KASDI MERBAH UNIVERSITY OUARGLA
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Department of Earth and Universe Sciences

FINAL STUDIES MEMOIR
In view of obtaining the Master's degree in Hydrogeology

THEME

Hydrogeochemical synthesis of the aquifer systems in the eastern basin of the northern Sahara

Presented by: :

Belahbib Mohammed

Supervisor: Mr. Nezli Imed Eddine Professeur Univ. Ouargla

Commettee chair: Mr .Ben Fardjellah Said . MCA Univ. Ouargla

Board of Examiner: Mr. Houari Idir-Menad . MCA Univ. Ouargla

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Dedication

I dedicate this humble work:

To my family, for their unwavering support and constant encouragement throughout my academic journey.

To my teachers, for their guidance, knowledge, and patience.

To my friends, for their companinship, motivation, and shared moments.

To everyone who, in one way or another, contributed to the completion of this work.

Acknowledgement

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CI: Continental Intercalair.

CT: Complex Terminal.

NWSAS: North Western Sahara Aquifer System .

SI: Saturation indicee

GENERAL INTRODUCTION

Groundwater is a vital resource in arid regions, where surface water is scarce and rainfall is both limited and irregular. In the Sahara, underground aquifers constitute the primary—often sole—source of water for domestic, agricultural, and economic needs. Among the most important aquifer systems in this region are the Continental Intercalair (CI) and the Complex Terminal (CT), which together form a vast and strategic water reserve.

In recent years, increasing demand, overexploitation, and climate variability have raised concerns about the long-term sustainability of these aquifers. This study hybothesies that a detailed hydrogeochemecal and isotopic investigation can provide critical insights into the recharge mechanisms , water -rock interaction . Such understanding is vital ror the sustainable managment og groundwater resources in arid region.

This study aims to analyze the hydrogeochemical and isotopic evolution of groundwater along major flow paths in both aquifers. By examining chemical and isotopic indicators, it seeks to improve understanding of the recharge history, water-rock interactions, and changes in water composition over time. The findings will provide valuable insights into the sustainability of these water resources, which are essential for maintaining water supply in the arid regions of Algeria..

Chapter I: General Overview and Physical Setting of the Study Area

geology , climatology , hydrogeology .

Summary of previous studies on the hydrochemestry on the CI and CT aquifers :

Chapter II: material and methodes

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Hydrogeochemical Results and Interpretations

CHAPTER I:

General Overview and Physical Setting of the Study Area

Chapter I: General Overview and Physical Setting of the Study Area

Introduction :

The northen sahara sedimentary basin extend over some 780,000km2 mainly in algeria (fig.1) it formes part of one of the largest and most aride desert in the world and contains two important aquifer system : the continental intercalair (CI) overlain by the complex terminal (CT). the CI has its recharge source in the atlas mountan . it is mainly confind and discharged in the chotts of tunisia and in the gabs gulf (mediterranean sea), by contrast the CT is unconfind oe semi confind with it is main recharge area in the central sahara .

1.Geographical Situation:

The study area is located in the eastern part of the Northern Sahara, within the arid zone of southeastern Algeria. It lies between the Saharan Atlas in the north and the vast sand dune systems of the Grand Erg Oriental in the south. This region forms part of the Sahara platform and belongs to the broader North Western Sahara Aquifer System (NWSAS), which extends across Algeria, Tunisia, and Libya.(Figure 1)

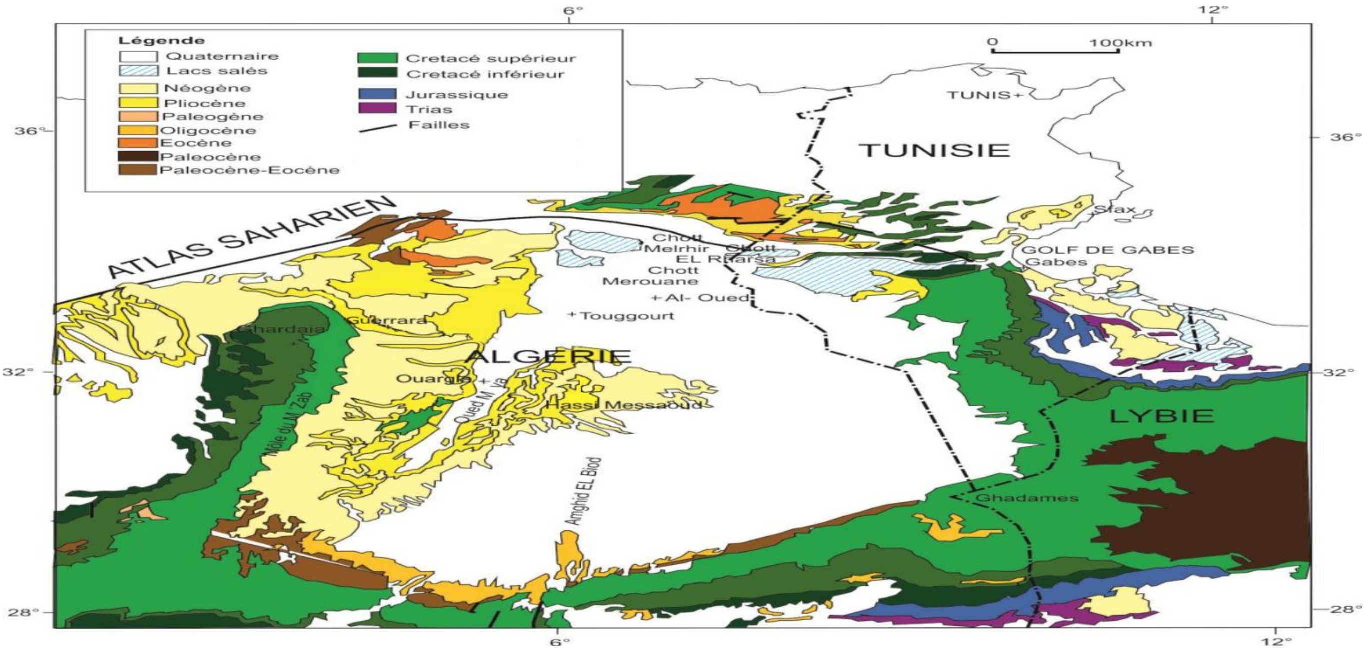


Fig 1: location and geological map of the great oriental erg and the study region. (Guendouz et al 2003)

2.Geology and Hydrogeology :

2.1.Geologie:

The Eastern Basin of the Northern Sahara in Algeria is part of the vast Saharan platform, which has experienced mainly epeirogenic (broad, gentle) movements since the Paleozoic era. The region is characterized by a thick sequence of sedimentary rocks, including clastic (sandstone and shale), evaporitic (gypsum, anhydrite, and salt), and carbonate deposits. The Paleozoic strata are largely clastic, with marine and continental origins, while the Mesozoic and Cenozoic periods saw the deposition of thick evaporites (notably during the Triassic and Liassic) and lagoonal dolomites and shales. The area is structurally influenced by major anticlinoria and fault systems, with the Erg Oriental basin forming a significant sedimentary depression. The region has also been affected by several tectonic events, including the Hercynian and Alpine orogenies, which have shaped the current basin architecture and influenced the distribution of aquifers and hydrocarbon reservoirs. (Bishop, William 1975)

2.1.1.Stratigraphy :

Paleozoic and Pre-Mesozoic Basement:

The region's stratigraphic record begins with a Paleozoic and older basement, which is locally exposed and forms the substrate for later sedimentary sequences. In some areas, such as the Ben Zireg section, late Devonian (Frasnian) calcilutites are present, organized into sedimentary cycles and indicating outer platform to ramp settings with predominantly oxygenated conditions6. The Pan-African orogeny also left a significant imprint, with thick clastic units (e.g., the Tiririne Formation) deposited before 660 Ma, reflecting high-strain tectonic environments.

Triassic:

The Triassic is marked by significant sandstone deposition, particularly in the northwest and Berkine Basin to the east. The Lower Triassic sandstones were deposited on a post-Hercynian erosion surface, with thicknesses varying due to paleotopography. These sandstones are generally unfossiliferous and were derived from local uplifts and folds10. In the Berkine Basin, the late Triassic TAG-I sequence is subdivided into four depositional sequences: ephemeral fluvial, perennial fluvial, fluvio-lacustrine, and coastal plain/shallow marine systems, reflecting shifts in base level, tectonics, and climate.

Jurassic:

Early Jurassic (Toarcian) deposits in NW Algeria and the Sahara Basin are characterized by calcareous nannofossil assemblages and evidence of stratified water columns, reflecting warm, arid climates and episodic anoxic events.

Cretaceous:

The Cretaceous is a key interval, especially for the Continental Intercalaire aquifer system. The Lower Cretaceous is divided into two main formations:

In Salah Formation: A 200 m thick alluvial succession with meandering channels and flood basins, indicating humid conditions.

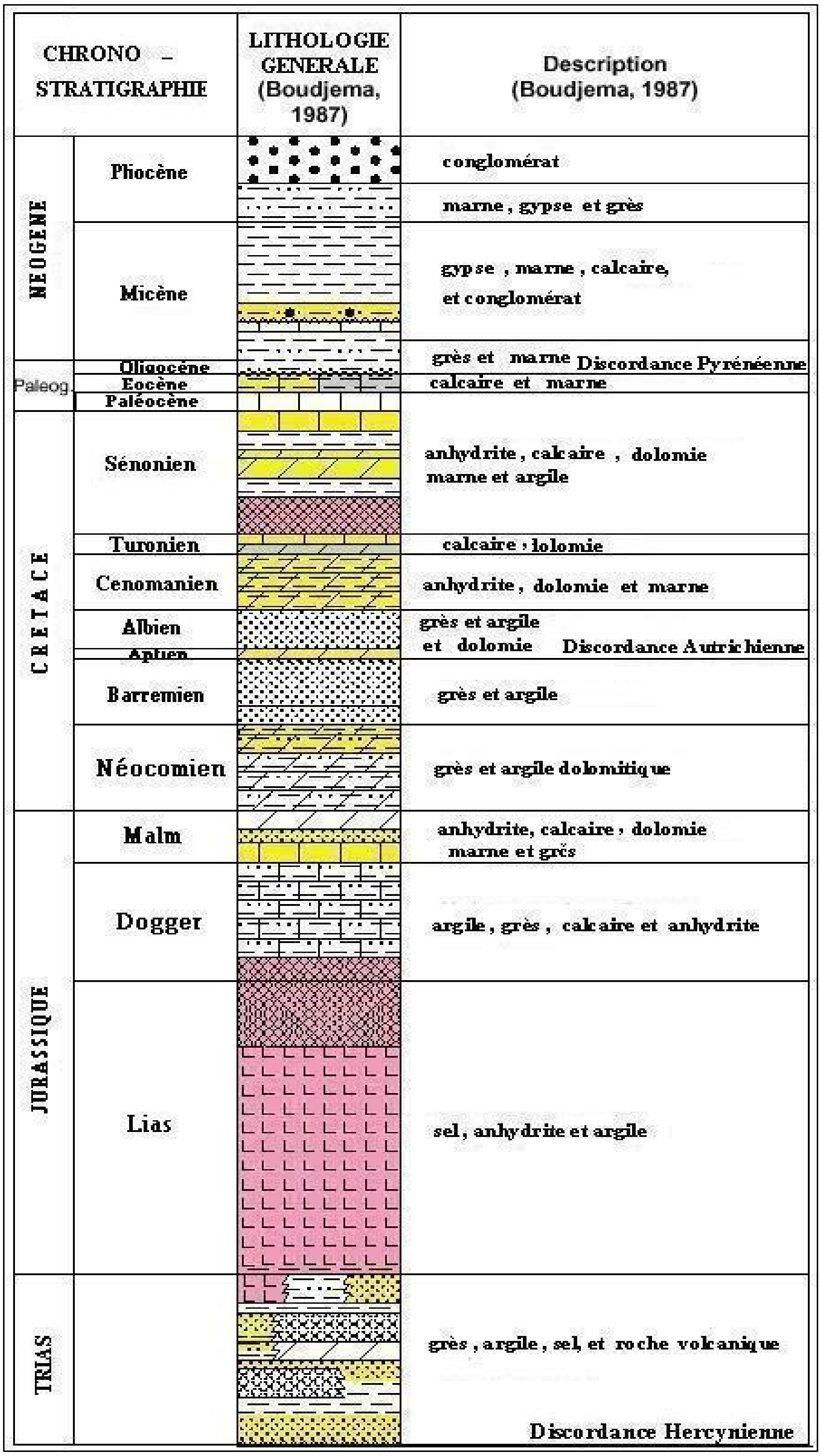
Krechba Formation: A 500 m thick succession of aeolian quartz sands and sandstones, interbedded with oxidized mudstones, marking a transition to arid conditions in the late Aptian–Albian3.

Upper Cretaceous stratigraphy is well documented in the Tademait region, with a succession from the Gara Samani Formation (early Cenomanian clastics), through El Golea Clays (lower–middle Cenomanian), Gour Louazouaza Formation (upper Cenomanian, with ammonite-rich limestones and marls), to the Ain El-Hadjaj Formation (Campanian). These units record a transition from fluvial and aeolian environments to marine ramp systems, reflecting a second-order sea-level rise along the southern Tethys margin.

At the Cenomanian–Turonian boundary, the region experienced widespread marine flooding in two phases, with deposition of bioturbated mudstones, black shales, and ammonite-rich chalks, especially in intra-cratonic basins like Tinrhert.

