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**Hydrogeological and hydrochemical study of
groundwater in the Béni Ounif region (SW Algeria)**

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Dedication

It is with all my affection that I dedicate this modest

work;

My parents

My brothers and sisters, and my whole family, the Arfa

family.

All my colleagues and friends.

All geology teachers and students.

ABDELLAH ARFA

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Abstract

This research focuses on the Beni Ounif region, located in the southwest of Algeria, covering an area of 42,730 km² with an estimated population of 13,000 inhabitants. The primary goal of this study is to enhance the understanding of the hydrogeology and hydrogeochemistry of the Beni Ounif aquifers through a series of hydrogeological investigations and analyses of groundwater samples collected from the area. The results identify three main aquifers: the Continental Intercalary (CI) aquifer, which is the most significant with a thickness varying between 100 m and 300 m; above it, the Turonian aquifer, which is of lesser interest in the region; and the superficial free aquifer, composed of Quaternary alluvium, varying in thickness from 300 m to 380 m. Water quality assessments using the Water Quality Index (WQI) revealed that the water quality of the superficial aquifer is predominantly good, with portions classified as mediocre (6.67%) and excellent (13.33%). The water from the CI aquifer was primarily deemed suitable for consumption. Agricultural suitability was assessed using the Irrigation Water Quality Index (IWQI), rating most groundwater samples as good or excellent. Industrial evaluations focused on the water's corrosive potential and scaling capacity, highlighting some samples requiring treatment to meet industrial standards. Additionally, hydrochemical signatures and mineralization processes were extensively studied using Piper, Schoeller, and Gibbs diagrams, along with binary diagrams and saturation index calculations. These analyses indicated that mineralization is primarily influenced by the weathering of silicates and carbonates, the dissolution of evaporites, cation exchange, and anthropogenic inputs, primarily affecting water chemistry in these aquifers. This comprehensive understanding aids in the effective management and use of groundwater resources in the Beni Ounif region. The Beni Ounif region faces increasing water demand (8.46 million m³/year), met by a transfer project delivering 30,000 m³/day from the Albien aquifer, while also being highly vulnerable to floods affecting over 241 hectares. An integrated strategy is recommended, including early warning systems, infrastructure reinforcement, urban planning regulations, community awareness, and sustainable water management.

Keywords: Beni Ounif, hydrogeological, hydrochemical, WQI, Continental Intercalaire, irrigation.

Résumé

Cette étude se penche sur la région de Beni Ounif, localisée dans le sud-ouest de l'Algérie, qui s'étend sur 42 730 km² et abrite environ 13 000 résidents. Son but principal est de renforcer les connaissances en hydrogéologie et hydrogéochimie des aquifères de Beni Ounif par des investigations hydrogéologiques et des analyses d'échantillons d'eau souterraine prélevés dans cette zone. L'étude identifie trois aquifères principaux : l'aquifère Continental Intercalaire (CI) qui est le plus significatif avec une épaisseur variant entre 100 m et 300 m; au-dessus de celui-ci, l'aquifère du Turonien, qui présente un intérêt moindre, et enfin l'aquifère superficiel libre, formé d'alluvions quaternaires avec une épaisseur fluctuant de 300 m à 380 m. L'évaluation de la qualité de l'eau selon l'indice de qualité de l'eau (WQI) a révélé que la qualité de l'eau de l'aquifère superficiel est en majorité bonne, avec des portions jugées médiocres (6,67 %) et excellentes (13,33 %). L'eau de l'aquifère CI a été principalement considérée comme bonne pour la consommation. L'aptitude à l'irrigation a été évaluée avec l'indice de qualité de l'eau d'irrigation (IWQI), classant la plupart des échantillons comme bons ou excellents. Des analyses industrielles ont également été menées pour évaluer le potentiel corrosif et la capacité d'entartrage de l'eau, révélant la nécessité de traitements pour certaines eaux afin de respecter les normes industrielles. Par ailleurs, les signatures hydrochimiques et les processus de minéralisation ont été approfondis via diverses méthodes d'analyse telles que les diagrammes de Piper, Schoeller, Gibbs, ainsi que des diagrammes binaires et des calculs d'indices de saturation. Ces études montrent que la minéralisation est principalement due à l'altération des silicates et carbonates, la dissolution des évaporites, les échanges cationiques et les influences anthropogéniques, influençant ainsi la chimie des aquifères. Ces connaissances contribuent à une gestion plus efficace des ressources en eau souterraine de Beni Ounif. La région de Beni Ounif connaît une forte demande en eau (8,46 hm³/an) couverte par un projet de transfert de 30 000 m³/j depuis la nappe albiennaise, tout en étant exposée à de graves risques d'inondation affectant plus de 241 ha. Une stratégie intégrée est recommandée, combinant alertes précoces, renforcement des infrastructures, aménagement du territoire et gestion durable des eaux.

Mots clés : Beni Ounif, hydrogéologique, hydrochimique, WQI, Continental Intercalaire, irrigation.

تركز هذه الدراسة على منطقة بني ونيف، الواقعة في جنوب غرب الجزائر، وتغطي مساحة 42,730 كم² مع تعداد سكاني يقدر بـ 13,000 نسمة. الهدف الرئيسي لهذه الدراسة هو تعزيز فهم علم الهيدروجيولوجيا والهيدروجيوكيمياء للخزانات الجوفية في بني ونيف من خلال سلسلة من التحقيقات الهيدروجيولوجية وتحليل عينات المياه الجوفية التي تم جمعها من المنطقة. تحدد النتائج ثلاثة خزانات رئيسية: الخزان الجوفي للمتداخل القاري، والذي يعتبر الأكثر أهمية مع سمك يتراوح بين 100 م و 300 م؛ فوقه، خزان تورونيان، الذي يعتبر ذا أهمية أقل في المنطقة؛ والخزان السطحي الحر، المكون من الرواسب الرباعية، ويتفاوت سمكه بين 300 م و 380 م. أظهرت تقييمات جودة المياه باستخدام مؤشر جودة المياه أن جودة مياه الخزان السطحي جيدة بشكل أساسي، مع أجزاء تصنف على أنها متوسطة (6.67%) وممتازة (13.33%). وقد تم تقييم المياه من الخزان المتداخل القاري على أنها مناسبة بشكل أساسي للشرب. تم تقييم الصلاحية الزراعية باستخدام مؤشر جودة مياه الري، حيث تم تصنيف معظم عينات المياه الجوفية على أنها جيدة أو ممتازة. ركزت التقييمات الصناعية على القدرة التآكلية للمياه وقدرتها على التآكل، مما يسلط الضوء على بعض العينات التي تتطلب معالجة لتلبية المعايير الصناعية. بالإضافة إلى ذلك، تم دراسة التواقيع الهيدروكيميائية وعمليات التمعدين بشكل واسع باستخدام تخطيطات بيير، شويلر وجيبس، إلى جانب التخطيطات الثنائية وحسابات مؤشرات التشبع. أشارت هذه التحليلات إلى أن التمعدين يتأثر بشكل أساسي بتجوية السيليكات والكربونات، وذوبان البخريات، وتبادل الكاتيونات، والمدخلات الأنثروبوجينية، مما يؤثر بشكل أساسي على كيمياء المياه في هذه الخزانات. تساعد هذه الفهم الشامل في الإدارة الفعالة واستخدام الموارد المائية الجوفية في منطقة بني ونيف. تعاني منطقة بني ونيف من طلب متزايد على المياه (8.46 مليون م³ سنوياً) يُلبى من خلال مشروع نقل 30,000 م³ يومياً من طبقة المياه الجوفية الألبية، كما تواجه مخاطر كبيرة من الفيضانات التي تغمر أكثر من 241 هكتاراً. ويوصى باعتماد إستراتيجية شاملة تشمل أنظمة إنذار مبكر، وتعزيز البنية التحتية، وتنظيم العمران، والتوعية المجتمعية، والإدارة المستدامة للموارد المائية.

الكلمات المفتاحية: بني أونيف، الهيدروجيولوجية، الهيدروكيميائية، WQI، المتداخل القاري، الري.

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General Introduction

General Introduction

The Beni Ounif region, located in the B  char Province, has experienced rapid population growth, reaching 11,778 inhabitants. This growth has been accompanied by significant expansion in the agricultural, industrial and tourism sectors. Alongside this development, water demand has increased sharply, prompting the greater use of advanced techniques for extracting and exploiting groundwater to meet rising needs. This dynamic shift has also prompted farmers to move towards large-scale agricultural development projects, putting further pressure on surface water resources and aquifers in the area.

In April 2019, hydraulic resource managers initiated a major project to transfer groundwater from Beni Ounif. This project involves redirecting 30,000 cubic metres of water daily through a network of ten deep wells, each ranging from 400 to 500 metres deep, primarily exploiting the Continental Intercalary (CI) aquifer. The system is designed to fill two large reservoirs with capacities of 15,000 and 20,000 cubic metres respectively, supplying potable water to the local municipalities of Bechar, Kenadza, Abadla, Mechraa Houari-Boumediene and Erg Farradj.

Despite these advancements, our understanding of the hydrogeology of the Beni Ounif region is limited, particularly with regard to aquifer geometry, recharge dynamics and the hydrodynamic and hydrochemical properties of the groundwater.

This thesis aims to improve knowledge of the hydrogeology and hydrogeochemistry of the Beni Ounif aquifers by conducting comprehensive hydrogeological, hydrodynamic and geophysical studies and detailed analyses of groundwater samples. The structure of the thesis is organised as follows:

Chapter 01 – General framework of the study: This chapter provides a comprehensive introduction to the study area, discussing its geography, land use, socio-economic characteristics, geology and climatology.

Chapter 02: Hydrogeological Study: This chapter delves into the hydrogeological characteristics of the area, detailing aquifer identification, piezometric analysis, and the evaluation of hydrodynamic data and drilling logs.

Chapter 3: Geophysical Study: This section analyses the results of geophysical surveys conducted in the region, with a focus on electrical and diagraphic techniques.

Chapter 04 – Hydrochemical Study: This chapter assesses the quality of groundwater through physico-chemical properties and its suitability for various uses, such as drinking, irrigation and

industrial processes. This is supported by advanced hydrochemical analyses, including Piper, Schoeller and Gibbs diagrams, as well as saturation index calculations.

Chapter 5: Water Resource Management: This chapter addresses management strategies in response to the intense exploitation of the regional capture field.

The thesis concludes with an overall summary of the main findings of the study, with the aim of contributing to the more informed and sustainable management of water resources in the Beni Ounif region.

Chapter 01 :
General Framework of the Study

1. Study area

1.1 Geographical location

The study area is located in the wilaya of Bechar in south-west Algeria. The administrative centre of Béni Ounif is located 110 km from the city of Béchar (see Fig. 1), and covers an area of 4,230 km². It is situated between the longitudes 4° and 3° West, and the latitudes 30° and 33° North. The estimated population in 2017 was 13,000, giving a population density of 1.01 inhabitants/km². The commune of Béni Ounif also borders the Kingdom of Morocco. Administratively, it is bounded by:

- To the north: the commune of Djenein-Bourezg and the daïra of Moghrar (Naama wilaya) and the Algerian–Moroccan border.
- To the south: the communes of El-Oued and Kerzaz (in the wilaya of Béchar).
- To the west: the communes of Béchar, Taghit and Moughel.
- To the east: the commune of El Biodh Sidi Cheikh (wilaya of El Bayadh).



Figure 1: Administrative boundaries of the commune of Béni Ounif and its geographical location

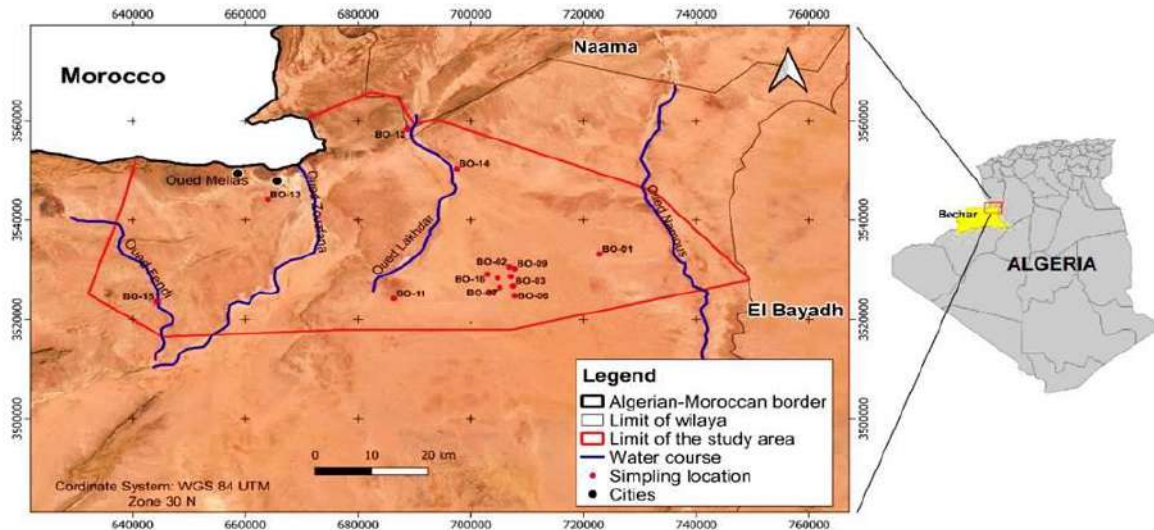


Figure 2: Geographical location of the study region

1.2 Background to the research

Unlike the other regions of the Saharan Atlas, the south-western end of the Ksour Mountains had not been subject of detailed geological and hydrogeological studies.

The work of Flamand (1911) on the Haut Pays de l'Oranais and the Sahara has served as a basis for all recent research.

Hydrogeological surveys were limited to a few publications carried out as part of drinking water supply for the village of Béni Ounif and the surrounding area. These works include

- **A. Cornet (1947)** Provides details of the Flemish stratigraphy, giving an idea of the various aquifers in the region and the possibilities exploitation based on purely statistical forecasts. His geological report was accompanied a 1:200,000 geological sketch.
- **G. Cheylan (1952)** For the creation of water points in the Daya de Mérises and Oued El Aouedj-Tahtani regions.

Two other reports were written by the same author;

- One in connection with the search for water improve national road no. 6 between Béni ounif and Bechar on 5 January (1955).
- The other, in February 1955, concerned improvements to the Beni ounif-Mograr section.
- **D. Galmier (1970)** As part of a 1:200,000 photogeological analysis of all the ksour mountains with nine sections to which the eastern part of the Révoil Béni ounif map is inserted.

- **Koulaguine (1975)** Under the direction of the D.H.W. of Béchar for evaluation of the hydric capacities and the improvement of drinking water supply of the town of Béni ounif. The other authors and researchers were mainly interested in the field of stratigraphy, tectonics and geomorphology and focused on the wider context of the Ksour Mountains in a fundamental synthesis to highlight the differences and similarities between the Saharan and Atlas domains.

Among the most recent are :

Bekhedda. B (1992) for his contribution to hydrogeological study of the Beni-Ounif syncline, engineering . This study was initiated by Professor P. VERDEIL, a pioneer of hydrogeology in Algeria, and supervised by Mr Mansour H., a teacher at the University of Es_sénia at the time.

- **Mansour H (2007)** For his state doctorate thesis, in which he collected all the old and recent works and linked them harmoniously, and was able to fill in the gaps both in knowledge and in the works provided, and answer all the questions asked to finally explain the hydrogeology of the Ksour mountains, the intercalary continental and the terminal complex.
- **ANRH and BETA-Consults (2011)** carried out geophysical study using electrical prospecting in the Beni Ounif area in the wilaya of Béchar.
- **Sghara N (2013)** he contributed with his magister thesis under the title: Protection de la ville de Béni-Ounif contre les inondations par l'application de logiciels HEC-HMS et HEC-RAS.
- **Bekhedda B (2016)** updated engineering work with a Master's thesis entitled Contribution à l'étude hydrogéologique des eaux souterraines de Béni-Ounif (Wilaya Béchar -Sud-Ouest Algérien).

1.3 Regional geology

Extended to the west by the Moroccan High Atlas and to east by the Aurès Mountains (Biskra), the Saharan Atlas can be subdivided into three main areas, west to east: the Western Saharan Atlas (Ksour Mountains), Central Saharan Atlas and Eastern Saharan Atlas.

The Western Saharan Atlas stretches over 700 km and is 50 to 70 km wide. Its summits are slightly higher than 2,000 metres to the south-west, but no higher than 1,500 metres to the north-east. They dominate the high steppes to the north, but overlook the Saharan Piedmont to the south ([DESPOIS, 1959](#)).

It forms part a folded mountain chain that has undergone intense tectonic activity over

geological time, with anticlinal folds that are generally capped, pinched, faulted, often overturned and parallel to the general north-east-south-west direction of the chain. These Jurassic-age anticlines are separated by depressed areas, sometimes perched, forming vast plains, filled in by continental sandstone-clay formations Lower Cretaceous age.

2. Socio-economic aspects

2.1. Agriculture: The agricultural sector underwent major expansion in the 1990s. State subsidies enabled the drilling of hundreds of boreholes and the cultivation of 5,400 hectares, 2,246.6 hectares of which are irrigated in the PMH, with an annual water requirement of 157 Hm³ in 2013. This was part of the development of large areas for producing cereals and other crops to make the region self-sufficient. The development perimeters are located in the northern part of the study area, upstream from the Oued Namous-Beni Ounif basins, a short distance from the hamlet. A 53-hectare agricultural perimeter has been selected for the settlement of 24 farmers, and the electrification of this area was initiated in the presence of Sonelgaz services and local authorities.

A similar operation involving the distribution of camel breeding stock was carried out in the villages of Fendi and Bén Zireg. The former is home to 60 families and is located 50 km north of Béchar, near National Route 6. The breeders in this small community of 60 registered families raised the issue of agricultural land ownership, which they claim has not yet been resolved. This would enable them to be recognised as owners of their agricultural land.

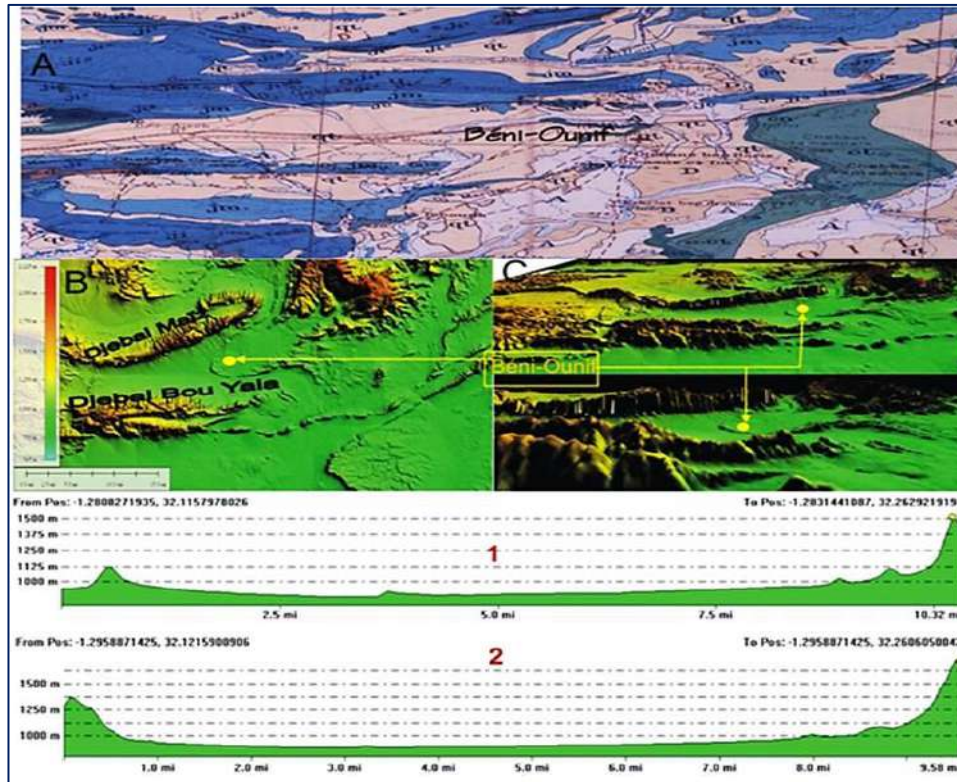
Several varieties of crop are grown in the palm groves, but yields are low due to the small size of the plots and the traditional irrigation methods used. These crops are generally grown for self-consumption.

Given the scarcity of rainfall and the aridity of the region, pastures are non-existent, which is the main obstacle to developing livestock farming here. The region's animal resources consist of a few species typical of Saharan regions: camels, goats, sheep and hundreds of cattle.

2.2 Industry: In recent years, the region has experienced accelerated industrial growth following the discovery of oil and gas deposits. There are around 20 oil and gas exploration wells in the south-east of the region, as well as 10 new water wells and an iron and steel extraction plant. The completion of the well field has turned it into an industrial hub, with several small factories being added (brickworks, flour mills, etc.).

2.3 Saharan tourism: Beni Ounif and Saoura are popular destinations. Like all the wilayas of the Deep South, the Beni Ounif and Saoura region is characterised by a high level of tourist activity, with more than 1,000 tourists visiting every year, especially during festival periods.

3. Geomorphological and topographical aspects.



A: geological map (taken from the Sud Oranais map), B: 3D DTM and topographical profiles.

Figure 3: Morphological map of the Béni Ounif region.

Using Global Mapper 11 software, the figure above gives an idea of the morphology of the Béni-Ounif region (**Fig3**). this region does not present a single morphological unit; on the contrary, we can distinguish:

- The southern reliefs of the Saharan Atlas are known as the Djebel Maïz, a veritable relief barrier. It rises to an altitude of 1750 m (**Fig3**, "Profile 2"), so this is the northern part.
- Southern relief: the Bou Yala Jebel at an altitude of 1,300 m (**Fig 3**, "profile2").

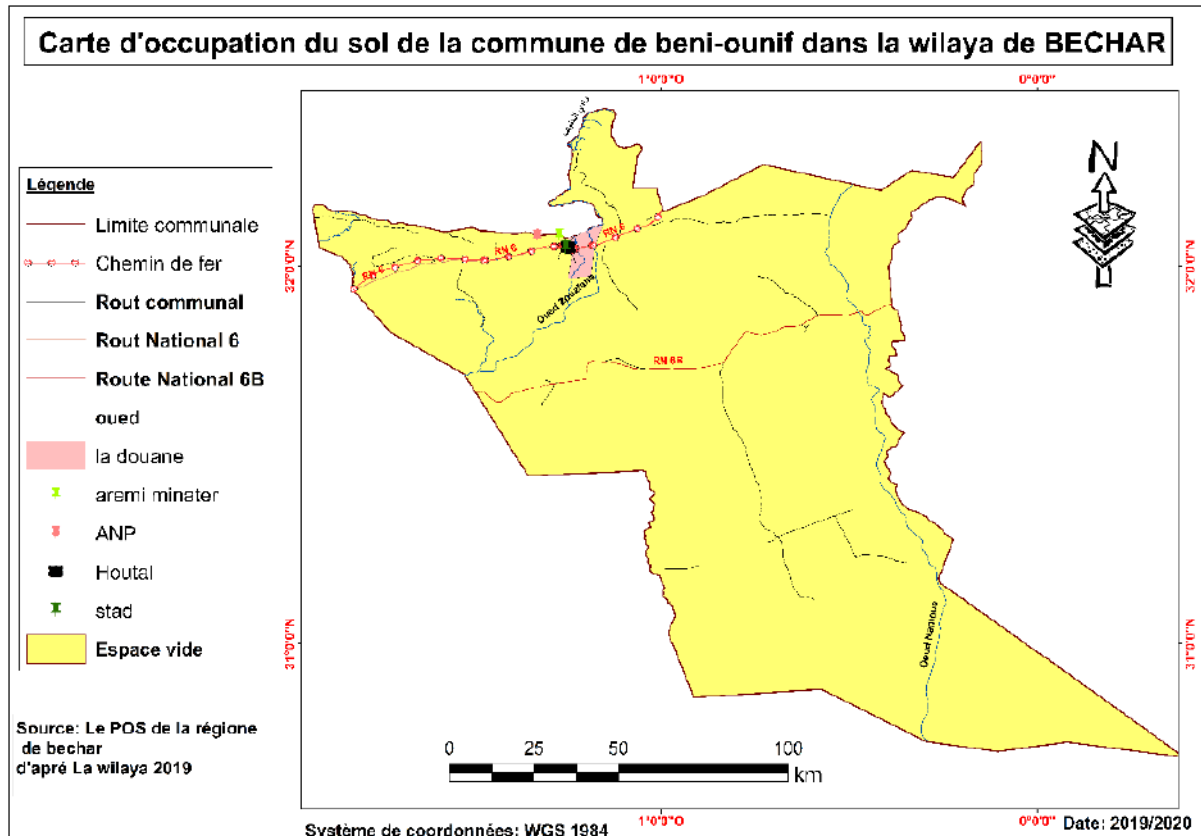


Figure 4: Land use map of the commune of Beni Ounif.

3.1. Bare rock: This is unaltered bedrock that does not support soil in the true sense. In some cases, it is polished by corrosion and coated in a black "desert varnish".

3.2. Regs: These regs are formed by the ablation and accumulation of pebbles, with a thickness of hardly more than one metre. There are two types: one autochthonous, where the elements have not been transported; they have simply been polished and burnished by the wind, and generally come from Cretaceous sandstones. The other type is allochthonous and consists of slope deposits formed from Jurassic limestone pebbles that have been rounded by the action of soft parts and grains of sand transported by the wind. The granulometry of the regs decreases from top to bottom.

3.3. Lacustrine limestone slabs: These have no vegetation and range in thickness from a few centimetres to four metres. The main deposits are found at the Zenaga Pass and in the Mélias Wadi, as well as in the Djenane-Tarf area to the south of Béni-Ounif. These deposits contain freshwater. Analysis has shown that they are formed from a mixture of sand grains, silts, clays and vacuolated limestones.

3.4. Alluvial soils: These are either stony soils formed on top of consolidated limestone.

Analysis has shown that the former are formed by stony limestone debris, around eighty centimetres thick, with an absence of soluble salts on the surface. The latter have fairly varied grain sizes, ranging from coarse sands at a depth of fifty centimetres to clays on the surface, where a concentration of soluble salts has been observed. The latter are generally clayey, two metres thick, and richer in soluble salts, which tend to migrate at depth. Analysis of the soil in the Beni Ounif palm grove shows that these salts generally accumulate on the surface following irrigation.

3.5. The dunes: They form along the large wadis (Zousfana) and can climb up the mountains on the outskirts of Chebket temednaia.

3.6. Solontchar: These soils only form in low-lying areas where water stagnates. Considerable salt accumulation occurs on the surface due to the evaporation of excess water during flooding or irrigation.

3.7. Hydrographic network: The Beni Ounif region belongs to the western basin unit of the northern Sahara. Due to low rainfall, the hydrographic network (Fig. 5) is the most developed; only the temporary Oued Namous has been dry for some years.

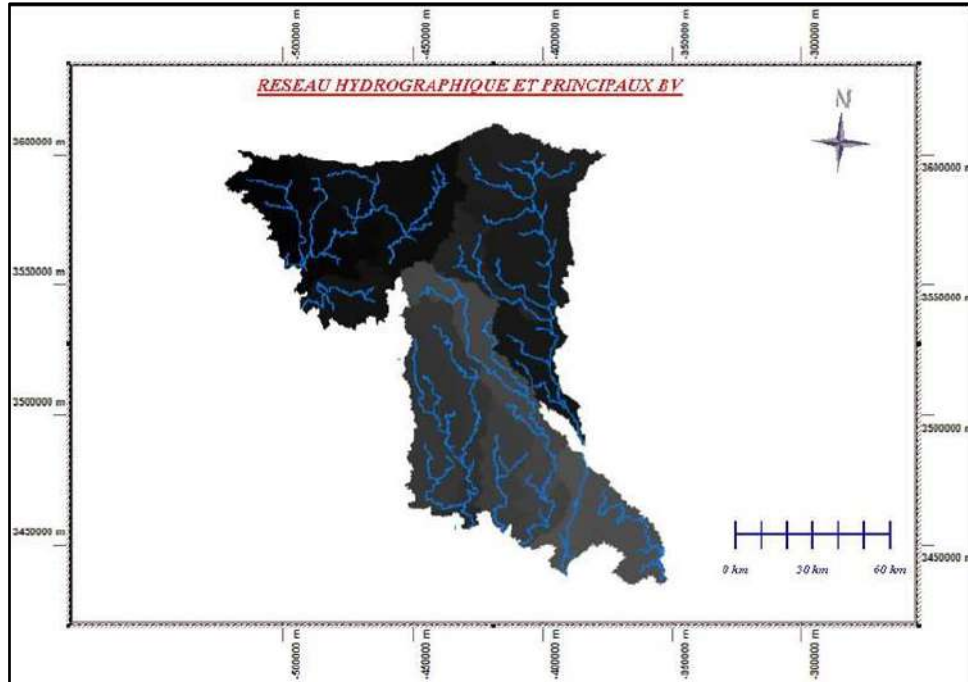


Figure.5 : Map of the Hydrographic Network in the commune of Beni Ounif.

4. GEOLOGY OF THE REGION

4.1. Situation of Oued Namous basin (Beni Ounif)

The study area is part of the great Saharan platform, located in the south Algeria, and belongs to the North African Craton. It is part of the Precambrian basement, which rests unconformably on a powerful sedimentary cover, structured in the Palaeozoic into several basins (**Fig. 6**), distinguished from west to east:

- The Tindouf Basin
- The Boubernous and Ougarta basins
- **The Béchar basin (Oued Namous / Beni ounif)**
- The Ahnet-Timimoun basin
- The Azzene and AzzelMatti pools
- The Sbaâ basin
- The Reggane basin
- The Mouydir and Aguemour-OuedMya basins
- The Illizi-Ghadamès Basin

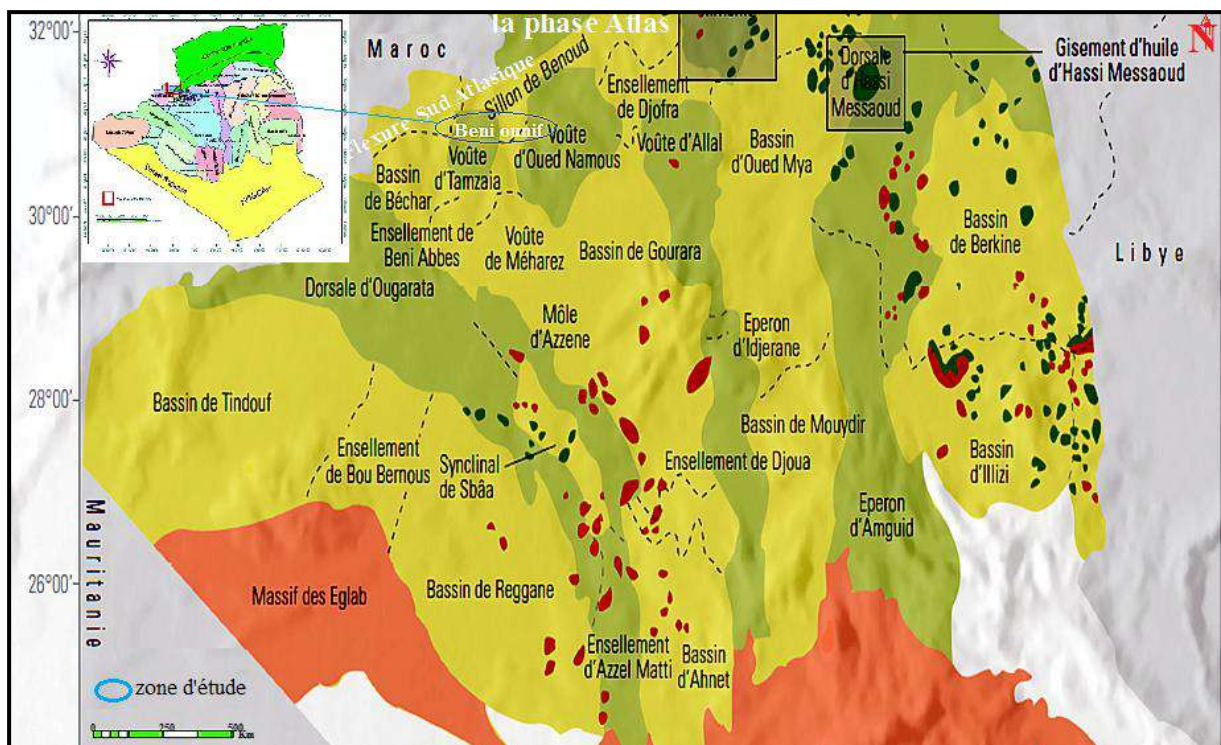


Figure 6: Distribution of basins in the Algerian Sahara (Wec2007).

The geological structure of the Oued Namous region (Fig. 7) is characterised by:

- a rugged basement attributed to the Precambrian era, which forms compartments within the Targui Shield (Hoggar) and is delimited by major faults. These compartments are part of the 'Pan-African Zone', which has been cratonised for 550 million years.

It is surrounded by Palaeozoic strata, which are covered by Mesozoic or recent formations (hamadas and ergs).

The sedimentary cover is angularly unconformable with the Palaeozoic basement, which extends from the Upper Cambrian to the Carboniferous and is characterised mainly by detrital deposits, platforms and cratonic features.

The sedimentary formations are up to 10 km thick.

