50	> 50
SAR	< 10	10–25	25–40	40–50	> 50
TDS	< 1000	1000–10000	/	10000–35000	>35000
Depth of water	/	>300	150–300	50–150	<50
WQI	< 5	5–15	15–25	25–45	> 45

4.2.9.1.Criteria Weighting for Irrigation Water Quality Assessment

Salinity represents one of the most critical challenges in the study area, evaluated through Total Dissolved Solids (TDS), which was identified as the most influential water quality parameter and assigned the highest weight (2.55). Other indices used to assess irrigation suitability include Kelly’s Ratio (KR), Magnesium Hazard (MH), Residual Sodium Carbonate (RSC), and the Permeability Index (PI), each assigned a

weight of 1.05, along with the Sodium Adsorption Ratio (SAR), assigned a weight of 1.21. These indices collectively reflect soil alkalinity risks, with SAR specifically indicating the potential for sodium accumulation in soils (Gunatilake et al., 2014).

Groundwater depth, while not directly limiting crop cultivation, influences groundwater quality and chemical composition; therefore, it was assigned a weight of 0.36. Soil properties and land use exert significant impacts as well, since soil salinity affects crop yield, growth, and irrigation water quality. Accordingly, the Normalized Difference Salinity Index (NDSI) was assigned a weight of 0.36, and Land Use/Land Cover (LULC) a weight of 0.31 (Table 4.13).

Table 4. 13 Comparison matrix and criteria weights of water quality

		TDS	RSC	MH	SAR	PI	KR	Depth of Water	NDSI	LULC	Weight
Water quality parameters	TDS	1	3	3	3	3	3	5	5	5	2.54
	RSC	0.333	1	1	1	1	1	5	3	3	1.05
	MH	0.333	1	1	1	1	1	5	3	3	1.05
	SAR	0.333	1	1	1	1	1	5	5	5	1.20
	PI	0.333	1	1	1	1	1	5	3	3	1.05
	KR	0.333	1	1	1	1	1	5	3	3	1.05
Water quantity parameters	Depth of Water	0.2	0.2	0.2	0.2	0.2	0.2	1	2	2	0.35
Soil characteristics	NDSI	0.2	0.333	0.333	0.2	0.333	0.333	0.5	1	2	0.36
	LULC	0.2	0.333	0.333	0.2	0.333	0.333	0.5	0.5	1	0.30

$$\lambda_{\max} = 9.277, \text{ CI} = 0.034717, \text{ RI}_8 = 1.45, \text{ CR} = 0.023943 \leq 0.1$$

4.2.9.2. Zoning of Irrigation Water Quality in the Wadi Righ Region

The Sodium Adsorption Ratio (SAR) indicates a medium sodium content, classifying groundwater in the Wadi Righ region as good to very good for irrigation (Figure 4.44D). Permeability Index (PI) values fall within the good to permissible categories in the northern and southern parts of the basin, whereas the central areas are classified as unsuitable for irrigation (Figure 4.44E). Residual Sodium Carbonate (RSC) values

confirm the groundwater as suitable for irrigation and categorize it as good irrigation water (Figure 4.44C).

The spatial distribution of Magnesium Hazard (MH) values reveals that groundwater is generally unsuitable for irrigation, with certain zones showing doubtful quality (Figure 4.44B). In contrast, Kelly's Ratio (KR) results classify most groundwater as very good for irrigation, with the northeastern areas rated as good (Figure 4.44F).

High Total Dissolved Solids (TDS) concentrations were recorded at most sampling points, exceeding 1000 mg/L across much of the region (Figure 4.44A). This classifies groundwater as brackish and unsuitable for irrigation. Soil salinity was further assessed using the Normalized Difference Salinity Index (NDSI). Low NDSI values across most of the Wadi Righ region indicate reduced salinity and better conditions for crop cultivation, as plants are less affected by salt stress. Conversely, the Chott Marouane area exhibits high NDSI values, reflecting elevated soil salinity that reduces crop productivity and requires careful irrigation management (Hammadi et al., 2023; Bettahar and Şener, 2024).