Cenozoic:

The Cenozoic is represented by post-Messinian series, including Oligocene and Miocene deposits, and is characterized by tectonic activity related to the opening of the Algerian basin and subsequent margin inversion. The sedimentary infill includes several unconformity-bounded units, reflecting rifting, collision, and flexural basin development.



Figue 02 : Typical stratigraphic column of the eastern Sahara (Boudjemaa A, 1987)

2.1.2. tectonic

Rifting and back-arc extension during the Late Oligocene–Lower Miocene, leading to crustal thinning and oceanic crust formation.

Collision events (e.g., AlKaPeCa blocks with Africa at 17 Ma) and subsequent post-rift sag basin development.

Quaternary inversion and flexural basin formation, with ongoing transpressive tectonics linked to Africa-Eurasia convergence.

Fault systems: NE-SW, E-W, ENE-WNW, and NW-SE trends dominate, with grabens and diapirs underlain by Triassic evaporites, facilitating basin opening and structural complexity.(Melouh et al ,2021)

Present-day stress field: Principally strike-slip faulting, with maximum horizontal stress oriented NW-SE/WNW-ESE, parallel to African plate motion.(Arab et al, 2016)

2.2.Hydrogeology:

The two principal aquifer systems in the Eastern Basin are the Continental Intercalaire (CI) and the Complexe Terminal (CT):(**Figure 03)**

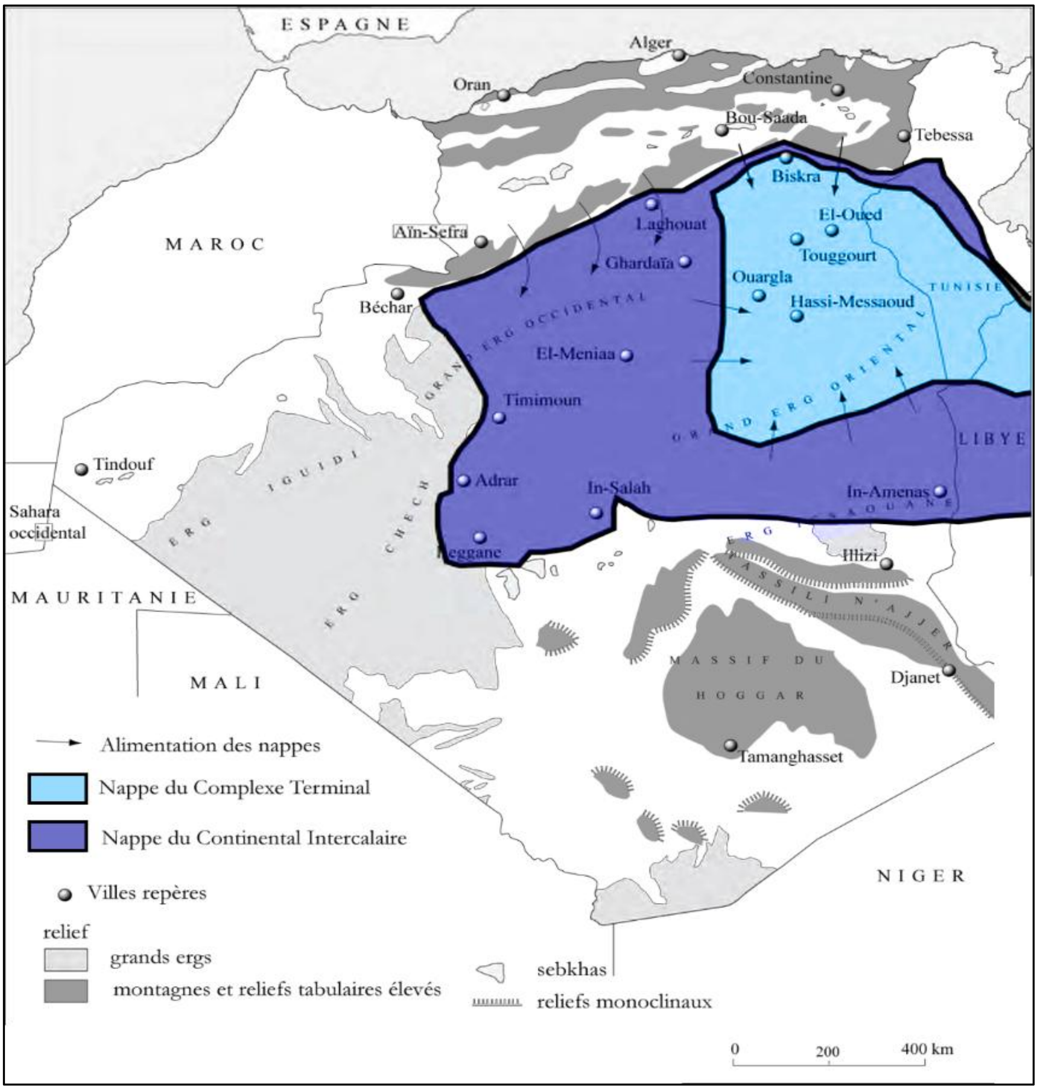


Figure 03: The aquifers of the Algerian Sahara, The Continental Intercalary - The Terminal Complex (UNESCO, 1972)

2.2.1.The Contenental Intercalair aquifer:

hydraulically continuous across the entire basin, spanning regions from the Saharan Atlas in the north to the Tassili Mountains of the Hoggar in the south, and from western Algeria to the Libyan border in the east. This means groundwater flows throughout the entire system, though the flow patterns are influenced by the heterogeneity of the sediments.(edmunds et al ,2003)

The aquifer is continuous across vast regions, with water moving from the northern to the southern parts of the basin. This wide continuity is influenced by the permeability of the different sedimentary units within the system.

There are significant variations in the **permeability** and **porosity** of the layers due to the alternating **detrital sediments** and **clay-rich layers**, which create zones of high permeability and low permeability. These heterogeneities directly affect the flow and storage of groundwater.

In the **southern regions**, changes in lithology and the **thickening** of the sediments likely result in varying **piezometric levels** and differing **chemical compositions** of groundwater. The tectonic activity in these regions, particularly faulting, can also impact groundwater flow by creating discontinuities in the aquifer, further complicating groundwater management.

2.2.2.The Complex Terminal :

The Complexe Terminal (CT) aquifer in the Algerian Sahara, , has been extensively studied by Professor Ahmed Guendouz and his collaborators. The CT is one of the two main aquifer systems in the Northern Sahara, along with the Continental Intercalaire (CI).

The Complexe Terminal is a multi-layer aquifer system that includes two main horizons:

Upper layer: composed of sandy and clayey formations from the Mio-Pliocene period.

Lower layer**:** made up of carbonate formations (limestone) from the Senonian age.

These two layers are often separated by evaporitic (salty) layers from the Eocene period, but they can still be hydraulically connected, allowing vertical water exchange.(Figure 04**)** **(**Guendouz et al 2005)

Depth: varies between 100 and 600 meters.

Average thickness: about 300 meters.

Recharge**:** very low, mostly fossil water, with limited contributions from rainfall infiltration and seasonal streams (wadis).

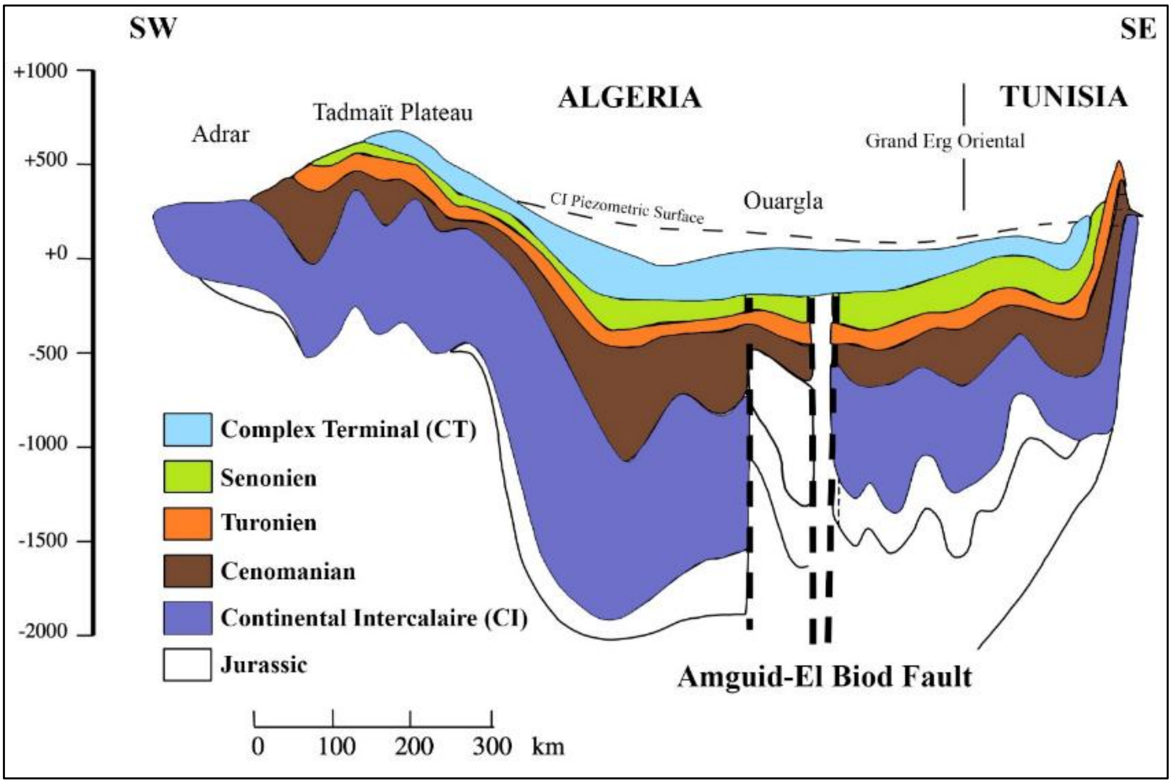


Figure 04 : Hydrogeological section of the CI and CT according to UNESCO 1972

3.Climatology of the Northern Oriental Sahara:

The Northern Oriental Sahara, located in the northeastern part of the Algerian Sahara, is characterized by an extremely arid desert climate. This climate is typical of Saharan regions and is marked by high temperatures, low precipitation, strong diurnal temperature variation, and very low humidity. (Nadhira & Omar, 2019 ; bouchahm ,2011)

3.1.Temperature:

Summer temperatures can reach extremely high levels, often exceeding 40°C (104°F) and sometimes even reaching 50°C (122°F) in areas such as the ergs (sand dunes). Days are very hot, but nighttime temperatures can be somewhat more tolerable.

Winters are milder, with daytime temperatures generally ranging from 15°C to 20°C (59°F - 68°F). However, nighttime temperatures can drop sharply, sometimes reaching 0°C to 5°C (32°F - 41°F), especially due to the altitude of the region, such as in the Hoggar Plateau.

The temperature difference between day and night is significant, especially in winter when the temperature range can reach 20°C to 30°C (36°F - 54°F) (Ayoub et al, 2017)

3.2.Precipitation:

The Northern Oriental Sahara receives very low rainfall, usually less than 100 mm (4 inches) per year. Precipitation is sporadic and irregular, typically occurring during the winter or early spring months.(Hamitouche et al, 2024)

Rain is often brief and not abundant, rarely sufficient to support lush vegetation. However, flash floods can occur after heavy rains.

3.3.Humidity:

The humidity is extremely low, typically ranging from 10% to 30% throughout the year. This results in a dry atmosphere, which contributes to the high daytime heat and low nighttime temperatures.

3.4.Winds:

The region is frequently affected by strong winds, including the Sirocco, a hot and dry wind coming from the southeast of the Sahara. This wind carries sand and dust, often causing sandstorms that reduce visibility and make the environment more hostile.

3.5.Solar Radiation:

Solar radiation is very high due to the lack of cloud cover and the sparse vegetation. The days are long and sunny, with intense sunlight, particularly during the summer months.

This high solar radiation results in high daytime temperatures and rapid cooling at night, as the dry air cannot retain heat

Conclusion :

The Continental Intercalaire (CI) and Continental Terminal (CT) aquifers form a vast and complex groundwater system beneath the Northern Oriental Sahara, shaped by intricate geological and climatic conditions. The CI aquifer, composed of Lower Cretaceous clastic sediments, displays significant heterogeneity due to alternating permeable and clay-rich layers, tectonic influences, and varying lithology, which directly affect groundwater flow and quality. The CT aquifer, primarily consisting of Mio-Pliocene sands and Late Eocene/Senonian carbonates, is mainly unconfined and supports localized agricultural and industrial activities.

Hydrologically, the CI aquifer demonstrates regional continuity across Algeria, influenced by structural features and sediment variation, while the CT aquifer's recharge zones and unconfined nature make it more responsive to climatic and surface conditions.

Despite the extreme aridity of the region, characterized by high temperatures, low precipitation, and frequent sandstorms, these aquifers remain important water sources for communities, oases, and oil operations in the Sahara.