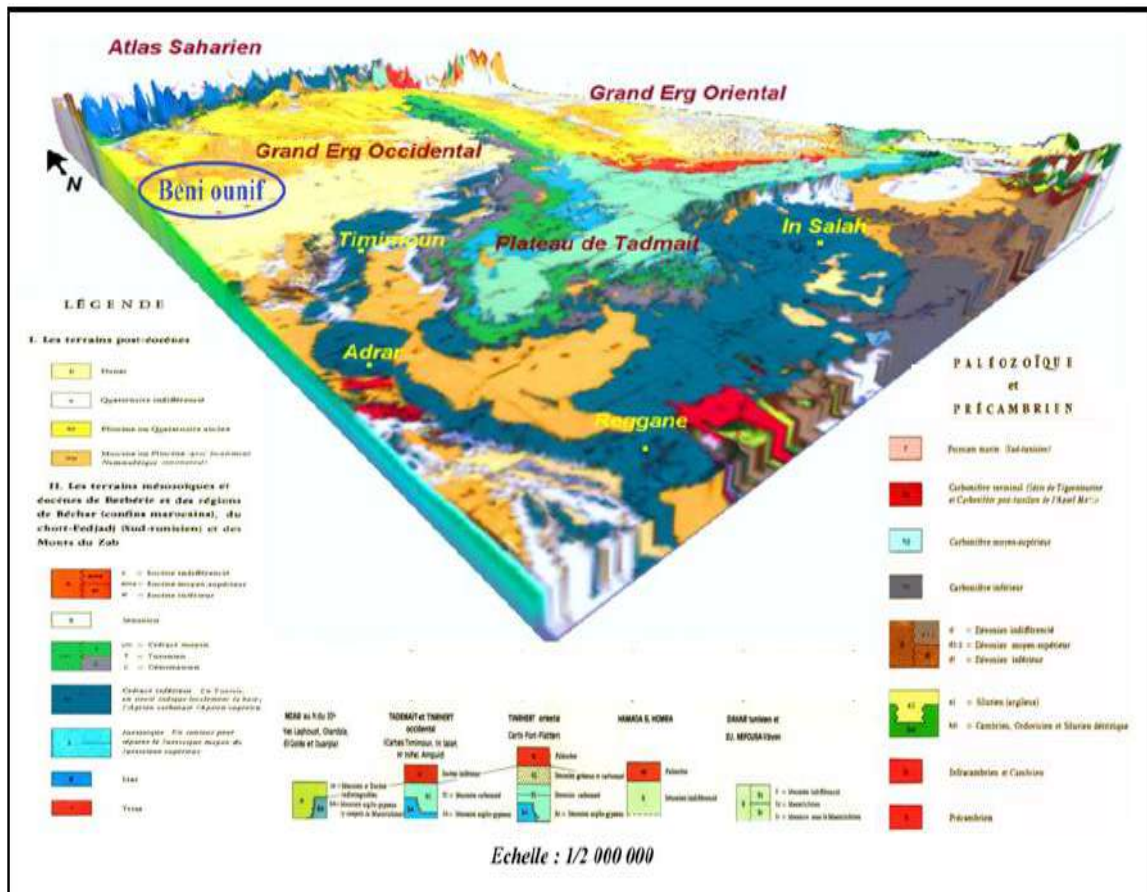


Figure 7: Geological map of the Algerian Sahara (Deleau 1952)

4.2. Regional lithostratigraphy of the Bechar

Analysis of the data (geological maps and drilling logs) has enabled us to identify the

stratigraphic levels crossed. Some of these have been grouped together to facilitate the correlation of the geological formations. Formations dating from the Palaeozoic era are grouped together under the name 'Palaeozoic', formations dating from the Jurassic to the Malm era are grouped together under the name 'Jurassic', and formations dating from the Lower Cretaceous era, from the Berriasian to the Albien, are grouped together under the term 'Continental Intercalaire C.I.'. The term 'Complexe Terminal C.T.' refers to formations dating from the Senonian to the Miocene-Pliocene. These groupings have enabled us to adopt a stratigraphic scale ranging from the Quaternary to the Palaeozoic. (Western Basin, 2005; Fabre, 2005).

The geological formations encountered in the study area (**Fig.8**) are described from bottom to top:

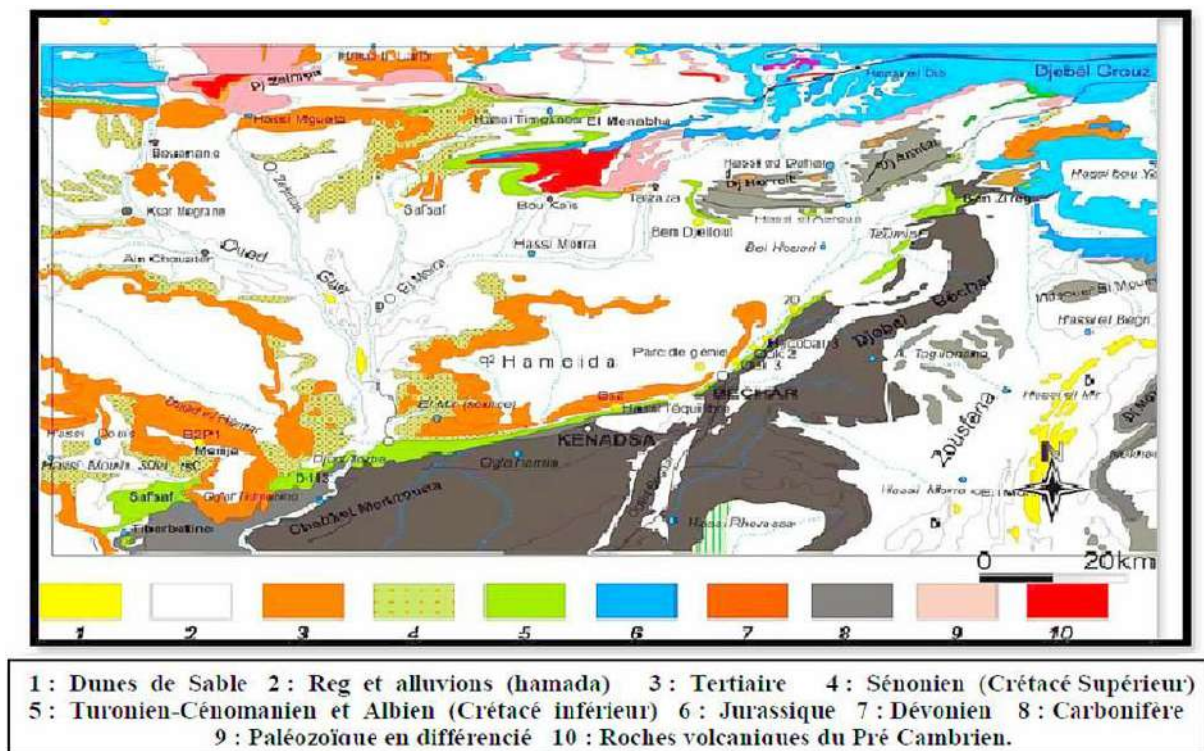


Figure 8: Geological map of Beni Ounif (Deleau, 1952).

4.2.1 The primary bedrock: The primary bedrock outcrops at the western edge of the study area near Zireg are formed by an anticline with a core of Cambro-Ordovician shales, sandstones and microconglomerates. To the north, it is unconformably overlain by glauconite sandstones and greenish Permo-Triassic marls. At Ben Zireg, the succession is more complete, with a Silurian represented by an intercalation of graptolite schists and limestones attributed to the Gotlandian, surmounted by an immense Devonian formation. To the west, the series becomes

younger and the Carboniferous rocks dominate at the foot of and along the Djebel Béchar, forming an impassable horizon

4.2.2 The Permo-Triassic: The Permo-Triassic terranes lie unconformably on the Cambro-Ordovician of Rocknet El Bettoum. At Meksem El Arich, further to the south, the Permo-Triassic rocks overlap the limestones of the Middle Cretaceous. The series is essentially made up of a greenish marl formation at the base, containing malachite mineralisation, then changing to glauconite sandstones and arkosic conglomerates. At the top are red clayey, ferruginous sandstones (Galmier 1970). It is also possible that Triassic clays and marls form the north-western base of the Djebel Haimeur relief to the north of Figuig. This outcrop could be exposed by an OSW-ENE fault.

4.2.3. Jurassi

a. The Lias: In the Béni-Ounif region, the liasic formations are mostly found along the djebel Grouz where they extend laterally and vertically, forming a veritable wall culminating at 1800 m. Observations in the field have enabled us to verify the descriptions of the geological photographs illustrated in Galmier's thesis (1970), while attempting establish a correlation.

Infralias: Above the conglomerates that mark the base of the lias and that can be followed along the southern flank of djebel Grouz , limestones and dolomites appear in small whites, then massive

Lower Lias: At Jebel Haimeur (north of Figuig), the Lower Lias is represented by a powerful mass of limestone and dolomite that crowns the chain. The cliff face features a series of alternately dark and very reserved limestone gullies, attributed to the Sinemurian by Roch (1950):

- A dolomitic formation with 70 m of beige dolomite.
- Gypseous marl and red clay with decimetre to centimetre-high banks of greenish limestone (40 to 50 m).
- Alternating metric to decimetric tubs of greenish limestone and dolomite platelets, whitish when broken and brownish when patinated.
- 20 to 25 cm of clay with limestone interlayers

Middle lias: On the southern flank of djebel Grouz, the transition from the light dolomitic limestones of the lower lias to the dark limestones arranged in a double bar of the middle lias is quite clear at djebel Rkina. The two bars follow each other in regular succession, separated

by a clay-marl depression. Further on, at djebel Haimeur, the double bar exists in a more complex morphology.

Upper Lias: The stratigraphic series of the Upper Lias corresponds to 70 m of massive black ferruginous limestone, significant micro-folds and a granular texture. With an abundant fauna of brachiopods and bivalves. To the south of the Ouazzani djebel, the layers are steeply inclined and come into contact with the dolomitic layers of the dogger. This contact is made by the South Atlasian fault. The Liassic formations also surface to the south of Beni Ounif, at Chebketcharef and Chebket-Fendi, where they are sometimes masked by recent deposits.

b. Dogger: Along the djebel Grouz, the dogger is laid down in more or less horizontal layers, forming a remarkable limestone ensemble at heart of a synclinal structure perched about 150 m high. This formation can be found on the northern flank of the Figuig hills, where the series is reversed on the Lower Cretaceous sandstone. To the south-west of the basin, the Dogger forms the anticlinal folds of Chebk et Charef and Chebk et Fendi.

4.2.4. Cretaceous (Albian, Cenomanian and Turonian): To the east of the study area, the Chebk et Temednaia forms a very spread out Turonian table with a gentle south-easterly or north-easterly dip, overhanging the Lower Cretaceous sandstone (Albian) deposits, forming a wide plateau with steep cliffs towards the Zouzfana valley. 30 km to the east of Beni Ounif, the Cenomanian-Turonian ledge changes direction to the east and south-east and is laid out in an inverted series beneath the Middle Jurassic of Djebel Kerdacha

A borehole drilled at El Aouedj Daklani, south-east of Béni Ounif, showed the existence of significant concentrations of manganese in the Turonian dolomites. The lithological section of the borehole showed from bottom to top :

- Cenomanian: marl with gypsum, interspersed with limestone containing bivalves and sea urchins. The limestones are centimetric at the base and become metric at the top. The whole is 50 m thick, underlain by Lower Cretaceous sandstones and clays.
- Turonian: 25 m of limestone with flint, iron oxide and manganese; these limestones are dolomitized at the top of the series.

4.2.5. Quaternary: Several studies have been devoted to the Quaternary ([Alimen, 1957](#); [Chavaillon 1964](#); [Conrad 1969](#) and [Beucher 1971](#)). These include terrace deposits, Sebkhah deposits and dunes. The small relief of Garet El Hamir, to the south of Béni Ounif, does not correspond to ancient Quaternary deposits. It extends northwards over the plain and under the

Zouzfana alluvium, then under the marl and limestone of the Chebket Temednaia (to the east and south-east).

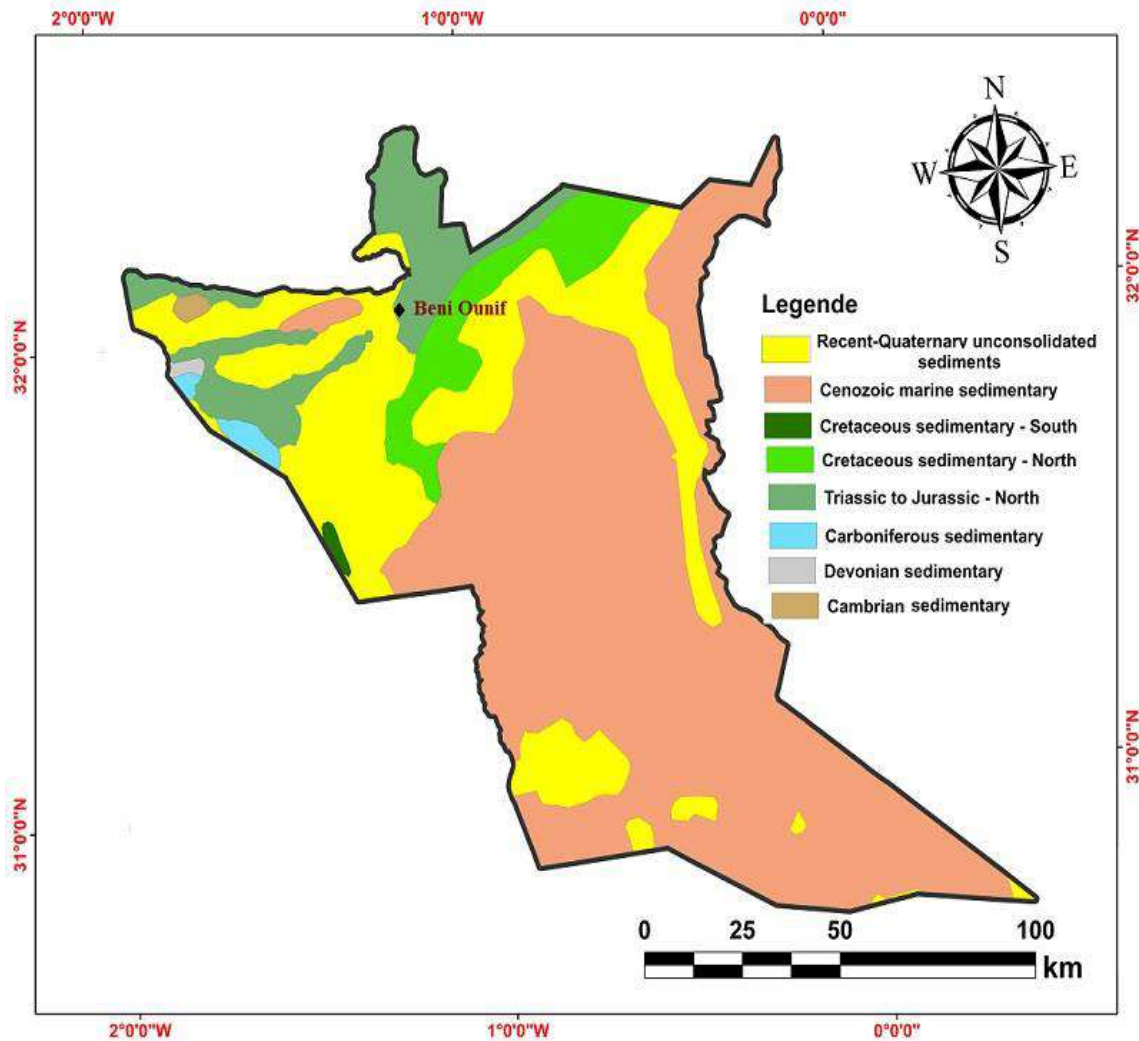


Figure 9: Geological map of the study area (DEM, 2023).

4.3. Geological setting of the Mountains

The 'Ksour Mountains', of which the Béni-Ounif syncline is part (see **Fig. 10**), are a mountainous region in the western part of the Saharan Atlas. They stretch from the Algerian–Moroccan border in the west to the Djebel Amour in the east. The name derives from the presence of around forty ksour, ancient constructions found in small oases such as Ain Sefra, Moghrar, Asla, Bousemghoune, Béniounif and Mougheul.

The southern Atlas flexure, formed by a succession of relay faults, runs along the southern flank of the anticlines, with rejection exceeding 2,000 metres in places. During the Secondary Period, slow movements led to alternating transgressions and regressions, while the major Eocene-age

folding phase definitively emerged the entire Saharan Atlas. The Ksour Mountains' more brittle style is due to the presence of more resistant material, particularly the thick Jurassic–Cretaceous sandstones.

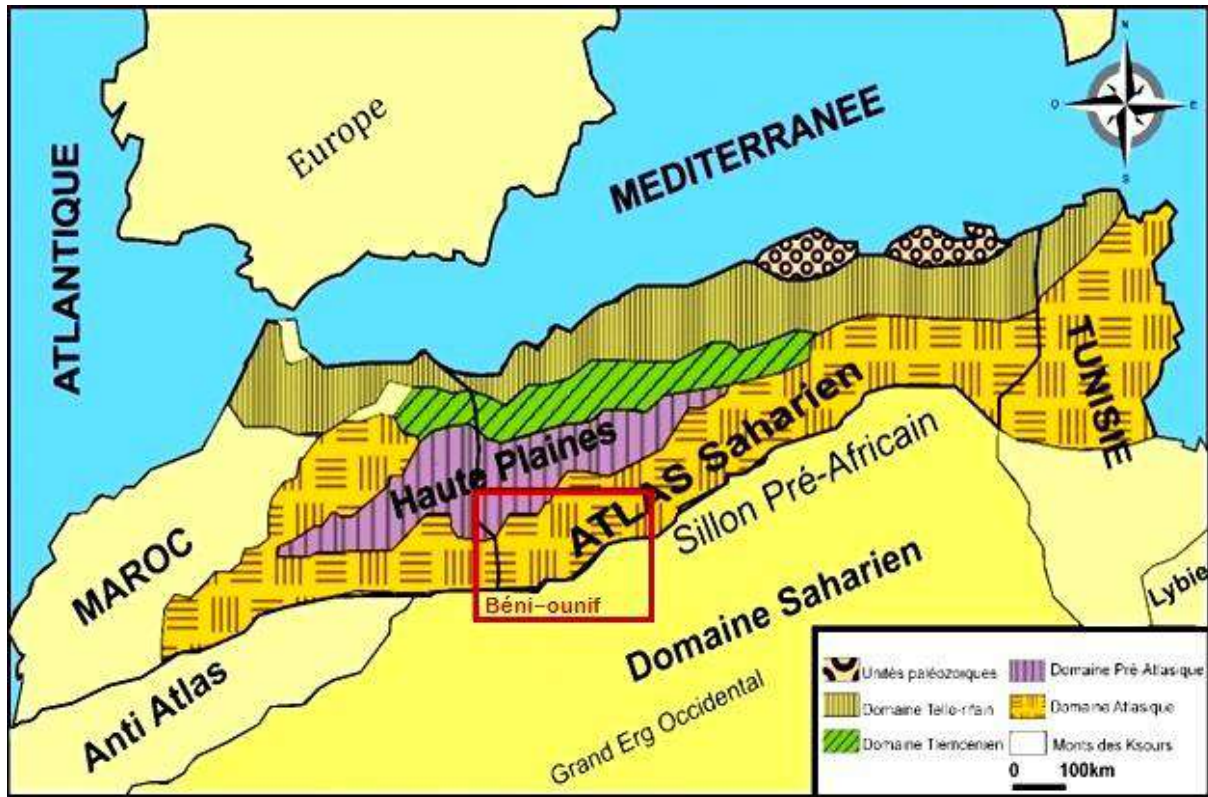


Figure 10: The Ksour Mountains on a regional scale (Benest, 1985)

The Ksour Mountains differ from the rest of Saharan Atlas in that their stratigraphic series is older and more continental and lagoonal in character. The stratigraphy is increasingly recent and marine west to east. It includes, from bottom to top :

- **Permo-Trias :**

The Triassic deposits, represented by conglomerates or gypsum marl, outcrop mainly at the heart of the anticlines. (El-Hendjir, Djeneien Bourezk, Djebel Melah)

- **Infralias :**

Refers to a 200 m thick dolomitic limestone formation at Djebel Chemarikh and Ain-Ouarka (Douihassni, 1976).

- **Lias :**

The Lias series is represented by :

- Limestone and limestone-marl 300 m thick, this series has been described at Djebel Chemarikh ([Douihasni, 1976; Mekahli, 1995](#)) and Djebel Kerdacha ([Galmier, 1970; Salhi, 2002](#)).
- Dolomitic limestone.

• Dogger :

Corresponds to the central part of the Monts des Ksour and the NE-SE lateral parts. The central parts are characterised by ([Bassoulet, 1973](#)):

- Light grey limestone (60 m) attributed to the Lower Aaleno-Bajocian.
- Grey clayey marl and limestone (35 m) dating from the Middle Bajocian.
- Alternating marl, sandstone and limestone (1200 m) dating from the Upper Bajocian. (Teneiet El-Klakh Formation).
- Alternating marl and limestone (700 m) of Bathonian date (Tifrit formation).
- Alternating sandstone and dolomite (470 m) dated to the Callovo-Oxfordian (Djara Formation).

The lateral parts of the Monts des Ksour represented at Djebel Kardacha (Béni-Ounif) and Djebel Antar (Mécheria).

According to [SALHI \(2002\)](#), Djebel Kardacha dated to the Aaleno-Bajocian is represented by :

- Alternating dolomitic limestone and sandstone attributed to the Upper Bajocian and Lower Bajocian.
- A lternation of sandstone, clay and dolomite dated to the Upper Bathonian.
- At Djebel Antar, the Dogger consists of a dolomitic series.

• Upper Jurassic - Lower Cretaceous :

- Aissa Formation ([Bassoulet, 1973](#)): Sandstone and clay alternation (30 to 40 m) located at Djebel Aissa and Djebel Mekther dated to the Portlandian (Upper Jurassic).
- Tiout Formation (Barremo-Albo-Aptian) with a thickness of 1500 m made up of dredge sandstones ([Douihasni, 1976](#)), located at Djebel Mehrize, Djebel Tiloula, Djebel Gharbi.

• Upper Cretaceous: Cenomano-Turonian :

These are the two formations: M'daouar (lower Cenomanian) and Khoundjaia (upper Céonomanian-lower Turonian) stretching from El-Abiod-Sid-Chikh to the confines of Béni-

Ounif.

• Quaternary

Described by the training courses :

- Ancient silts : Attributed to the Plio-Quaternary and ancient Quaternary and constituting alluvium by (GALMIER, 1970).
- Colluvium and foothills: Made up of pebbles cemented by carbonates, forming slope breccias. They cover the vast expanses to the south of Chemarikh and Boussemgoun.
- Ancient alluvial deposits: These are thin and located on flat areas or depressions with a gentle slope, characterised by a sandy-clay and conglomerate facies.
- Recent alluvial deposits: They line the wadi beds and consist of sand. These include the Atchane wadi (Chellala-Bousemgoun) and the Rhouiba wadi (south of Tiout).

Aeolian formations: These are fairly widespread, forming the dunes that line the north and north-east of Djebel Mekhter. Most of these dunes appear to be fossilised (Mansour, 2007).

4.3.1. Geology of the Beni-Ounif syncline

Our knowledge of the geology of the area is very limited and is based mainly on studies and reports: A.Cornet 1947 ; D.Galmier 1970 ; B. Bekhedda 1992, the geophysical campaign, etc.

On the scale of the Ksour Mountains, the relief forms a slight inflection, the centre of which is in the Béni Ounif region where sandstone formations of Lower Cretaceous age form the main outcrops of the syncline.

The geological map (Fig.11) shows the geological formations found in the Béni Ounif region.

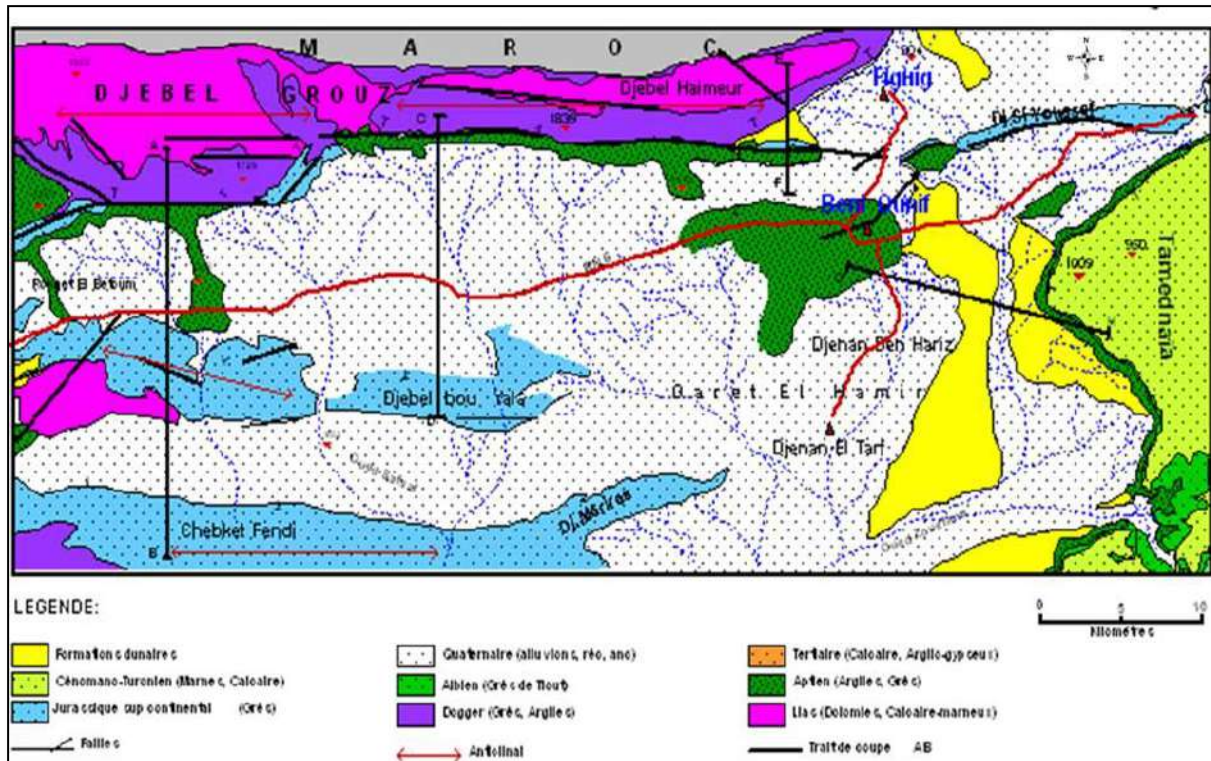


Figure 11: Geological map of the Béni-Ounif syncline (MANSOUR, 1992)

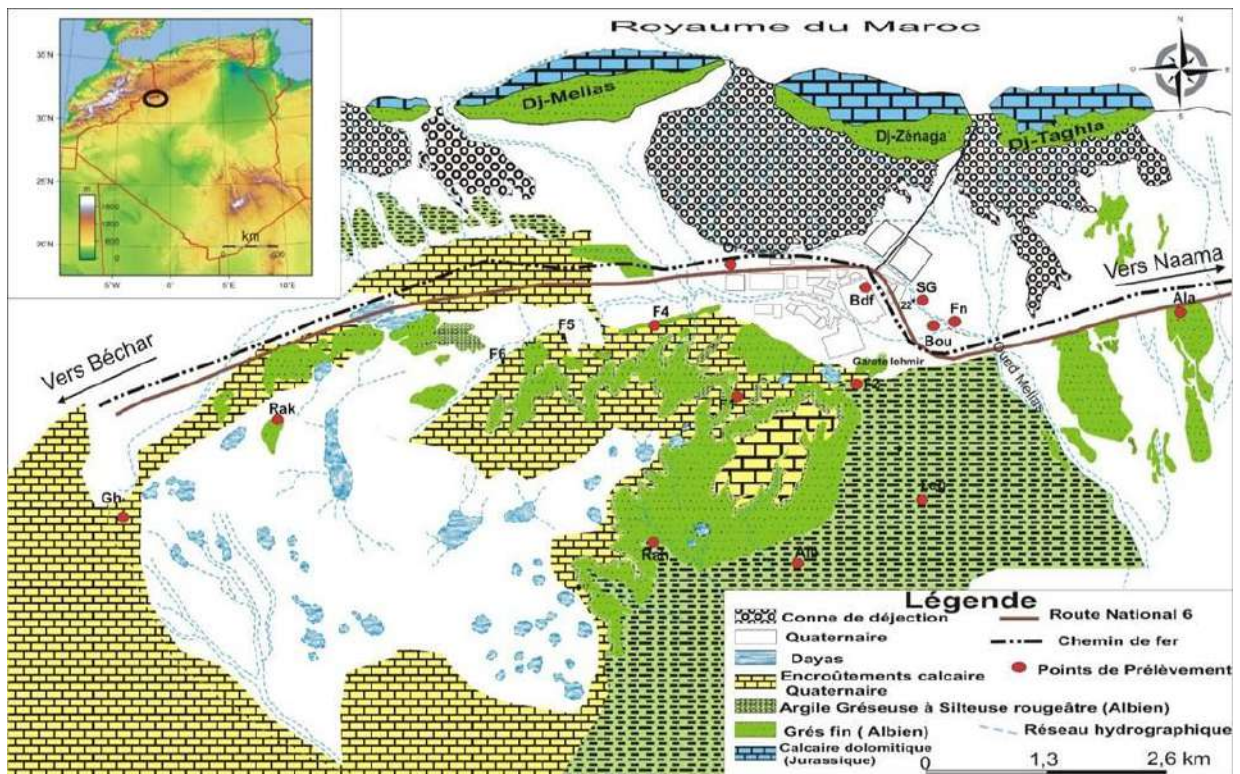


Figure 12: Outline geological map of the Beni-Ounif region

b- Jurassic

- **Lower Jurassic (Lias)**

In the Béni-Ounif region, the Lower Jurassic outcrops for the most part along the Djebel Grouz, forming a veritable wall (1800m).

- **Rhaetian and Hettangian (Infralias)**

Above the conglomerates that mark the base of the lias and which can be followed along the southern flank of djebel Grouz, limestones and dolomites appear in small banks, then massive then at Koudiet-El Haidoura, these conglomerates are surmounted by multicoloured clays on which limestones and dolomitic limestones rest a total thickness reaching 50 m, and showing a relief with break of slope in staircase.

- **Sinemurian (Lower Lias 140 to 150m)**

Represented at Djebel Haimeur (north of Figuig) by a powerful mass of limestone and dolomite that crowns the range. The cliff has a series attributed to the Sinemurian by **E. Roch (1950)**. The cross-section taken in the field shows from bottom to top:

- A dolomitic formation with 70 m of beige dolomite.
- Gypseous marl and red clay with greenish limestone banks (40 to 50 m).
- Alternating banks of greenish limestone and dolomite platelets, whitish when broken and brownish when patinated.
- 20 to 25 cm of clay with limestone interlayers.

- **Pliensbachian (Middle Lias 60m)**

On the southern flank of Djebel Grouz, the transition from the pale dolomitic limestones of the Lower Liassic to the dark limestones arranged in double bars of the Middle Liassic is quite clear at Djebel Rkina.

- **Toarcian (Upper Lias)**

The stratigraphic series of the Lias corresponds to 70 m of massive black ferruginous limestone. To the south of the Ouazzani djebel, the layers are steeply inclined and come into contact with the dolomitic layers of the Dogger. This contact occurs as a result of the South Atlasic fault. Liassic formations also surface to the south of Béni-Ounif, at Chebket Charef and Chebket Fendi, where they are sometimes masked by more recent deposits

- **Middle Jurassic (dogger)**

Along the djebel Grouz, the dogger is laid out in roughly horizontal layers, forming a remarkable limestone ensemble at heart of a perched synclinal structure, 2 km wide and

around 150 m high. It is represented by a succession of greenish dolomitic limestones and oolitic limestones with algae, polypieds and sandstone (**Fig.13**). This formation can be found on the northern flank of the Figuig hills (**Fig.14**).

To the south-west of Béni-Ounif, the dogger forms the anticlinal folds of Chebket Charef and Fendi.

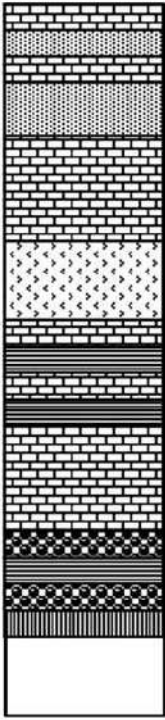
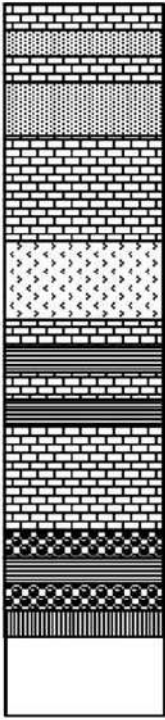
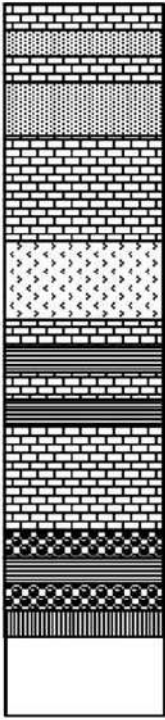
Age	Prof (m)	Série stratigraphique	Description
D o g g e r	0		Calcaires en plaquettes
	50		Marnes gréseuses
	100		Calcaires et marnes
	150		Marnes gréseuses
L i a s	200		Calcaires gréseux peu dolomitisés
	250		Marnes à gypses
	300		Calcaires dolomitiques et marnes
	350		dolomies massives
P T	400		Conglomérats Marnes
?	450		Conglomérats

Figure 13: Stratigraphic log of the Chebket Charef region (S.N.REPAL in 1952)

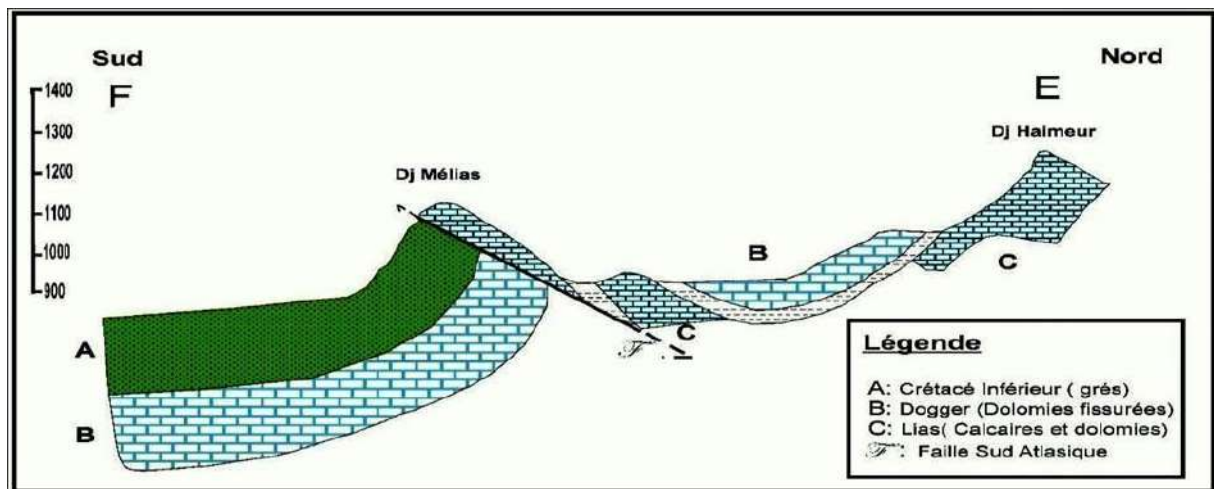


Figure 14: North-south geological section (EF) (Bekhedda, 1992)

c- Upper Jurassic-Lower Cretaceous

Some authors attribute the entire sandstone formation that extends across the Algerian Sahara to the Albian. In reality, this is a continental complex, largely sandstone, the stratigraphic limits of which vary from one region to another, known as the "intercalary continental".