Groundwater depths in the study area range from 50 to more than 300 m. Depths of 50–150 m dominate the southern regions, while central areas range between 150–300 m, and the extreme northeast exceeds 300 m (Figure 4.44H). Water depth influences irrigation suitability, as mineral concentrations often increase with depth, raising salinity and affecting soil quality and crop health. Although deeper groundwater may be less exposed to anthropogenic contamination, it often has lower oxygen content, which can impair soil aeration and reduce yields. Additionally, variations in groundwater temperature with depth may influence irrigation outcomes depending on crop type and local climate (Caswell and Zilberman, 1986; Xu et al., 2013).

Land use further shapes water quality and irrigation practices. Extensive bare land with minimal vegetation limits infiltration, enhances evaporation, and contributes to higher salinity in shallow groundwater. Palm oases, concentrated along the wadi, create localized humid microclimates and rely heavily on groundwater for irrigation. These oases, central to local agriculture and trade, are increasingly pressured by surrounding urban development. In the northeast near Chott Marouane (Figure 4.44I), localized

surface water bodies exist, but overall scarcity, salinity, and groundwater overextraction continue to threaten both water quality and agricultural sustainability.

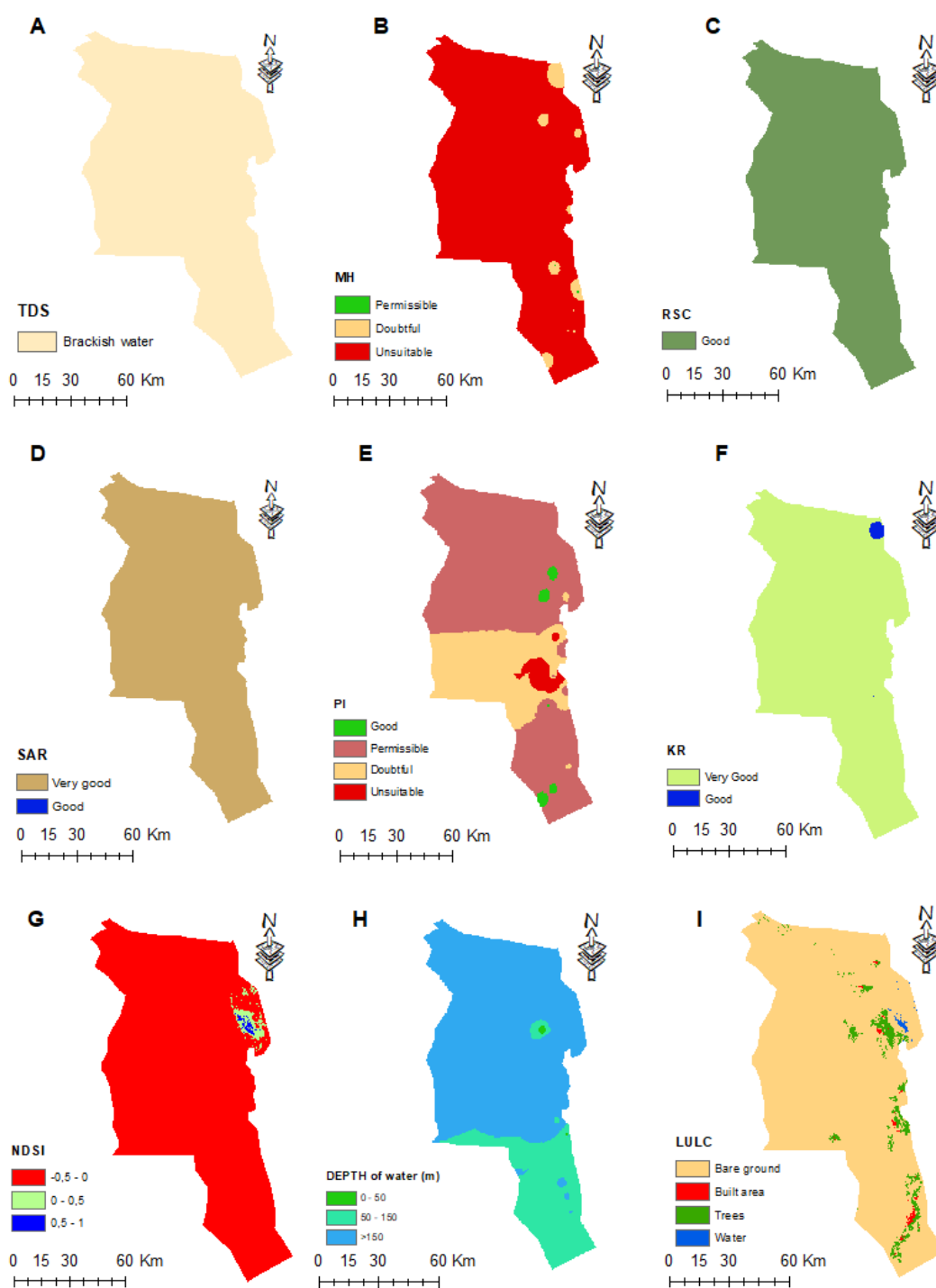


Figure 4. 44 Spatial distribution maps of A (TDS), B (MH), C (RSC), D (SAR), E (PI), F (KR), G (NDSI), H (Depth of water) and I (LULC)

To determine suitable areas for irrigation, a comprehensive groundwater suitability map was generated for the Wadi Righ region by overlaying all irrigation suitability indices (Figure 4.44). The analysis revealed that most groundwater falls within the Good or Permissible categories. Based on the AHP-derived water quality index, groundwater was classified into two categories (Good and Permissible), with a very low consistency ratio ($CR = 0.02$), indicating high reliability (Table 4.13). The Permissible class dominates the region (83%), particularly in the north and south, while the Good class covers the interior (17%), an area characterized by minimal urban development and agricultural activity, reducing risks of anthropogenic pollution. Soil type also influences water classification: calcic yermosols in the north, enriched with