Chaptre II:

materials and methods

CHAPTER 2 : Material and Methods

Introduction:

The research methodology is one of the most critical components of any scientific study, as it forms the foundation upon which observations, analyses, and interpretations are built. In this work, we relied on pre-existing physical and chemical data concerning groundwater in the eastern basin of the Northern Algerian Sahara. These data were processed using a scientific approach aimed at understanding the dynamics of the aquifer system and the evolution of its geochemical components

2.1.Data Preparation and Organization:

Given that the data used in this study were obtained from previously conducted fieldwork and laboratory analyses by official agencies or academic research projects, the focus of our contribution was placed on the critical treatment, organization, and interpretation of these results. The objective was to extract coherent patterns, understand geochemical behaviors, and link water composition to geological and anthropogenic factors without engaging in new field measurements.

The methodology was structured around three main axes: understanding the context of the data, organizing and preparing the data for analysis, and applying theoretical and interpretative frameworks to extract meaningful insights. This methodological structure ensures the traceability of every analytical step and enhances the academic rigor of the study.

2.2 Nature and Sources of the Data

The data set used in this research includes a variety of physical and chemical parameters related to groundwater samples. These samples were collected over several campaigns in different parts of the study area and analyzed in certified laboratories. The integrity and credibility of the data are assured by the reputation of the institutions that produced them and by cross-validation with similar studies in the region.

The types of data include:

Physical Parameters: Temperature, pH, and electrical conductivity (EC), measured at the time of sampling.

Chemical Parameters: Concentrations of major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-).

Additional Indicators: Total Dissolved Solids (TDS), water hardness, and saturation indices.

These parameters provide the necessary foundation for classifying water types, evaluating their suitability for different uses, and identifying possible pollution sources or natural enrichment processes. The data set also includes the geographic coordinates and depths of the wells or boreholes from which the samples were taken, allowing for spatial interpretation.

2.3 Data Organization and Pre-Processing

Before any interpretative analysis could be carried out, a comprehensive phase of data organization and pre-processing was conducted. This involved multiple technical steps:

Data Cleaning: Removal or flagging of erroneous entries, identification of missing values, and resolution of inconsistencies.

Normalization: Standardizing units and scales to allow for coherent comparisons between samples.

Classification: Grouping samples by location, depth, aquifer type, or collection period, which facilitates comparative analysis and pattern detection.

Deriving Secondary Variables: Calculating parameters such as ion balance errors, ionic ratios, and water quality indices like SAR (Sodium Adsorption Ratio) and RSC (Residual Sodium Carbonate).

This step ensured that the dataset used in the study was both statistically sound and scientifically robust. It also provided a strong base for subsequent geochemical and hydrogeological interpretation.

2.4 Analytical Approach

The analytical approach adopted in this study was both descriptive and interpretative. It aimed to elucidate the chemical nature of groundwater in the study area and to understand the processes governing its evolution. The approach can be broken down into the following dimensions:

a) Hydrogeological Contextualization:

Understanding the aquifer systems in the region was essential. This involved reviewing existing geological maps, previous hydrogeological studies, and structural data to contextualize the water chemistry within the geological environment. Factors such as aquifer lithology, recharge mechanisms, and groundwater flow direction were considered.

b) Chemical Typing and Classification:

Samples were categorized based on dominant cation and anion composition. Classifications such as Ca-HCO_3, Na-Cl, or mixed types were applied to identify trends in water-rock interaction and anthropogenic influence. This classification is critical for determining the water's origin and assessing its evolution.

c) Ion Ratio Analysis:

Using specific ionic ratios (e.g., Na^+/Cl^-, Ca^{2+}/Mg^{2+}, HCO_3^-/Cl^-), we investigated geochemical processes such as ion exchange, silicate weathering, and evaporite dissolution. These ratios act as fingerprints of the dominant geochemical reactions occurring in the subsurface.

d) Spatial and Vertical Variability:

Given the availability of sample coordinates and depths, a spatial and vertical assessment of water quality was performed. This helped identify zones of mineral enrichment, potential contamination, or interaction with specific geological formations.

2.5 Interpretation Framework

The interpretive phase of the methodology involved placing the analytical results within a broader hydrogeochemical framework. The goals included:

Identifying natural geochemical trends influenced by lithology and hydrodynamics.

Detecting anthropogenic impacts such as agricultural return flows or urban wastewater infiltration.

Evaluating the water's suitability for various uses (e.g., irrigation, domestic supply) based on international standards.

Formulating hypotheses about the origin and evolution of the groundwater, especially where unusual values or patterns were observed.

This interpretive work was not merely descriptive but aimed at building a conceptual model of the groundwater system, linking physical conditions, chemical results, and geological characteristics.

2.6 Methodological Limitations

While the adopted methodology offers a comprehensive approach to analyzing groundwater data, it is important to acknowledge certain limitations:

Dependence on Pre-Existing Data: Since no new fieldwork was conducted, the study had no control over sampling conditions or analytical methods.

Data Gaps: Incomplete records for some samples limited the application of certain interpretive tools.

Temporal Variation: The data were collected over different years and seasons, which may introduce variability not accounted for in the analysis.

Geographical Coverage: Some areas within the basin were underrepresented due to a lack of available data, limiting spatial generalization.

Despite these limitations, the methodology employed allowed for significant insight into the aquifer system and provided a valuable contribution to the understanding of groundwater behavior in the region.

2.7 Conclusion

This chapter has outlined a methodological framework centered on the analytical treatment of ready-made groundwater data. By focusing on rigorous data processing, contextual interpretation, and a multifaceted analytical approach, the study was able to derive meaningful conclusions about groundwater quality and geochemical evolution in the eastern basin. The chosen methodology, though limited by the absence of direct fieldwork, remains valid, coherent, and scientifically justified in the context of the study's objectives.

Chaptre III:

Results and Discussion

CHAPTER III : Results and Discussion

Introduction:

This section presents the key finding of the study and interprets their implication in the context existing knowledge.The results are organized to adress the research objectives and hypotheses, followed by critical analyses , where potential explanation for observed trends or anomalies are proposed .

1. Physicochemecal parameters of Groundwater:

1.1.CI Aquifer:

1.1.1.Temperature:

The deep waters of the CI exhibit high temperatures, ranging from 30°C to 70°C, SHOW significant geothermal conditions, especially in the central areas of the eastern basin where the aquifer reaches depths of 1500 to 2200 meters.(Edmuds et al,2003)

1.1.2. pH:

The pH is generally neutral to slightly alkaline, indicating chemically stable water in equilibrium with carbonate minerals LIKE calcite and dolomite.(Edmuds et al,2003)

1.1.3. Salinity:

Electrical conductivity ranges between 2000 and 6000 µS/cm, shows high mineralization. This is mainly due to the dissolution of evaporitic formations (halite – NaCl, gypsum – $CaSO_4 \cdot 2H_2O$, and sylvite – KCl), which are characteristic of the aquifer matrix.(edmunde et al ,2003)

1.2.CT Aquifer:

1.2.1. Temperature:

Water temperatures are moderate, between 20°C and 35°C, with thermal homogeneity across the two levels of the CT.(Goundouz et al,2003)

1.2.2. pH:

The pH is neutral to slightly alkaline, with a bicarbonate-alkaline character. This indicates chemical stability with carbonate and evaporitic rocks.(Goundouz et al,2003)

1.2.3.Salinity:

Salinity increases from recharge to discharge zones:In recharge areas, total dissolved solids are less than 2 g/L,In intermediate flow zones, between 2 and 5 g/L.(Goundouz et al,2003)

2.Evolution of major elements (CI&CT) :

2.1.CI Aquifer:

Gradual increases in some elements indicate that there are processes of mineral dissolution or water–rock interactions occurring during groundwater movement within the aquifer system Major elements like Cl^-, Na^+, SO_4^{2-}, Ca^{2+}, K^+, Mg^{2+}, and HCO_3^- note increase in concentrations along the groundwater flow. Cl^- ranges from 180 to 820 mg/L; Na^+ varies from 150 to over 630 mg/L, and Na^+/Cl^- ratios more then 1.5 suggest cation exchange or silicate weathering. Sulfates (250 to 1750 mg/L) idicates high presence of gypsum, with no significant reduction (SO_4^{2-}/Cl^- ratio high(5)). Ca^{2+} (90 to 400 mg/L) and Mg^{2+} (variable) are related to carbonate dissolution. K^+ (5 to 110 mg/L) often increases because feldspar weathering. HCO_3^- concentrations stay relatively stable because carbonate saturation. (Edmund et al 2003) (Figure 13)

The concentration of chloride (Cl^-) varies between 65 mg/l and 605 mg/l, with an average of 333.10 mg/l. It exceeds the permissible limit (250 mg/l) for drinking water according to WHO standards in most of the studied samples. The increase in chloride concentration may be due to the dissolution of halite or the influence of anthropogenic activities (fertilizers, wastewater...).(Edmuds et al,2003) (Figure 13)

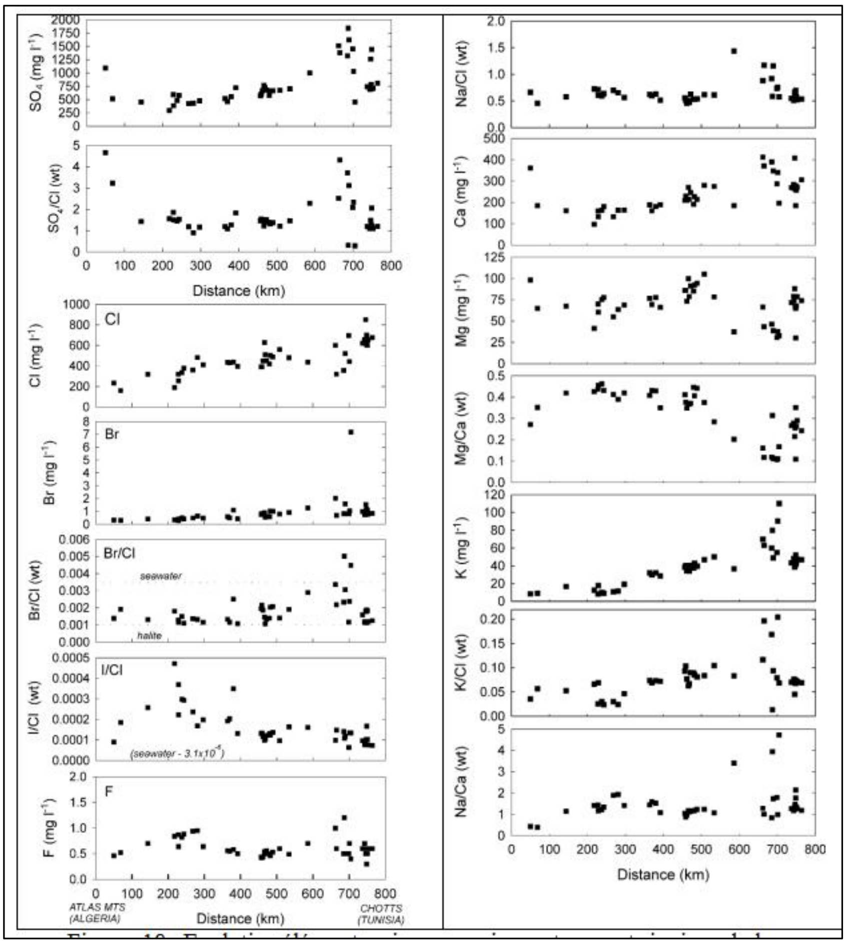


Figure 05:Evolution of minor and major elements and ionic ratios of the recharge and (Edmunds, 2003)

2.2.Complex terminal:

Chloride increases from 164 to 2500 mg/L, Na^+ up to 1450 mg/L, and SO_4^{2-} from 600 to 1550 mg/L. Ca^{2+} ranges from 67 to 796 mg/L, K^+ between 10 and 50 mg/L, and Mg^{2+} from 23 to 630 mg/L, with a slight downstream decline. HCO_3^- remains relatively constant (58 to 351 mg/L).(gounduz et al ,2003)

Na/Cl Ratio (wt) Most samples cluster around Na/Cl ≈ 1 (or slightly below), consistent with simple dissolution of halite (NaCl).

A subset of points with Na/Cl > 1 suggests additional sodium input from processes such as:Weathering of feldspars (releasing Na^+),Cation-exchange reactions (Na^+ released to solution in exchange for Ca^{2+} or Mg^{2+} on clay surfaces).(Gounduz et al ,2003)

Very high Na/Cl values (>1.5) may reflect localized water–rock interactions or deep-seated geochemical processes adding extra Na.