In the Sud-Oranais, the Barremian-Aptian-Albian group rests, according to [Cornet in 1952](#), on the marine Hauterivian containing a continental sandstone bed at its base.

Closer to the Sahara, this intercalation becomes thinner and the Hauterivian continental tends to join the Barremo-Albian complex.

This carbonate intercalation tends to disappear towards the south and south-west, and the sandstone series extends uninterrupted from the top of the Jurassic to the Cenomanian, even descending much further into the Jurassic with the disappearance of the recital Kimmeridgian, which is clearly visible the east. It should be noted, however, that in this context, the lower part (Jurassic and base of Cretaceous) retains a facies that is distinctly different from the typically continental sandstones of the Cretaceous (Hauterivian to Albian). These continental deposits are relatively extensive in the study area in question, where they develop into a wide, undulating syncline, forming the Béni-Ounif plain, filled in by recent infill ([Bekhedda, 1992](#)).

d- Cenomanian and Turonian

To the east of the study area, the Tamednaia chebket forms a very spreading Turonian table with a shallow south-east to north-east dip (**Fig.15**), overlying the Lower Cretaceous sandstone deposits. It forms a broad plateau with steep cliffs towards the Zousfana valley. At 30 K m east of Béni- Ounif, the Cenomanian-Turonian ledge changes direction to the east and south-east and is arranged in an inverted series beneath the Middle Jurassic of Djebel Kerdacha.

- **Cenomanian:** gypsum marl interbedded with limestone containing bivalves and sea urchins. The limestones are centimetric at the base and become metric at the top. The thickness of the Lower Cretaceous.
- **Turonian:** limestone formation, with 25 m of flint, iron oxide and manganese limestones; these limestones are dolomitized at the top of the series ([Bekhedda, 1992](#)).

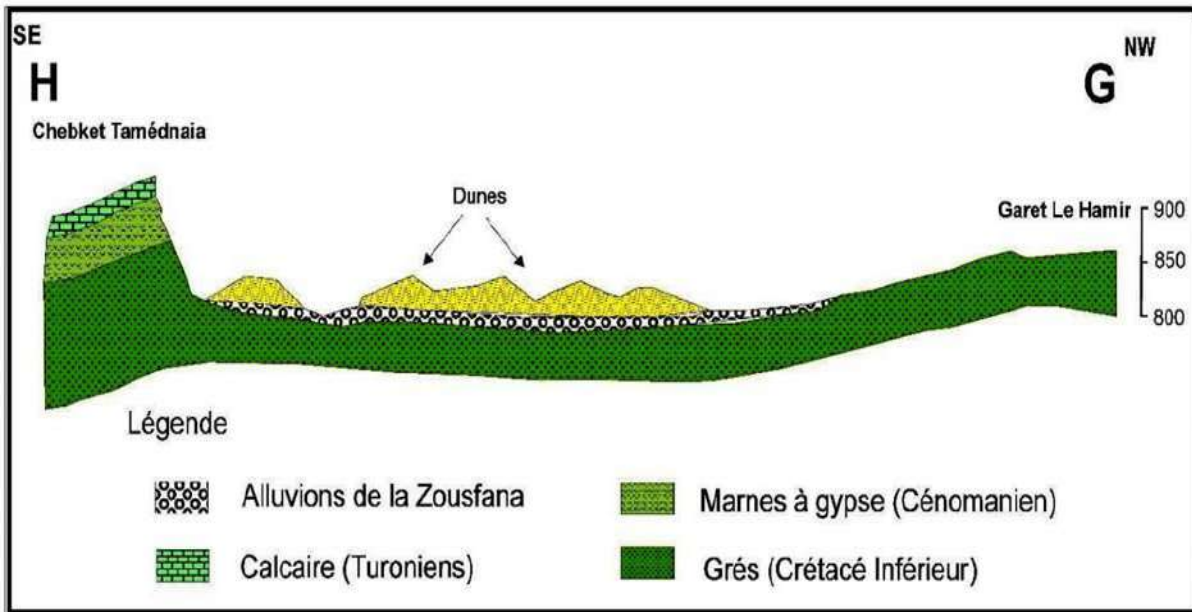


Figure 15: Geological section SE-NW (HG) (Bekhedda, 1992)

Cenozoic

Thin and located on flat areas or depressions with a gentle slope, characterised by a sandy-clay facies.

4.3.2 Structural framework

From a structural point of view, the Béni Ounif syncline occupies a special position. It marks the eastern boundary of the primary formations onto which the Atlasic phase was superimposed. The South Atlasic Fault, comprising a series of faults and flexures, runs in several different directions from the Djebel Ouazzani to the Figuig Ranges. Small SW-NE faults affect the Grand Melias, Zenaga, and Djebel Taghla areas. At Djebel Sidi Youssef, two approximately perpendicular NW-SE and NE-SW faults replace the main fault.

Brittle tectonics played a very important role, particularly the density of fracturing extending parallel to the direction of compression. This direction is approximately N35°–N30°E and can be seen in the continental sandstones of the Béni-Ounif syncline and the dolomitised limestones of Chebket Tamedaiïa and Chebket El Beïda, which are located to the south of Djebel Kerdacha.

To the north, Djebel Grouz takes the form of a series of synclines and anticlines with a complex structure. The perched Dogger strata give rise to high cliffs with steep slopes and plunge back under the continental sandstones near Figuig after a slight tilt. This fossilises an anticline with a Liassic core in the border landscape.

To the south-west, Chebket Charef and Chebket Fendi correspond to anticlinal folds,

extended to the east by small, asymmetrical anticlinal structures. At Djenane-Tarf, Djebel Merires, with its pinched south-eastern flank, is bordered to the north by a series of faults running at an angle of approximately 50° east. (Mansour, 2007).

From a geological point of view, we **conclude that** the study area is part of the transition zone between the Saharan Atlas and the Saharan platform. It comprises :

- The Jurassic: well developed in the Djebel Maïs with limestone and dolomite. On the other hand, at the level of Djebel Bou Yala and Fendi, the Jurassic may be developed, represented by evaporite clays and dolomites.
- The Cretaceous: poorly exposed, it is essentially the Lower Cretaceous (Albian) of a sandstone nature and is an excellent reservoir of water.
- Tertiary: can also be found in the Beni-Ounif region. Forms a thin limestone shell.
- The Quaternary: represented by the alluvium of the oueds, the regs and the Sebkh.

5. Climatological context

In order to address the climatic aspect, we only used data from the Bechar station, given that there is no climatic data available for the Beni Ounif region. The data covers the period from 2002 to 2018, i.e. 20 years of observations. The station is located 13.3 km east of Béchar and 111 km from Beni Ounif. (Table 1.1).

Table 1 : Characteristics of the Bechar rainfall station.

Station	Code Codes	X (Lon)	Y (Lat)	Z	Year observation
Bechar	60571, DAOR	2°22'W	31°62'N	785 m	1999-2018

5.1. Temperature

Temperature is a fundamental element of climate. Its variation influences the transformation of water into vapour, whether at the surface or within the atmosphere. It also influences the degree of evapotranspiration, which consequently affects the salinity level of the water. However, temperature plays a key role in the variation of the components of the water balance and is the main factor that determines the region's climate. This temperature analysis is based on data from the Bechar station for the period from 1999 to 2018.

Analysis of **the mean annual temperature** histogram (Fig. 16) shows that 2018 was the hottest year, with an average temperature of 27.37 °C, and 2000 was the coldest year, with an average temperature of 24.07 °C. The interannual mean temperature is 25.89 °C.



Figure.16: Interannual Variability of Mean Annual Air Temperature during the Period 1999–2018

Analysis of the average monthly temperature histogram (Fig. 17) shows that July is the hottest month, with an average temperature of around 38.33 °C, while January is the coldest month, with an average temperature of around 12.94 °C. The average monthly temperature is approximately 27.37°C.

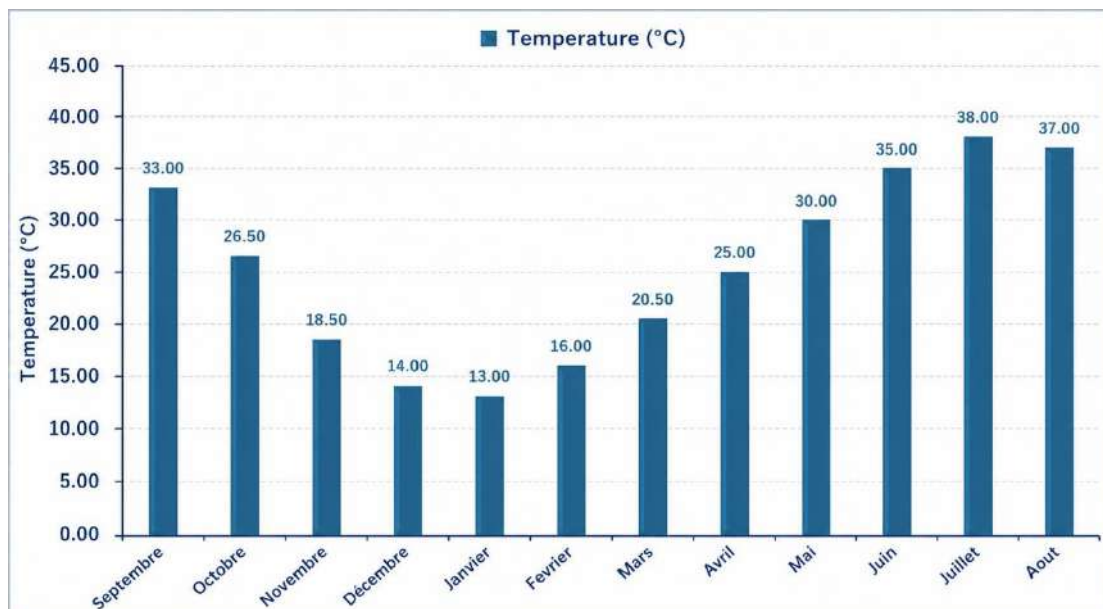


Figure 17: Histogram of variations in average monthly temperatures (1999-2018).

5.2 Precipitation

Rainfall in all its forms is extremely rare and irregular in the Ouargla basin. According to Dubief (1963), this precipitation only occurs in the form of rain in small quantities

Analysis of average monthly rainfall shows a maximum in March and a minimum in July and August (Figure 18). However, it should be noted that these monthly values can vary greatly from one year to next (Dubief. 1963; Meddi&Meddi. 1998).

The map of the spatial distribution of rainfall (Figure 15) shows that rainfall decreases from north to south and that our region fluctuates between 30 and 50 mm/year (Meddi&Meddi. 1998). Precipitation is very scarce and irregular, being low in winter and almost non-existent in summer

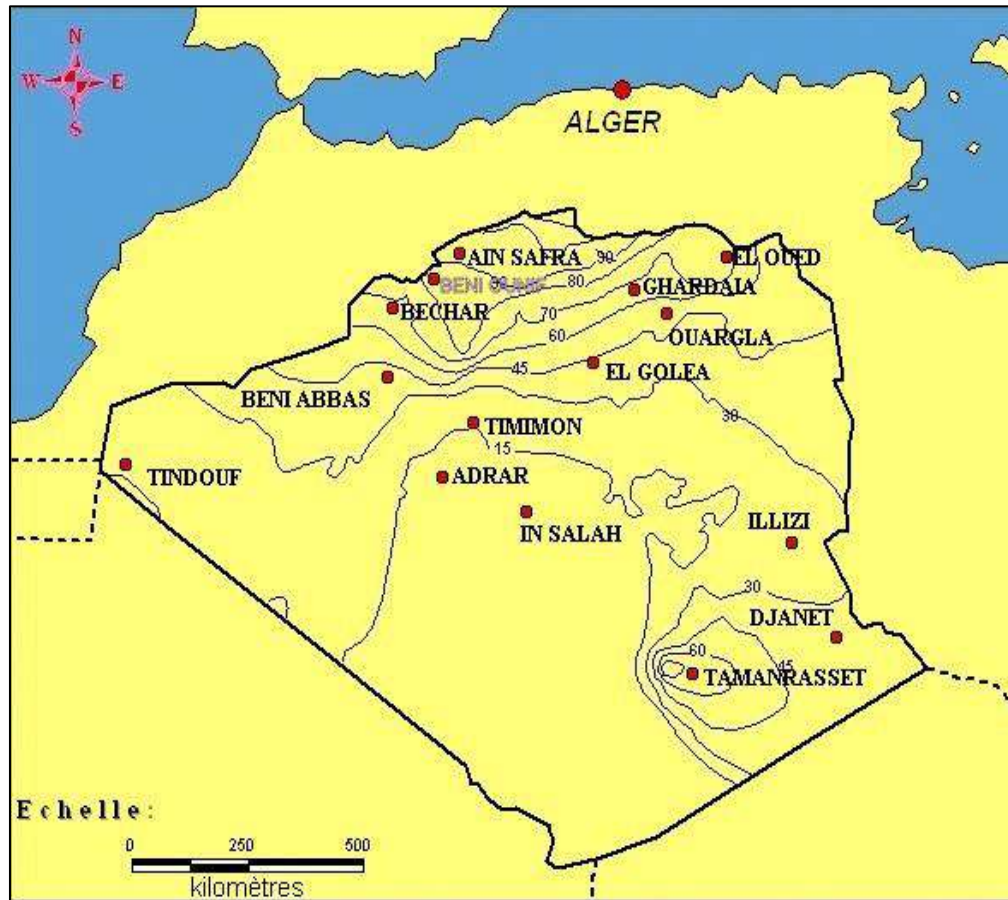


Figure.18: Isohyet map of mean annual rainfall in the Algerian Sahara (Meddi&Meddi. 1998) Modified).

Low rainfall is a fundamental characteristic of Saharan regions, with an average annual rainfall of just 32 mm.

According to the histogram in Fig. 19, the annual rainfall in the Beni Ounif region varied between 1.2 and 31.5 mm over the study period (1999–2018). 2005 was the wettest year (31.5 mm), while 2006 was the driest (1.2 mm).

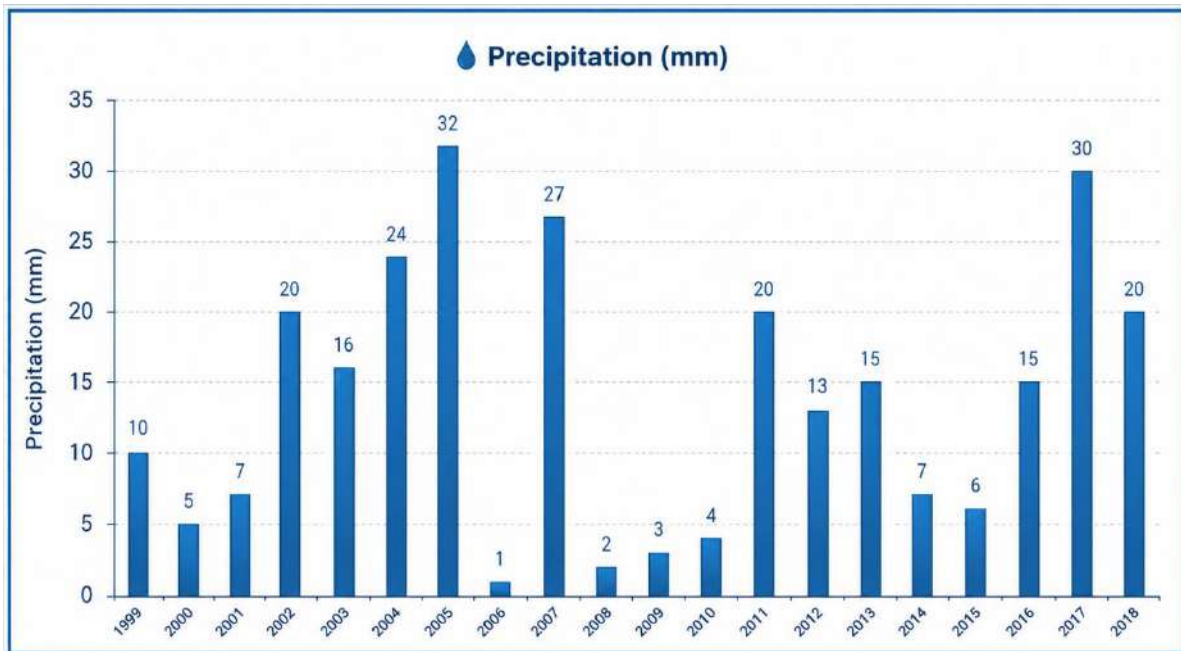


Figure.19: Histogram of variations in average annual precipitation (1999-2018)

Analysis of the histogram showing variations in the average monthly rainfall over a 20-year period reveals that November is the wettest month, with an average rainfall of 1.94 mm, while August is the driest month, with an average rainfall of 0.48 mm. The monthly average is approximately 1.10 mm/month.

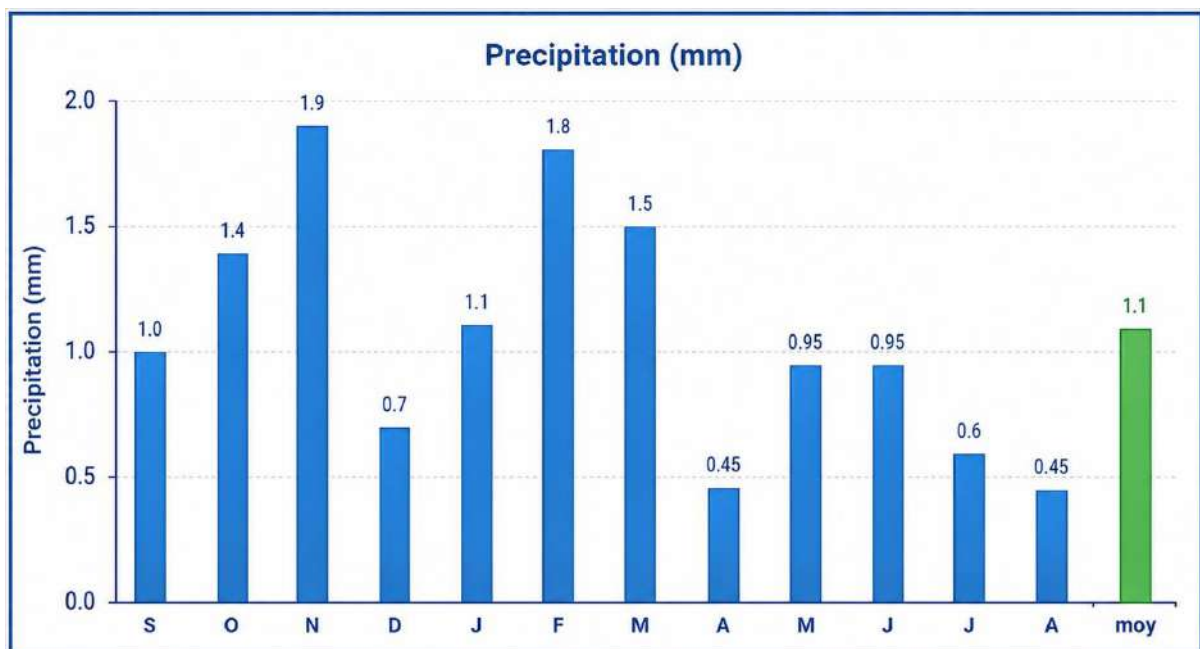


Figure.20: Histogram of variations in average monthly rainfall (1999-2018)

5.3. GAUSSEN umbrothermal diagram

GausSEN's umbro-thermal diagram (Fig.21) can be used to calculate the length of the dry season. In our case, the rainfall curve falls well below the temperature curve, which means that the dry

period is spread out over whole year.

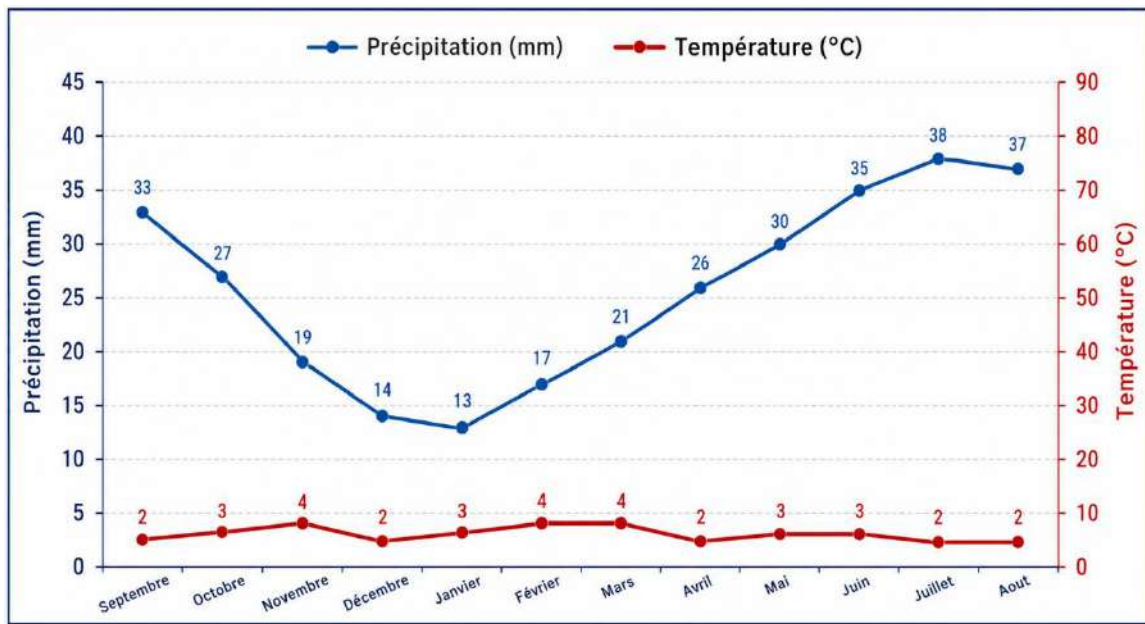


Figure.21: Umbrothermal diagram for the period (1999-2018)

5.4. The wind

The wind is one of the most distinctive features of the Béchar region. Winds are frequent throughout the year, but it is during the spring (March and April) that violent sandstorms occur, with wind speeds in excess of 20 m/s (72 km/h) being recorded in the region.

Table 2: Wind speed data for the Béchar station (1999-2018)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Avg
Speed m/s	5,7	5,6	6,6	6,3	6,0	5,5	5,8	5,6	5,6	5,5	5,3	4,8	5,7

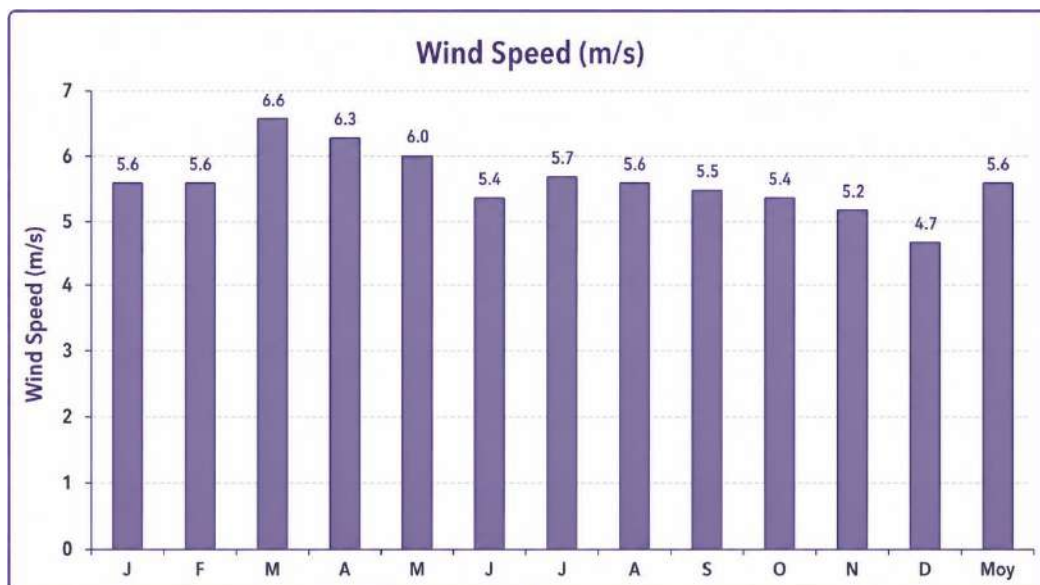


Figure.22: Histogram of wind speeds at the Béchar station (1999-2018)

5.5. Relative humidity

The distribution of humidity measurement results is the inverse of the temperature distribution. Maximum humidity is obtained in winter (December–January), while minimum humidity is obtained in summer (June–July), as shown in Table 1.3 and **Figure 23**. Relative humidity is low, below 40%.

Table 3 :Relative humidity data for the Béchar station (1999-2018)

Month	J	F	M	A	M	J	JL	A	S	O	N	D	Avg
Humidity %	22	27	33.8	38	35.5	29	23	19.7	17.2	13.5	12	15	23.8

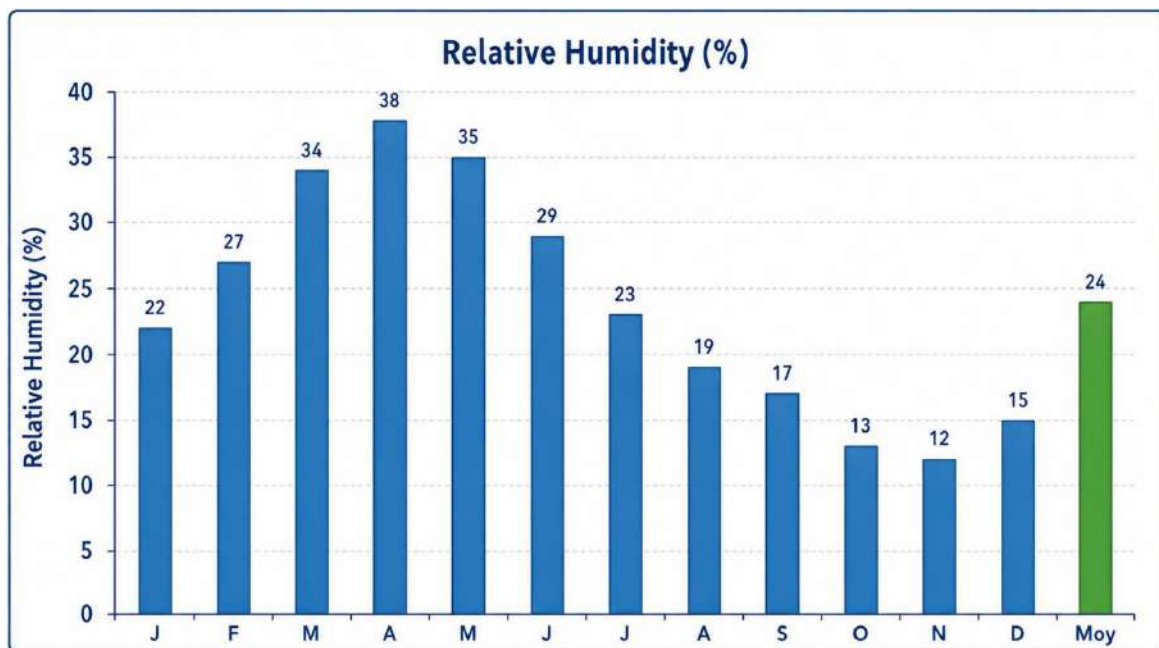


Figure 23: Histogram of relative humidity at Béchar station (1999-2018)

5.6. Sun exposure

This is the period sunshine on the ground with clear skies, which is the opposite of cloudiness. Table 4 below shows the sunshine values in **fig 24**. It averages 10.85 hours per day, with the maximum insolation recorded in June (13.2 hours per day) and the minimum in December (8.2 hours per day).

Table 4: Insolation for the Béchar station (1999-2018)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Avg
Insolation (h)	9.6	10	11.2	11.6	12	13.2	13	12.4	10.8	9.6	8.7	8.2	10.8

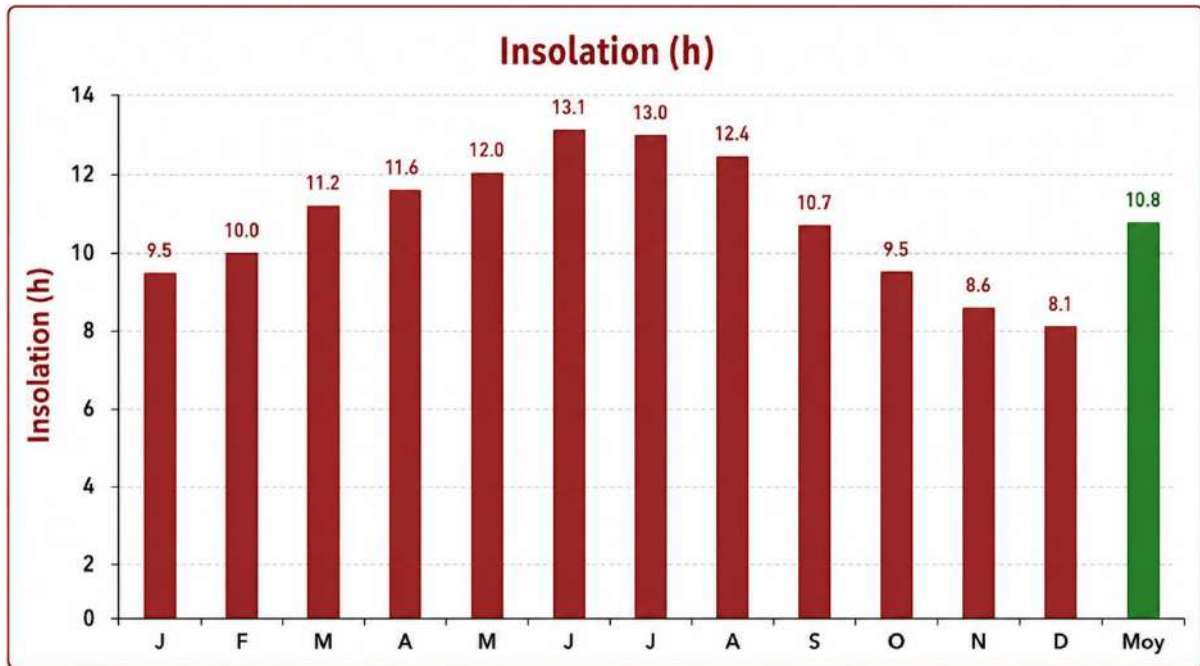


Figure.24:Insolation histogram at Bechar station (1999-2018)

5.7. Determination of Climate Indices for the region

To determine the climate, Emberger proposed a rainfall quotient, Q_2 , which depends on the average annual rainfall and the average minimum and maximum temperatures of the coldest and warmest months. This makes it possible to plot a station on a diagram. He therefore proposed the following formula:

$$Q_2 = P \cdot 1000 / [((M+m)(M-m))/2]$$

With : **P**: Average annual precipitation (mm)

M: Average maximum temperature for the warmest month (in degrees Kelvin)

m: average minimum temperature for the coldest month (in degrees Kelvin)

P= 13.25 mm **M**=311.48°K **m**= 286.09 °K This gives: **$Q_2=1.74$**

The value of Q_2 calculated makes it possible to position our study region on the Emberger climagram (Fig.25); it is characterised by a Saharan-type climate with very warm winters.

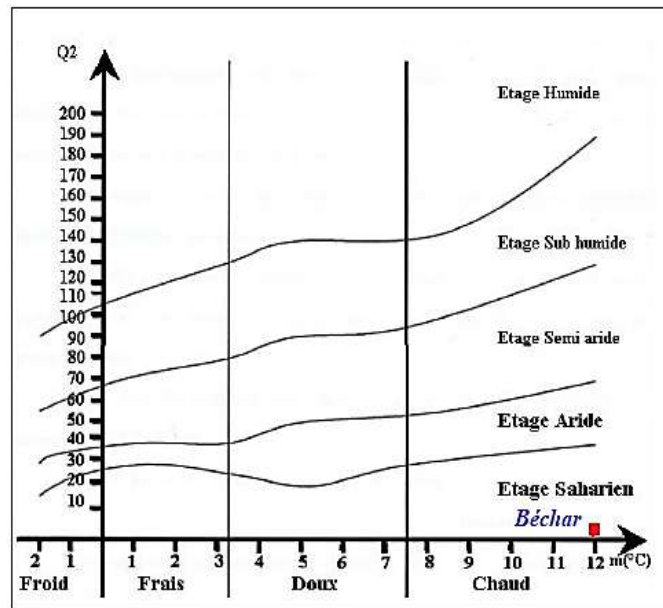


Figure 25: Emberger climagram for Béchar station

5.8. Evapotranspiration

5.8.1. Using Thornthwaite's formula: In 1948, C.W. Thornthwaite proposed a formula based essentially on air temperatures:

$$E_{tp} = 16 \cdot \left(10 \frac{I}{I}\right)^a \cdot K$$

with : $i = (t/5)^1 \cdot 5I = \sum i_a = (1.6 \cdot I/100) + 0.5$

ETP: Average monthly potential evapotranspiration (mm).

i: Monthly thermal index and I: Sum of monthly thermal indices.

a: arbitrary temperature parameter.

t: Average monthly temperature (c°).

k: monthly adjustment coefficient.