calcium carbonate, increase soil alkalinity and reduce water retention, while southern soils are affected by salt deposits that elevate salinity and decrease agricultural suitability. Excessive salt leaching from these soils may further contribute to groundwater contamination (Feng et al., 2005). Groundwater depth in this region ranges between 150–300 m, offering greater natural protection against surface contamination.

Compared with earlier studies in the region (Kadri et al., 2022; Bettahar and Şener, 2024), the AHP approach provided more robust and precise results, as it assigns each parameter a weight proportional to its influence, enhancing the accuracy of irrigation suitability mapping. Widely applied in water quality assessment (Şener et al., 2022; NCIBI et al., 2022), the AHP method accounts for both natural geochemical processes and human pressures, making it one of the most effective decision-support tools for groundwater evaluation (Abdelkarim et al., 2023). The findings underscore the significant interplay between natural hydrogeochemical conditions and anthropogenic activities in shaping groundwater quality in Wadi Righ.

Beyond the local scale, these results carry broader implications for groundwater management in arid regions. From a spatial planning perspective, GIS-AHP irrigation suitability maps provide decision-makers with clear spatial guidance to direct irrigation development toward areas with lower risks of salinization or over-abstraction. Regarding resource allocation and investment, the maps can guide regional water authorities in prioritizing infrastructure such as drip irrigation systems, wells, and water storage facilities, thereby maximizing agricultural productivity and efficiency. In terms of risk reduction and aquifer protection, the identification of marginal or unsuitable zones supports proactive strategies to prevent overexploitation

and degradation of ecologically fragile areas. From a policy and governance perspective, the approach offers a replicable decision-support framework that can be institutionalized into groundwater management strategies, particularly in light of climate change, increasing demand, and uncertain rainfall patterns. Finally, in terms of community and livelihood resilience, sustainable groundwater management based on these findings strengthens food security, stabilizes rural employment, and enhances socio-economic resilience in Wadi Righ.