Mg/Ca Ratio (wt) The Mg/Ca ratio ranges roughly from 0.1 to 0.5, showing significant scatter.This ratio is controlled by:

Host-rock lithology (dolomitic vs. calcitic composition)

Extent of dolomitization (replacement of Ca by Mg in carbonate minerals)

Cation-exchange processes in the aquifer matrix

Low Mg/Ca (< 0.3) indicates Ca dominance—typical of calcite-rich systems or gypsum dissolution.Higher Mg/Ca (> 0.4) suggests input from dolomite dissolution or precipitation of calcite (which removes Ca preferentially).(Figure 14) (Goundouz et al ,2003)

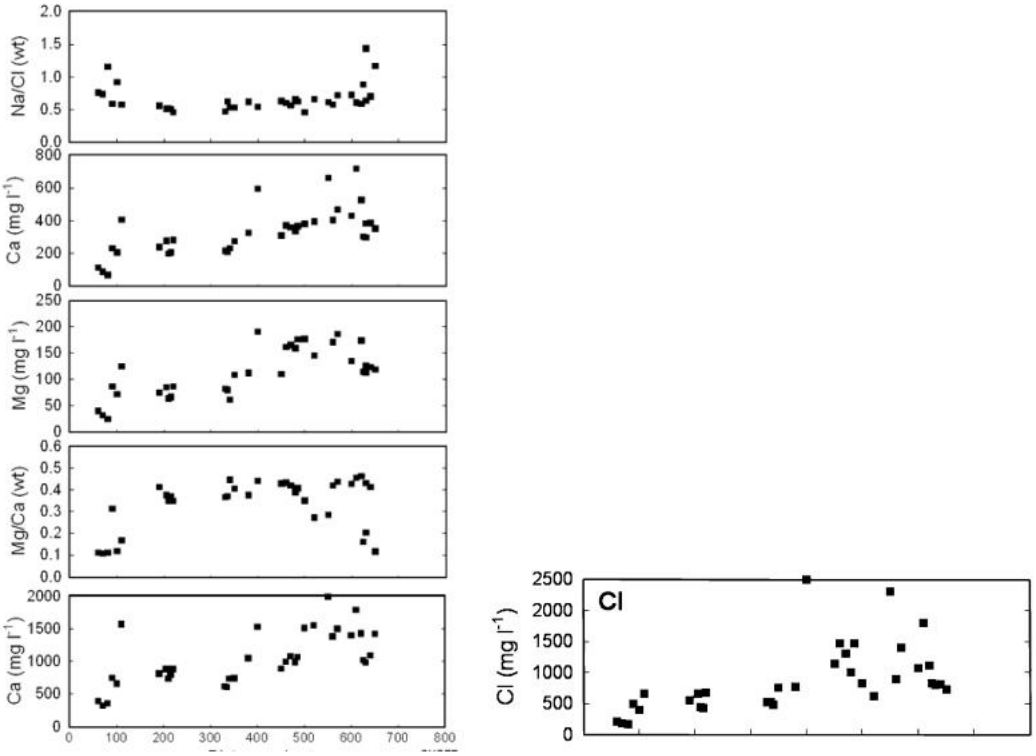


Figure 06:Evolution of major elements and ionic ratio (Geunduozet al, 2003)

3.Chemical facies:

3.1.CI Aquifer:

The piper diagram shows us that CI waters exhibit a sodium-chloride or sodium-sulfate facies, consistent with evaporitic mineral input.(Figure 15) (Edmund et al ,2003)

The Stabler diagramme also demonstrates the competetion of 4 element : Na+, SO4—,Ca2+, Cl– (Figure 16).

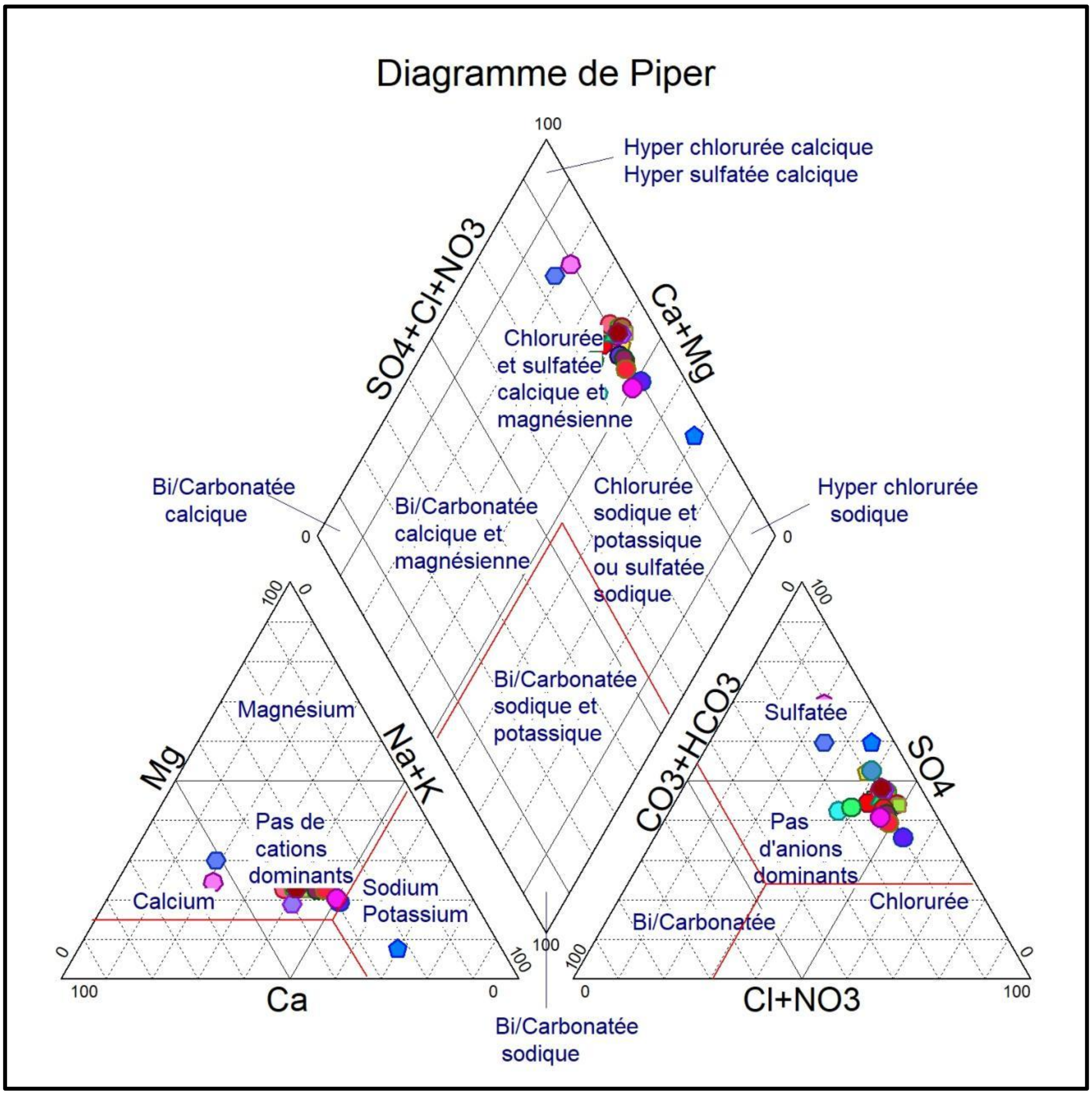


Figure 07: Diagramme de piper _contenental intercalair_

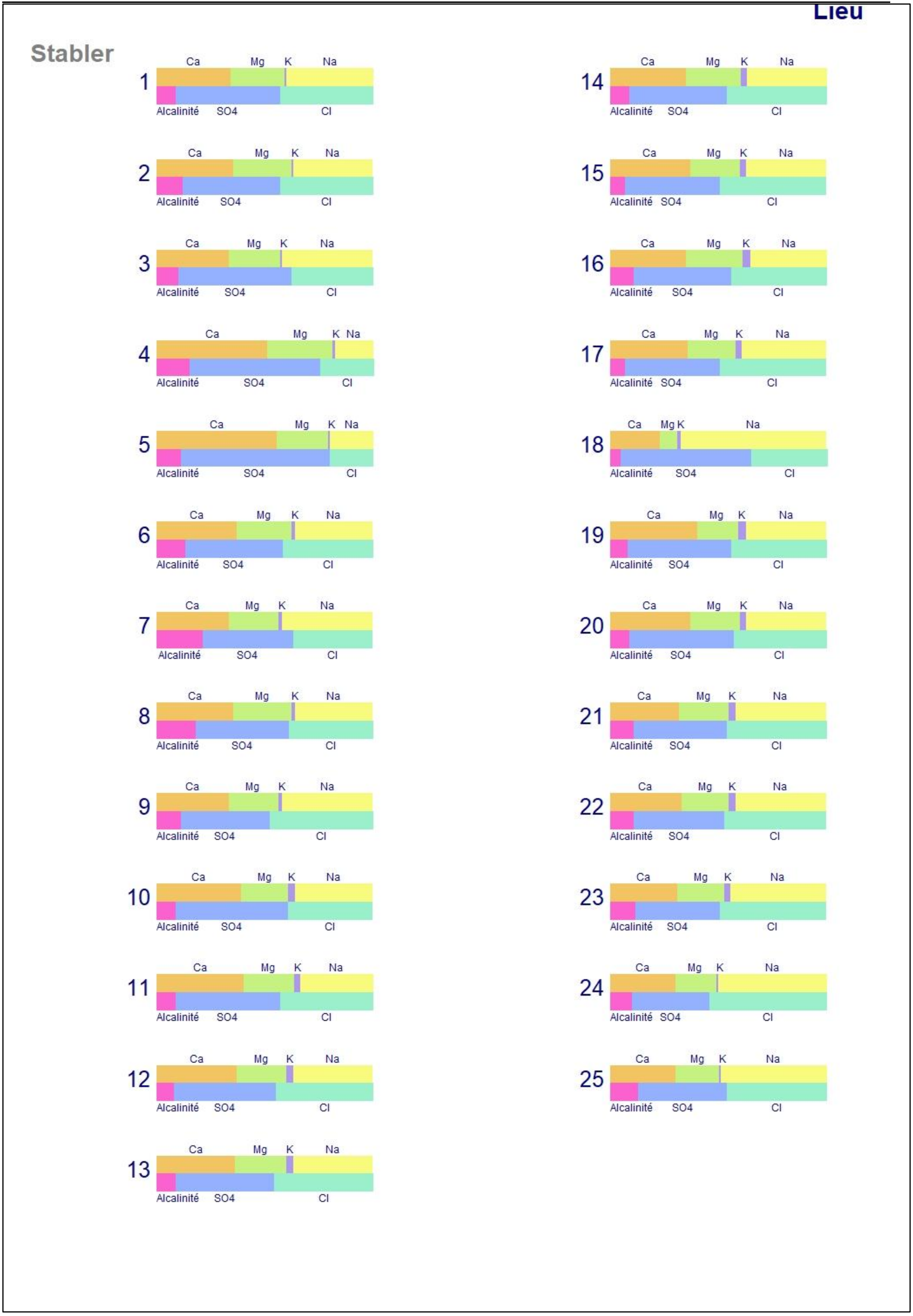


Figure 08: stabler diagramme _contenental intercalair_

3.2.CT Aquifer:

The piper diagramme shows that the CT exhibits a sodium-chloride-sulfate and magnesium facies due to its heterogeneous lithology. (Figure 17)

The Stabler diagramme also demonstrates the competetion of 4 element : Na^+, SO_4^{--}, Ca^{2+}, Cl^- (Figure 18)