The calculated Potential Evapotranspiration is 1336.6 mm/year (see balance table).

The actual evapotranspiration calculated is 13.25 mm.

5.8.2. Using Turc's formula: real evapotranspiration can also calculated using Turc's

$$E_{tr} = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}}$$

formula:

With $L = 300 + 25 T + 0.05 T^3$

Etr: Real evapotranspiration (mm).

P: average annual precipitation (mm).

L: arbitrary parameter linked to temperature

T: mean annual temperature (°C).

A comparison between the two calculated values actual evapotranspiration shows that the two methods give very similar results. Table 5.

Table 5: Comparison of Annual ETR by the Turkish and Thornthwaite Methods.

Station	Turkish ETR (mm/year)	ETR Thornthwaite (mm/year)
Béchar	13.96	13.25

5.9. Water balance

The water balance using the Thornthwaite method, in which potential evapotranspiration (PTE) and actual evapotranspiration (AET) are defined as a function of rainfall, temperature and taking into account latitude and variation in the readily usable reserve (URR), confirms the aridity of the region, which has already been concluded. Table 6 shows that the water balance in the study area is in deficit, with ETP higher than rainfall during the eleven months of year, which is why actual evapotranspiration is equal to rainfall (13.25 mm). The readily usable reserve is zero and the agricultural deficit is present in every month (Fig.26).

Table 6: Water balance according to C.W. Thornthwaite at the Béchar station (1999-2018)

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Augu	Total
P (mm)	1.04	1.43	1.94	0.76	1.16	1.85	1.56	0.48	0.95	0.97	0.63	0.48	13.25
T (°C)	33.18	26.7	19.0	14.2	12.9	16.4	20.8	25.4	30.22	35.33	38.33	37.4	25.84
ETP (mm)	162.3	84.1	28.2	12.1	9.43	18.0	42.0	78.8	140.5	219.67	285.7	255.3	1336.6
RFU (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ETR (mm)	1.04	1.43	1.94	0.76	1.16	1.85	1.56	0.48	0.95	0.97	0.63	0.48	13.25
DA (mm)	161.3	82.6	26.3	11.3	8.27	16.2	40.4	78.3	139.6	218.70	285.1	254.8	1323.3
EX (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

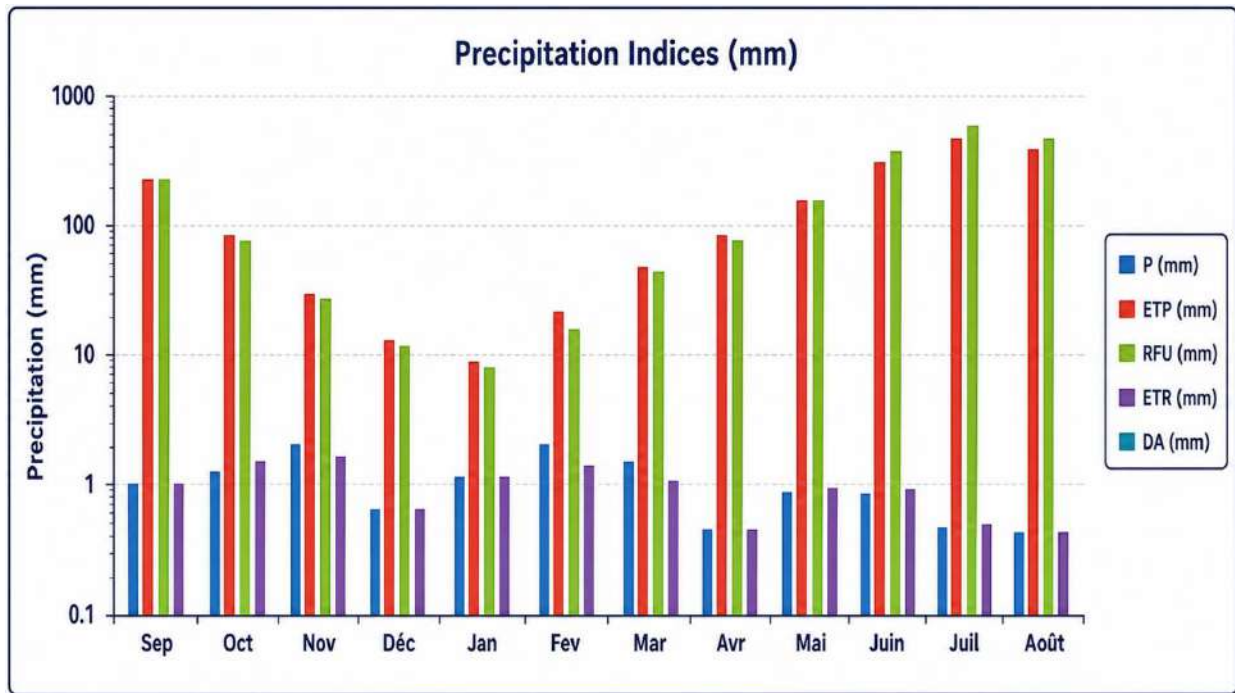


Figure 26: Presentation of water balance terms at the Béchar station (1999-2018)

6. Hydrology of the study area

The commune of Béni-Ounif is located in the foothills of the southern Atlas Mountains. It marks the transition between the Saharan Atlas to the north and the vast expanse of the Sahara Desert to the south. The Oued Namous (Beni Ounif) catchment area comprises two tributaries: the Oued Lakhdar and the Oued Zoubir. The Oued Lakhdar catchment area comprises the Oued Sidi Aïssa and Oued Mélias sub-catchment areas. These two sub-catchment areas converge at the north-eastern edge of the town of Béni Ounif, near the railway crossing, a few dozen metres (110 m) from the RN6 bridge and around 3.5 km south of the Algerian–Moroccan border. The nearest Moroccan town, Figuig, is around 7 km away.

The hydrographic network of the Oued Namous catchment area is fairly dense, characterised by an NW–SE flow that joins the Oued Saoura. The Saoura is the main artery for all the wadis which currently flow into the Grand Erg Occidental.

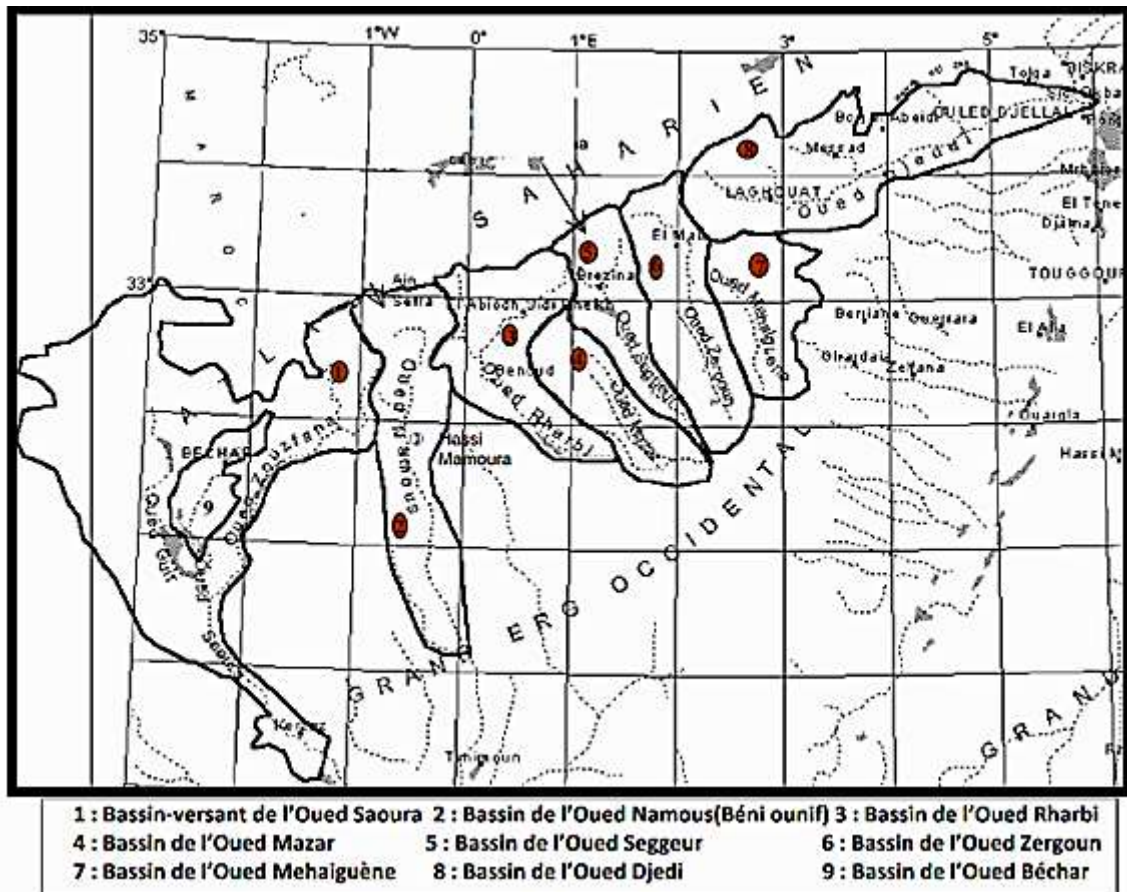


Figure 27: Map of Oued Namous catchment area in the Grand Erg Occidental.

6.1. Oued Namous catchment area

The Oued Namous catchment area is limited to Hassi Mamoura, as there are no active tributaries downstream of this point. In these conditions, its surface area is 8,900 km². If we adopt the beginning of the Oued El Breïdj as the source of the Oued Namous, it originates at an altitude of around 1,900 metres in the Monts des Ksours.

Slightly upstream of Hassi Mamoura, the gradient increases and the wadi flows into a wide valley, which was carved out of the hamada. Here, the riverbed gradually fills with sediment. The Oued Namous reaches the Grand Erg Occidental and disappears into the sand 370 km from its source. On average, the river floods for 2.6 months of the year. In the lower Namous, floods are no longer observed every 13 years. These floods can be extremely violent.

6.2. The situation of the town of Beni Ounif in these contexts

The town of Béni-Ounif lies downstream of the Oued Melias and Oued Sidi Aissa rivers, near their confluence. The wadis cross the town on both the left and right sides, flowing in a north-

westerly direction. During periods of flooding, the water leaves the minor channel to occupy the major channel through direct overflow of the watercourse.

As the two wadis cross the town, there are several bridges and footbridges to facilitate pedestrian and vehicular traffic. However, these structures are considered to aggravate the flow of water and degrade flood control. (Fig.28).



Figure.28: Railway structures with narrow openings.

6.3. Extracting the hydrographic network and prioritising it in ArcGis

The hydrological network of the sub-basins was produced on the basis a DTM (Digital Terrain Model) a resolution of 30 metres, which made it possible to reproduce the hydrographic network, with its orders.

A digital terrain model (DTM) is a 3D representation of a terrain or planetary surface, created from terrain elevation data. The DTM does not take into account objects that exist on the surface of the ground, such as plants and buildings.

The elevation data from the Digital Terrain Model was used to map the slopes, delimit the catchment area and determine the hydrographic network draining the area.

The sub-catchments and hydrographic networks were extracted using the ArcHydro tool in ArcGIS 10.3, following the model shown in **Figure 29**.

When you delimit catchment areas or define hydrographic networks, you go through a series steps.

At the start of the model, this study used the "fill" tool to correct input elevation model, as the DTM contains errors, generally classified as depressions called troughs. Then calculate flow direction and flow accumulation of each cell location. The choice of threshold when extracting the network determines the quality of the network. For the same DTM resolution, the lower the threshold, the denser the hydrographic network.

Once the flow directions and hydrographic networks have been created, you can use other hydrological analysis tools to determine the hydrographic orders and properties of the watercourses.

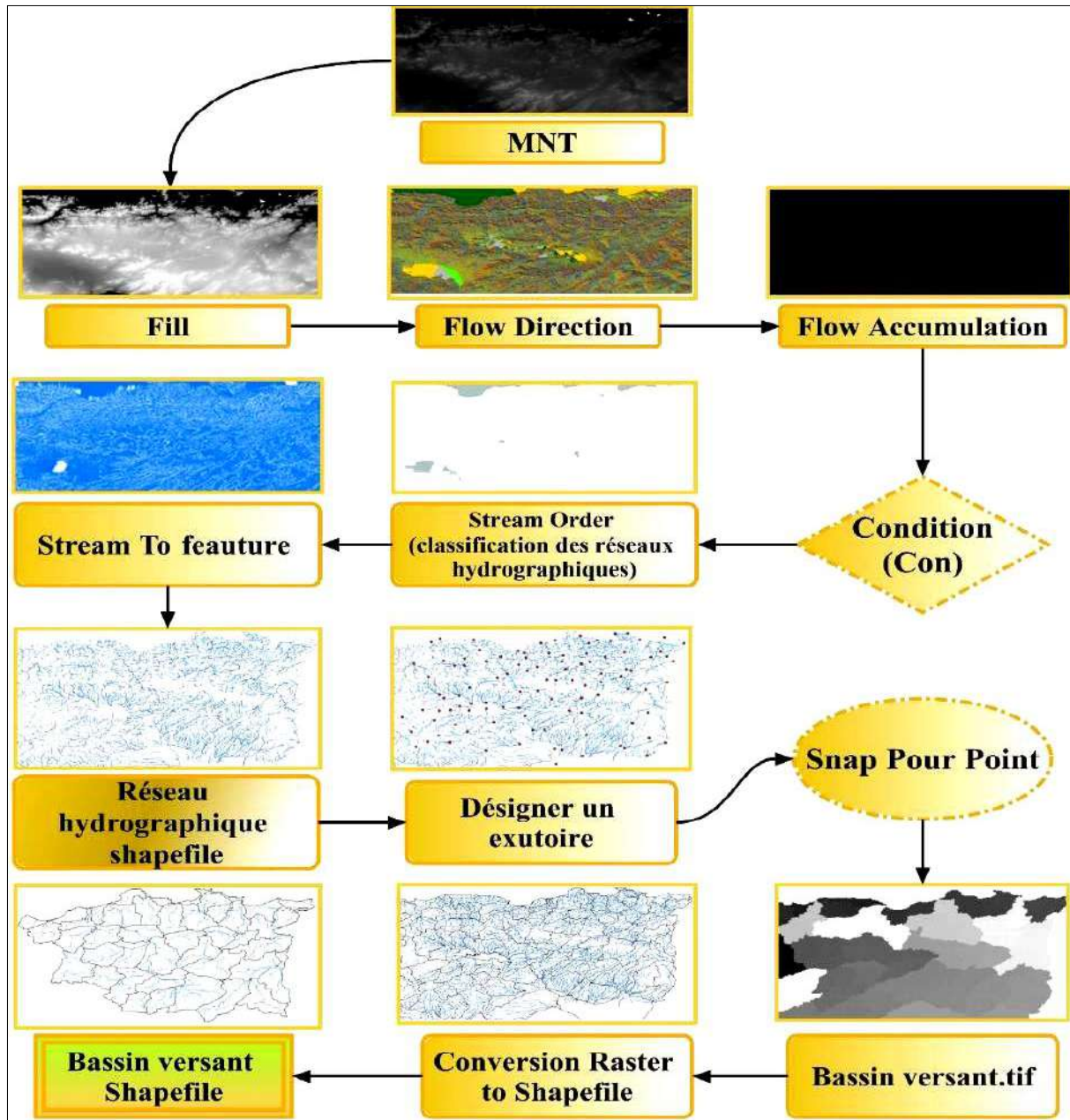


Figure.29: Flowchart for the delimitation and extraction of catchment areas

6.4. Hydrographic characteristics of the sub-catchments

Figure 24 illustrates the sub-watersheds of the two wadis under consideration with the hydrographic network of their numerous tributaries (Figure 30). The physical, geographical and hydrographical characteristics of the site were calculated on maps at a scale of 1:50,000 (Revoil-Beni Ounif sheet no. 725).

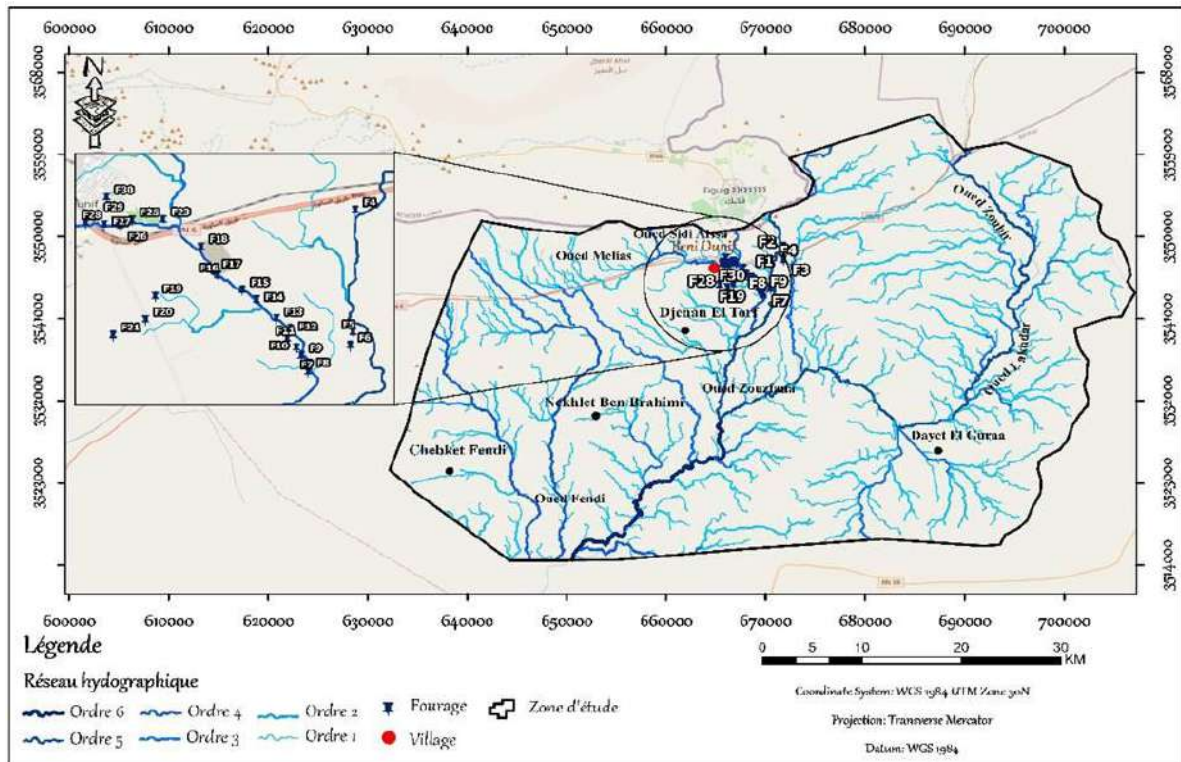


Figure.30: Map of the catchment area of the commune of Beniounif .

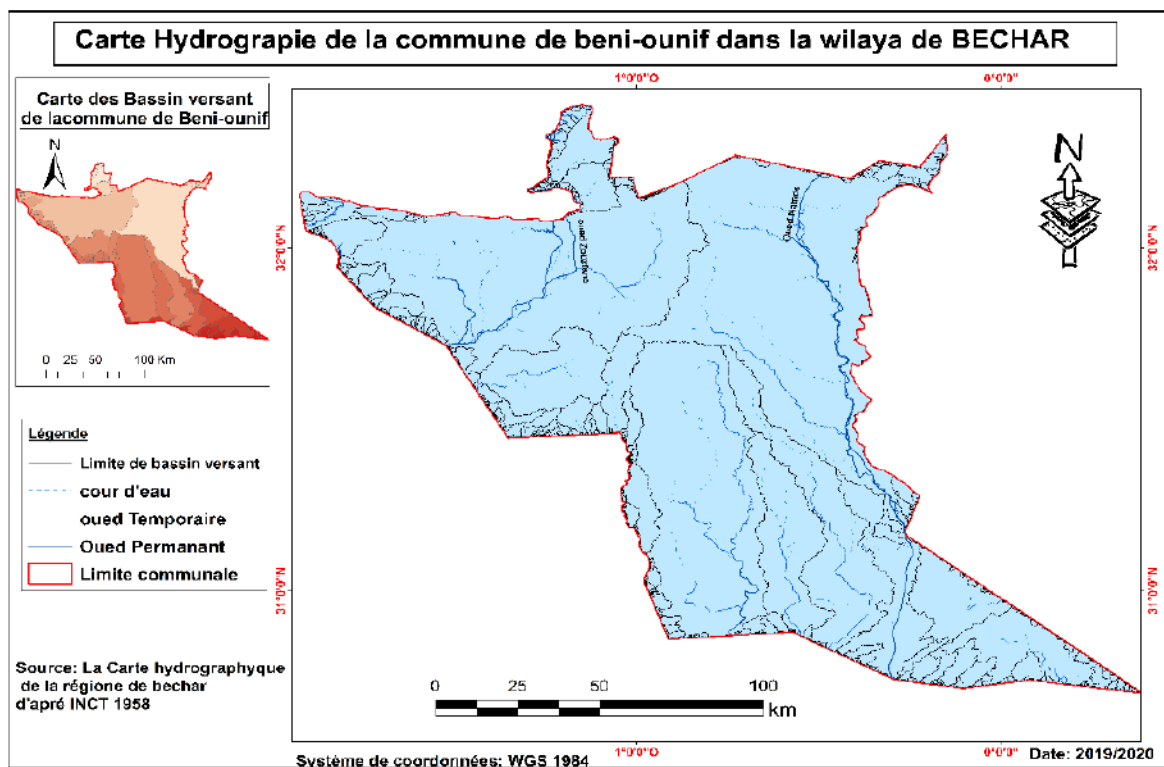


Figure 31: Hydrographic map of the Beni Ounif commune (large scale).

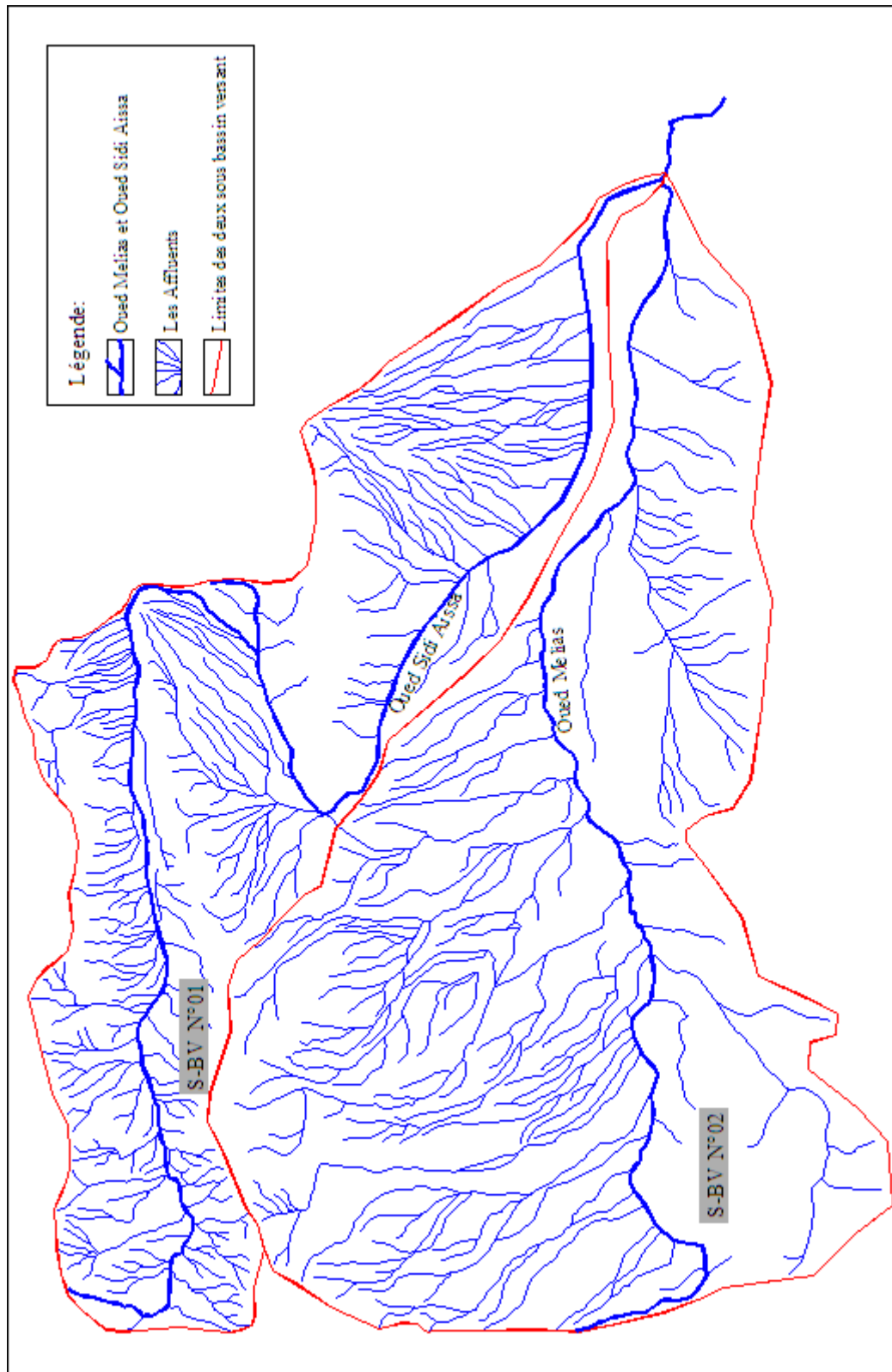


Figure 32: Hydrographic network of the Sidi Aïssa and Mélias wadi sub-basins.

6.4. Morphometric characteristics :

The relief plays an essential role in the flow regime. It is indicated by contour lines and characterised by the hypsometric curve.

A steeper slope results in rapid runoff, which means a shorter concentration time and a faster rise in flood levels.

Our aim is to determine the relief class **Figure 33**.

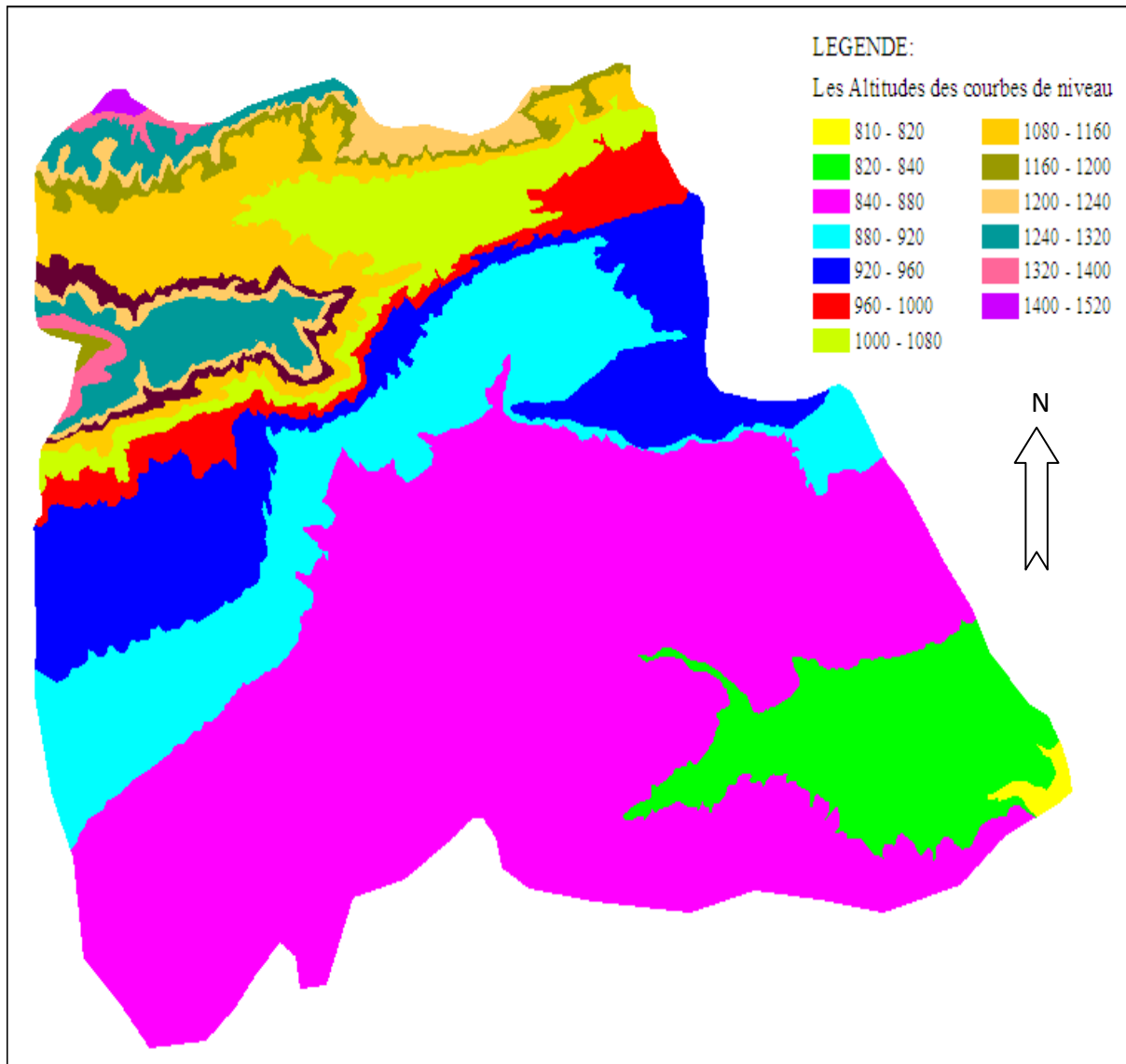


Figure 33: Topography of the Beni ounif catchment area

6.5. Hypsometric curve:

To estimate these parameters, we need to present the hypsometric distribution, after planimetry, of the partial areas between the master contour lines and the various elevations.

Table 7: Distribution of surface area as function of altitude within the boundaries of S.B. Sidi Aïssa

Altitude (m)	Average altitude (m)	Partial surfaces		Total surface area		The sum
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (%)$	$\sum S_i (km^2)$	$\sum S_i (%)$	$\sum S_i * H(i) (m.km^2)$
1520 - 1400	1460	0.183	0.425	0.183	0.425	266.450
1400 - 1320	1360	0.445	1.036	0.627	1.461	604.914
1320 - 1240	1280	1.323	3.081	1.950	4.541	1693.219
1240 - 1160	1200	3.700	8.616	5.650	13.157	4439.760
1160 - 1080	1120	5.862	13.652	11.512	26.807	6565.440
1080 - 1000	1040	4.587	10.682	16.099	37.488	4770.480
1000 - 920	960	6.609	15.391	22.708	52.878	6344.352
920 - 840	880	17.192	40.037	39.900	92.912	15128.960
840 - 810	825	3.044	7.089	42.944	100.000	2511.300
$H_{moy} = \sum S_i * H_i (m.km^2) / 42.944 Km^2$					Tota=	42324.875
					Hmoy=	985.592

Table 8: Distribution of surface area as function of altitude within the boundaries of S.B Mélias

Altitude (m)	Average altitude (m)	Partial surfaces		Cumulative surface area		The sum
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (%)$	$\sum S_i (km^2)$	$\sum S_i (%)$	$\sum S_i * H(i) (m.km^2)$
1460 - 1400	1430	0.071	0.109	0.071	0.109	101.583
1400 - 1320	1360	0.263	0.403	0.334	0.512	357.578
1320 - 1240	1280	2.011	3.083	2.345	3.595	2573.606
1240 - 1160	1200	1.203	1.844	3.547	5.439	1443.480
1160 - 1080	1120	0.887	1.360	4.434	6.798	993.300
1080 - 1000	1040	1.083	1.660	5.517	8.458	1125.984
1000 - 920	960	7.893	12.101	13.410	20.559	7577.280
920 - 840	880	46.052	70.602	59.462	91.162	40525.320
840 - 810	825	5.765	8.838	65.227	100.000	4756.125
$H_{moy} = \sum S_i * H_i (m.km^2) / 65.227 Km^2$					Tota=	59454.256
					Hmoy=	911.504

Table 9: Distribution of surface area as function of altitude within the boundaries of the total BV

Altitude (m)	Altitudemoy (m)	Partial surfaces		Total surface area		The sum
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (%)$	$\sum S_i (km^2)$	$\sum S_i (%)$	$\sum S_i * H(i) (m.km^2)$
1520 - 1400	1460	0.254	0.234	0.254	0.234	370.164
1400 - 1320	1360	0.708	0.654	0.961	0.889	962.492
1320 - 1240	1280	3.333	3.082	4.295	3.970	4266.825
1240 - 1160	1200	4.903	4.532	9.197	8.503	5883.240
1160 - 1080	1120	6.749	6.239	15.946	14.742	7558.740
1080 - 1000	1040	5.670	5.241	21.616	19.983	5896.464
1000 - 920	960	14.502	13.406	36.118	33.390	13921.632
920 - 840	880	63.244	58.467	99.361	91.856	55654.280
840 - 810	825	8.809	8.144	108.170	100.000	7267.425
$H_{moy} = \sum S_i * H_i (m.km^2) / 108.17 Km^2$					Tota=	101781.262

The Gravelius compactness index for the two sub-catchments of Melias and Sidi Aissa are respectively $K_c = 1.41$ and $K_c = 1.71$. These values indicate that the two sub-catchments are elongated.

The equivalent rectangle, which represents a rectangle with the same surface area as the sub-basins, the same compactness index and identical hypsometric distribution, is equal to $L = 16.36$ km and $l = 3.99$ km for the Melias sub-catchment, it is equal to $L = 17.51$ km and $l = 2.45$ km for the Sidi Aissa sub-catchment.

The height of the land plays an essential role in the flow pattern: a steeper slope causes rapid flow, and therefore a shorter time of concentration and faster rise and fall. It is indicated by the contour lines and characterised by the curve.

To estimate these parameters, we need to present the hypsometric distribution after planimetry of the partial areas between the master contour lines and the various elevations. According to figure 18, the two sub-basins are located at an altitude of over 810 m, the altitude class between 880 m and 960 m being the most dominant, with an area around 50.04% for the Sidi Aissa sub-basin and 70.61% for the Melias sub-basin.