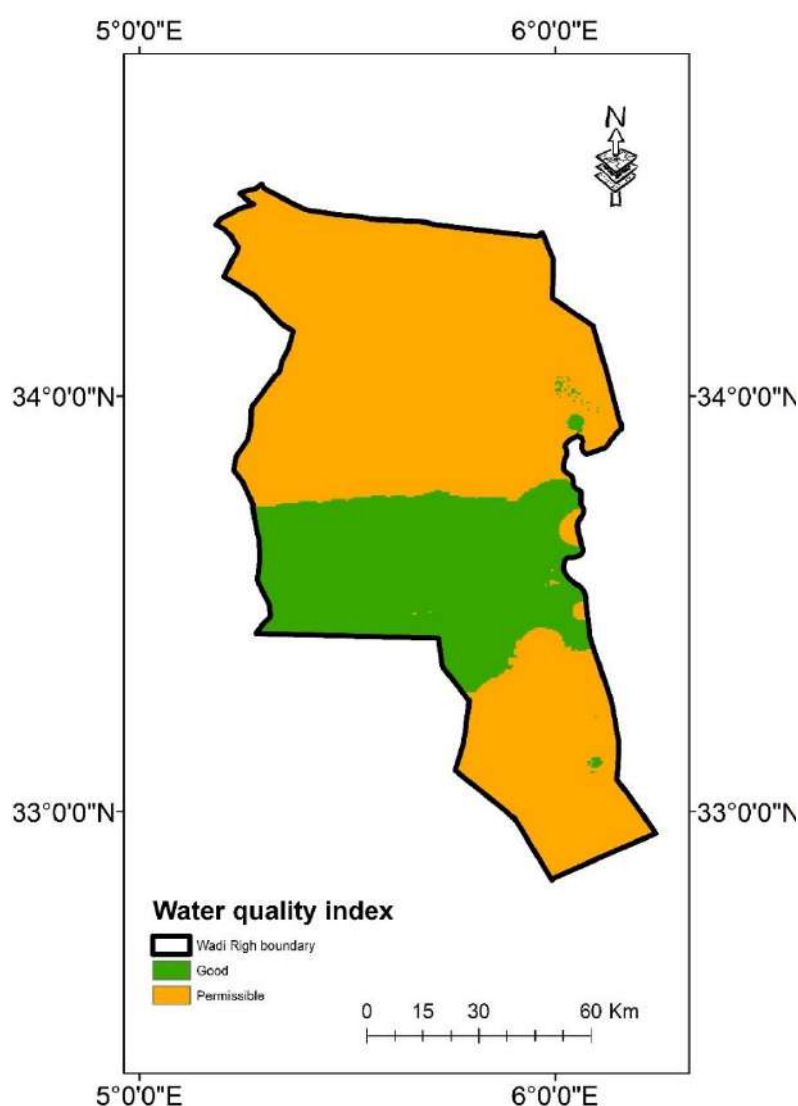


Figure 4. 45 Spatial distribution of the Water Quality Index (WQI) for irrigation of groundwater in Wadi Righ region

5. DISCUSSION and CONCLUSION

The primary objective of this thesis is to investigate the **geology and geochemistry of groundwater within the aquifer system of the eastern basin of the Northern Sahara in Algeria, with a specific focus on the Wadi Righ region**. To achieve this goal, analyses and assessments of the hydrogeochemical properties of groundwater were conducted both temporally and spatially. Furthermore, the data obtained from hydrogeochemical studies were evaluated using statistical methods.