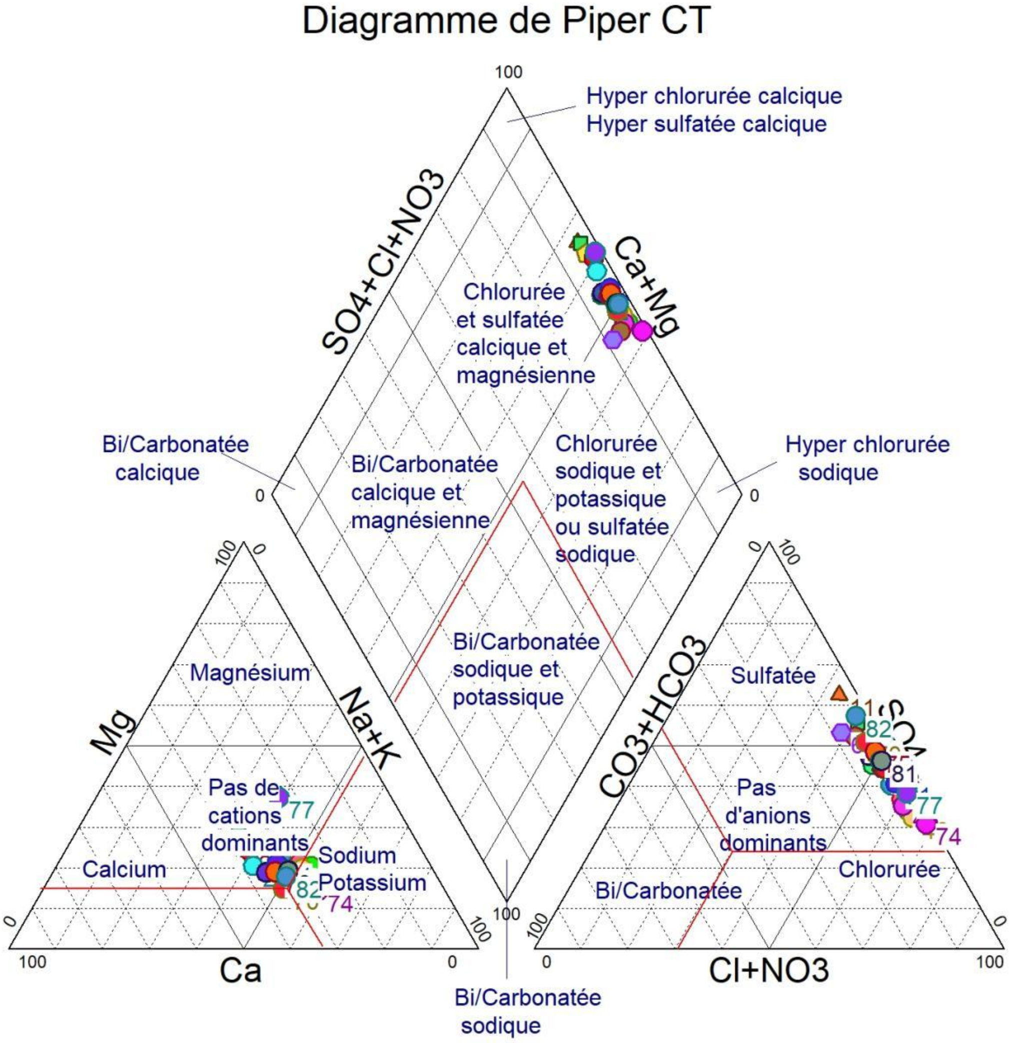


Figure 09: piper diagramme of complex terminal

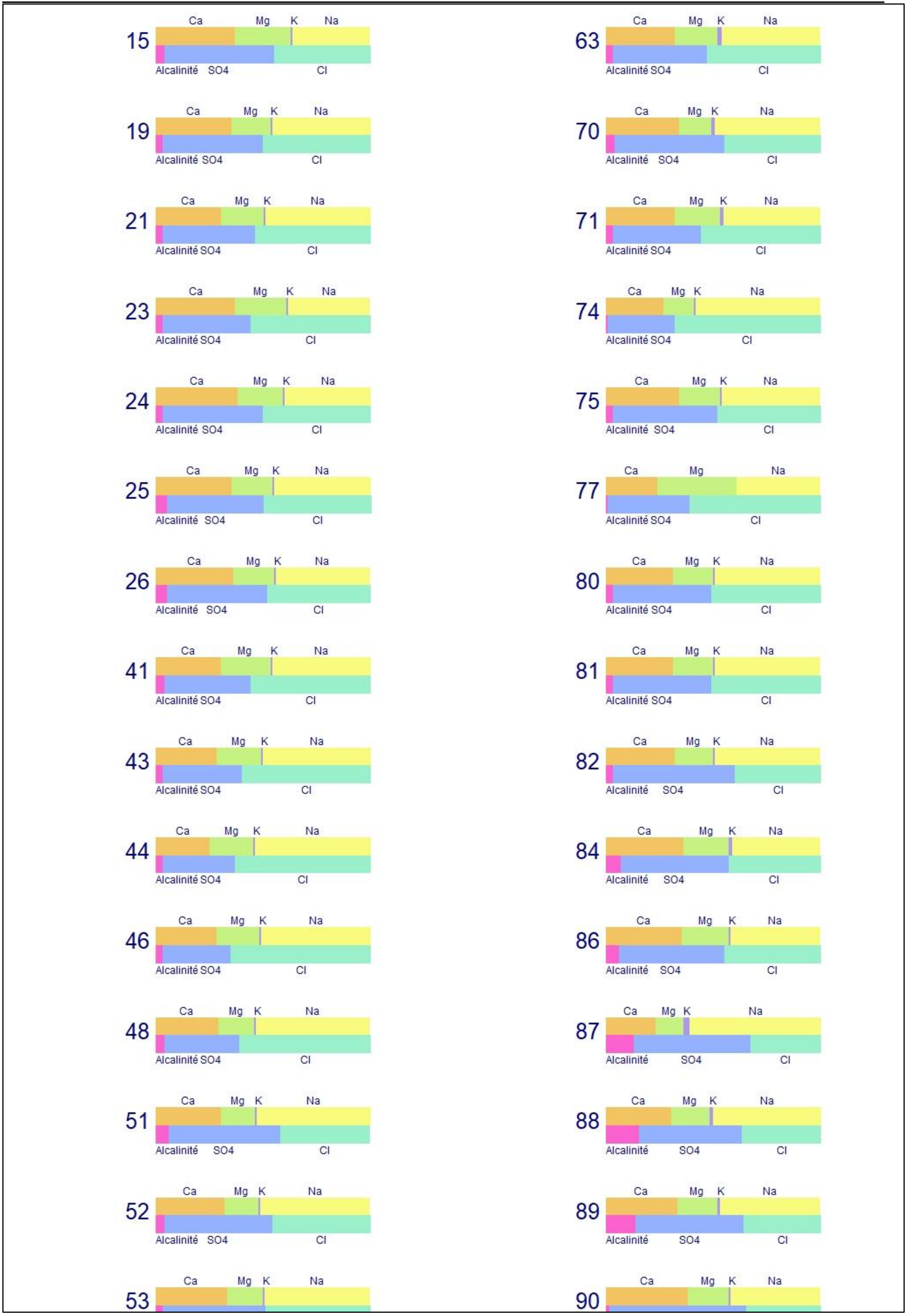


Figure 10: Stabler diagramme of complex terminal

4. Evolution of Trace Elements (CI & CT):

4.1.CI Aquifer:

The study by Edmunds (2003) shows that minor elements in the Continental Intercalaire aquifer vary along the flow path due to ongoing water–rock interactions. Iron (Fe) and manganese (Mn) concentrations are higher in deeper, reducing zones, while fluoride (F^-) remains low, likely sourced from rainfall. Bromine (Br) and iodine (I) help trace salinity sources, with I higher near recharge zones, indicating rock interaction. Elements like lithium (Li), boron (B), and strontium (Sr) increase progressively, reflecting long residence times. Barium (Ba) remains low, possibly limited by barite solubility. Chromium (Cr) and uranium (U) are more abundant in oxidizing zones and decrease under reducing conditions, highlighting the influence of redox state on trace element distribution.(Figure 19)

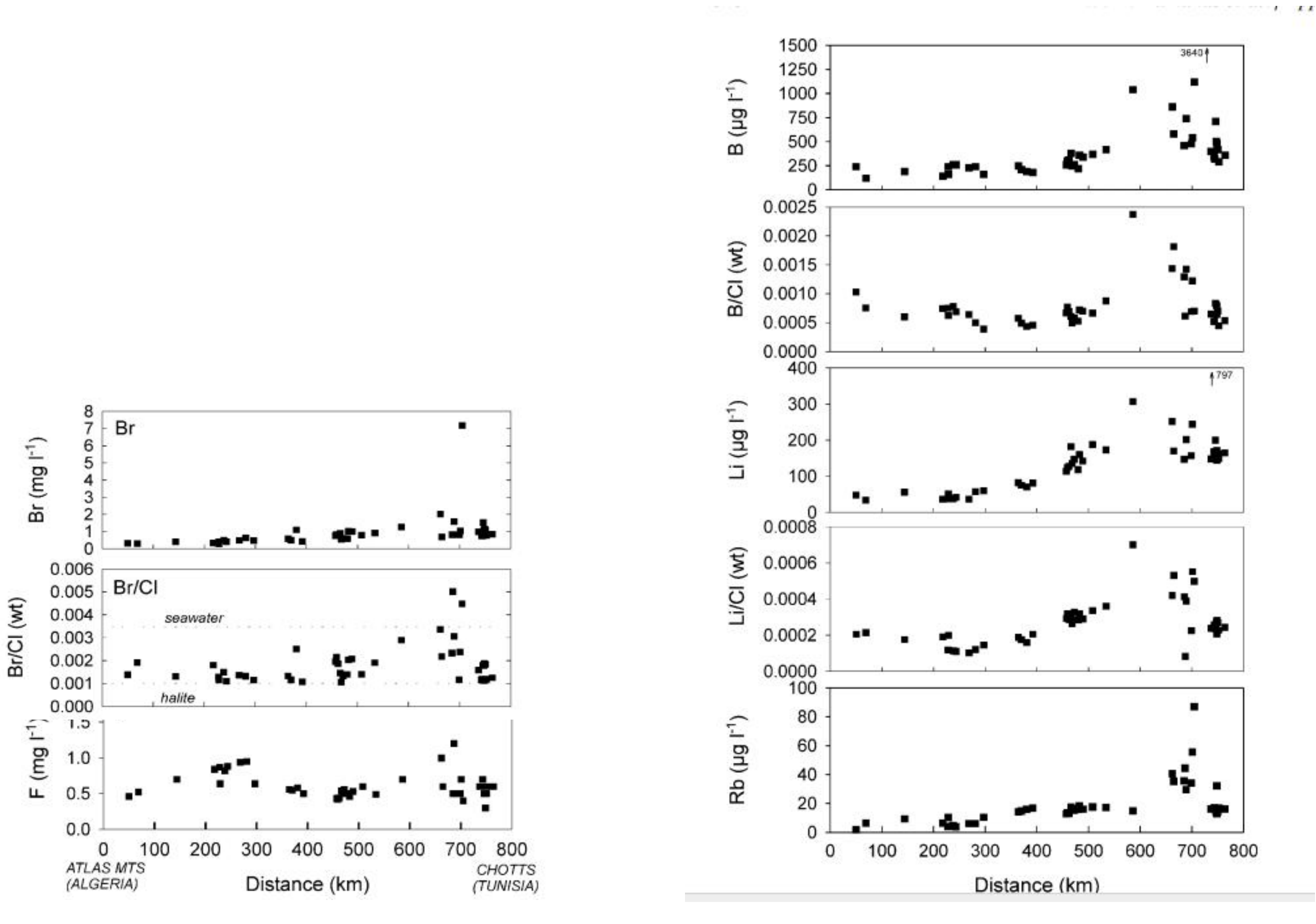


Figure 11:Evolution of minor elements and ionic ratios of the recharge and (Edmunds, 2003)

4.2.CT Aquifer:

The minor elements (Br^-, Sr^{2+}, Li^+, B^{3+}, F^-, I^-, Rb^+) in the groundwater of the Complexe Terminal aquifer exhibit a clear distribution pattern that aligns with the general flow direction from the recharge areas in the south (Tinrhert Plateau) toward the discharge zones in the north (Chotts region). The concentration of most of these elements gradually increases along the flow path, attributed to prolonged water–rock interactions, particularly with evaporitic minerals such as halite (NaCl), gypsum ($CaSO_4 \cdot 2H_2O$), and celestite ($SrSO_4$). For example, strontium (Sr^{2+}) concentrations rise from about 1,000 to 14,000 µg/L near the Chotts, while the Br^-/Cl^- ratio decreases along the path, indicating an increasing contribution of chloride (Cl^-) from halite dissolution. Fluoride (F^-), iodide (I^-), and bromide (Br^-) also display behavior linked to mineralogical control by evaporite deposits. These distributions reflect the hydrogeochemical evolution and the complex chemical interactions experienced by the groundwater as it flows through the aquifer system.(Figure 20) (Guendoz et al ,2003)

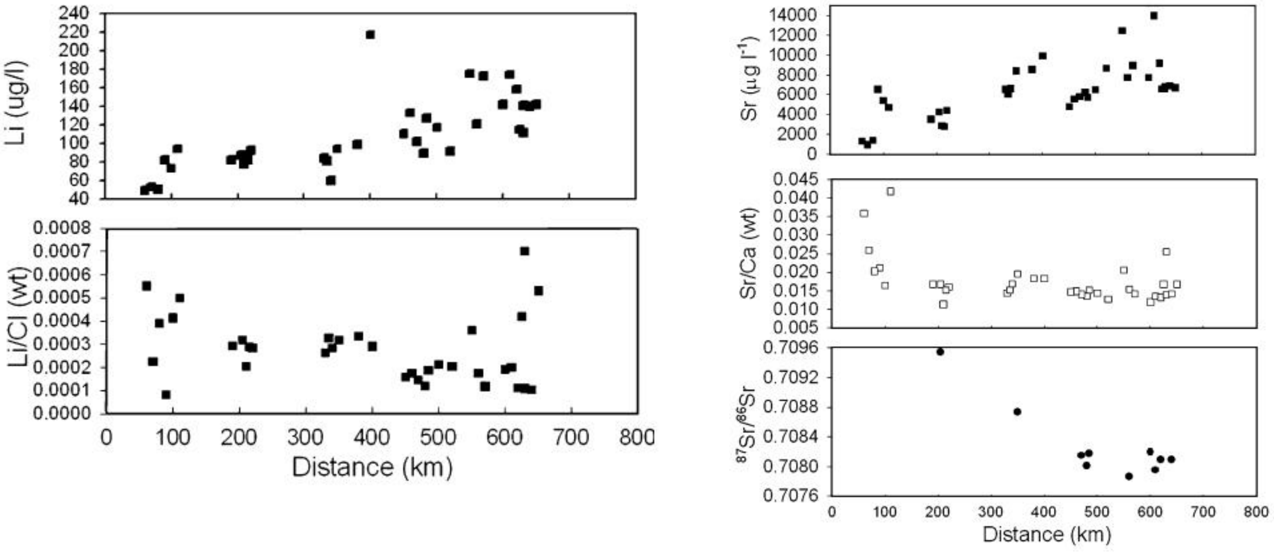


Figure 12:Evolution of minor elements and ionic ratios (Goundouz et al, 2003)

5. Ionic Ratios and Hydrogeochemical Processes:

5.1. CI Aquifer:

5.1.1Geochemical Analysis of the Cl^- vs SO_4^{2-} :

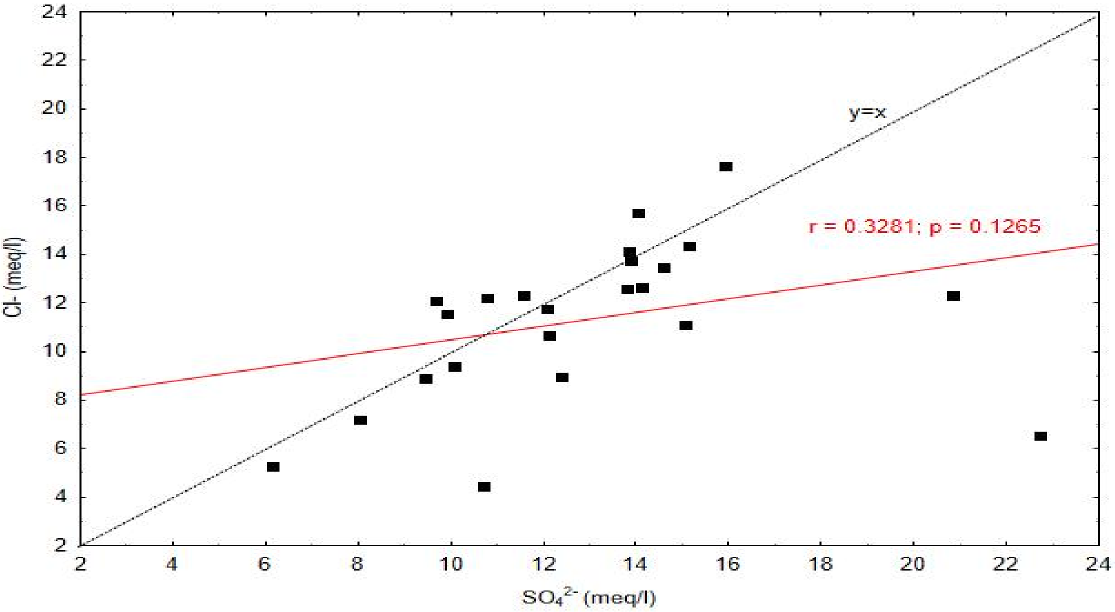


Figure13:Chloride vs Sulfate correlation diagram

The aim is to distinguish water quality based on the dominant anionic component: Cl^- (Chloride): Often indicates seawater intrusion or sewage contamination.