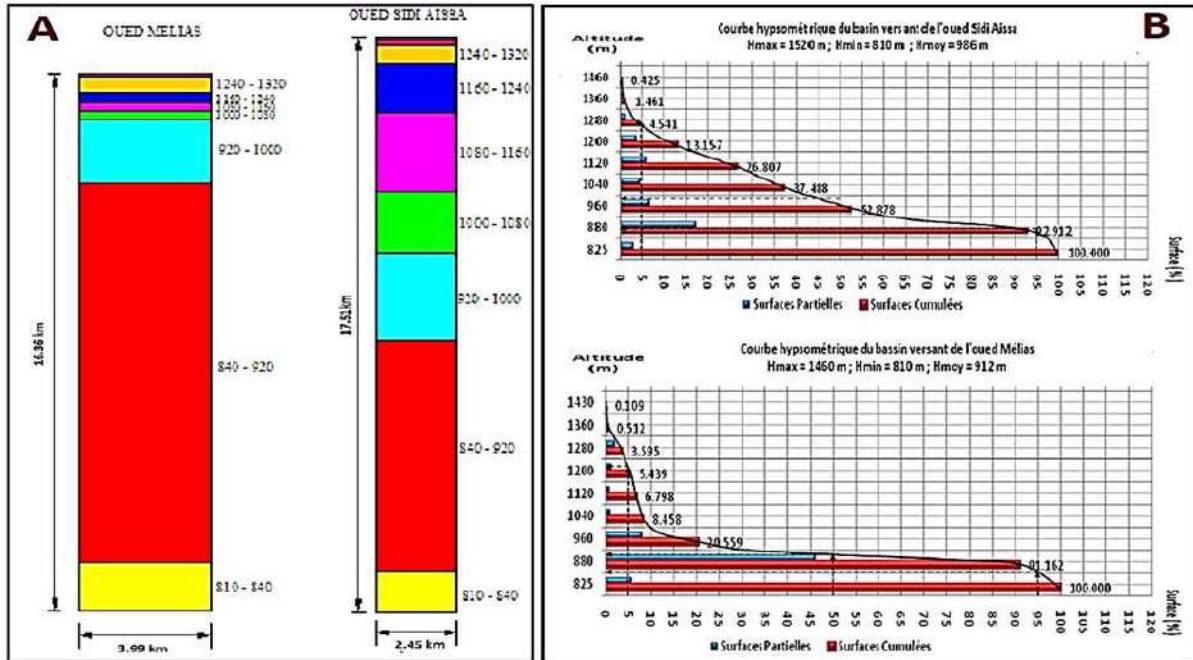


Figure 34: Equivalent rectangles (A) and hypsometric curves (B) for the Melias and Sidi Aissa sub-basins.

The maximum altitude represents the highest point in the basin, while the minimum altitude is generally the point at the outlet. These two datasets become all the more important when developing certain relationships involving climatic variables such as temperature and precipitation. So, according to the staff map, for Oued Sidi Aïssa: (Hmax=1520m;Hmin=810m) and for Oued Melias: (Hmax=1460m;Hmin=810m).

This profile is based on the topographic map {1:50,000 scale (Revoil- Beni Ounif taking into account the altitude and the length of the watercourse (the outlet).

Table 10: Altitudes as a function of cumulative distance

Hi - Hi+1	Hi(m)	Dist (km)	DistCumulated (
1320	1320	0.000	0.000
1320 - 1240	1280	0.183	0.183
1240 - 1160	1200	0.692	0.875
1160 - 1080	1120	3.167	4.042
1080 - 1000	1040	4.440	8.482
1000 - 920	960	4.139	12.621
920 - 840	880	8.075	20.696
840 - 810	825	4.471	25.167

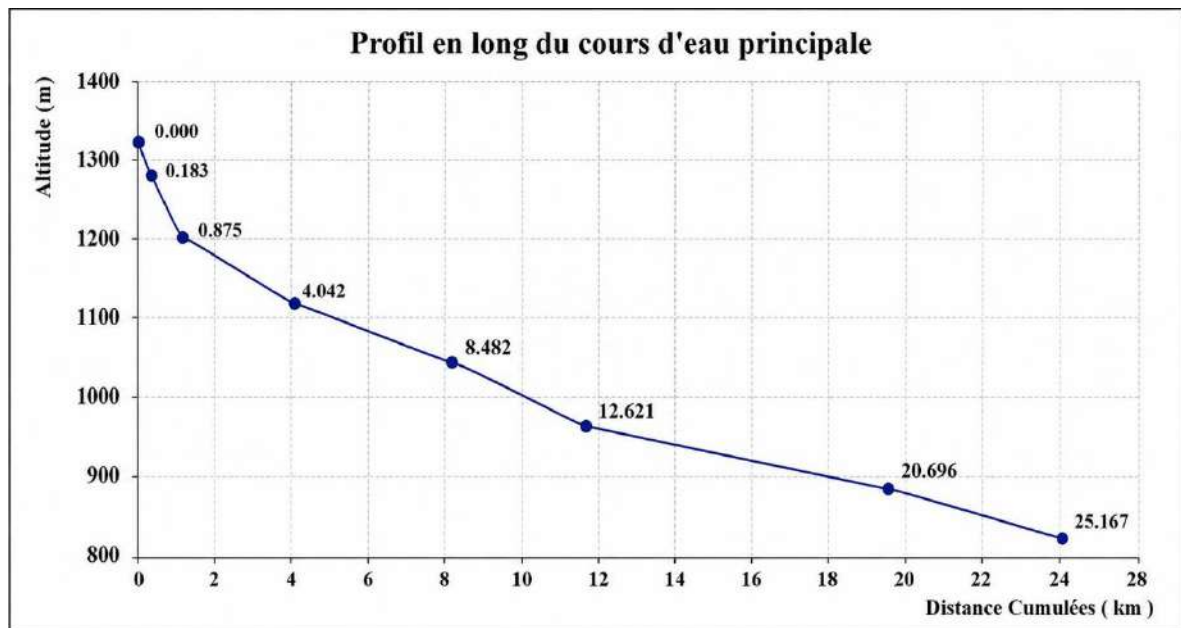


Figure 35: Longitudinal profile of the main watercourse.

The overall slope index (**I_g**), From the hypsometric curve, we deduce the altitudes H₅ % and H₉₅ %.

$$I_g = \frac{H_{5\%} - H_{95\%}}{LR}$$

g

LR

H5%: Frequency altitude corresponding to 5% of total surface area

H95%: Frequency altitude corresponding to 95% of the total surface area.

LR: length of rectangle in km

We have therefore estimated that: $I_g = 21.38 \text{ m/km} = 2.138\%$.

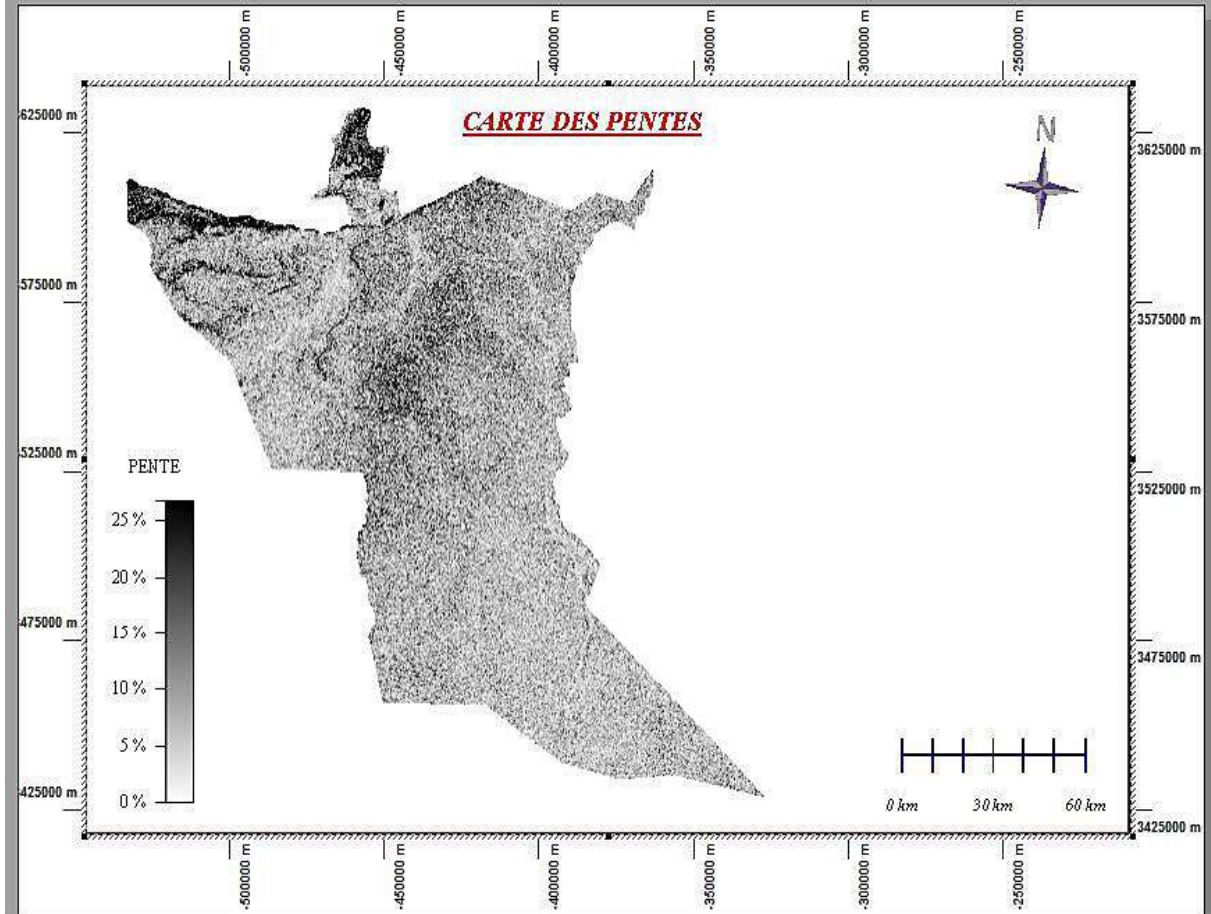


Figure 36: Map of slopes in the Beni Ounif region.

The rock slope index :

Is the average of the square root of the slopes measured on the equivalent rectangle, weighted by the areas between two contour lines H_i and H_{i-1} . It is given by the following formula :

$$I_p = \frac{1}{\sqrt{L}} \sum_{i=1}^n (S_i * H_i) \quad (06)$$

With

L: length of equivalent rectangle (m).

S_i : partial area (%) between 2 consecutive contour lines H_i and H_{i+1}

Table 11: Determination of the slope of Roche Ip (Oued Sidi Aïssa sub-basin)

<i>Altitude (m)</i>	<i>Average altitude (m)</i>	<i>Partial surfaces</i>		<i>The sum</i>
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (%)$	$\sum \sqrt{S(i)} * H(i)$
1520 - 1400	1460	0.183	0.425	7.142
1400 - 1320	1360	0.445	1.036	9.103
1320 - 1240	1280	1.323	3.081	15.699
1240 - 1160	1200	3.700	8.616	26.254
1160 - 1080	1120	5.862	13.652	33.047
1080 - 1000	1040	4.587	10.682	29.233
1000 - 920	960	6.609	15.391	35.089
920 - 840	880	17.192	40.037	56.595
840 - 810	815	3.044	7.089	14.583
The Somme		42.944	100.00	226.746

Table 12: Determination of the slope of Roche Ip (Oued Melias sub-basin)

<i>Altitude (m)</i>	<i>Average altitude (m)</i>	<i>Partial surfaces</i>		<i>The sum</i>
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (%)$	$\sum \sqrt{S(i)} * H(i)$
1460 - 1400	1430	0.071	0.109	2.556
1400 - 1320	1360	0.263	0.403	5.679
1320 - 1240	1280	2.011	3.083	15.704
1240 - 1160	1200	1.203	1.844	12.146
1160 - 1080	1120	0.887	1.360	10.429
1080 - 1000	1040	1.083	1.660	11.523
1000 - 920	960	7.893	12.101	31.114
920 - 840	880	46.052	70.602	75.154
840 - 810	825	5.765	8.838	16.283
The Somme		65.227	100.00	180.589

Table 13: Determining the slope of Roche Ip (Total Catchment Area)

<i>Altitude (m)</i>	<i>Average altitude (m)</i>	<i>Partial surfaces</i>		<i>The Somme</i>
$H(i) - H(i+1)$	$H(i) (m)$	$S_i (km^2)$	$S_i (km^2)$	$\sum \sqrt{S(i)} * H(i)$
1520 - 1400	1460	0.254	0.234	5.303
1400 - 1320	1360	0.708	0.654	7.235
1320 - 1240	1280	3.333	3.082	15.701
1240 - 1160	1200	4.903	4.532	19.042
1160 - 1080	1120	6.749	6.239	22.341
1080 - 1000	1040	5.670	5.241	20.477
1000 - 920	960	14.502	13.406	32.749
920 - 840	880	63.244	58.467	68.391
840 - 810	825	8.809	8.144	15.630
The Somme		108.17	100.00	206.871

The average slope index :

$$I_{pm} = \frac{H_{max} - H_{min}}{L_R} \quad (07)$$

L_R : Length of equivalent rectangle in km.

H_{max} and H_{min} : Maximum and minimum height in m.

Average slope of the catchment area :

$$I_{pi} = \frac{\Delta H(0.5L_1 + L_2 + \dots + 0.5L_n)}{S_{BV}} \quad (08)$$

With :

ΔH : difference in level between two successive contour lines (m).

$L_1, L_2, \dots, L_n$: contour lengths (Km).

S_{BV} : catchment area (Km^2).

The results of the measurements are shown in the table below.

Table 14: Oued Sidi Aïssa sub-basin

N°	Level curve (m)	ΔH (m)	Length (km)
1	840	80	15.706
2	920		9.477
3	1000		7.24
4	1080		6.965
5	1160		6.595
6	1240		6.254
7	1320		1.917
8	1400		1.62

Table 15: Oued Melias sub-basin

N°	Curved level(m)	ΔH (m)	Length (km)
1	840	80	3.782
2	920		15.054
3	1000		8.258
4	1080		20.263
5	1160		17.08
6	1240		7.795
7	1320		3.793
8	1400		0.824

Table 16 : Total catchment area :

N°	Curved level(m)	ΔH (m)	Length (km)
1	840	80	19.488
2	920		24.531
3	1000		15.498
4	1080		27.228
5	1160		23.675
6	1240		14.049
7	1320		5.71
8	1400		2.444

The overall slope index: I_g

However, as the Roche index takes too long to evaluate for rapid studies, an even simpler index has been proposed: the global slope index. From the hypsometric curve, we deduce the altitudes $H_{5\%}$ and $H_{95\%}$ [2].

$$I_g = \frac{H_{5\%} - H_{95\%}}{L_R} \quad (09)$$

$H_{5\%}$: Frequency altitude corresponding to 5% of the total surface. $H_{95\%}$:

Frequency altitude corresponding to 95% of the total surface area.

L_R : Length of equivalent rectangle in km.

$$I_g = 21.38 \text{ m/km} = 2.138 \%$$

Table 17 : ORSTOM classification of relief based on the overall slope index

<i>Relief</i>		<i>Value of I_g</i>
1	Very low	$I(g) < 0.002$
2	Low	$0.002 < I(g) <$
3	Fairly low	$0.005 < I(g) <$
4	Moderate	$0.01 < I(g) <$
5	Fairly moderate	$0.02 < I(g) <$
6	Fort	$0.05 < I(g) <$
7	Very strong	$0.1 < I(g)$

This table outlines the ORSTOM classification system for characterising land relief using the overall slope index (I_g). It establishes seven distinct categories of relief, ranging from 'very low' ($I_g < 0.002$) to 'very strong' ($I_g > 0.1$). The classification framework provides a standardised method of correlating qualitative descriptions of relief with specific numerical ranges of the slope index. Higher I_g values correspond directly to increasingly pronounced relief intensity. The example provided ($I_g = 0.0214$) correctly classifies the catchment area's relief as 'fairly moderate' according to this scheme.

The overall slope index **$I_g = 0.0214$** means that the relief of the entire catchment area is fairly moderate.

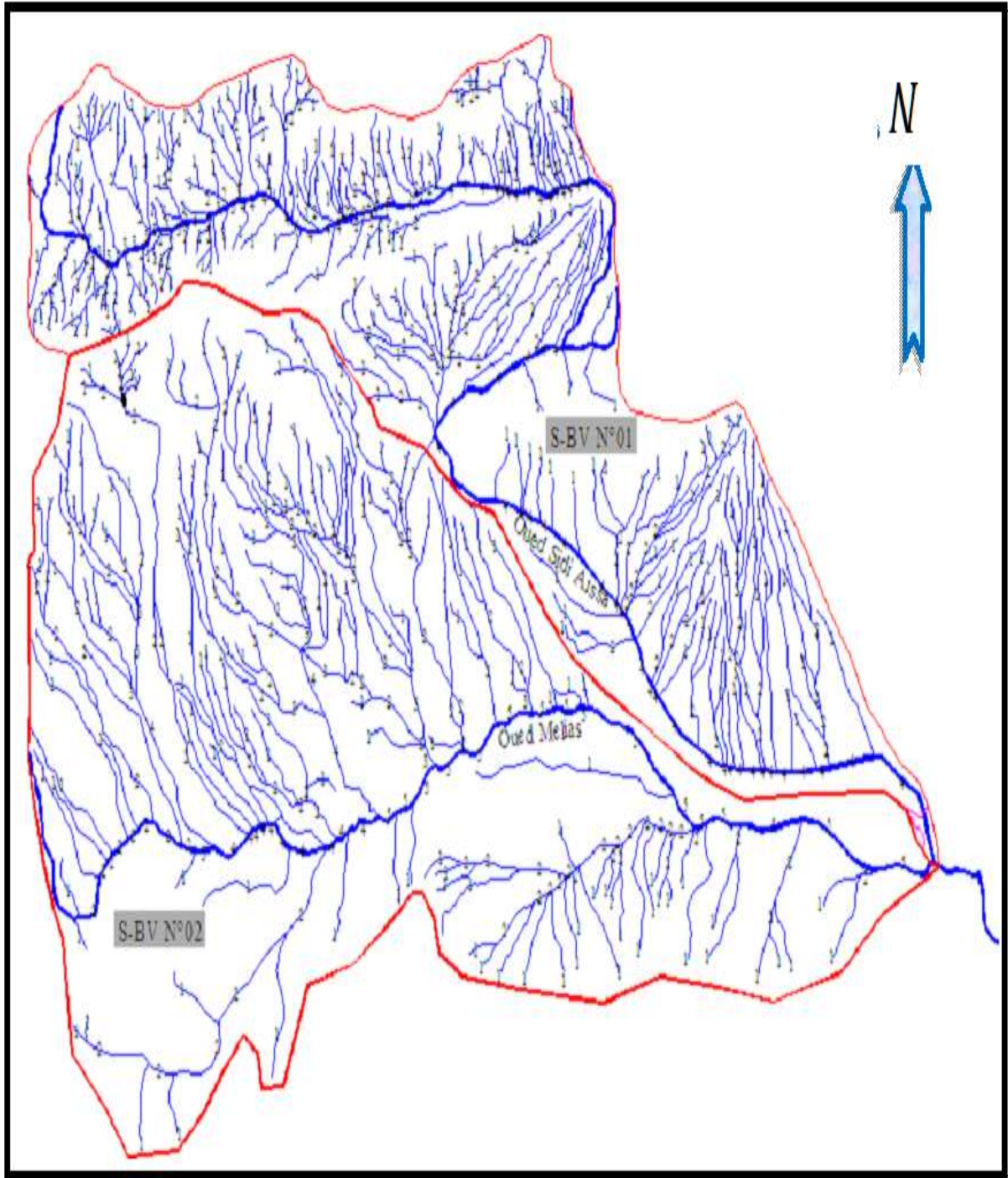


Figure 37: Hydrographic network of the catchment (Horton classification).

Other geomorphological characteristics of the sub-catchments are summarised *in Table 18*.

Table 18: Geomorphological characteristics of the sub-catchments

Designation		Symbol	Units	B. Oued Sidi Aissa	B. Oued Mélias	Basin Versant Total
Catchment area		SBV	Km ²	42.94	65.23	108.17
Catchment area		PBV	Km	39.92	40.70	48.03
Length of main thalweg		LCP	Km	25.17	18.00	25.17
Compactness coefficient		Kc	-	1.71	1.41	1.29
Equivalent rectangle	length	Lr	Km	17.51	16.36	18.01
	Width	Ir	Km	2.45	3.99	6.01
Area of equivalent rectangle		Seq	Km ²	42.94	65.23	108.17
Perimeter of the equivalent		Peq	Km	39.92	40.70	6.01
Elongation coefficient		δ	-	14.45	4.97	5.86
Altitudes	maximum	H_{max}	m	1520.00	1460.00	1520.00
	average	H_{moy}	m	986.00	912.00	941.00
	minimum	H_{min}	m	810.00	810.00	810.00
	frequency	$H_{5\%}$	m	1250.00	1200.00	1240.00
	frequency	$H_{95\%}$	m	860.00	852.50	855.00
	altitude of	$H_{50\%}$	m	960.00	900.00	920.00
Total slope index		I_g	m/Km	22.28	21.24	21.38
Catchment slope		I_{bv}	m/Km	28.21	36.11	28.21
IndicedepentedeM Roche		I_p	%	1.71	1.41	1.54
Average slope of B. V		lm	%	8.78	9.14	9.00
BV average slope index		lpm	%	4.06	3.97	3.94
Specific denivels		D_s	m	145.98	171.54	222.33
Length of watercourses		ΣLi	km	220.57	222.73	443.31
Number of order I weirs		ΣNI	-	233.00	149.00	382.00
Drainage density		D_d	Km/Km	5.14	3.41	4.10
Density of separate		F_I		5.43	2.28	3.53
Correntiality coefficient		C_t	-	27.87	7.80	14.47

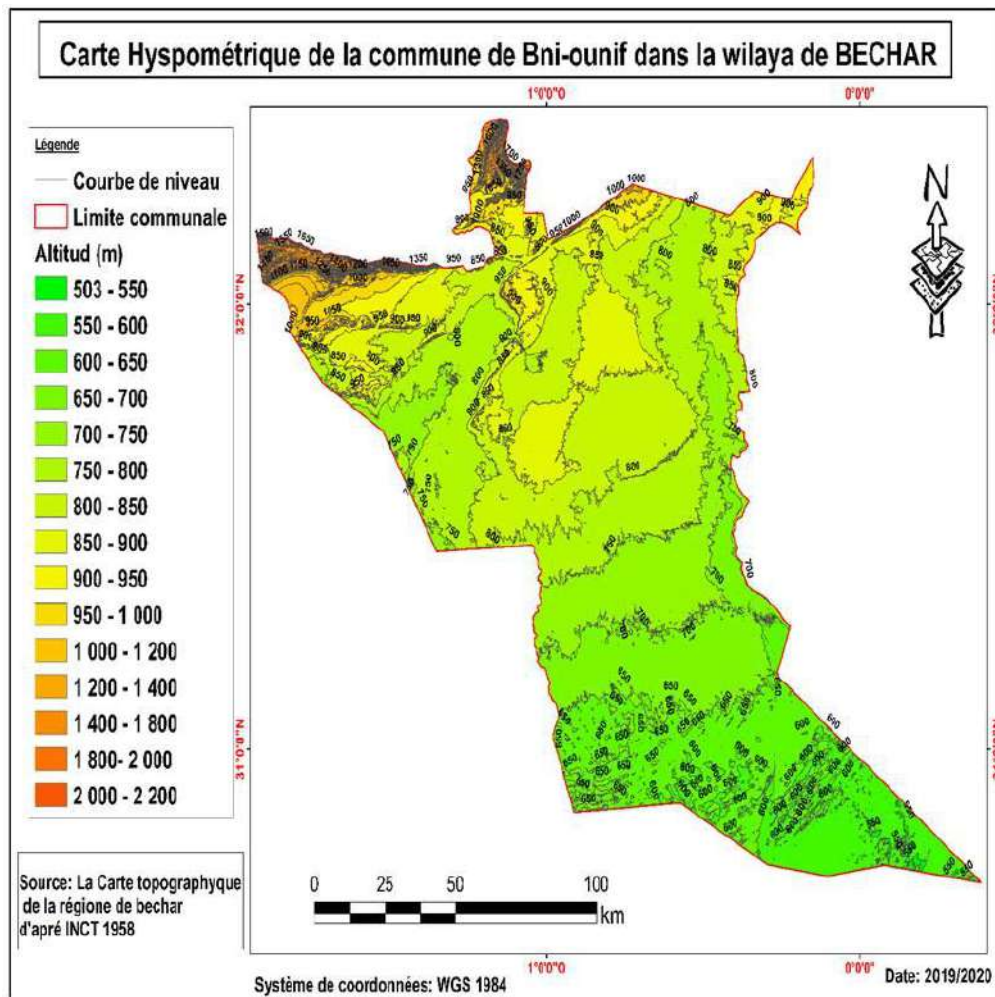


Figure 38: Hypsometric map of the commune of Beni Ounif.

7. conclusion

The study area of Béni Ounif is located in the wilaya of Béchar in south-west Algeria and marks the border with Morocco. Spanning 42,730 km², it had a population of around 13,000 in 2017. Geologically, the region forms part of the vast Saharan platform and belongs to the North African craton. Here, a Precambrian basement rests on top of a thick sedimentary layer. The Oued Namous basin is characterised by a rugged Precambrian basement, which is surrounded by Paleozoic layers that are covered by Mesozoic or recent formations, such as hamadas and ergs, which are up to 10 km thick.

The region has a Saharan climate with warm winters. Average annual rainfall does not exceed 32 mm, with monthly rainfall remaining below 2 mm. The average annual temperature is 27.37 °C, reaching a maximum of 38.83 °C in July and a minimum of 12.94 °C in January. The water balance is poor due to low rainfall and high evapotranspiration. There are no readily usable water reserves throughout the year and recharge from effective rainfall is negligible.

Chapter 02:

Hydrogeology.

1. Introduction

In order to exploit groundwater properly, it is necessary to understand the properties of the aquifer in question, such as the speed and direction of flow in the subsoil and the nature of the aquifer.

Due to the vast area occupied by the syncline, this study only focuses on the aquifer system exploited in the town of Béni-Ounif.

In this chapter, we will use the collected data to determine the hydrodynamic characteristics of the aquifer system and compare changes in piezometric levels.

Groundwater in the study area

Geological and hydrogeological studies in the Béni Ounif syncline suggest that Lower Cretaceous sandstones are present throughout the study area, either in outcrops or at depth. These are covered by Cenomanian strata or Tertiary to Quaternary landfill. Quaternary alluvial groundwater is exploited by local farmers in the palm groves.

1.1 Groundwater recharge

The Béni-Ounif aquifer system is supplied by (Mansour, 2007):

- flooding of the Zousfana and Oued Lakhdar rivers
- the area is fed by runoff during floods from the Ksour mountains (Djebel Grouz, Mélias, etc.), which often flow down from the mountain ranges (Zousfana and Oued Lakhdar), or in the form of permanent underflows from the same wadis.
- Vertical or lateral inflows through the South Atlasique fault.

In fact, it is impossible to talk about Jurassic aquifers in this region without referring to the Lower Cretaceous sandstones. The two units are hydrodynamically linked, with one recharging the other via deep fractures.

Surface geological studies and qualitative groundwater analysis allow us to adopt a supply model essentially governed by vertical or lateral inflows through the South Atlasique fault, originating in the sandstone and limestone-dolomite formations of the Jurassic (Dogger and Kimmeridgian).

1.2 Thermal emergence: the deep fractures in the southern Atlas relay are the source of the natural thermal springs located between Mélias (north of Béni Ounif), Figuig (Morocco) and Dermel (Oued Zoubia) (southwest of Djenien Bourezk).

Around Figuig, the emergence temperature reaches 47°C at Hammam El Foukani.

At Mélias, in the bed of the eponymous wadi, the water from the Mélias spring mixes with the lower flow, with an emergence temperature between 24°C and 27°C.

- The overturned series of the Oued Dermel, where water flows in hidden resurgences under the alluvium from the calcarenite-dolomite formations, particularly the Dogger formation, through the Dermel fault.

2. Hydrogeological context

The hydrogeological study aims to determine the potential of underground aquifers. The study will examine the piezometry, geometry, and hydrodynamic functioning (transmissivity and permeability) of the aquifers.

2.1 The Northern Sahara Aquifer System (SASS)

The Northern Sahara aquifer system (SASS) extends over North Africa and is shared by Algeria, Tunisia and Libya ([Allia. 2018](#); [OSS. 2003](#); [Satouh et al, 2021](#)), covers an area of around 1,000,000 km², 70% of which is occupied by Algeria and comprises two superimposed deep reservoirs: the Continental Intercalaire and the Complexe Terminal separated by a ridge of the M'zab ([OSS. 2003](#); [Bouselsal et al. 2015](#)).

In the northern Sahara, the sedimentary basin forms a vast hydrogeological basin with a surface area of 780,000 km² and a maximum thickness of 4,000 to 5,000 m ([Castany. 1982](#)). It is limited:

- In the north-east, in southern Tunisia, near the Gabes region and the Cretaceous Dahar, the eastern border with Libya is purely conventional;
- To the north by the foothills of the Saharan Atlas;

To the south-east by an east-west alignment of plateaux (Hammada) in the Tihert and Tadmaït.

- To the west by the Oued Saoura-Reggane submeridian ridge.

The SASS aquifer system extends over an area of 700,000 km² in Algeria, and is characterised by two heterogeneous units ([Figure 39](#)):

- The western hydrogeological sub-basin of around 280,000 km², drained to the south and partially covered by the Grand Erg Occidental;
- The eastern hydrogeological sub-basin, the largest with a surface area of 500,000 km², drains towards the north-east and largely occupies the Grand Erg Oriental ([Nezli. 2009](#)).

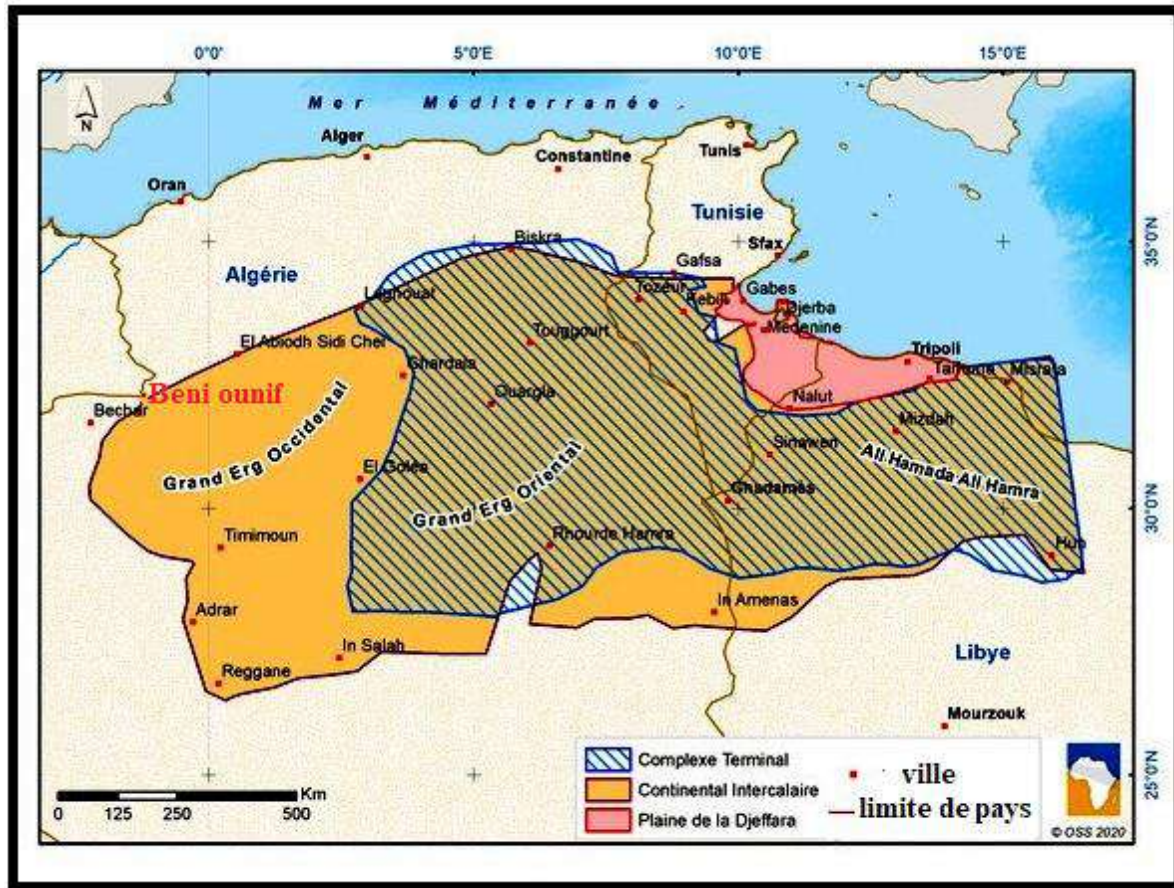


Figure 39. Extension of the SASS formations (OSS. 2020).

*** Definition of the aquifer system and regional extension of the Intercalary Continental**

The Northern Sahara Aquifer System (SASS) covers a vast area of over one million km², divided between three countries: Algeria (700,000 km²), Tunisia (80,000 km²) and Libya (220,000 km²) (OSS, 2003; Bouselsal et al 2014a; UNESCO, 1972). It extends from the Saharan Atlas in the north to the outcrops of the Tidikelt and the southern edge of the Tinrhert in the south, and from the Guir-Saoura valley in the west to the Hun Graben in Libya in the east. This basin contains a series of aquifers which have been grouped into two reservoirs known as the Terminal Complex (TC) and the Continental Intercalary (CI). The SASS basin is subdivided into three sub-basins: the Grand Erg Occidental basin in the west, the Grand Erg Oriental basin in the centre and the Hamada El Hamra plateau in the east Figure 40.