Within the scope of the study, Wadi Righ is first one of the three major regions of the Sahara, alongside Ziban and Souf. It is a key area where sands, salts, and artesian waters fed by the Terminal Complex aquifers are concentrated. The regional capital is the city of Touggourt, with other significant municipalities including El Oued, Meghair, and Ouargla. The region is notably homogeneous, extending approximately 150 km from north to south. Date palm cultivation has long been the primary livelihood in this area. There are over two million date palms irrigated by dug wells and boreholes, mostly tapping into the Miocene-Pliocene. The geological structure of the Wadi Righ region is predominantly composed of sedimentary formations, reflecting its location within the northern Sahara. It represents a stable plateau that has undergone minimal tectonic activity since the Paleozoic Era. The bedrock consists mainly of sandstones, shales, and limestones dating back to the Paleozoic and Mesozoic Eras (Guendouz et al., 2003; Melouah and Pham, 2021). Previous studies (Bel and Demargne, 1966; Busson, 1970, 1972; Fabre, 1976) identified three main aquifer units in the region: the first and second Mio-Pliocene sand aquifers and the Lower Eocene limestone aquifer. The shallowest unit, corresponding to the first sand aquifer, occurs at depths of 50-100 m. It is mainly composed of fine to medium sand, sandstone, and silty sand of Mio-Pliocene age. These sandy deposits exhibit lateral facies variations, with clay layers occurring at the base, while clay and evaporitic horizons are more prevalent in the upper sections (Cornet, 1964).

Wadi Righ region is characterized by an extremely arid desert climate, characterized by very low annual rainfall, often below 50 mm, which is highly irregular and usually occurs in the form of short, intense storms (Bettahar and Şener, 2022). The region is also marked by high temperatures, with scorching summers where temperatures frequently exceed 45°C, and mild winters with temperatures ranging between 10°C

and 20°C. The area also has high evaporation rates and extremely low humidity, contributing to severe aridity (Bettahar and Şener, 2023).

To investigate the hydrogeochemical characteristics of groundwater within the Terminal Complex aquifer and assess the spatial and temporal variations in water chemistry and quality in the Wadi Righ region, chemical analysis results of 117 groundwater samples collected in 1995, 2012, 2015, and 2017 were evaluated. The analysis and measurement results of groundwater from the Wadi Righ area indicate that electrical conductivity (EC) values exceed the potable water threshold of 2800 $\mu\text{S}/\text{cm}$. Moreover, EC values exhibit notable variability across the years. Groundwater samples collected from the central and southern parts of the study area show significantly higher EC levels compared to other zones. The pH values range from 6 to 8.5, which is within the acceptable limits for drinking water as defined by WHO (2017) and Algerian standards. Calcium concentrations in the groundwater of the Terminal Complex aquifer are generally above permissible limits. A declining trend in calcium concentrations over time is evident. Additionally, elevated calcium concentrations ($> 400 \text{ mg/l}$) are observed in wells located in the northern parts of Wadi Righ, specifically in the Tendla, Sidi Amran, and Tegdidine areas. These areas are characterized by formations of claystone, limestone, and sand where water-rock interactions lead to the enrichment of calcium in groundwater (Houari, 2020).

Sodium concentrations in the groundwater of the Terminal Complex in Wadi Righ have shown a consistent temporal increase, frequently exceeding the permissible limit of 200 mg/l. The elevated sodium levels in the southern of the study region are primarily attributed to contamination caused by the return flow of irrigation water, which dissolve salts in the soil and bedrock, as well as from chemical fertilizers used in agricultural activities (Houari, 2020). In areas where minerals rich in sodium such as rock salt or halite are present, elevated sodium concentrations in groundwater are commonly observed. Additionally, regions characterized by high evaporation rates or low precipitation tend to accumulate salts in the soil, leading to increased sodium levels in groundwater (Salama et al., 1999; Hailu and Mehari, 2021). Magnesium concentrations in the groundwater of the Terminal Complex aquifer in Wadi Righ have also been recorded above the acceptable limit of 150 mg/l, with a marked and rapid increase observed over time. The highest magnesium levels ($>300 \text{ mg/l}$) were found