SO_4^{2-} (Sulfate): Typically reflects interaction with gypsum or anhydrite rocks, or industrial activity (e.g., mining).

If points are centered along the line $Cl^- = SO_4^{2-}$ (1:1):This suggests a relative balance between the two sources. Like the region:

- (Sidi-Slimane 2 ,Sidi-Slimane1) :Sidi Slimane lies in a large area of palm plantations on an oasis network that extends from here past Touggourt through to Balidat Ameur. Beyond the oases is the arid and barren landscape of the Sahara, featuring areas of sand dunes (ergs) and flat rocky plains (regs). with Coordinates: 33°17′19″N 6°5′41″E

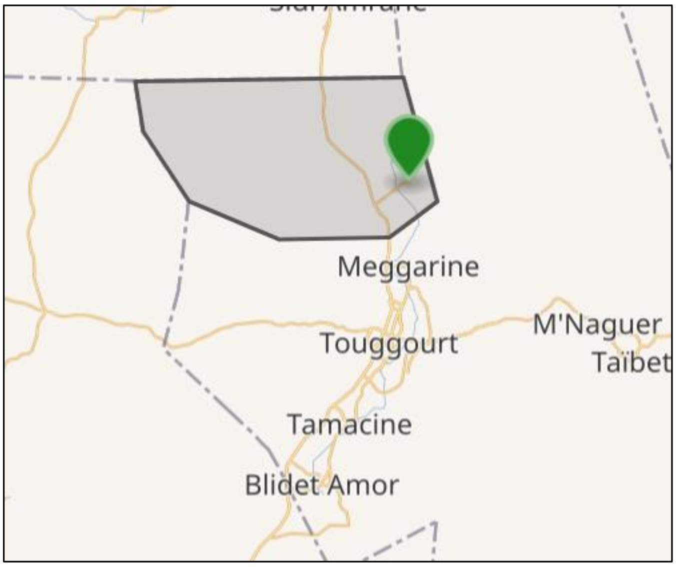


Figure14: sidi slimane location (google map)

-If points lie above the line ($Cl^- > SO_4^{2-}$): The water has a chloride-dominant nature, which may indicate: Seawater intrusion ,Sewage leakage ,Dissolution of saline rocks (e.g., halite - NaCl)

-If points lie below the line ($SO_4^{2-} > Cl^-$): The water is sulfate-dominant, likely due to:

Dissolution of gypsum rocks ($CaSO_4 \cdot 2H_2O$),

Evaporation processes (Figure 15)

We can notice that the dominant element is sulfate in the area numbered 6 (Djebel Makrane (U1)) (Figure 15) , This suggests the groundwater strongly interacts with gypsum or anhydrite rocks (e.g., $CaSO_4$ or $CaSO_4 \cdot 2H_2O$).

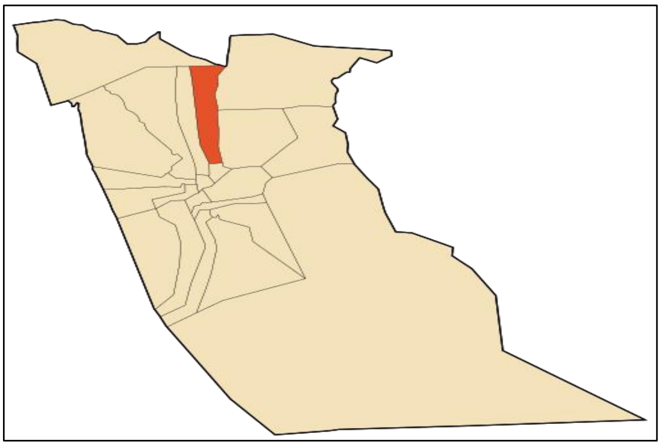


Figure 15:Djebel Makrane location (google map)

High sulfate concentrations often indicate evaporite-rich geological layers in the region.

The relatively low Cl^- suggests limited marine or anthropogenic saline intrusion.

If there are igneous or sedimentary rocks rich in sulfides, oxidation of these minerals might increase sulfate levels.

The high sulfate concentration (22 meq/L ≈ 1056 mg/L) exceeds the WHO recommended limit (250–500 mg/L), potentially causing digestive issues in humans and soil salinity problems in agriculture.

5.1.2.Graph Analysis of Na^+ vs Cl^- :

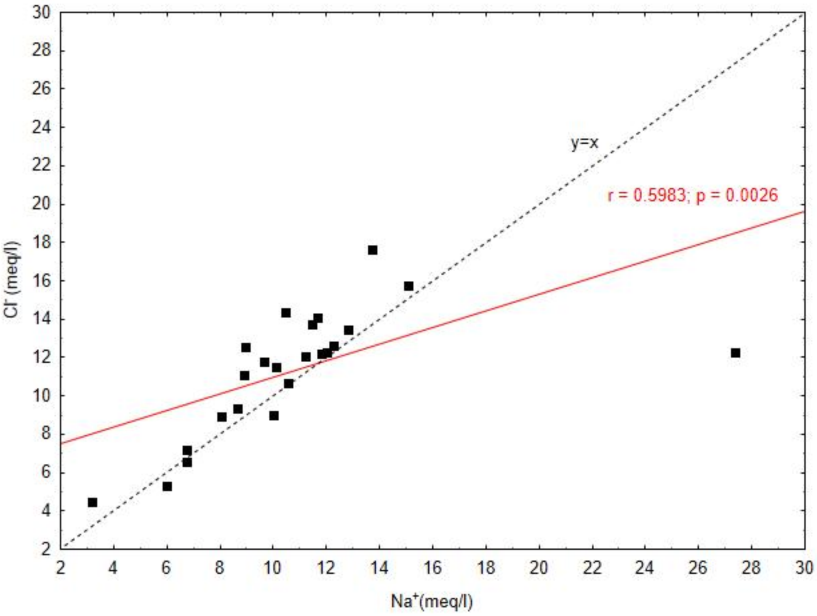


Figure16:Chloride vs Sodium correlation diagram

The extracted text indicates a relationship between the concentration of sodium (Na^+) and chloride (Cl^-), with a regression line equation: r = 0.5983 ; p = 0.0026

This suggests a moderate positive correlation between Na^+ and Cl^-, which is statistically significant ($p < 0.01$). (Figure 16)

Relationship between Na^+ and Cl^-: Both elements are often associated with a common chloridic source as: Dissolution of saline rocks (e.g., halite)

The linear relationship between Na^+ and Cl^- suggests that both ions may originate from the same source or follow a common geochemical pathway.

If reference lines (such as the 1:1 line) are present, the point distribution can be interpreted as follows:

On or near the line $Na^+ = Cl^-$ (1:1) Indicates a source of pure halite (NaCl) or marine water

$Na^+ > Cl^-$ Suggests additional sodium input, possibly from cation exchange reactions with clay minerals

$Cl^- > Na^+$ May indicate an additional chloride source as sodium loss due to ion exchange

There is an area shows a clear dominance of sodium (Sehane El Berry) , which indicates active ion exchange or geological/human sources rich in sodium.The water is very saline, and it may be harmful for both irrigation and drinking without treatment.(Figure 16)

5.2. CT Aquifer:

5.2.1.Geological Distribution Analysis of Data Points:(SEC & SO_4^{2-}–Cl^-):

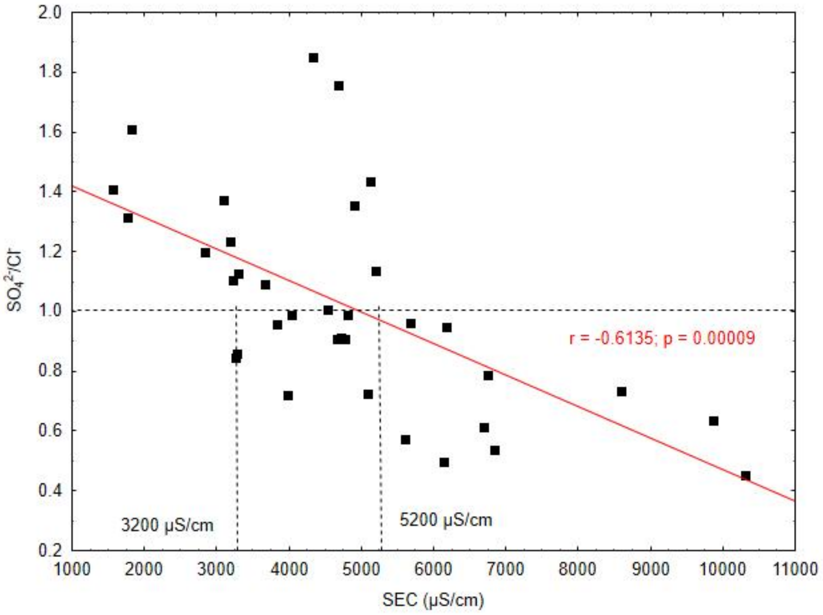


Figure 17:Hydrochemical Facies Distribution Based on SEC and SO_4^{2-}–Cl^- Relationship

-Points in (Low SEC & Negative SO_4^{2-}–Cl^-):Water characteristics: Low salinity with chloride dominating over sulfate. These could represent old groundwater or water slightly influenced by a chloride source such as minor seepage through halite-rich soils**.**

Points in (High SEC & Negative SO_4^{2-}–Cl^-):Water characteristics high salinity with dominant chloride content. Often indicates seawater intrusion, leakage from wastewater, or dissolution of halite-bearing formations.

- Points in (Low SEC & Positive $SO_4^{2-}–Cl^-$):Low salinity but dominated by sulfate.

Likely fresh or young groundwater that has passed through sulfate-rich rocks such as gypsum or anhydrite.

- Points in (High SEC & Positive $SO_4^{2-}–Cl^-$): High salinity and sulfate-dominated.

Likely results from evaporation, dissolution of sulfate-rich rocks, or influence of mining or industrial activities.