Our study region is part of the Grand Erg Occidental basin, most of which encompasses the Intercalary Continental (IC) nappe. In stratigraphic history, this refers to a continental episode intercalated between two marine sedimentary cycles (Bouselsal, 2017; Bouselsal et al. 2025):

- At the base, the essentially marine cycle of the Palaeozoic, which completes the Hercynian orogeny.
- At the top, the Upper Cretaceous marine cycle, the result of the Cenomanian transgression.

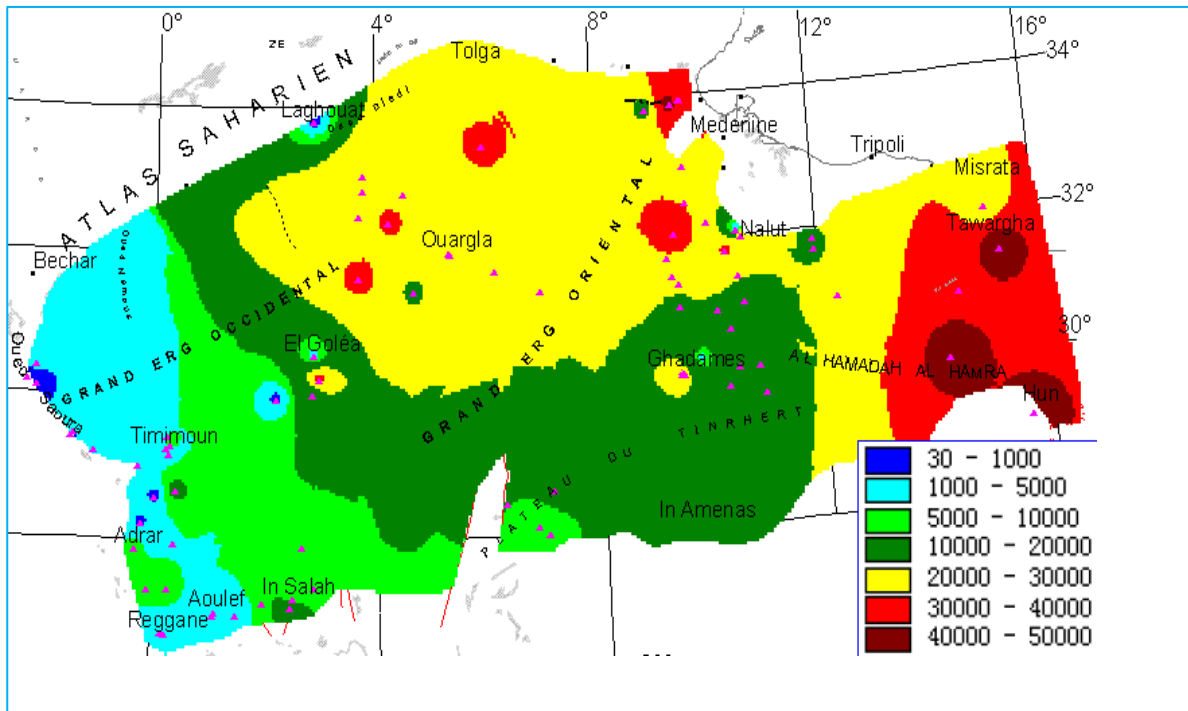


Figure 41: Age of CI waters according to carbon-14 content (OSS, 2004).

According to several authors, it is during the wet Holocene period that the recharge of the Intercalary Continental aquifer takes place. Paleorecharge simulations of the OSS model show that recharge is zero in the Saharan Atlas, the Dahar, Jebel Nefusa and the M'zab. Figure 22 shows that the carbon14 " ^{14}C " content in the waters of the Intercalary Continental aquifer in the Becher region is between 1,000 and 5,000 years old.

2.2 Hydrogeological context of the Bechar region

The aquifers identified in the Béchar region can be classified, according to their interest, into three groups:

- **The Turonian and Carboniferous (Viséen) limestone aquifers**, which by their extent and thickness, contain appreciable quantities of water. However, the water from these aquifers can only be exploited in the vicinity of the town of Béchar. To the west, towards Kenadsa, the water is salty, due to the presence of the saliferous Senonian. According to Hydrotechneco, the boreholes tapping this water table produce a total flow of 80 l/s ($2.5\text{Hm}^3/\text{year}$).
- **The Ouakda aquifer as a whole**, made up of two aquifer levels (Turonian and Quaternary). The volume of water exploited from this aquifer is estimated by ANRH at $3.5\text{Hm}^3/\text{year}$.
- **The Intercalary Continental Table (ICT) and the Carboniferous sandstone table** are only of local interest. A. Roche, estimated the volume of water extracted from the Continental Terminal in the Béchar region at 36 l/s ($1.1\text{Hm}^3/\text{year}$).

In the béni ounif region, to the north-east of Béchar, near the Algerian-Moroccan border, 10 boreholes tapping the Jurassic CI and limestone for Béchar's drinking water supply recently came on stream. The total flow rate from these boreholes is around 120 l/s (3.8 Hm³/year).

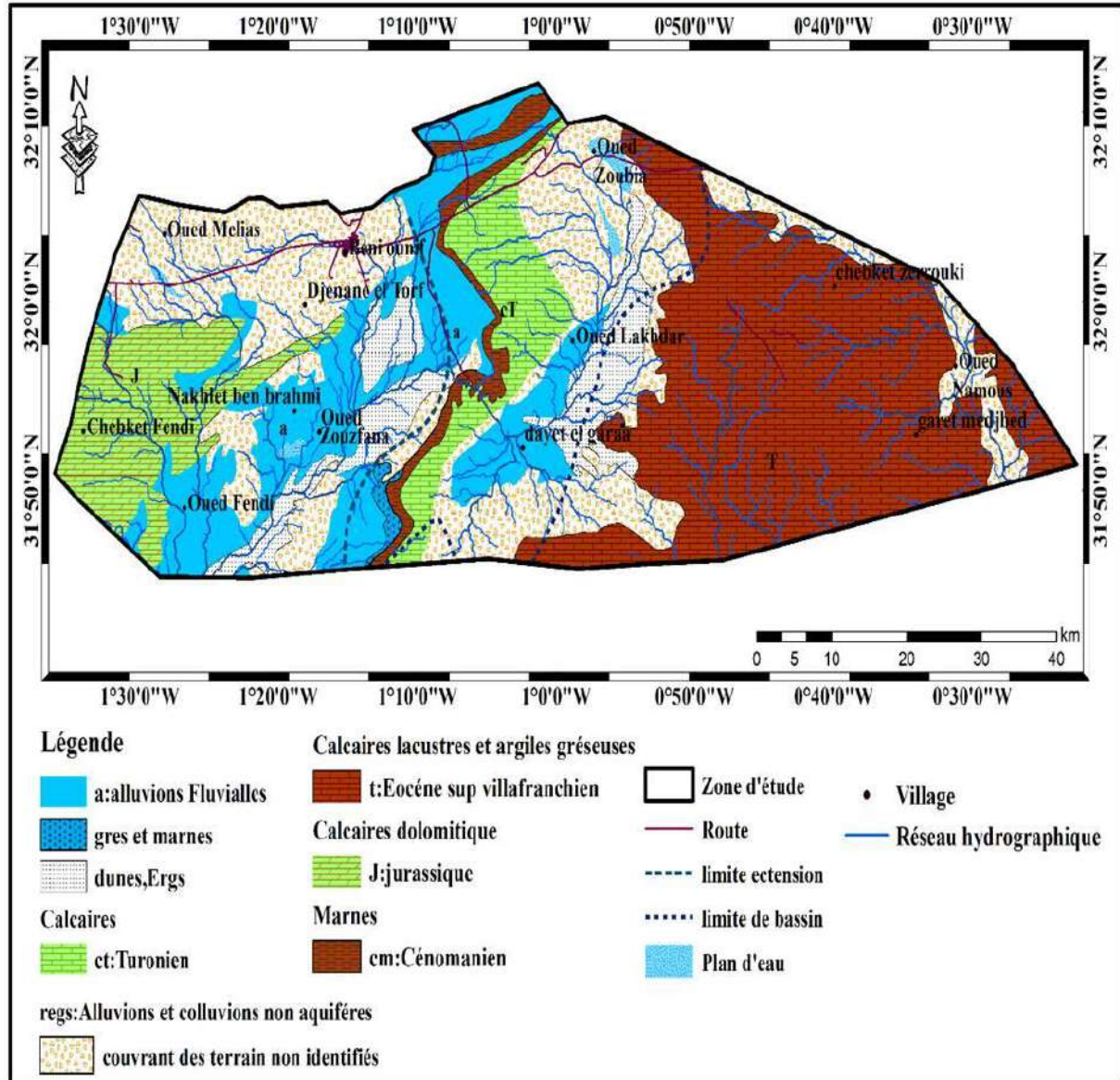


Figure.42: Hydrogeological map of the Beni ounif region.

The Beni Ounif sector occupies a special structural position in the Western Basin, forming part of the Oued Namous basin. It marks the eastern limit of the formations on which the Atlas phase was superimposed. The geological formations exposed at Beni-Ounif belong to the Mesozoic. Their litho-stratigraphic succession is represented from the base by the Jurassic outcrop to the north of the study area. The Lower Cretaceous, made up of deposits of sand and clay, overlies the Jurassic and at the top is the Quaternary, made up of alluvium, sand dunes and Erg, which usually cover the lower areas.

The aquifer system in the **Béni Ounif region** is represented by four superimposed aquifer units, shown from top to bottom in [Figure 43](#):

- The quaternary alluvial units include those in the Zousfana valley, which form a major water table, fed annually by winter and especially spring flooding.
- The Turonian calcareous-dolomitic unit is underlain by an impermeable clay-gypsum wall and a permeable substrate of clay and gypsum marl of Cenomanian age. This groundwater, which is of little local importance, is fed only by infiltration of some of the atmospheric water falling on the fractured limestone and dolomite.
- The intercalary continental unit is made up of alternating sandy-gravelly and clayey layers and is fed mainly by the water that feeds the Lower Cretaceous unit contained in the underlying captive aquifer of the Jurassic carbonate by vertical and lateral inflows through the southern Atlas flexure. The aquifer is also fed during heavy flooding by major wadis such as Wadi Lakhdar, Wadi Zouzfana, Wadi Namous and Wadi Laouedj
- The Jurassic calcareous-dolomitic unit which, decreasing in thickness in this region, has its water meeting that of the Cretaceous sandstone.

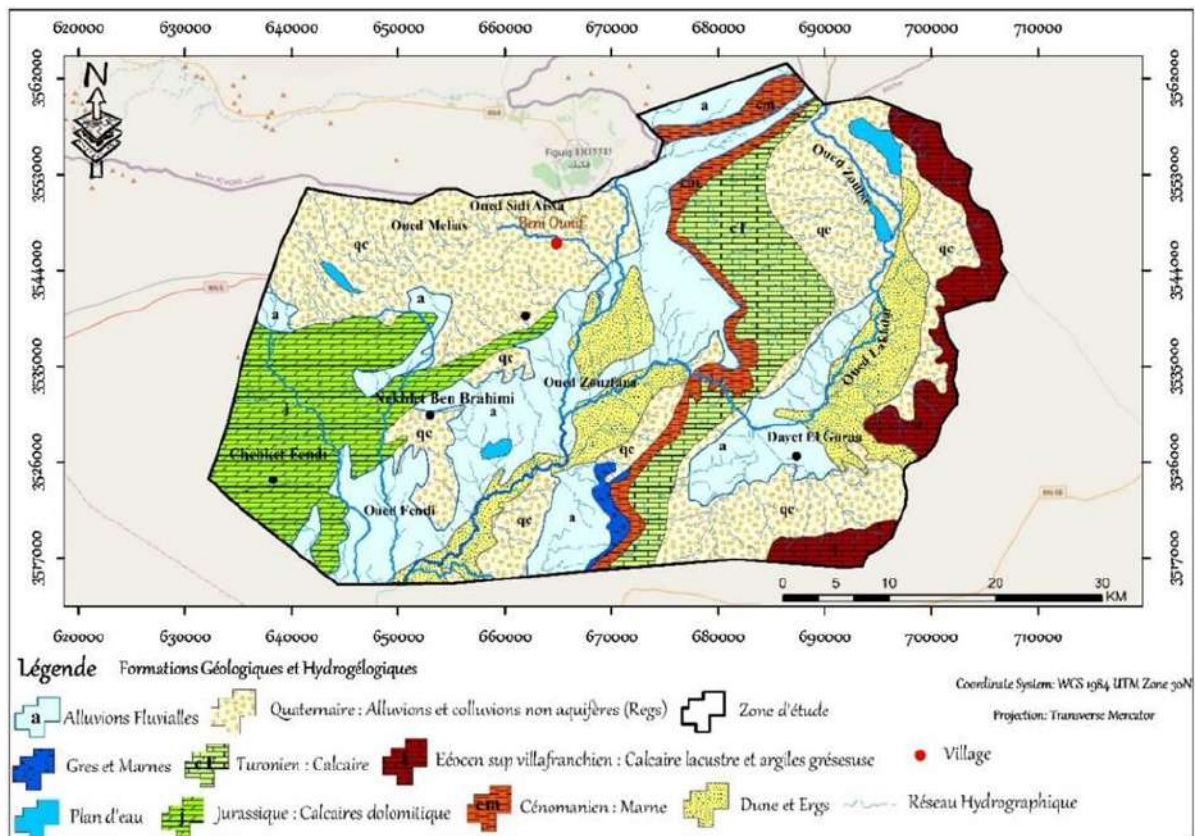


Figure.43: Geological and hydrogeological map of the Beni ounif region .

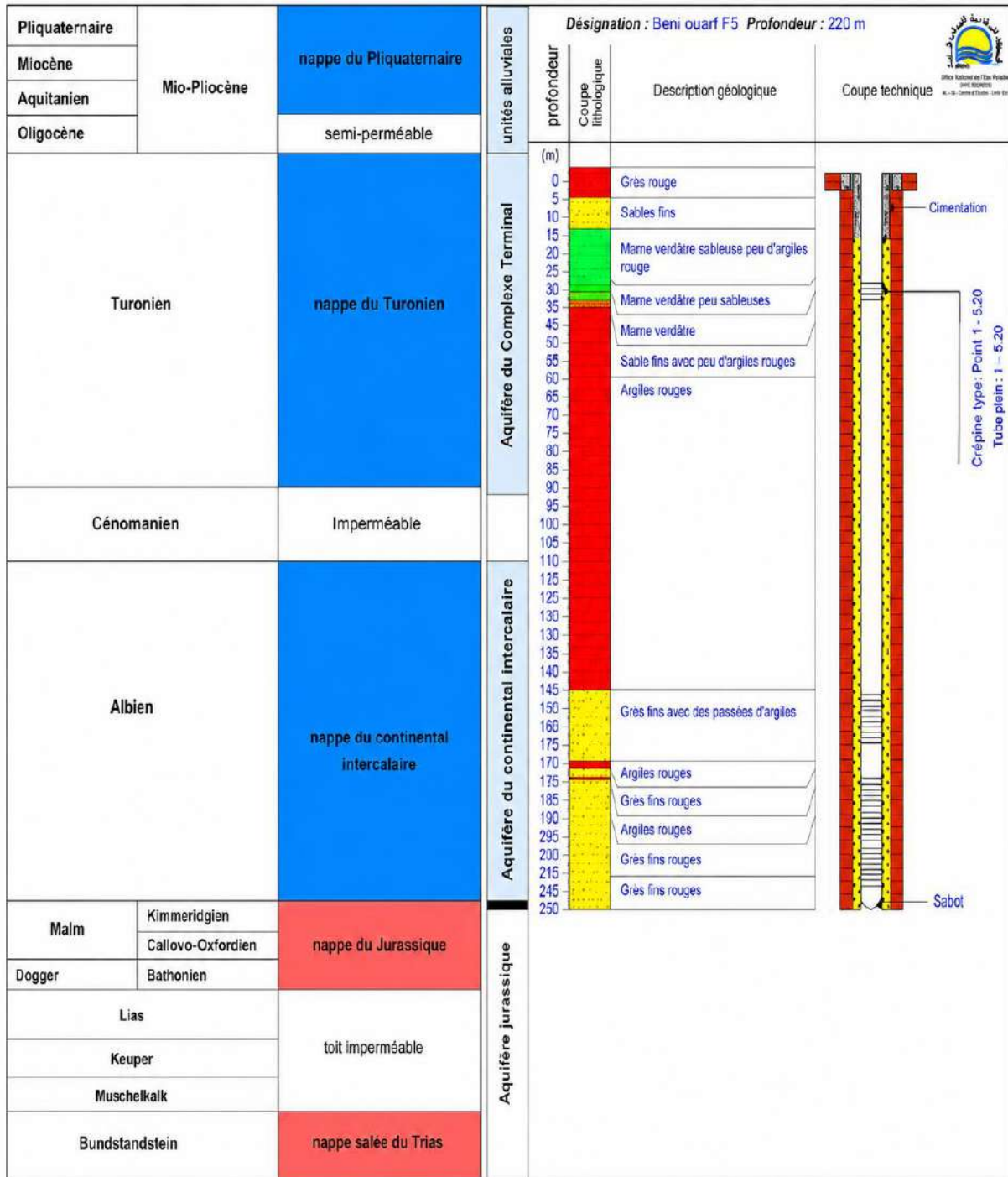


Figure 44: lithostratigraphy showing different aquifers in the study area.

3. Hydrodynamic study

Underground hydrodynamics covers all the quantitative aspects of hydrogeology. It is the part relating to groundwater flow, the laws that govern it and their applications.

The study of long-term pumping tests and, more specifically, the measurement of drawdowns as a function of time enabled us to estimate the values of the hydrodynamic characteristics: transmissivity and permeability by applying the JACOB formula.

The curves (downwelling and/or upwelling) are interpreted according to the semi-logarithmic approximation of Jacob (1947) for the calculation and interpretation of hydrodynamic parameters, whose formulae are listed as follows:

- **Transmissivity "T"**

$$T = \frac{0,183 \times Q}{C} \dots \dots (1)$$

- **The storage coefficient "s"**

$$s = \frac{2.25 \times t_0 \times T}{x^2} \dots \dots (2)$$

- **Hydraulic conductivity "K"**

Once the transmissivity has been obtained, it is possible to calculate the hydraulic conductivity "K", which is obtained by dividing the transmissivity by the thickness (e) of the aquifer crossed, according to the stratigraphic data.

The following parameters are essential in hydrogeology and can only be determined through a long-term pumping test, which is considered one of the best investigative methods. Transmissivity (T) is expressed in m²/s, while the pumping rate (Q) is in m³/s. The equivalent drawdown (C) is determined according to the logarithmic modulus, and the storage coefficient is denoted as (s). The fictitious time at origin is represented by (t₀) in seconds. The distance between the borehole and the observation piezometer is designated as (X₂) in meters. The permeability of the aquifer is characterized by (K) in m/s, while its thickness is denoted as (E) in meters.

Hydrodynamic characteristics of the water table Albienne

Several boreholes have been drilled in the Béni-Ounif syncline (F1, F2, F3, F4, F5, F6).

Due to a lack of data, we only have data from three boreholes **Fig 45**: F4, F5 and F6, located in the Béni-Ounif syncline and tapping the Lower Cretaceous aquifer at depths ranging from 120 m to 255 m.

The slope curves were drawn using the semi-logarithmic method of JACOB, (1947) applicable in the case of captive and semi-captive aquifers but may also be applicable to flows in unconfined aquifers insofar as the variations in levels caused by pumping are small in relation to the thickness of the aquifer (BRGM, 1972).

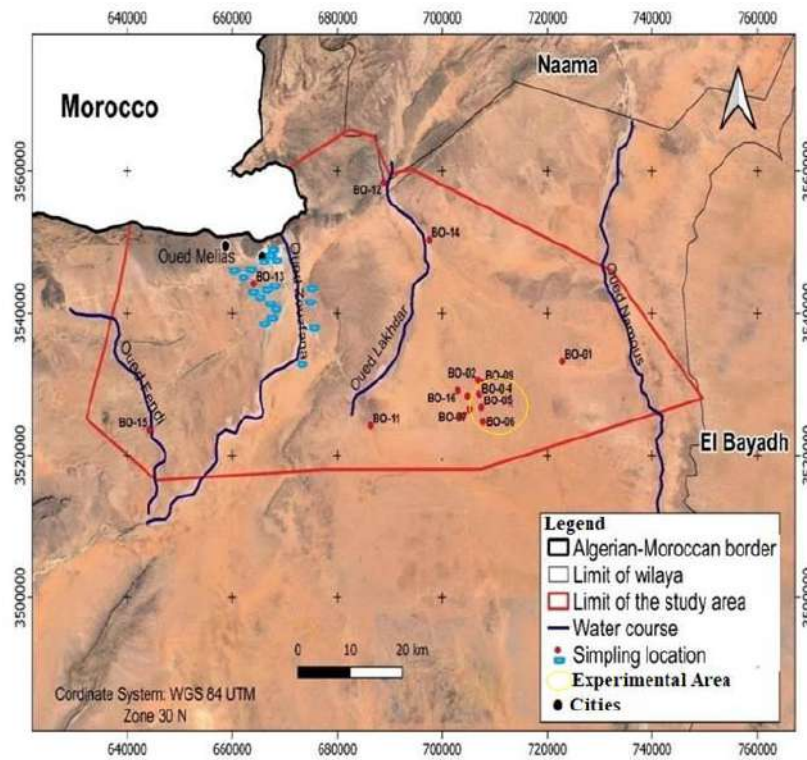


Figure 45: Experimental Area.

Drilling F4 was constructed in 1990 by the Water Resources Department (DRE) of the Béchar wilaya. At the time of its construction, the static water level was recorded at 24 meters. The well operates at a flow rate of 15 liters per second. The results of the long-term pumping test are illustrated in the curve below (Fig. 46).

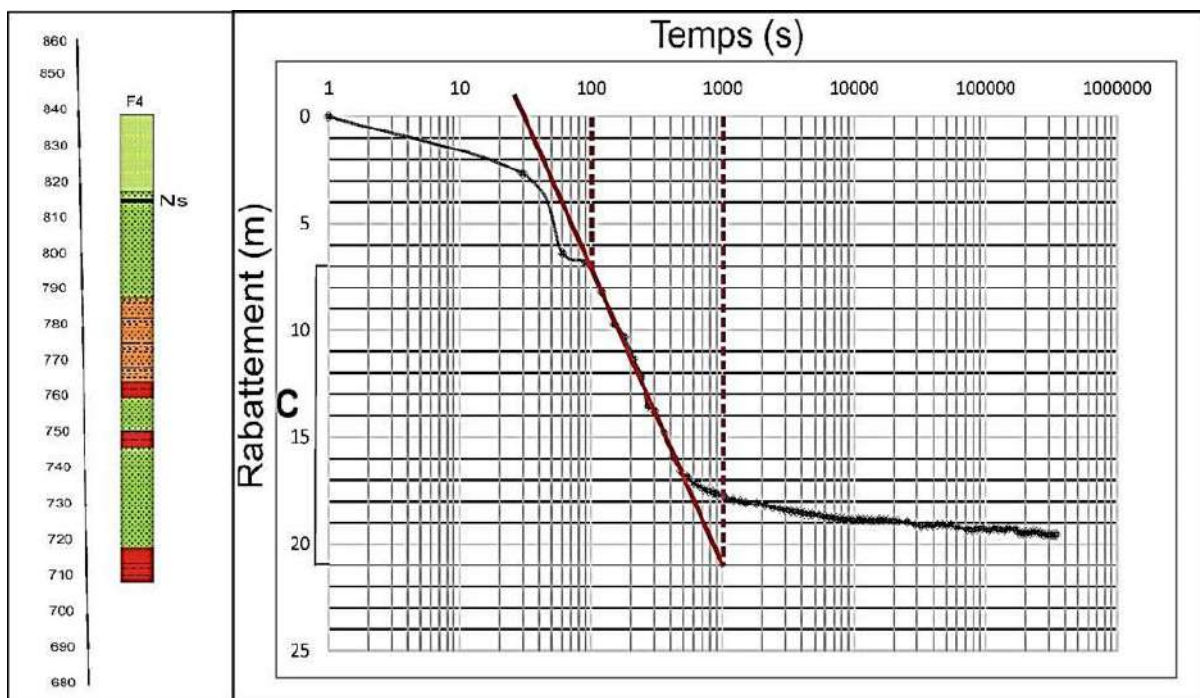


Figure 46: Cross-section and slope of borehole F4

Three intervals can be deduced from the curve:

Interval I: from 0 to 30 seconds represents the emptying time

Interval II: from 30 to 6000 seconds, this is the transient regime

Interval III: from 6000 to the end of pumping, this is the Permanent Regime.

Drilling F5 was carried out in 2007 under the direction of the Water Resources Department (DRE) of Béchar. At the time of its construction, the static water level was recorded at 28 meters. The well operates at a flow rate of 14.5 liters per second. The results of the long-term pumping test are illustrated in the curve below (Fig. 47).

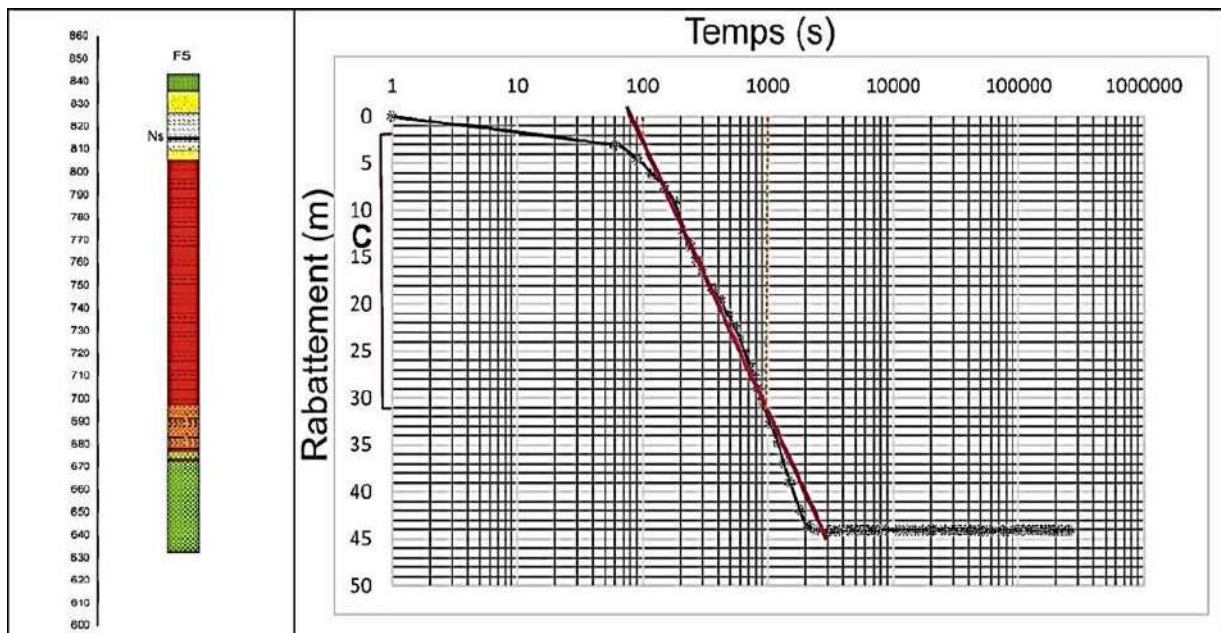


Figure 47: Cross-section and slope of borehole F5.

Three intervals can be deduced from the curve:

Interval I: from 0 to 60 seconds represents the emptying time

Interval II: from 60 to 2000 seconds, this is the transitional regime

Interval III: from 2000 seconds to the end of pumping, this is the Permanent mode.

Drilling F6 was carried out in 2008 by the Water Resources Department (DRE) of Béchar. At the time of its construction, the static water level was recorded at 28 meters. The well operates at a flow rate of 10 liters per second. The results of the long-term pumping test are illustrated in the curve below , (MERZOUGUI F.Z) (Fig. 48).

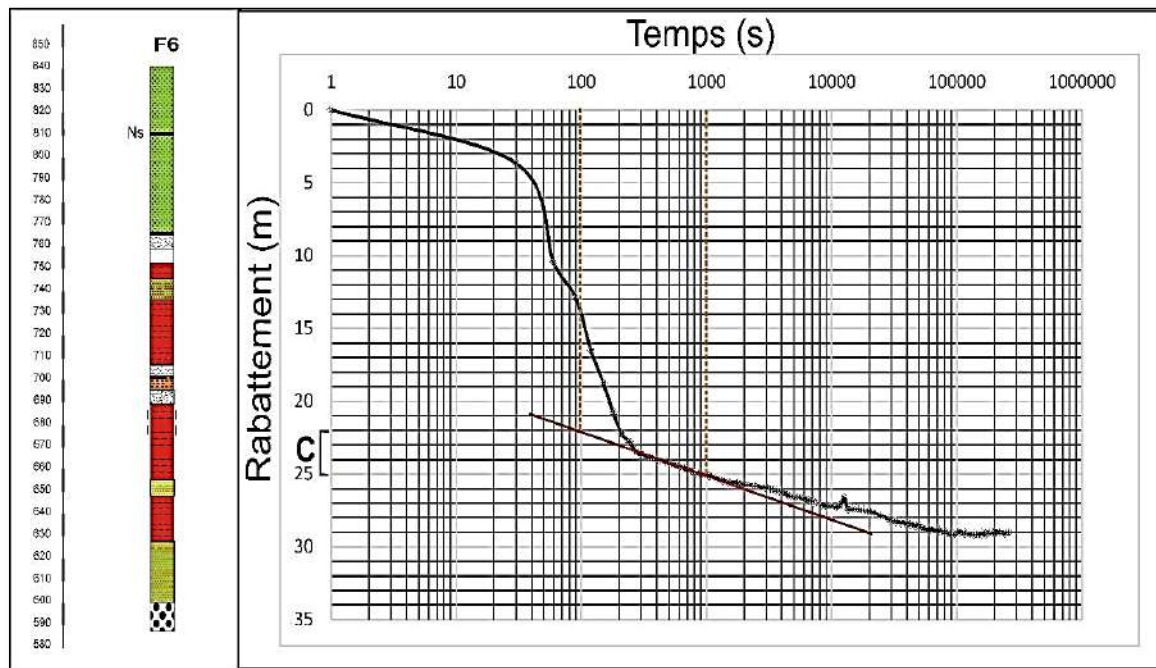


Figure 48: Cross-section and slope curve for Borehole F6 .

Three intervals can be deduced from the curve:

- **Interval I:** from 0 to 30 seconds represents the emptying time
- **Interval II:** from 30 to 10,000 seconds, this is the transient regime
- **Interval III:** from 10,000 seconds to the end of pumping, this is the Permanent mode.

In the three pumping tests, we noted a stable drawdown (Interval 3 in the curves) and therefore a stable flow rate (flow rate leaving the borehole = flow rate entering the borehole horizontally through the well screens), which assures us that we are in the aquifer formation.

Given the absence of piezometers, it was impossible to estimate storage coefficients.

Table (Tab.19) summarises the results of applying the JACOB formula to the pumping tests.

Table 19: Summary of pumping test results

Drilling	Aquifer	Depth (m)	Q expl (l/s)	Test duration(h)	Ns (m)	T (m ² /s)	K (m/s)
F4	Lower Cretaceous	140	15	96	24	1.96*10 ⁻⁴	3.26*10 ⁻⁶
F5		220	14.5	72	28	9.15*10 ⁻⁵	1.42*10 ⁻⁶
F6		253	10	72	28.13	6.1*10 ⁻⁴	4.51*10 ⁻⁶

According to **MANSOUR (2007)**, it is clear that the continental sandstones of the Béni Ounif syncline are highly permeable to cracks in places. Elsewhere, they may be poorly transmissive due to frequent clayey intercalations.

Drilling F10 was carried out on November 6, 2023, by ANBT SALAR Travaux Hydraulique. At the time of its construction, the static water level was recorded at 250 meters. The well operates at a flow rate of 30.81 liters per second.

Hydrodynamic characteristics of well 10 at Beni Ounif:

Location and type of well: The well is located at Beni Ounif and targets a 250-metre-thick aquifer. It is a "Well" type well with a "chained flow rate stages" pumping system.

Characteristic curve: The well characteristic curve shows variations in flow rate (L/s) from 0 to 35. This curve is used to understand the behaviour of the well under different pumping conditions.

Pumping in stages: Pumping tests were carried out at four levels (10, 15, 25, 35 L/s). The drawdown of the water table was measured for each pumping level. For example, at a flow rate of 10 L/s, the measured drawdown was 16.8 metres.

Results and calculations: The linear and quadratic drawdowns were calculated for each pumping level. For example, at a flow rate of 25 L/s, the calculated linear drawdown was 8.8 metres and the quadratic drawdown 58 metres.