in groundwater samples collected from the Djamaa and Sidi Amrane areas, located in the central part of Wadi Righ. Elevated levels of calcium and magnesium in groundwater contribute to water hardness, a common issue in the region. Hard water is defined by its high content of dissolved minerals such as magnesium and calcium. When heated, these minerals may precipitate and accumulate inside pipes, appliances, and fixtures, thereby reducing their efficiency and potentially causing long-term damage. This issue represents one of the most significant water quality challenges in the Wadi Righ area, as documented by various studies (Bettahar, 2011; Touahri and Mansouri, 2017; Rahal and Belaid, 2018; Mahboub, 2020; Mehibel and Dorbi, 2022). Potassium concentrations in the groundwater of the Terminal Complex in Wadi Righ slightly exceed the standard threshold of 20 mg/l. These levels have shown a gradual increase over time, a trend that is clearly illustrated by the potassium distribution map. Notably, the area classified with concentrations of 40 mg/l or higher has expanded significantly in the southern part of the region.

Chloride levels in the groundwater of the Terminal Complex aquifer in Wadi Righ have been recorded above the permissible limit of 500 mg/l, with a significant temporal increase. The highest chloride concentrations were observed in the central and southern parts of the region, decreasing progressively toward the north. The rise in chloride concentrations is primarily attributed to the dissolution of evaporitic formations prevalent in the area. Similarly, sulfate concentrations in the groundwater have exceeded the allowable limit of 400 mg/l and have also shown a considerable increase over time. The highest sulfate levels exceeding 2400 mg/l were found in groundwater samples from the southern part of the region. This substantial enrichment is linked to the dissolution of gypsum formations present in the subsurface geology. The groundwater of Terminal Complex in Wadi Righ exhibits generally low bicarbonate concentrations, with higher values predominantly concentrated in the northern part of the region. This pattern is attributed to the presence of carbonate-rich geological formations, including sandstone cemented with lime and limestone, observed in the northern areas.

Ion analysis of groundwater samples from the Terminal Complex aquifer in Wadi Righ indicates that the dominant hydrochemical facies are primarily Na–Cl–SO₄ and Ca–Mg–Cl–SO₄. The presence of calcium and magnesium ions is a result of water-rock

interaction involving limestone and carbonate-bearing rocks found in the study area. Elevated concentrations of sodium, chloride, and sulfate are associated with the dissolution of gypsum, anhydrite, and evaporitic units. The observed excess of Cl^- relative to Na^+ in the groundwater is indicative of cation exchange processes (Hem, 1985; Ouarani et al., 2020), a characteristic feature of sedimentary environments containing evaporitic minerals such as halite and sylvite (Klimchouk, 2000; Zakaria et al., 2015). This interpretation is supported by the geological background of the study area. Overall, the dominant processes governing the chemical composition of groundwater are closely linked to lithological characteristics. The variability in groundwater types within the study area reflects the heterogeneity of the geological formations that make up the Terminal Complex aquifer (Guendouz et al., 2003; Bettahar et al., 2017; Houari et al., 2019).

According to the saturation index analysis of groundwater samples from the Terminal Complex aquifer in the Wadi Righ region, there is a general trend of increasing precipitation of carbonate minerals (calcite, aragonite, and dolomite) and dissolution of evaporite minerals (gypsum, anhydrite, and halite) from north to south. Due to the generally slow groundwater flow across the Wadi Righ region, groundwater in the southern areas tends to have longer residence times. As a result, extended periods are required for rock–water interactions to occur and for equilibrium to be established between groundwater and the surrounding host rocks (Edmunds et al., 2003; Gurmesssa et al., 2022).