6.Geochemical Modeling using PHREEQC:

6.1.CI Aquifer:

Field no.	Locality	Number	Calcite	Dolomite	Gypsum	Quartz	Chalcedony	Fluorite	Barite	Celestite
1	Bouheraroua	1	−0.07	−0.12	−0.80	−0.07	−0.49	−1.09	0.07	−0.93
2	Bensmara 1	2	−0.12	−0.18	−0.89	−0.09	−0.50	−1.18	−0.02	−1.04
3	Daia Ben Dahoua	3	0.12	0.31	−0.83	−0.14	−0.54	−1.17	0.10	−0.95
5	El-Assafia 1	4	0.04	−0.00	−0.77	0.10	−0.35	−1.38	−0.02	−0.91
6	Djebel Makrane (U1)	5	0.39	0.48	−0.34	−0.14	−0.55	−1.43	−0.26	−0.51
7	Hassi-Dalaa	6	0.07	0.20	−0.91	−0.13	−0.54	−1.31	−0.16	−1.00
8	Berriane 2	7	0.22	0.72	−1.24	−0.11	−0.53	−1.30	−0.15	−1.44
9	Laroui	8	0.23	0.60	−1.03	−0.10	−0.52	−1.43	−0.13	−1.18
10	Guerrara:Laameyed	9	0.32	0.76	−0.91	−0.12	−0.51	−1.49	−0.07	−1.02
12	El-Mir	10	0.63	1.32	−0.72	−0.16	−0.51	−1.81	0.03	−0.89
14	Blidet Omar 1989	11	0.68	1.39	−0.72	−0.12	−0.49	−1.84	0.02	−0.75
16	Ain-Sahara	12	0.58	1.18	−0.68	−0.13	−0.48	−1.77	0.04	−0.75
17	Sidi-Slimane 1	13	0.72	1.44	−0.70	−0.12	−0.47	−1.83	0.05	−0.63
18	Sidi-Slimane 2	14	0.56	1.13	−0.71	−0.15	−0.50	−1.75	−0.01	−0.67
20	Meggarine	15	0.58	1.07	−0.60	−0.12	−0.47	−1.66	−0.02	−0.64
22	Ain-Choucha	16	0.88	1.84	−0.80	−0.08	−0.45	−1.76	0.05	−0.81
37	Etteibat	17	0.81	1.53	−0.63	−0.03	−0.38	−1.56	0.03	−0.59
38	Sehane El Berry	18	0.43	0.90	−0.66	0.11	−0.29	−1.45	0.19	−0.52
39	El Oued	19	0.12	0.15	−0.61	−0.05	−0.39	−1.74	−0.02	−0.52
40	Sidi-Mahdi	20	0.47	0.88	−0.66	0.13	−0.27	−1.48	0.14	−0.73
42	Khchem Er'rih	21	0.64	1.38	−0.84	−0.11	−0.47	−1.67	−0.04	−0.90
45	Hassi Ben Abdelleh 3	22	0.90	1.90	−0.85	−0.12	−0.48	−1.69	−0.06	−0.90
47	Hassi Ben Abdelleh 4	23	0.64	1.43	−0.94	−0.13	−0.49	−1.75	−0.08	−1.00

Table 01:Saturation indices for commonly occurring minerals calculated using PHREEQC for groundwaters in the Continental Intercalaire aquifer, Algeria (edmund et al 2003)

III.6.1.1 Analysis of Major Minerals:

Calcite and Dolomite most samples show positive values (especially samples 12-47), indicating water saturation with these carbonate minerals and potential for their precipitation. Values increase significantly in areas like Sidi-Slimane and Hassi Ben Abdelleh, which may suggest:

Increased concentration of calcium and magnesium ions, Higher pH levels, Loss of carbon dioxide

- Gypsum

All samples show negative values (-0.34 to -1.44), indicating:

Dissolution of gypsum in groundwater, Deficiency in sulfate or calcium ion concentrations

Unfavorable conditions for gypsum formation

- Quartz and Chalcedony

Most samples are slightly undersaturated, but the difference is minimal, suggesting:

Near-ideal equilibrium with these silicate minerals and relative chemical stability in the system

All Fluorite samples are significantly undersaturated (-1.09 to -1.84), indicating:

Low fluoride ion concentration

High solubility of fluorite in these waters

Barite: Some samples are supersaturated (especially 1, 3, 12-17, 38, 40), which may lead to its precipitation

Celestite: All samples are undersaturated, indicating its dissolution

6.1.2 General Trends:

- There is a gradient in calcite and dolomite saturation from west to east (values increase in later samples)
- Most samples are in equilibrium with quartz and chalcedony
- Sulfate minerals (gypsum, barite, celestite) show variable behavior

6.1.3Hydrogeochemical Implications:

- Carbonate saturation with sulfate undersaturation suggests carbonate processes dominate the system

- - These patterns may reflect: Different water-rock interactions in various areas ,Variations in water sources or flow paths,

Potential anthropogenic influences in some regions.

III.6.2.CT Aquifer:

LOCALITY	Calcite	Dolomite	Gypsum	Anhydrite	Celestite	Barite	Fluorite
El-Alia	0.38	0.69	–0.26	–0.46		–0.11	–0.19
DASE	0.80	1.62	–0.30	–0.51	–3.35	–0.06	–0.36
Blidet Omar 1964	0.09	0.14	–0.31	–0.53	–3.31	–0.08	–0.27
Sidi-Slimane	0.41	0.65	–0.29	–0.51	–3.31	–0.06	–0.11
Touggourt Ville	0.30	0.52	–0.27	–0.50	–3.27	–0.12	–0.20
Djamâa (Ain Zerrouk)	0.43	0.78	–0.10	–0.33	–3.10	–0.01	0.04
Sidi-Khellil	0.51	0.88	–0.23	–0.45	–3.27	–0.02	0.00
El-Meghaïer (El Alia) 1987	0.49	0.83	–0.42	–0.65	–3.46	–0.11	0.00
El Meghaïer	0.48	0.81	–0.39	–0.61	–3.42	0.02	0.13
Khchem Er'rih	0.17	0.36	–0.49	–0.71	–3.51	–0.15	–0.43
Sidi-Belkheir	0.36	0.72	–0.46	–0.68	–3.54	–0.10	–0.54
El-Bekrat	0.02	0.07	–0.48	–0.70	–3.56	–0.15	–0.55
Istikama (Hassi Ben Abdellah)	0.16	0.31	–0.49	–0.70	–3.59	–0.04	–0.64
Ain-Djrad	0.32	0.53	–0.55	–0.76	–3.64	–0.13	–0.62
Gassi-Touil, GT3	–0.89	–1.93	–0.69	–0.90	–3.82	–0.17	–1.39
Gassi-Touil, HT4	–0.77	–1.69	–0.61	–0.81	–3.72	–0.12	–1.32
Gassi-Touil, GT2	–0.20	–0.54	–0.55	–0.74	–3.63	–0.14	–1.34
Gassi-Touil, M3	–0.49	–1.12	–0.54	–0.74	–3.62	–0.13	–1.25
Gassi-Touil, P	0.04	–0.04	–0.66	–0.86	–3.80	–0.14	–1.44
Rhourde El Baguel, MP103	–0.49	–1.03	–0.73	–0.94	–3.52	–0.07	–0.66
Rhourde El Baguel, MP106	–0.40	–0.85	–0.74	–0.95	–3.56	–0.07	–0.61
Rhourde El Baguel, P1	–0.31	–0.83	–0.64	–0.84	–3.45	0.12	–0.47
Rhourde El Baguel, MP105	–0.14	–0.31	–0.62	–0.82	–3.41	0.02	–0.65
Hassi-Messaoud Sagra, S1	0.39	0.67	–0.25	–0.45	–3.30	0.03	–0.32
Hassi-Messaoud, H2	0.71	1.30	–0.44	–0.31	–3.21	–0.52	–0.69
Djamâa Sidi-Yahia, MP5	–0.17	–0.02	–0.20	–0.42	–3.21	–0.07	–0.11
Hamraïa, HAM6	0.05	0.10	–0.52	–0.70	–3.44	–0.13	–0.23
Hamraïa, HAM4	–0.06	–0.15	–0.50	–0.68	–3.43	–0.13	–0.21
M'Guebra, GUEB	0.20	0.32	–0.34	–0.54	–3.33	–0.13	–0.07
Rhourde Nouss, RN15	–0.28	–0.70	–0.70	–0.92	–3.56	0.02	
Rhourde Nouss, RN17	0.22	0.38	–0.64	–0.85	–3.47	–0.04	
Rhourde Nouss, ALCIM	0.12	0.14	–1.24	–1.46	–4.22	–0.10	
El-Hamra, HRA	0.14	0.22	–1.19	–1.39	–4.44	–0.13	
El-Hamra, HRA1	0.31	0.53	–1.03	–1.24	–4.26	–0.10	
Rhourde Nouss, St. Pompage	0.30	0.40	–0.24	–0.47	–3.46	0.00	

Table 02:Saturation indices for commonly occurring minerals aquifer, Algeria (Goundouz et al ,2003)

6.1.1.Analysis of Major Minerals:

Positive values: Indicate oversaturation, meaning the mineral may precipitate (e.g., calcite and dolomite in some areas).

Negative values: Indicate undersaturation, meaning the mineral may dissolve (e.g., gypsum and anhydrite in most areas).

- Calcite and Dolomite: Mostly positive values, suggesting oversaturation and potential precipitation.
- Gypsum and Anhydrite: Consistently negative values, indicating undersaturation and potential dissolution.

- Celestite, Barite, and Fluorite: Values vary between positive and negative, reflecting differing chemical conditions across locations.

Areas like *Gassi-Touil* and *Rhourde El Baguel* show highly negative values for calcite and dolomite, suggesting dissolution. In contrast, regions like Hassi-Messaoud* exhibit high saturation, favoring mineral precipitation .(Figure 26)

7. Distribution of Isotopes Elements (CI & CT):

7.1.CI Aquifer:

CI groundwater is highly depleted in stable isotopes ($\delta^{18}O$ and δ^2H) compared to modernrainfall, especially in the Great Oriental Erg sub-basin. The most depleted values (as low as $\delta^{18}O = -6‰$) indicate ancient recharge during cooler, wetter periods, likely the late Pleistocene.(Figure 26)

Radiocarbon (^14C) ages are at or near detection limits except near outcrops, confirming the fossil nature of most CI groundwater and indicating minimal modern recharge.

In some areas, isotopic enrichment suggests mixing between old CI water and more recent, evaporation-affected water infiltrating through dunes. (Figure 26) (Edmunds et al ,2003)

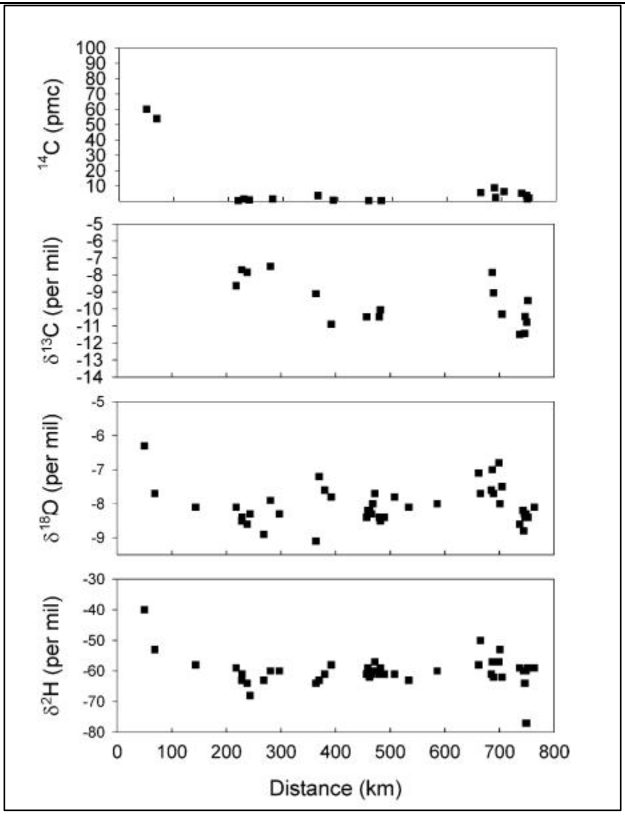


Figure 18: Hydrogeochemical cross section through the CI aquifer with 14C, d13C, d18O, d2 H.

7.1.1 the Isotopic Analysis of Hydrogen and Oxygen in :

The stable isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) are widely used as tracers in hydrology to determine the origin, age, and history of water. These isotopic signatures help distinguish between modern meteoric water, evaporated water, and fossil groundwater. This report presents an isotopic analysis of several water samples compared to standard meteoric water lines in order to identify their source and evaluate their hydrological significance.(Figure 27)

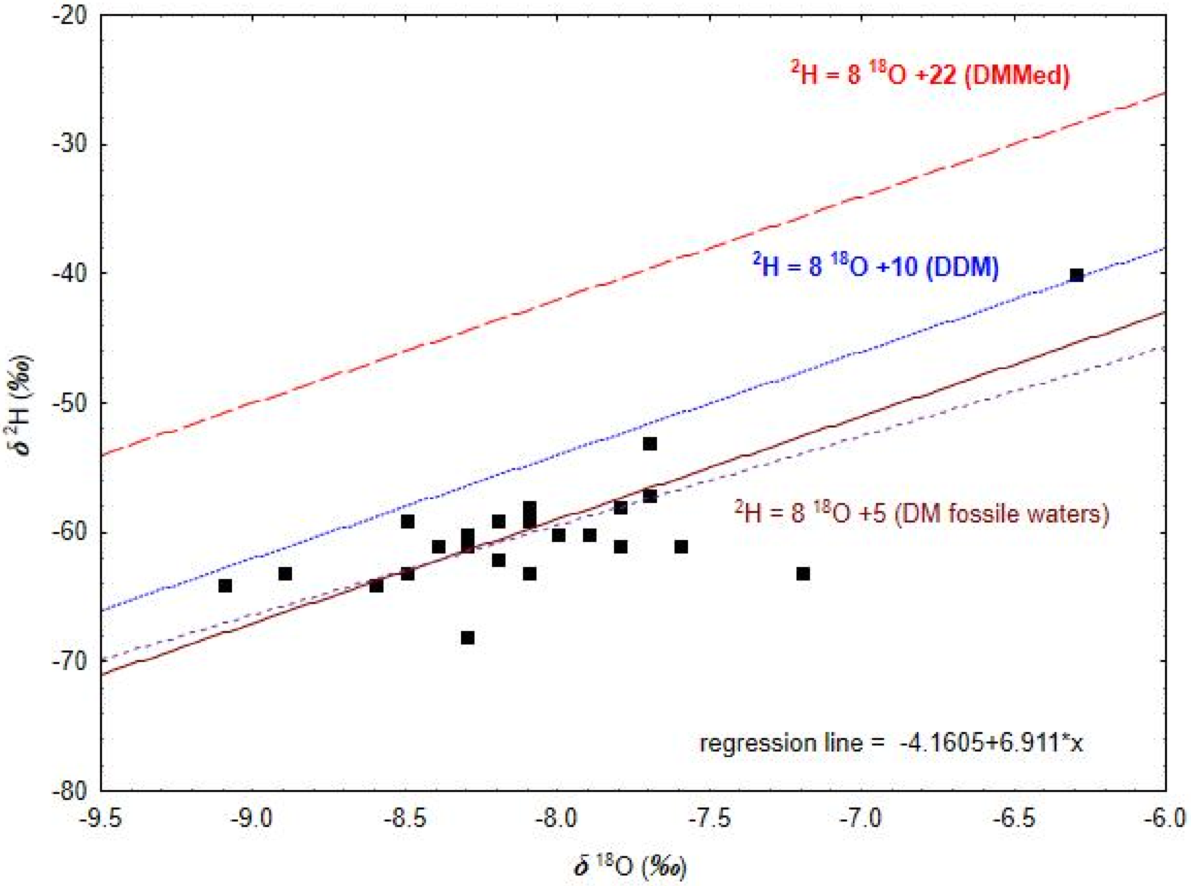


Figure 19:Plot of d18O, d2H of (CI) diagram in relation to the global meteoric water line

The provided graph plots the isotopic composition of the water samples (black squares) using δ^2H values on the y-axis and δ^{18}O values on the x-axis. Three reference lines are included for comparison:

Red dashed line: $\delta^2H = 8 \cdot \delta^{18}O + 22$

This represents the Mediterranean Meteoric Water Line (DMMed), typical for precipitation in the Mediterranean region.