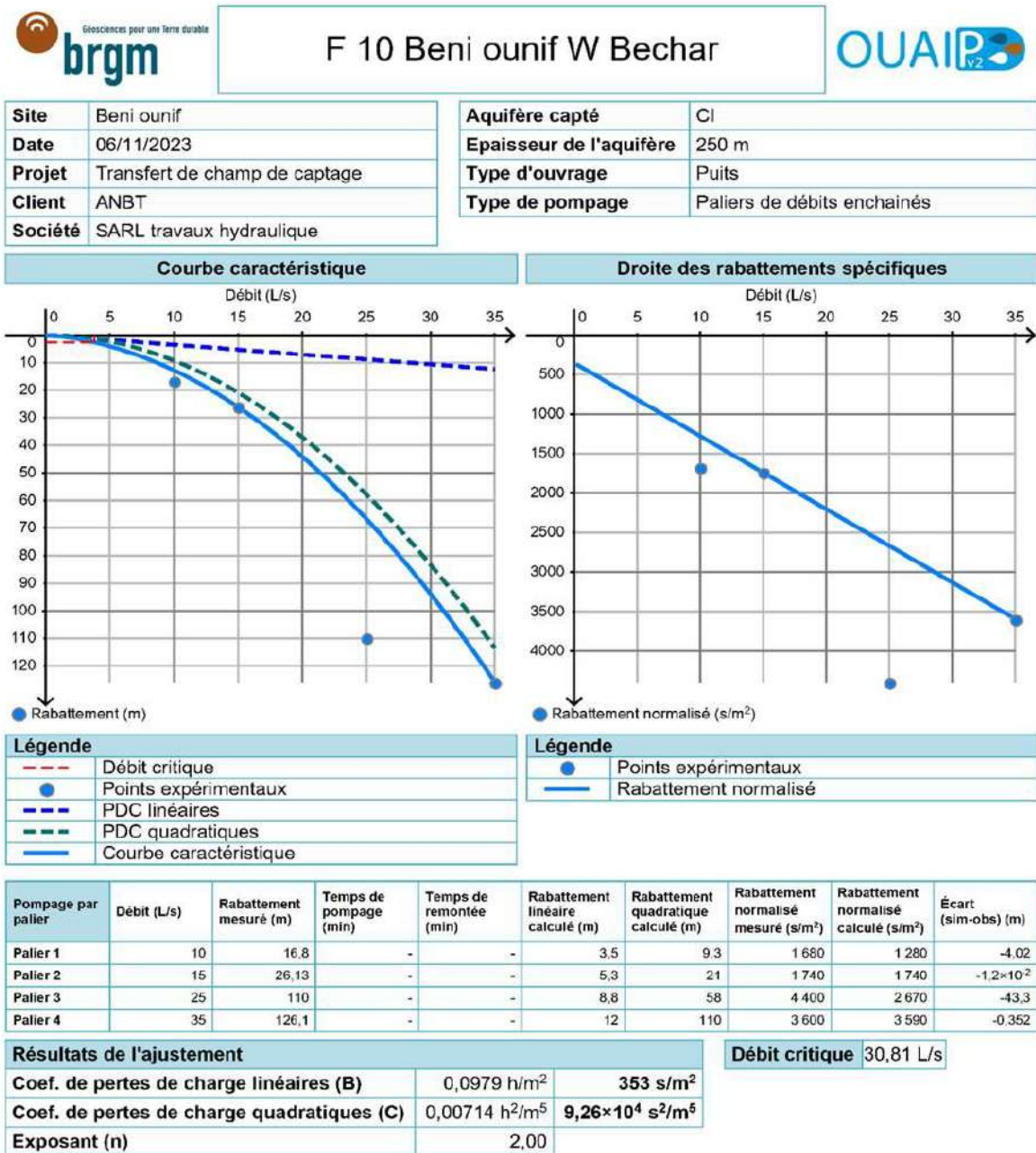
Head loss coefficients: The linear head loss coefficient (B) was determined at 0.0979 h/m² and the quadratic head loss coefficient (C) at 0.00714 h²/m⁵.

The exponent (n) is 2.00.

Conclusion: The results indicate that the well suffers a significant loss of head as the pumping rate increases, particularly at the upper levels. This may indicate a need to improve pumping management to maintain well efficiency.

This analysis provides an overview of the well's performance and helps to make more effective water management decisions.

The long-term pumping test is shown in the curve below (**Fig.50**)



arfa.ouaip (OUAIP v2.3)

<http://ouaip.brgm.fr>**Figure 50:** Cross-section and slope of borehole F6

4. Groundwater piezometry

4.1 Piezometric variation in the Superficial Aquifer

The piezometric level is the level reached by the water in an underground aquifer at a given point in time.

A piezometric map shows water levels in the subsoil. These levels are represented by curves of equal altitude.

In our case, we have data on piezometry in the Béni Ounif region from three campaigns:

Several hydrogeological campaigns have been conducted over the years to study the region's water resources. The first campaign took place in 1975, led by Kulaguin, followed by another in 1992, conducted by Bekkhedda. More recently, Sonatrach Exploration carried out campaigns in 2017. Our team conducted further investigations in 2018 and again in 2024 to continue monitoring and assessing the water resources.

4.2 Changes in piezometry in the Beni-Ounif syncline

***Piezometry in 1975**

The piezometric level at Béni-Ounif was little disturbed in 1975, and the curves (**Fig.52**) show a single general direction of groundwater flow following the NW-SE axis, with a clear reduction in the hydraulic gradient to the east of the water table. Despite the age of these piezometric data and the fact that they only concern a restricted part, this shows us that the groundwater is fed in the northern part of the area studied (southern Atlasic fault and the southern flank of Djebel Grouz).

***Piezometry in 1992**

The water table is represented by shallow waters flowing in heterogeneous sandstone-clay soils, folded and affected by relatively dense fissuring. Wells and boreholes do not reach the wall of the aquifer, estimated to be 200 metres deep.

The piezometric map (**Fig.53**) shows a general flow in a North-West - South-East direction. The water flows along an average West-East drainage axis. On either side of this axis, the flow lines show that the water drained comes from the north (Djebel Grouz) and the south (Chebket Charef and Fendi).

Further to the east, the main drainage axis is subdivided into two other secondary axes due to the presence of a water divide, which may correspond to the uplift of a clay lens. The southern axis drains water towards Djenane Tarf and then towards the Chebket Tamednaïa.

The northern axis drains some of the groundwater towards the town of Béni Ounif and its wellfields. At this point, the piezometry appears to be very disturbed due to the pumping carried out in the wells and boreholes that have been installed.

The fairly constant hydraulic gradient in the west with values of 8 ‰ decreases in the centre and takes on a value of 2 ‰ around the water points in the centre of the palm grove. This decrease can be explained by the thickening of the aquifer from west to east ([bekkhedda, 1992](#)).

***Piezometry in 2017**

During our campaign, eight water points were accessible to us (Tab.20).

Table 20: Structures accessible for piezometric measurements (2017 campaign)

Work	Y latitude	X longitude	Z	Depth	Ns (m)	Np (m) 2017
Ala	32° 2.971'N	1° 11.997'O	812	62	5,7	806,3
Leg	32° 1.326'N	1° 14.458'O	820	75	14,8	805,2
Alb	32° 0.799'N	1° 15.782'O	829	40	24,5	804,5
Fn	32° 2.880'N	1° 14.077'O	816	31,5	4	812
RaK	32° 1.992'N	1° 20.089'O	862	100	41	821
Gh	32° 1.121'N	1° 21.427'O	867	90	45	822
Rah	32° 0.839'N	1° 17.014'O	838	65	27	811
Bou	32° 2.806'N	1° 14.285'O	818	15	9,5	808,5

The distribution of structures in the town of Béni-Ounif is shown on the map below (Fig. 51). provides detailed geospatial and hydrogeological data for eight measurement points. Each entry includes coordinates (latitude and longitude), elevation (Z), total well depth, static water level (Ns), and piezometric level (Np) recorded in 2017. The elevations range from 812 m to 867 m, indicating varying topographical conditions across the sites. The static water levels (Ns) vary significantly, from shallow (5.7 m) to deep (45 m), reflecting differences in local groundwater conditions. Notably, the piezometric levels (Np) remain within a relatively narrow band, suggesting a somewhat consistent regional aquifer pressure. This data is essential for evaluating groundwater flow and storage characteristics across the monitored area.

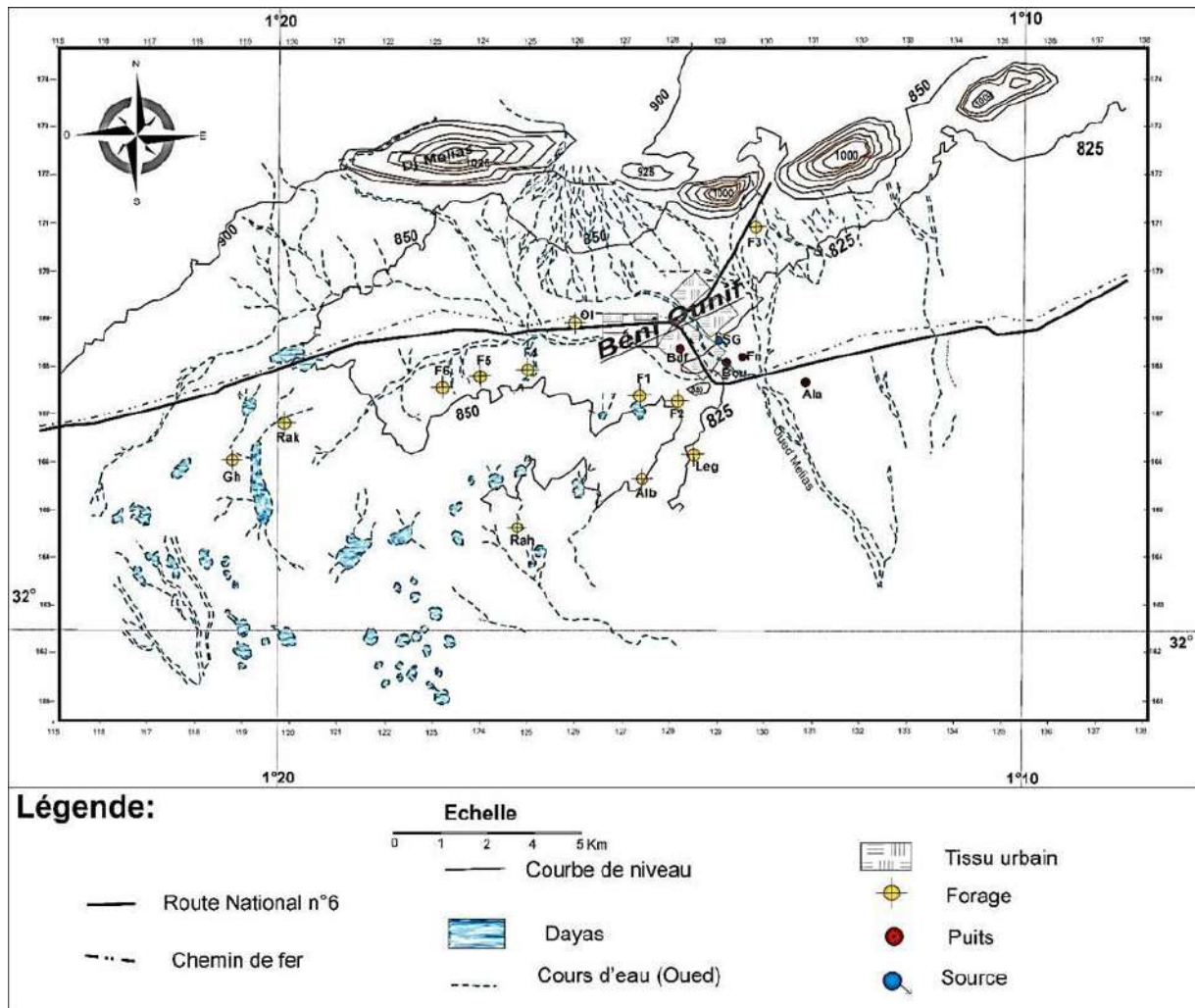


Figure 51: Distribution of structures in the town of Béni-Ounif (map extracted from the topographic map of the Béni-Ounif revoil 1/50000th).

These structures, which were accessible for measuring the piezometric level (**Tab.20**), are few in number and give us limited information on the underground flow in this part of the town. The piezometric levels measured vary between 804 m and 822 m.

The production of a piezometric map seems to be meaningless in our case because the number of measurement points is insufficient and does not cover all or even half of our study region.

We took our measurements of the piezometric levels anyway and tried to draw a piezometric sketch (**Fig.53**) using the Surfer v.9 software. We observe that the direction of flow is more or less similar to that obtained by Bekhedda (1992).

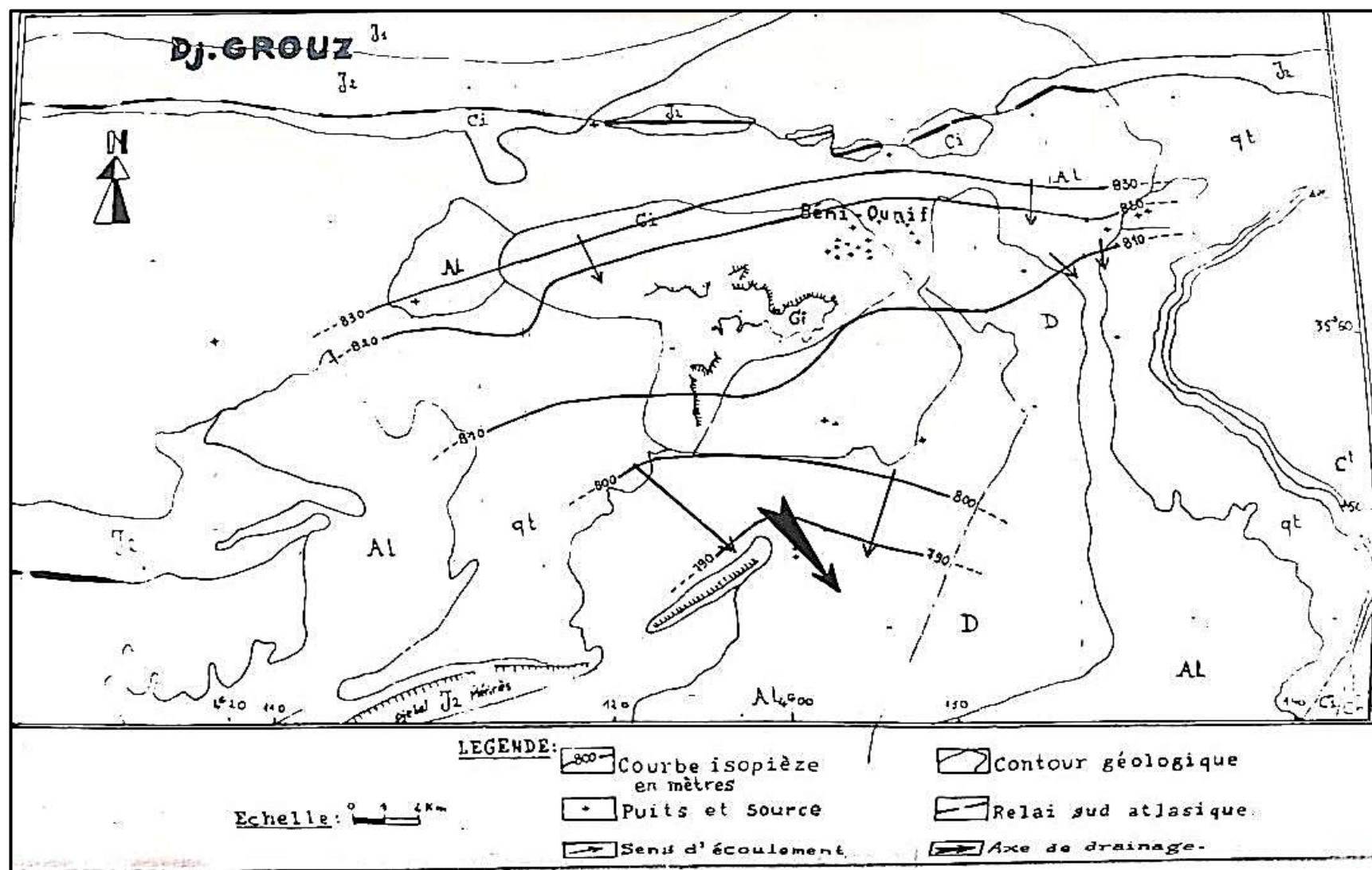


Figure 52: Piezometric map (May 1975 campaign) (Bekhedda, 1992)

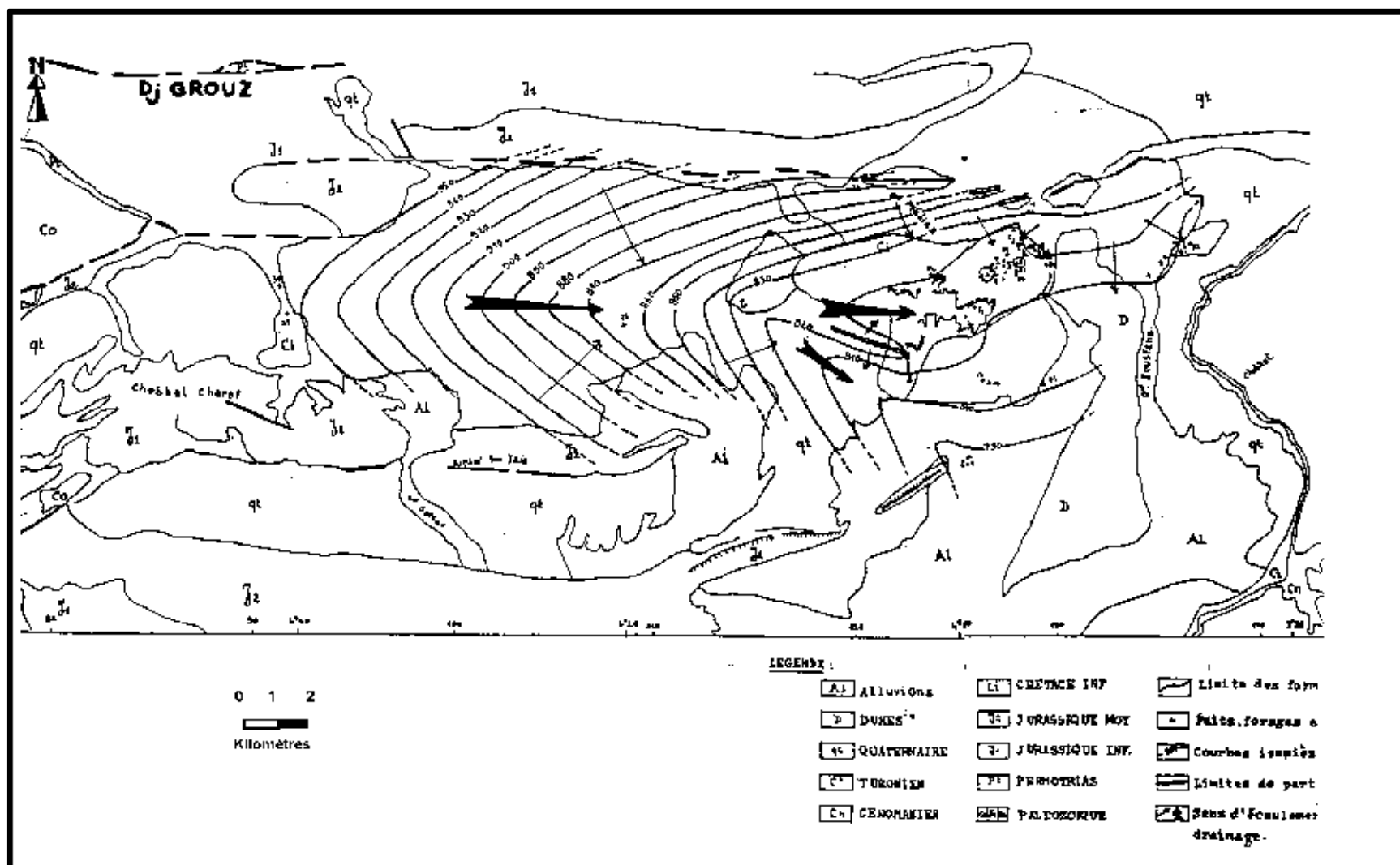


Figure 53: Piezometric map (February 1992) (Bekhedda, 1992).

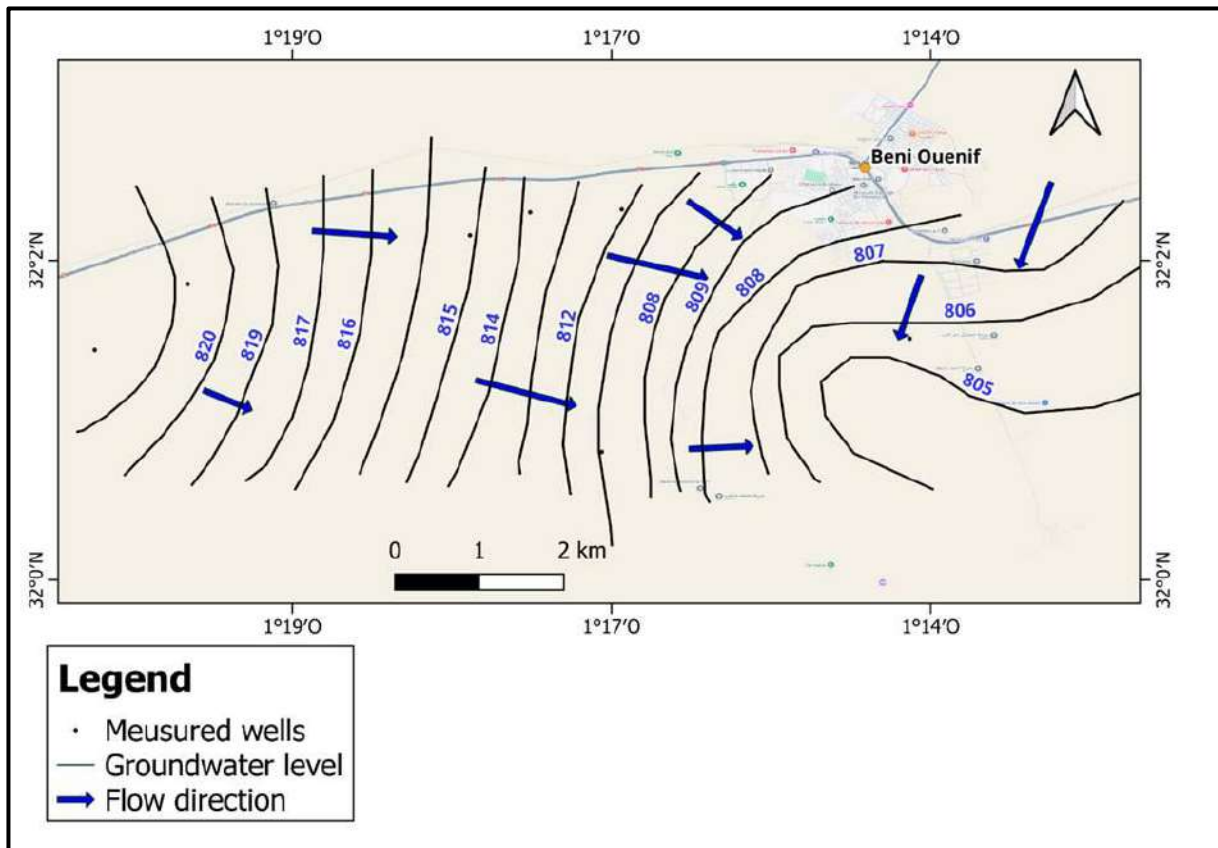


Figure 54: Piezometric map (March 2017).

A comparison of the two surveys (**Fig.53 and Fig.54**) shows that the water table at borehole F4 has dropped by 8 m (from 820 m in 1992 to 812 m in 2017). This is due to intensive pumping in the town of Béni-Ounif (increase in the number of boreholes used for irrigation).

4.3. The Béni Ounif Intercalary Continental Aquifer (CI)

The Continental Intercalaire of Beni Ounif is the main water table used for water supply in the region. It is semi-free along the northern axis of Beni Ounif, becoming captive in the southern and south-eastern parts.

In the north-eastern part, upstream of the Beni Ounif region, the Intercalary Continental water table has been encountered at a depth of 103 metres and is exploited by boreholes that provide a total flow rate of 15 m³/h. In the catchment area, the maximum depth of the Continental Intercalaire is 270 metres, with boreholes producing flows of 35 to 47 l/s.

The Beni Ounif Intercalary Continental aquifer is the only source of fresh water exploited in the Béchar basin. Its reservoir is exploited at medium depths to meet the region's domestic, agricultural and industrial water needs.

An isopaque map of the Beni Ounif region shows a thickening of the Intercalary Continental sediments from south-west to south-east and north **Fig. 55**.

- To the north-west: ADJ-101 (538m) and BIR-101bis-101(991m).

- To the south-west: TLA-101 (70m), RJC-101 (70m) and TRZ-101 (120m)
- To the south-east: ECF-101 (240m) and MSO-101 (334m).

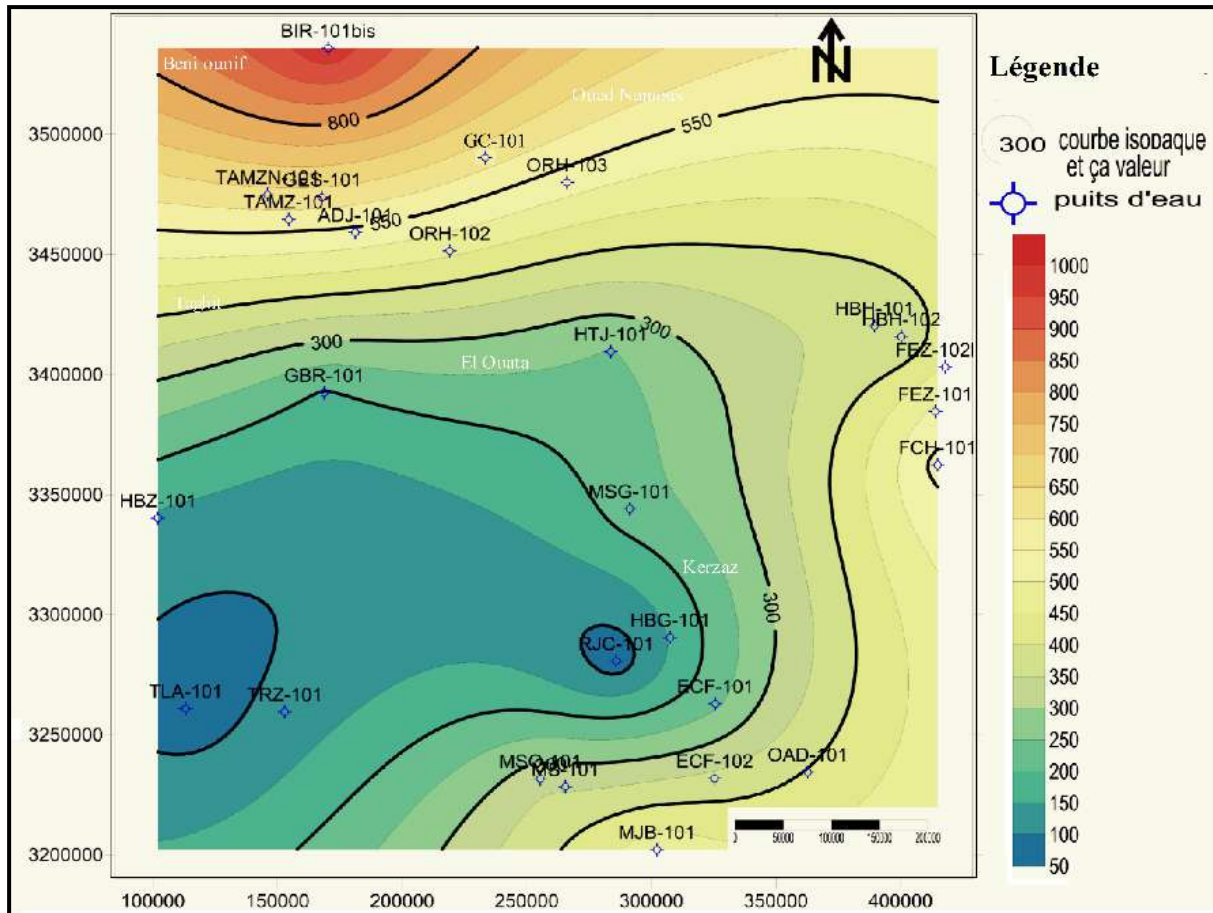


Figure. 55: Isopaque map of the CI in the Beni Ounif region.

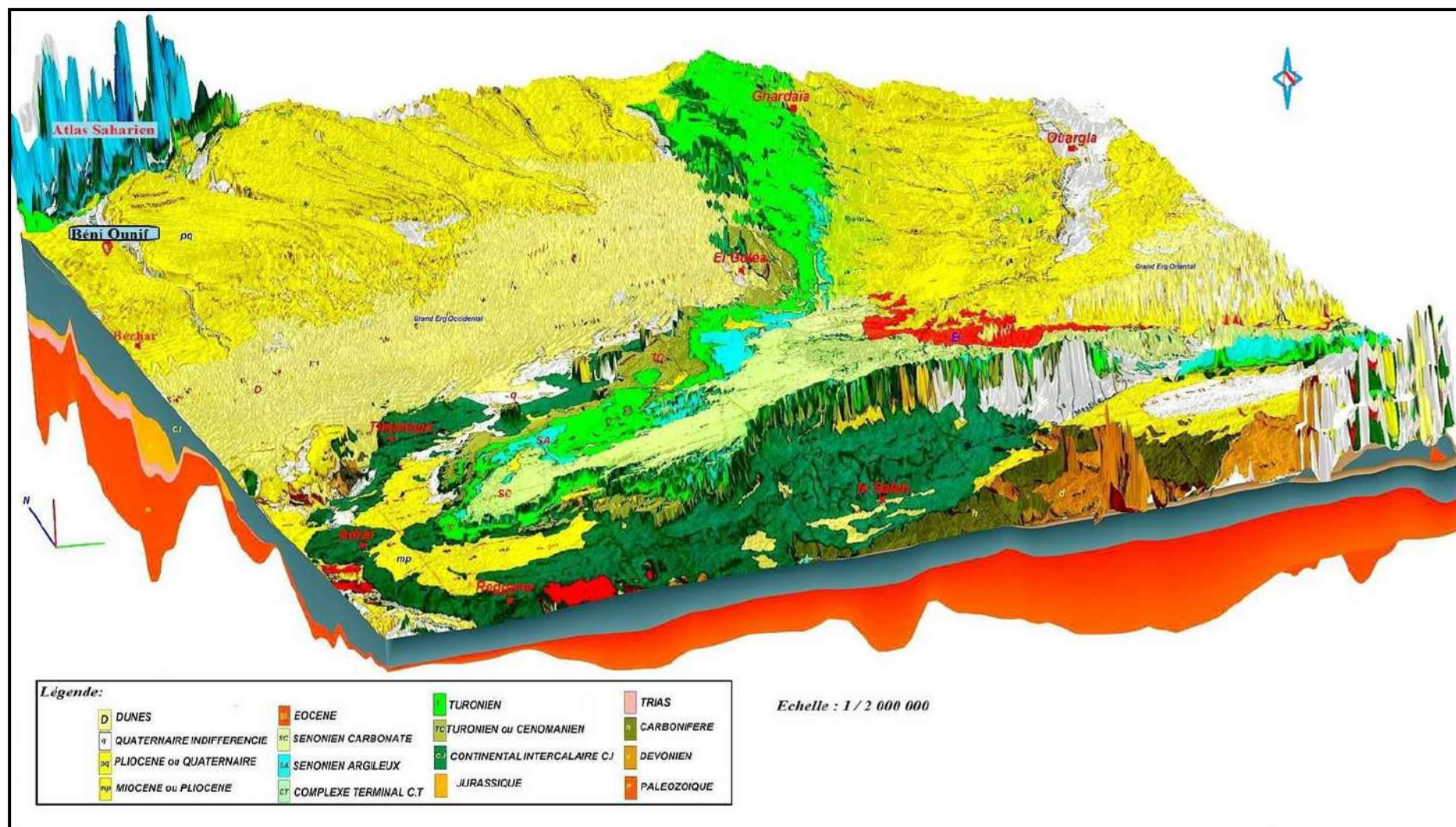


Figure.56: Geological map draped over a hydrogeological diagram of the western basin

* Piezometry of the Beni Ounif CI water table

Analysis of the piezometric map (**Fig. 57**) of the Intercalary Continental water table, carried out at basin level in 2018, highlights the following observations:

The main direction of regional groundwater flow is from north-west to south-east.

In the extreme north-west: the isopiez lines are closer together than in the north-east and south, with relatively constant and regular spacing. This indicates a uniform groundwater flow, characterised by a hydraulic gradient of around 2.3×10^{-3} .

To the south-west and east: The isopiezied lines also show a constant and regular spacing, revealing a uniform underground flow with respective hydraulic gradients of 1.03×10^{-3} and 5.8×10^{-4} .

To the south: A north-south water drainage axis can be seen at wells MSO-101 and MS-101.

These elements illustrate the dynamics of groundwater flow in the region, with hydraulic gradients and flow directions varying from one area to another.

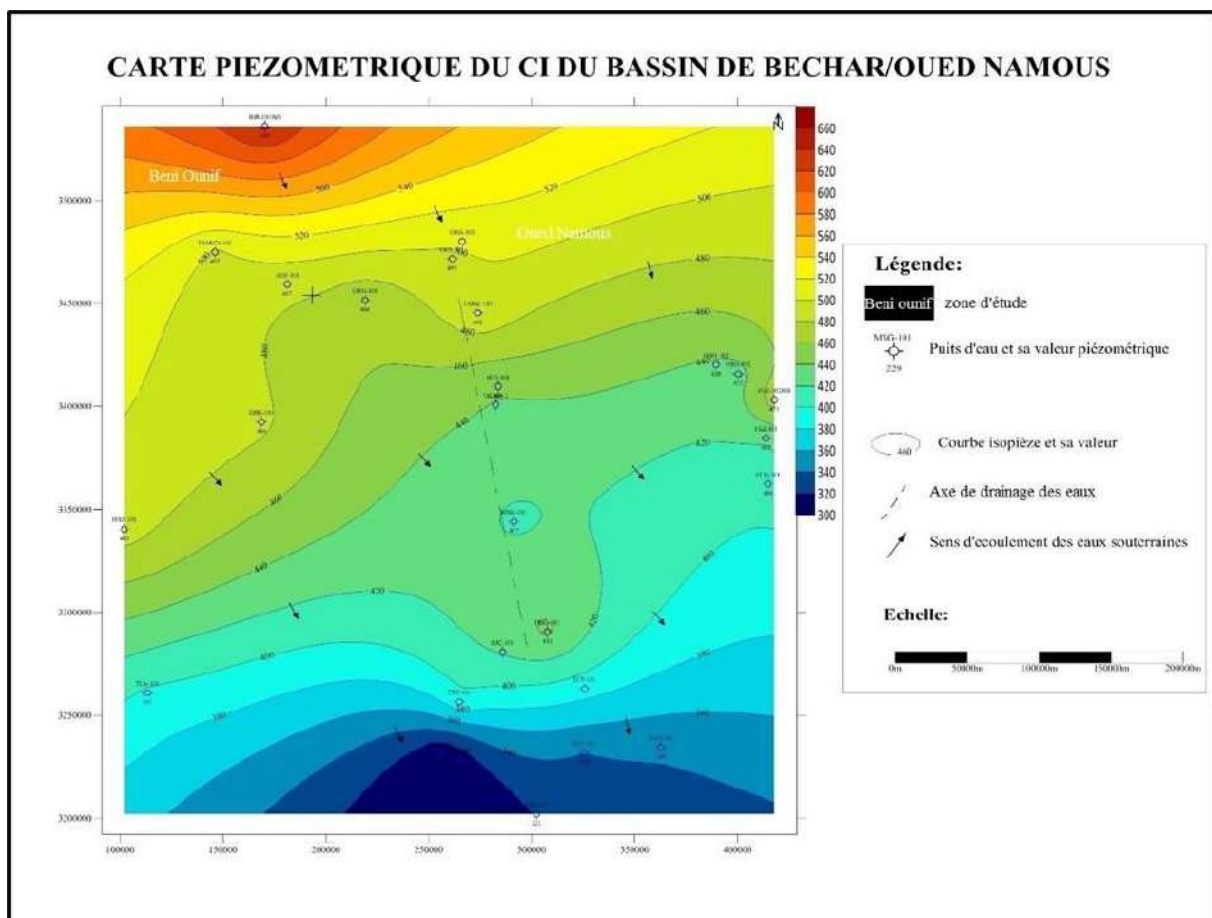


Figure 57: Piezometric map of the Beni Ounif intercalary continental water table.