To assess groundwater quality for drinking purposes, Water Quality Index (WQI and CCME WQI) values were calculated. According to the results, groundwater from the Terminal Complex aquifer in the Wadi Righ region falls predominantly within the categories of poor (101–200), very poor (201–300), and extremely poor (301–500) quality. WQI values were found to be highest in water samples collected from the central and southern parts of the study area, indicating lower water quality in these zones compared to others. Overall, based on both threshold limits and WQI values, the groundwater in the study area is generally unsuitable for drinking purposes. In contrast, based on the Sodium Adsorption Ratio (SAR) classification, groundwater samples from the Terminal Complex aquifer in Wadi Righ are categorized as excellent (low-sodium water) to good (moderate-sodium water) for irrigation use. Water within this

classification is suitable for all types of crops and soils. Further assessments of groundwater quality using parameters such as Sodium Percentage (Na%), Permeability Index (PI%), Residual Sodium Carbonate (RSC), Magnesium Ratio (MR%), and Kelley Index (KI) confirm that the majority of groundwater samples are either good (suitable) or permissible for irrigation purposes. These findings are consistent with those reported in previous studies (Kouli et al., 2013; Beggas and Meissa, 2017; Kadri et al., 2022).

The temporal variation of groundwater levels in the Terminal Complex aquifer has been analyzed, revealing that the general direction of groundwater flow is from south to north, in alignment with the region's topographic gradient. In recent years, a noticeable rise in groundwater levels has been observed in the southern and central parts of the region, particularly in areas dominated by date palm groves. This increase is believed to result from the infiltration of irrigation water and wastewater from nearby irrigation canals into the aquifer (Zahi et al., 2011; OSS, 2003; Bettahar, 2011; Belksier et al., 2015; Kouidri, 2016; Kermadi, 2017). Between 1998 and 2017, the groundwater level of the Terminal Complex aquifer declined by approximately 14.7 meters, with the maximum depth recorded increasing from 35.6 meters in 1998 to 50.3 meters in 2017. According to the OSS (2003) report, simulations predict a further decline in the piezometric level of the Terminal Complex aquifer by about 30 meters by the year 2050. This anticipated drop is attributed to both the intensive exploitation of the aquifer (Barrez et al., 2004; Jamaa et al., 2017) and the impacts of prolonged drought conditions (MacDonald et al., 2012; Bettahar and Şener, 2022).

The Pearson correlation results of calculated groundwater indexes values indicate a number of important correlations. Correlations have been observed with EC, TDS and Water Quality Index. TSD, PI, SAR and RSC. In addition, Mg is correlated with the Magnesium Hazard (MH) index, Na and SAR, KR and Na%, and also HCO₃ and RSC. Finally, the IWQI value correlated with EC, TDS, Na, Ca, KR, SAR, PI and WQI. These correlations provide valuable insights into the interrelationships between water quality indices and the variability of chemical constituents in the Wadi Righ region. The strong associations observed among sulfate, calcium, and magnesium ions reflect the geochemical composition of the groundwater, indicating the influence of gypsum and carbonate mineral dissolution within the aquifer system. Typically, the association

of sodium with chloride can be explained by the dissolution of halite, which lies in the geological formations underneath the Wadi Righ area (Sajil Kumar and James, 2016; Rahimi Shahid et al., 2023). The detection of sodium, even in the absence of a strong correlation with other elements, could reflect the impact of increased agricultural and industrial operations in the area. This presence is likely influenced, at least in part, by human-induced pollution sources such as the use of agrochemicals and the release of industrial effluents (Houari, 2020; Samtio et al., 2023). The strong positive correlations among the irrigation water suitability indices can be attributed to the use of similar input parameters in their calculation. Furthermore, all variables that exhibit a positive relationship with the water quality index values play a role in influencing the quality of groundwater. Overall, most of these relationships can be explained by the region's hydrogeochemical characteristics (Helena et al., 1999).

The decline in groundwater levels within the aquifer has led, over time, to a slight decrease in electrical conductivity and a mineralization. This indicates a clear inverse relationship between groundwater recharge and conductivity (Gurmessa et al., 2022). Anthropogenic influences such as unregulated groundwater abstraction further reduce recharge rates by increasing the volume of water extracted from the aquifer, thereby significantly affecting groundwater levels. In North Africa, regions with limited natural recharge are typically characterized by highly mineralized and saline groundwater wells (Bettahar et al., 2017; Houari, 2020; Gurmessa et al., 2022; Al Haj et al., 2023).