Blue dotted line: $\delta^2H = 8 \cdot \delta^{18}O + 10$

This is the Global Meteoric Water Line (GMWL), a worldwide average relationship between hydrogen and oxygen isotopes in precipitation.

Brown solid line: $\delta^2H = 8 \cdot \delta^{18}O + 5$

This line represents the Fossil Water Line, which characterizes groundwater that was recharged during past climatic conditions (usually colder and less humid than today).

Most of the sample points lie close to the fossil water line, and below both the global and Mediterranean meteoric water lines.

The isotopic values are relatively low, especially for δ^2H, which typically suggests:

- Minimal evaporation effects
- Recharge during colder climatic periods (possibly during glacial or post-glacial times)

The linear trend of the samples aligns more closely with fossil water characteristics than with modern meteoric water.

The isotopic signatures of the analyzed samples shows that the water is not of recent meteoric origin. Instead, the data suggest that the water likely represents fossil groundwater, possibly recharged thousands of years ago under climatic conditions different from those of the present. The alignment with the $\delta^2H = 8 \cdot \delta^{18}O + 5$ line supports this .
Such fossil groundwater is typically stored in deep aquifers, often isolated from current hydrological cycles, and is considered a non-renewable resource. Identifying this origin is important for the sustainable management and protection of these ancient water reserves.

7.2. CT Aquifer:

In some areas, isotopic enrichment suggests mixing between old CI water and more recent, evaporation-affected water infiltrating through dunes
CT groundwater shows a range of $\delta^{18}O$ values, all enriched relative to deuterium, indicating evaporative enrichment from parent rainfall with $\delta^{18}O$ around –11‰. This points
to recharge under cooler conditions in the late Pleistocene and possibly heavy monsoon rains during the Holocene.(Figure 28)
14C data reveal two main recharge periods: late Pleistocene (0–8.4 pmc in deeper groundwater) and Holocene (24.7–38.9 pmc), with a hiatus corresponding to hyper-arid conditions.(Gounduz et al ,2003)

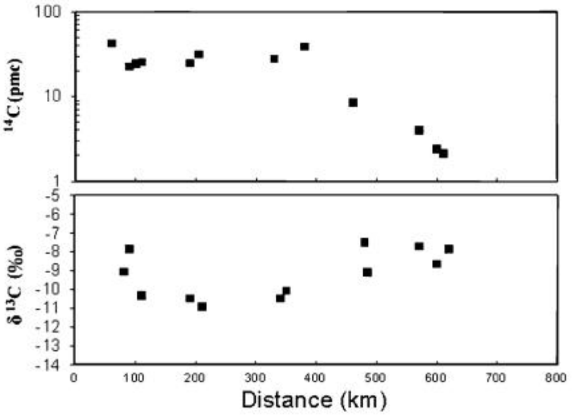
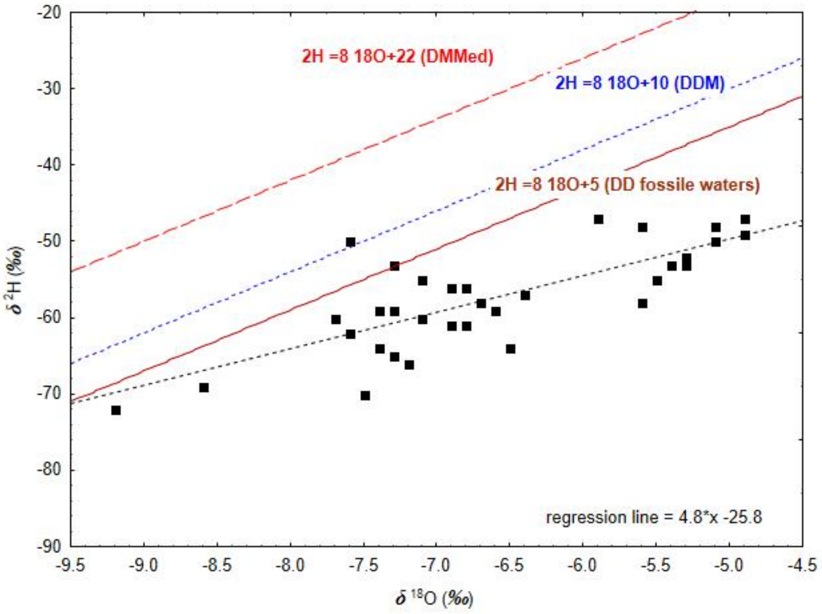


Figure 20:Isotopic Evolution (Edmunds et al, 2003)

7.2.1.Hydrogeological Interpretation of the D2H vs O18 Graph:



Figuer 21:Relationship between δ^2H and $\delta^{18}O$ Isotopic Signatures in the Complex Terminal

The graph showing the relationship between the isotopes deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) for the Complex Terminal aquifer system reveals a linear correlation between the values. This indicates that the groundwater likely originates from a relatively uniform hydrological source, possibly resulting from direct recharge by precipitation. This relationship is a strong indicator of the absence or limited influence of evaporation or mixing with surface waters or other distinct sources, suggesting isotopic and chemical stability within the aquifer system. (Figure 25)

7.3. Comparison of Isotopic Diagrams: CI vs CT

The following analysis compares two isotopic diagrams illustrating the relationship between stable hydrogen (d²H) and oxygen (d¹⁸O) isotopes in water samples. The left diagram represents the CT region, while the right one pertains to the CI region.

7.3.1. Data Range and Point Distribution:

We can notice that in (CT) Diagram $\delta^{18}O$ values range from approximately -9.5‰ to -6.0‰ ,and δ^2H values range from -75‰ to -45‰

Data points are relatively clustered, suggesting a consistent isotopic signature and potentially a single recharge source.

But in (CI) $\delta^{18}O$ values span from -9.5‰ to -4.5‰ and δ^2H values extend from -85‰ to -40‰

The distribution is more scattered, indicating diverse sources or significant post-recharge processes.

III.7.3.2.Sample Regression Line:

CT region have regression line is not explicitly shown, but visual alignment suggests close proximity to the fossil water line, reinforcing the hypothesis of paleowater origin.

CI region have regression line is included: $\delta^2H = 4.8\delta^{18}O - 25.8$

This slope is significantly lower than 8, hinting at evaporation effects or mixing processes affecting the isotopic composition

III.7.3.3 Hydrogeological Interpretation:

The CT Region have isotopic signature suggests ancient, stable groundwater with minimal influence from recent precipitation or evaporation.

Likely a homogeneous recharge source, possibly dating back to wetter climatic periods.

The CI Region have wider isotopic range and deviation from the GMWL and fossil water line imply a more complex hydrological history.Likely influenced by multiple recharge.

Conclusion :

In the eastern basin of the Northern Sahara in Algeria, the hydrogeochemical study reveals a progressive evolution of major and minor elements, influenced by both natural geochemical processes and the hydrogeological framework of the region. Major ions such as Na^+, Cl^-, SO_4^{2-}, and HCO_3^- dominate the water chemistry, reflecting long water-rock interaction pathways, especially in deep and confined aquifers. Minor elements, including trace metals, show spatial variability associated with lithological differences and redox conditions.

Isotopic analyses ($\delta^{18}O$, δ^2H, and ^3H) confirm the presence of both ancient (fossil) water of Saharan origin and more recent recharge in shallower zones, indicating complex mixing processes. The isotope data also provide crucial information about evaporation trends and paleoclimatic conditions during recharge events.

Saturation index calculations indicate that groundwater is generally saturated or oversaturated with respect to carbonate minerals such as calcite and dolomite, suggesting precipitation or equilibrium states, while often undersaturated with respect to evaporite minerals like gypsum and halite, reflecting ongoing dissolution. These patterns confirm the maturity of groundwater and the influence of both geochemical evolution and aquifer confinement in shaping water quality in the region.

General Conclusion:

This hydrogeochemical study of the Eastern Basin of the Algerian Sahara has provided valuable insights into the complex interplay between geology, hydrogeology, and groundwater chemistry in an arid environment. The region is characterized by diverse geological formations ranging from ancient sedimentary layers to more recent deposits, which significantly influence the physicochemical properties of groundwater. These formations act as both reservoirs and reactive media, controlling the mineralization processes and water quality.

From a hydrogeological perspective, the basin hosts multiple aquifer systems with varying productivity and depths, notably the Continental Intercalaire and the Complex Terminal. These aquifers are essential for supporting local populations and agricultural activities, but they are increasingly threatened by overexploitation and climatic stress. Understanding their behavior and recharge dynamics is therefore critical for sustainable management.To investigate the geochemical evolution of groundwater, a comprehensive analytical approach was adopted. This included the use of classical diagrams such as Piper and Stabler for water classification, as well as the calculation of saturation indices using the PHREEQC software. These tools enabled the assessment of equilibrium states with respect to various minerals and provided clues about dissolution and precipitation processes within the aquifer system.

The study also revealed the spatial distribution of major ions (such as calcium, magnesium, sodium, bicarbonate, and chloride) , highlighting the influence of both natural geochemical processes and potential anthropogenic inputs. Additionally, the integration of environmental isotope data (such as $\delta^{18}O$ and $\delta^{2}H$) allowed for a better understanding of the origin of groundwater, recharge sources, and mixing phenomena.

Overall, the findings underline the importance of a multidisciplinary approach that combines geology, hydrogeology, geochemistry, and isotopy to evaluate the status and evolution of groundwater in arid regions. This study contributes to the scientific basis necessary for informed water resource planning and highlights the urgent need for sustainable groundwater management in the Eastern Sahara, where water is a scarce and vital resource

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الملخص

تهدف هذه الدراسة إلى دراسة الخصائص الهيدروجيوكيميائية للمياه الجوفية في الحوض الشرقي لصحراء الجزائر، من أجل تقييم تم اعتماد مقاربة متعددة التخصصات شملت توصيفًا .نوعيتها وفهم العمليات الجيولوجية والجيوكيميائية التي تؤثر على تطورها لتحديد نوعية تم استخدام مخططات مثل بايبر وبرنامج PHREEQC.جيولوجيًا وهيدروجيولوجيًا، وتحاليل كيميائية ونظائرية أظهرت النتائج تأثير التكوينات الجيولوجية، .كما تم تحليل توزيع العناصر الرئيسية والثانوية .المياه وتوازنها مع المعادن تساهم النتائج في فهم تطور المياه الجوفية ودعم إدارتها المستدامة .الصخر، والأنشطة البشرية–وتفاعلات الماء.

2. Abstract

This study explores the hydrogeochemical characteristics of groundwater in the Eastern Basin of the Algerian Sahara to assess water quality and identify the main geochemical processes at play. Using a combination of geological and hydrogeological analysis, chemical testing, and stable isotope data ($\delta^{18}O$ and $\delta^{2}H$), the research reveals the influence of geological formations, water-rock interactions, and human activities on groundwater composition.

Tools such as Piper diagrams and PHREEQC modeling were employed to classify water types and evaluate mineral saturation. The spatial distribution of major and minor elements highlights both natural and anthropogenic impacts. The findings contribute to a better understanding of groundwater evolution in arid regions and support sustainable water resource management.

3. Résumé

Cette étude examine les caractéristiques hydrogéochimiques des eaux souterraines du bassin oriental du Sahara algérien afin d’évaluer leur qualité et d’identifier les principaux processus géochimiques. En combinant analyses géologiques et hydrogéologiques, tests chimiques et données isotopiques stables ($\delta^{18}O$ et $\delta^{2}H$), la recherche met en évidence l’influence des formations géologiques, des interactions eau-roche et des activités humaines sur la composition des eaux.

Des outils tels que les diagrammes de Piper et la modélisation avec PHREEQC ont été utilisés pour classifier les types d’eau et évaluer la saturation en minéraux. La distribution spatiale des éléments majeurs et mineurs reflète des impacts à la fois naturels et anthropiques. Les résultats apportent une meilleure compréhension de l’évolution des eaux souterraines en milieu aride et soutiennent une gestion durable des ressources en eau.