In this study, a comprehensive irrigation water suitability map was developed for the Wadi Righ region. The results show that most groundwater is suitable for irrigation, falling within the Good or Permissible categories. Based on the AHP-derived water quality index, groundwater was classified into two classes (Good and Permissible) with a very low consistency ratio (CR), indicating high reliability of the results. The "Permissible" category covered the majority of the region both to the south and north, while the "Good" category covered the interior areas of Wadi Righ. This area is largely free from urban development and intensive agricultural activity, factors that typically degrade water quality through pollution and fertilizer use. Soil type also plays an important role in groundwater classification. In the far north, calcic yermosols, enriched with calcium carbonate, alter soil pH and reduce water retention capacity. In

the south, yermosols are influenced by salt deposits that elevate soil salinity, decreasing agricultural suitability; excessive leaching of salts from the soil and crop root zone may further contribute to groundwater contamination (Feng et al., 2005). Groundwater depths in this region range from 150 to 300 m, offering greater protection from surface contamination compared to shallower aquifers. The AHP-based water classification produced more precise results than earlier studies in the region (Kadri et al., 2022; Bettahar and Şener, 2024), as the method assigns weights to each parameter according to its relative influence. Since the AHP model directly reflects the criteria that affect water quality (Abdelkarim et al., 2022), it has been widely applied in groundwater and irrigation suitability studies (Şener et al., 2022; NCIBI et al., 2022).

In conclusion, the major ion chemistry of groundwater in the Terminal Complex aquifer of the Wadi Righ region is primarily influenced by geochemical processes resulting from interactions with evaporitic and carbonate rocks that constitute the aquifer. Elevated evaporation rates enhance the duration of water-rock interaction, thereby increasing the degree of water mineralization (Caruso, 2002; Momblanch et al., 2015; Mosley et al., 2012; Bettahar et al., 2017; Gurmessa et al., 2022; Al Haj et al., 2023). Climate change has a detrimental impact on groundwater resources, both in terms of recharge and water use. Increasing rates of evaporation and transpiration, particularly in arid and semi-arid regions, contribute to soil salinization, which in turn negatively affects soil moisture quality and the associated groundwater systems. Overall, it is imperative to implement effective management strategies to better govern groundwater resources and mitigate the vulnerability of groundwater-dependent sectors to climate change and hydrological risks. The adoption of informed and sustainable water management policies is essential to ensuring long-term water security in such sensitive environments.

Overall, the Wadi Righ aquifer system is a highly sensitive arid-zone groundwater environment, where water quality and quantity are increasingly threatened by climate aridity, overexploitation, and land-use practices.

Based on the obtained results, several key measures are recommended to ensure the sustainable management of groundwater resources in the Wadi Righ region:

- First, it is essential to rationalize water use, particularly in agriculture, by adopting efficient irrigation techniques such as drip irrigation and reducing water losses.
- Second, agricultural practices should be adapted to local conditions through the selection of salt-tolerant crops and optimized irrigation scheduling, especially under high evaporation rates.
- Third, salinity control must be strengthened by improving drainage systems, promoting soil leaching where feasible, and continuously monitoring salt accumulation.
- Furthermore, it is crucial to regulate groundwater abstraction by limiting uncontrolled pumping and implementing monitoring systems for groundwater levels and quality.
- In addition, enhancing groundwater recharge through artificial recharge techniques and rainwater harvesting can help mitigate the effects of limited natural replenishment.
- Moreover, regular monitoring and hydrochemical analysis should be maintained using modern tools such as GIS and statistical modeling to track spatial and temporal variations in water quality.
- Finally, the reuse of treated wastewater for irrigation purposes should be encouraged to reduce pressure on groundwater resources.

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