Analysis of the piezometric map produced in 2024 **Fig. 58** reveals the following characteristics:

Location and orientation: The map covers an area between longitudes $0^{\circ}48'W$ and $0^{\circ}53'W$, and latitudes $31^{\circ}50'N$ and $31^{\circ}53'N$. The measurement points (wells) are spread across this area, with piezometric levels varying between 100 and 136 metres.

Piezometric levels: The piezometric values measured show spatial variation, indicating heterogeneity in the distribution of groundwater levels.

Direction of flow: The legend indicates the presence of a groundwater flow direction. Although the map does not explicitly show isopiezied lines, the layout of the wells and the piezometric levels suggest a general flow trend.

Measurement wells: Identified wells (F01, F02, F03, etc.) are used to measure piezometric levels. These measurement points are essential for understanding groundwater dynamics in the region.

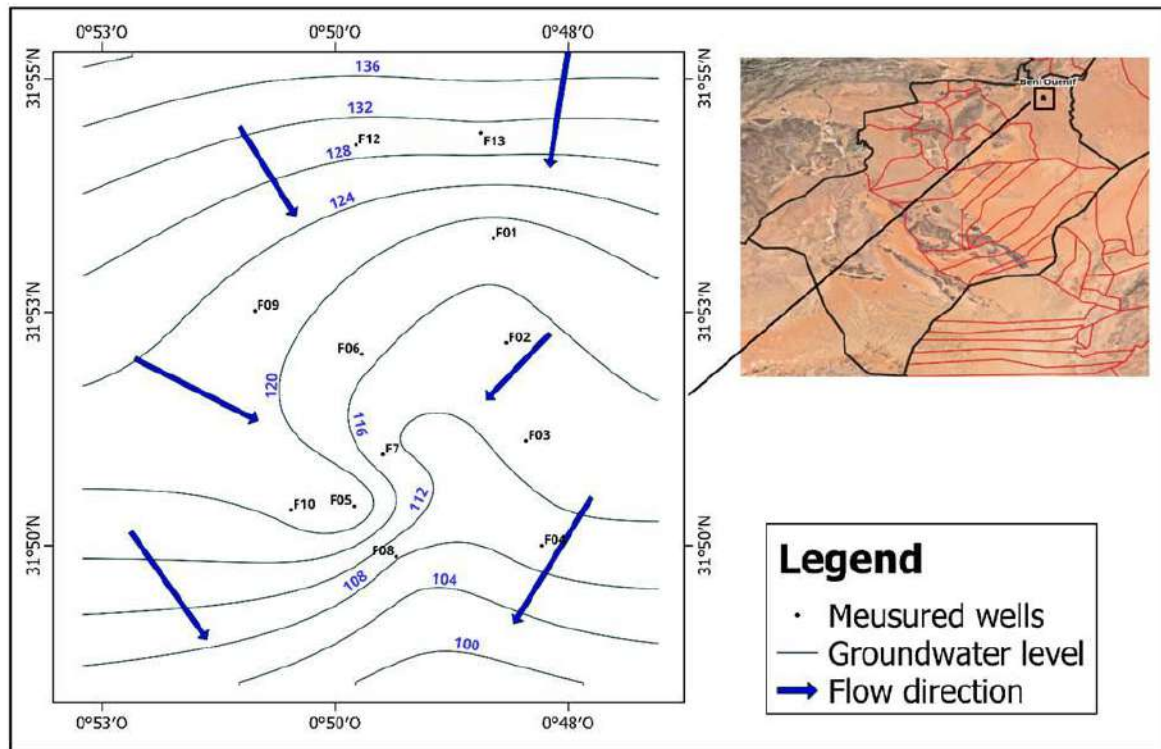


Figure 58: Piezometric map of the Beni ounif 2024 CI water table.

Analysis of the borehole logs shows a drain between the intercalary continental water table and the surface water table. This back aquifer rests unconformably on the IC with hydraulic continuity. This has recently been confirmed by the GC water well (**Fig.59**).

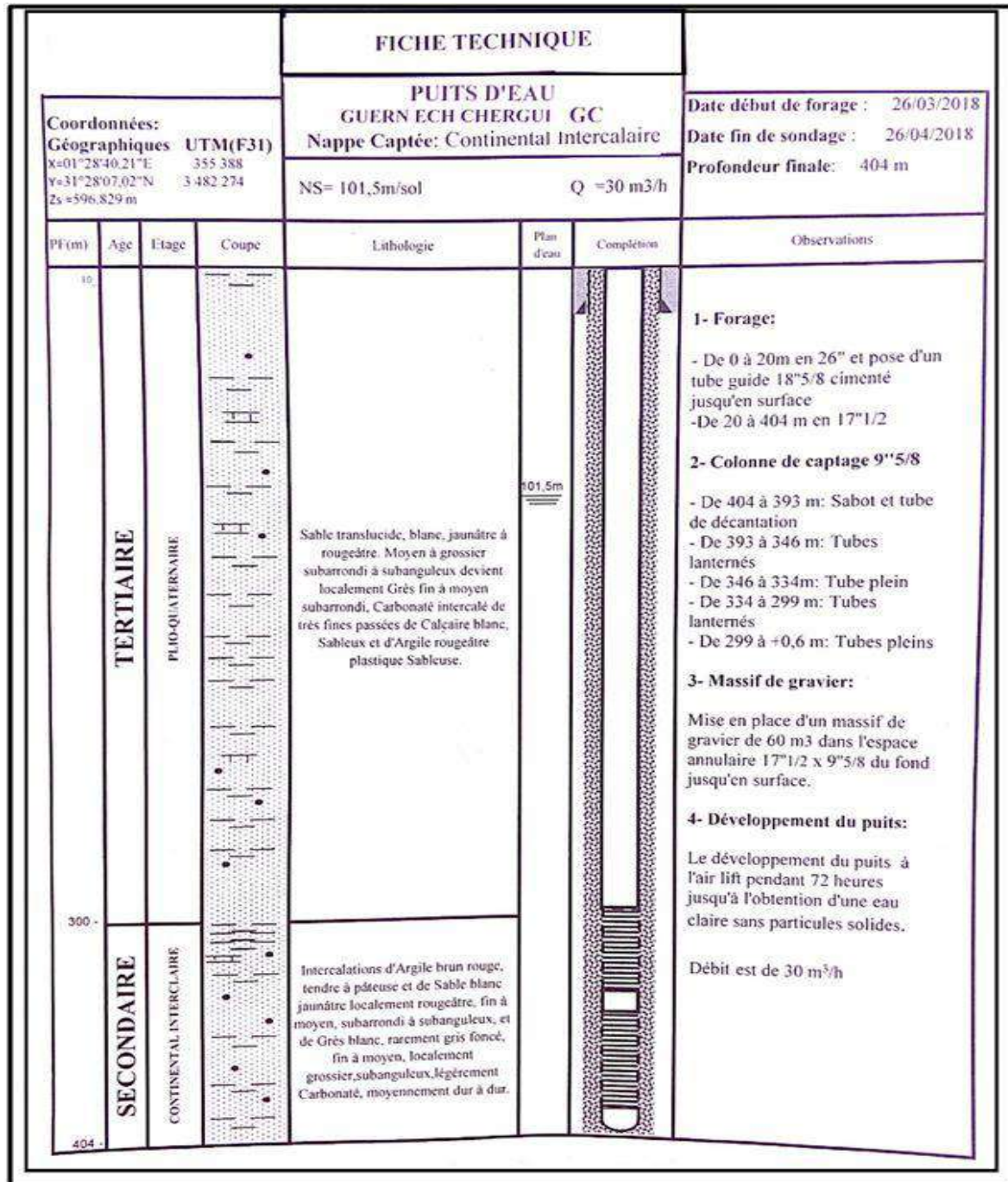


Figure59: Litho-stratigraphic section of a borehole tapping the Béni Ounif CI aquifer.

5. Conclusion

The aquifer system in the Béni-Ounif syncline, located in the foothills of the Djebel Grouz, is a major groundwater resource. It is used to supply drinking water to the local population, as well as for irrigation, an activity that has developed considerably in recent years.

A hydrogeological study of the region reveals that the aquifer system contains two deep aquifers, separated by an impermeable evaporite-gypsum wall.

The Béni Ounif aquifer system comprises three layers: two captive aquifers and an intercalary continental water table. The terminal complex aquifer is represented by the Turonian calcareous-dolomitic unit ($e = 50$ m), which rests on an impermeable clayey-gypsum wall and a permeable substratum of clay and gypsum marl of Cenomanian age ($e = 60$ m). The intercalary continental water table is represented by the Lower Cretaceous unit, consisting of alternating sandy and gravelly layers and clay layers. It is fed primarily by water from the CI unit in the underlying captive aquifer of calcareous-dolomitic Jurassic rock, as well as by vertical and lateral contributions through the South Atlas flexure. This flexure decreases in thickness in this region and meets the Cretaceous sandstone, which has an average thickness of 100–300 m. The water table is fed each year by winter and spring floods, as well as by the heavy flooding of major wadis such as Oued Lakhdar, Oued Zouzfana, Oued Namous and Oued Laouedj. It is topped by a free surface water table (Quaternary alluvial units with an average thickness of 5 to 10 m), such as those in the Zousfana valley, which constitute an important water table.

Examination of the piezometric map of the Continental Intercalaire water table, drawn up on a basin-wide scale, reveals the following:

Two aquifers are exploited: the Lower Cretaceous sandstone aquifer (also known as the Albian aquifer) and the Quaternary alluvial aquifer. It is assumed that these aquifers are interconnected and communicate with each other. This assumption will be confirmed in the following section. The water tables are fed by inflow from the oueds (Zousfana and Mélias), as well as from the South Atlas flexure, which acts as an imposed potential flow (lateral flow). Regional groundwater flows in one main direction: north-west to south-east.

Chapter 03:

GEOPHYSICS

1. Introduction

Geophysics is an essential complementary tool for hydrogeological studies, providing additional data for vast and complex study areas. It can detect irregularities, as well as the strength, shape and structure of the formation being studied. At the request of the Agence Nationale des Ressources Hydrauliques (ANRH), the BETA-Consults consultancy carried out a geophysical measurement campaign in the Béni Ounif region. The method used was vertical electrical sounding (VES), and the measurements were acquired between 2nd and 15th June 2011. The main objectives of the study were to determine the geometry and geological structure of the Mesozoic terrain and to identify areas suitable for installing water catchment structures.

*The objectives set out in the specifications were to:

- define the geological structure and tectonics of the study area;
- determine the depth, extent, thickness and geometry of aquifer formations;
- define areas favourable to the installation of water wells.

To gain a better understanding of the lithology and geological structure of the Beni Ounif area, existing bibliographical data was taken into account to determine the aquifer levels, and their respective geometry and thickness where possible.

Generally speaking, these levels relate to the detrital formations of the Intercalary Continental. This complex (CI) consists of clay with relatively large sandstone and sand interlayers, forming the sandstone-clay aquifer complex.

The current geophysical study of the northern zone of Béni Ounif should allow for theoretical depths of investigation of between 400 and 500 metres using electric line boreholes (AB=2000 m).

Due to the presence of clay and clay-sandstone layers, the injected current is absorbed, which can considerably reduce the depth of investigation.

The formations affected by electrical prospecting within the depth range are the entire Continental Intercalaire and part of the Upper Jurassic.

1.2 implementation

The technique used in the field is vertical electrical probing. This involves injecting a direct electric current into the ground via two steel electrodes and measuring the potential difference created at the terminals of two other copper electrodes.

Together, the electrodes form what is known as a quadrupole.

By measuring the electric current and the potential difference using a resistivity meter, the apparent resistivity of the medium can be determined using the following formula:

Where:

$$R_a = K \cdot dV / I_{AB}$$

R_a : apparent resistivity of the medium

K : geometric factor which depends only on the relative position of the electrodes and is expressed by :

$$K = \frac{3.1415 \cdot AM \cdot AN}{MN}$$

MN

dV : potential difference across the MN electrodes.

I_{AB} : intensity of the electric current flowing in circuit AB .

Once the resistivity has been determined, the length AB is extended to obtain another resistivity value, corresponding to a greater depth, until the maximum length of the device, 2000 metres, is reached.

In this study, the Schlumberger system was used, with 16 electrical sounding measurements (see appendix).

68 electrical boreholes at a depth of 2000m, divided into 13 profiles, were drilled in the northern area of Béni Ounif.

Table 21. Number of electrical surveys carried out. (ANRH, 2011)

Total number of profiles	13
Total number of electrical surveys	68
Equidistance between electrical probes	1 Km
Equidistance between profiles	1 Km
Surface area in km²	51 Km

The profiles run north-south, perpendicular to the road axis. (Fig.59)

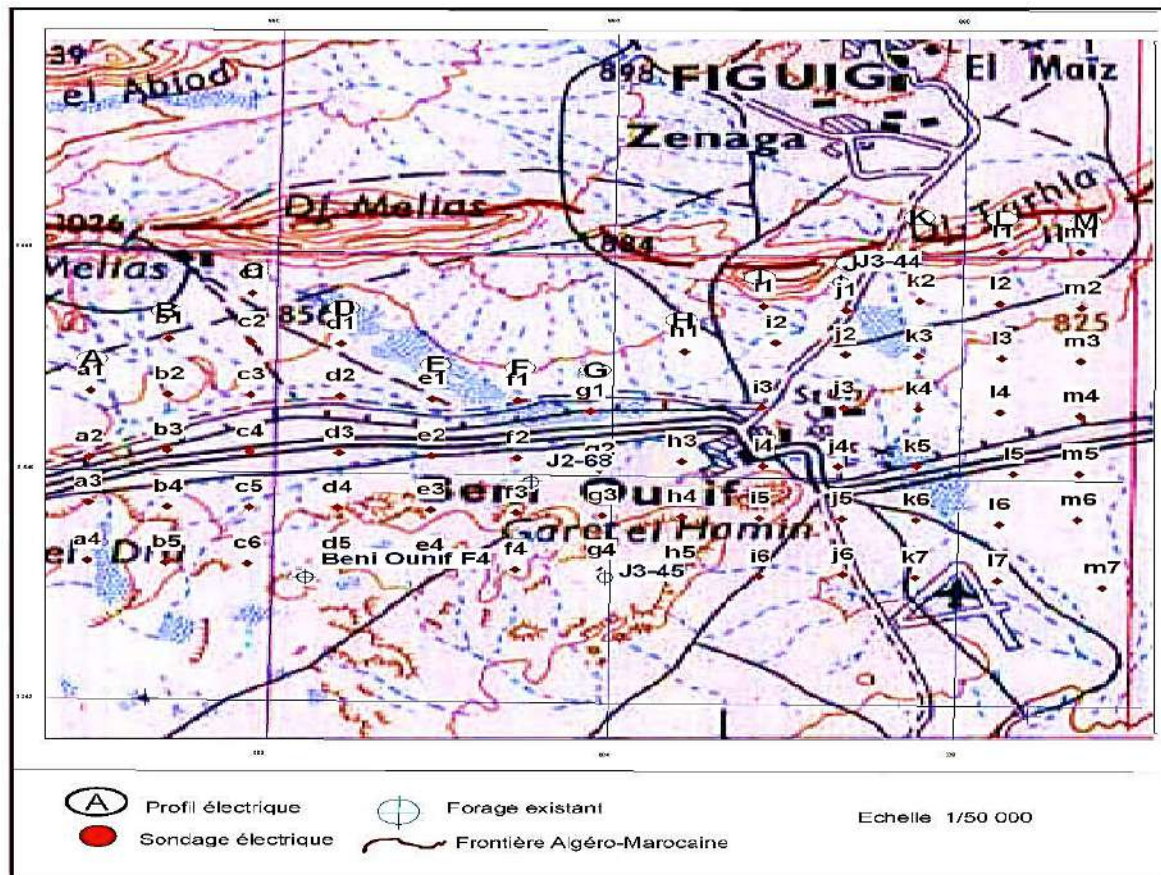


Figure 59: Location map of electrical boreholes. (ANRH, 2011)

2. Geophysical exploration of the Beniounif region

2.1. Theoretical aspects of the electrical prospecting survey method

2.1.1. Electrical prospecting methods

Electrical resistivity is generally measured using the Schlumberger quadripole (Fig.60). An electrical current of intensity I , created by a generator (battery), is sent through the ground using two electrodes A and B. The receiving electrodes M and N measure the potential difference ΔV caused by the current flow:

$$\rho = K \Delta V / I ; \text{ deduced from Ohm's law}$$

Or: K = is a coefficient that depends only on the geometry of the device, for the Schlumberger device ($K = \pi AM \cdot AN / MN$ for a symmetrical quadripole).

ΔV and I are measured using a voltmeter and an ammeter respectively. The depth of investigation of such a device depends on the spacing of the transmitting electrodes A and B, as well as the thicknesses and resistivities of the formations are approximately and empirically of the order of $(1/4 \text{ to } 1/10) \cdot AB$.

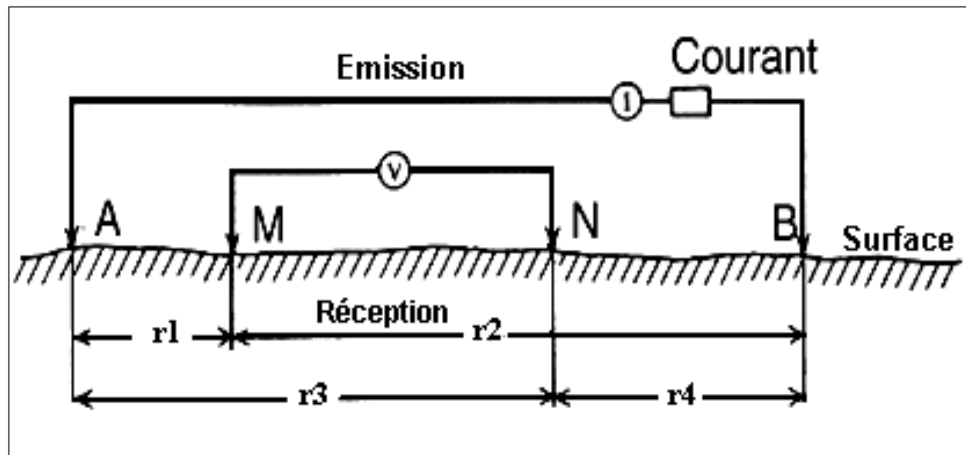


Figure 60: Schlumberger quadrupole



Figure 61: Electrical sounding equipment.

When the current flows entirely through the same homogeneous level, the resistivity measured corresponds to the true field resistivity. This is the case in particular for test or parametric measurements carried out on sub-surface formations of sufficiently great thickness and extension in relation to the spacing of the emission line (AB). In this case, the resistivity is a function of the resistivities of the different layers and their thicknesses. The resistivities measured are called apparent resistivities, and from these values we try to determine the true resistivities ρ_i and the thicknesses h_i characterising each level.

The presence of a structure in the ground is manifested by an anomaly in the apparent resistivity ρ_a which depends on a number of parameters (size and depth of the structure, dimensions of the device, electrical contrast between the structure and the surrounding environment. In order to deduce information about the causes of anomalies observed in the field, it is necessary to know

the relationship between a structure and its anomaly. To do this, two techniques are used: trailing and vertical electrical sounding. These two methods are complementary.

If the subsoil is homogeneous and isotropic, the true resistivity will be obtained with a device of this type. If, on the other hand, the subsoil is heterogeneous, the apparent resistivity will be measured, which depends on the nature of the subsoil and the size of the device used (the Schlumberger): The distance MN is small compared with AB. In general, $MN < AB/5$.

2.1.2. Electrical drag: In the drag technique, the AMNB device is moved across the field. The profiles are more or less parallel, while keeping the spacing AB constant. The measurement thus obtained corresponds to the centre. The geological horizons explored by this method correspond to a roughly constant depth. The apparent resistivity results are plotted on maps, enabling levels of similar electrical resistivity to be deduced and their extensions delimited. These maps complement the geological interpretation and help to decide on the location of potential electrical boreholes.

2.1.3. Vertical electrical sounding: In the electrical sounding method, geological information is gathered vertically from a given point, by taking the investigation ever deeper. To do this, a series of measurements is taken, each time increasing the length of the transmission line AB, while keeping the centre of the device fixed.

By plotting the values of the apparent resistivities measured as a function of the line length AB on a bi-logarithmic graph, we obtain an electrical sounding curve, the interpretation of which will be used to determine graphically the resistivities ρ_i and the thicknesses h_i of the different lithological levels.

The variation in the resistivities of rocks and water (**Tab.22**), is of the order of 1 to a few tens of $\Omega.m$ for clays and marls, from a dozen to a few hundreds of $\Omega.m$ for sands and marly sandstones and from a hundred to several thousand $\Omega.m$ for limestones, sandstones, granite and eruptive rocks.

Table 22: Range of variation in rock resistivity

Resistivities ($\Omega.m$)	Lithological characteristics	Training age
10 à 70	Surface silty alluvium	Quaternary
100 à 200	Dry sandy alluvium	
50 à 100	Wet sandy alluvium	
Up to 1000	Dry coarse alluvium (pebbles and	
80 à 90	Wet coarse alluvium	
3 à 5	Marls	Miopliocene
Up to 40	Marly sandstone	
7 à 10	Marls	Miocene
Up to 500	Sandstone and Poudingues	
< à 3	Marls	

Up to 500	Sandstone-clay flysch	Oligocene
50 to 80	Chalky marl	Cretaceous
40 à 50	Volcanic tuffs	/

The conductivity of an electrolyte depends on the ion content and mobility of the various ions in solution and the degree of dissociation (Chapellier.D, 2000). The resistivity of water is inversely related to the degree of mineralisation (Tab 23).

Table 23: Range of variation in water resistivity.

Types of water	Concentration	Resistivity	Conductivity MS/cm
Drinking water	500	12	833
Poor water	1000	6	1666
Bad water	2000	2.8	3571
Non-drinking water	8000	0.75	13333
Sea water	35000	0.2	50000
Vichy water	5167	1.2	8000
Tap water	311	18	550

2.2 Vertical electrical soundings in the Béni Ounif region

BETA-Consults carried out 68 vertical electrical boreholes (AB= 2000m) in the northern area of Béni Ounif. The boreholes are grouped into 13 profiles, the distance between boreholes is approximately 1km, and the area explored is 51km² (Fig.62).

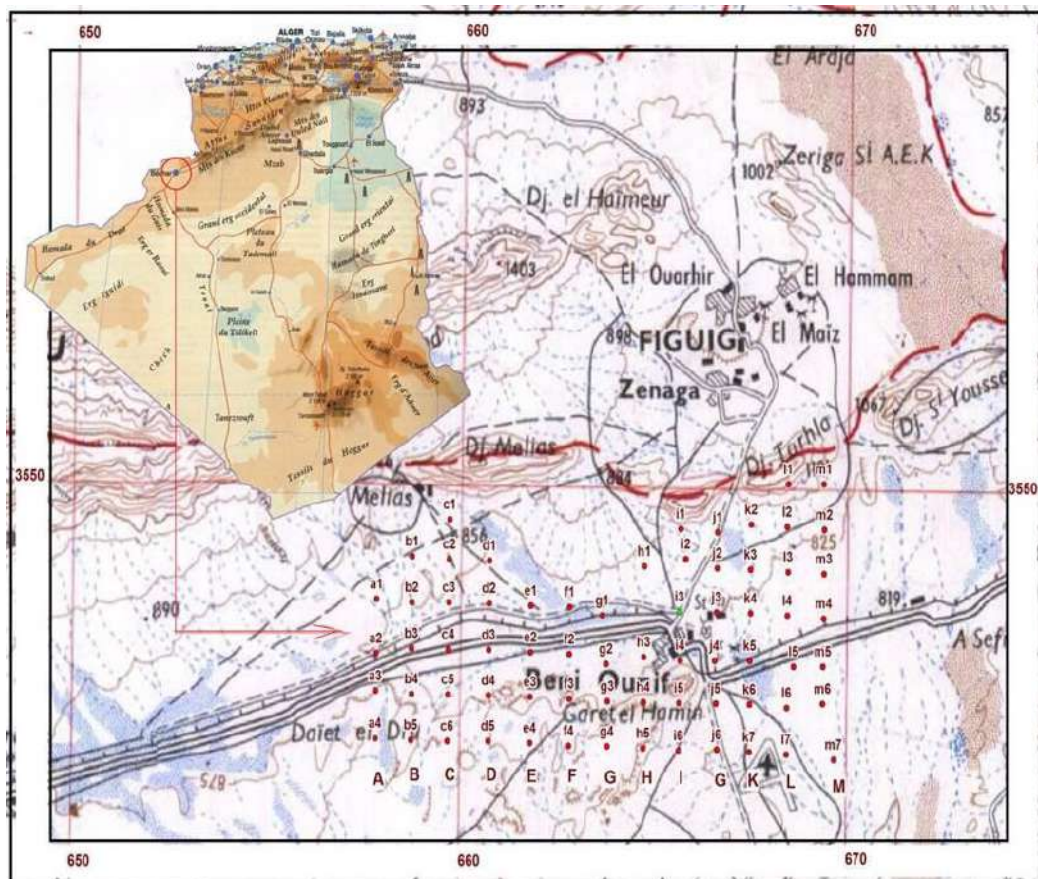


Figure. 62: Location map of vertical electrical boreholes (SEV)

- **Calibration of measurements**

In order to establish a reliable resistivity scale to be used as a basis for interpreting the electrical boreholes, a calibration of the results (**Fig.63**) of the electrical prospecting was carried out using the lithological sections of two boreholes F3 and F1. (**ANRH, 2011**)

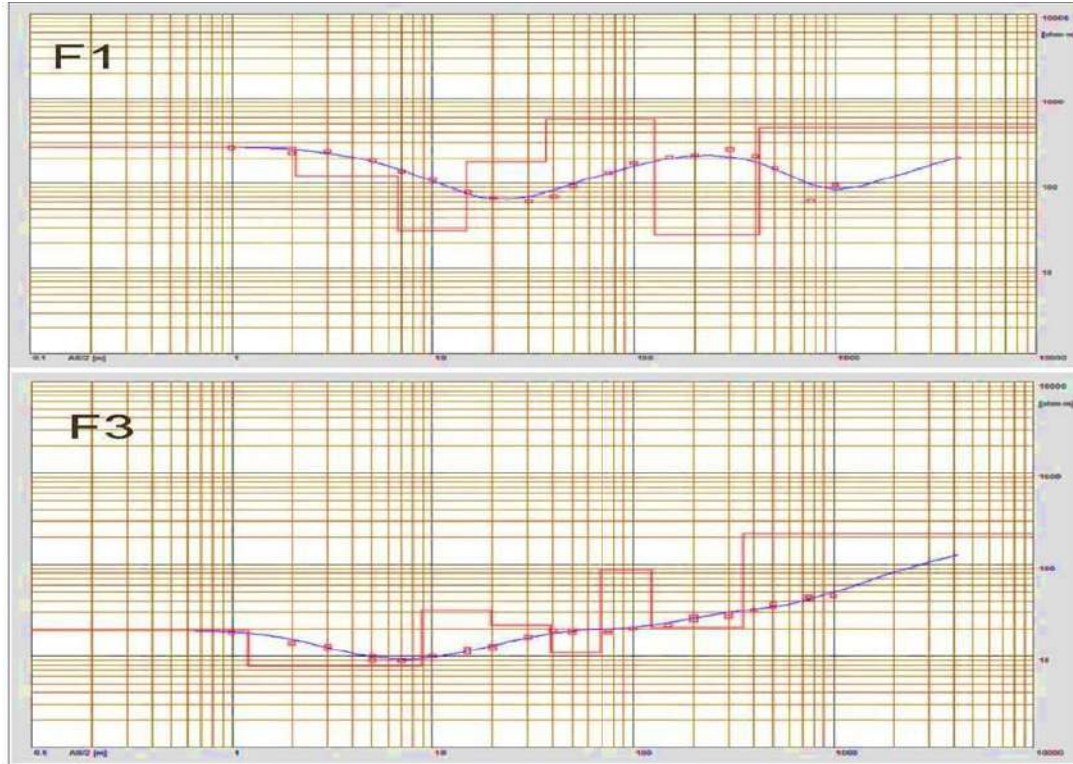


Figure 63: Calibration curve for boreholes F1 and F3 (**ANRH, 2011**)

Interpretation of the geophysical work yielded the results shown in the table below.

Table 24: Results of geophysical work. (ANRH, 2011)

Ere	Lithology	Age	Resistivities (Ohm.m)
Mesozoic	Alluvium, dunes and Regs	Quaternary	4 à 3177
	Clay and marl	Cretaceous Lower	6 à 28
	Sandstone clays		33 à 77
	Hard sandstone +/- clay		250 à 1782
	Sandstone, sand		82 à 120
	Limestone and dolomitic limestone	Upper Jurassic	106 à 2480

In order to establish a reliable resistivity scale on which to base the interpretation of the electrical boreholes, the results of the electrical prospecting were calibrated using lithological sections from two boreholes (Fig.64) drilled in the study area (**J3-44**, **J3-45**)

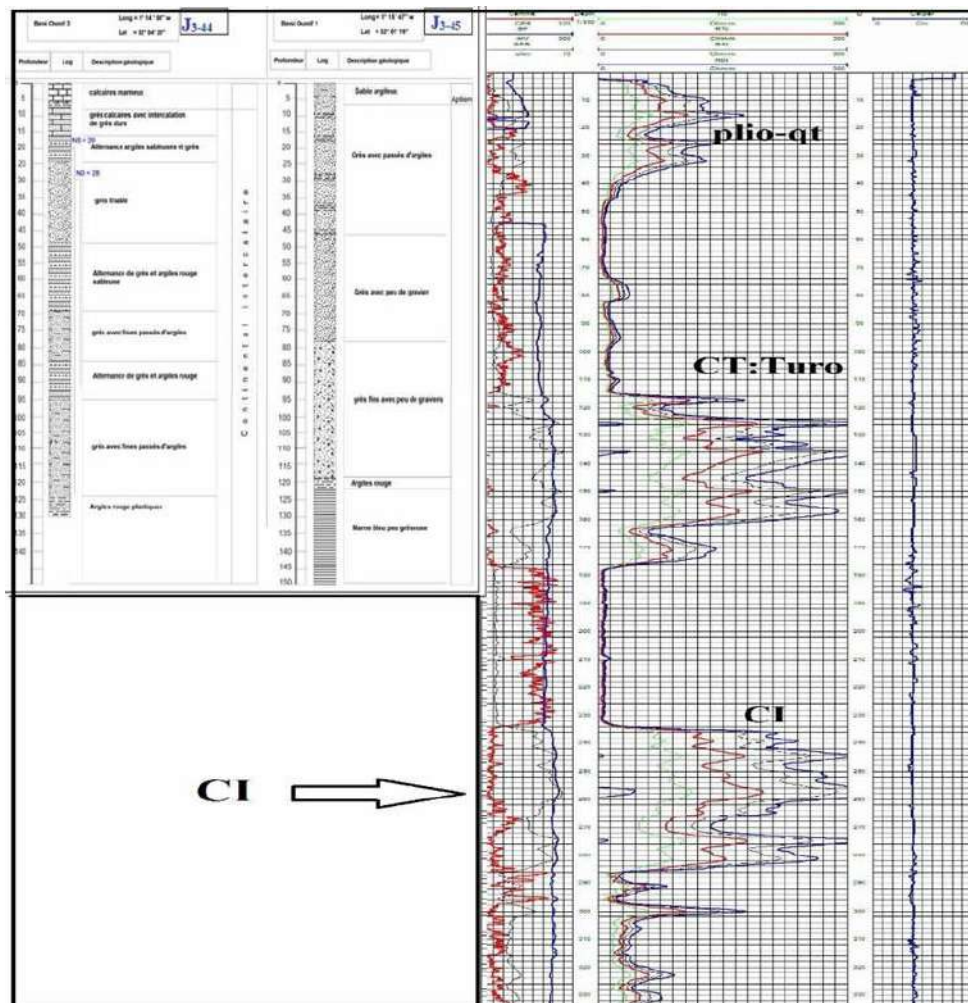


Figure. 64: Log simulation of calibration boreholes with logging.

2.2.1 Calibration using borehole J3-44 : Standard borehole S1 (Fig.65 and Tab 25) drilled near borehole J3-44 located at UTM coordinates: X= 666 611/Y= 3 549 534 intersected a depth of 130 m :

- A conductive level with a resistivity of 8 to 19 Ohm.m for a thickness of 9 m corresponding to marl and marl-limestone.
- alternating clayey sandstones and clays with a resistivity of 11 to 32 Ohm.m 60m thick sandstones with a clay layer 55m thick, with a resistivity of around 88 Ohm.m.
- A horizon with a resistivity of 21 Ohm.m for a thickness of 233m corresponding to the plastic red clays.
- A resistant bedrock with a resistivity of 215 Ohm.m, which probably corresponds to dolomitic limestone from the Upper Jurassic.

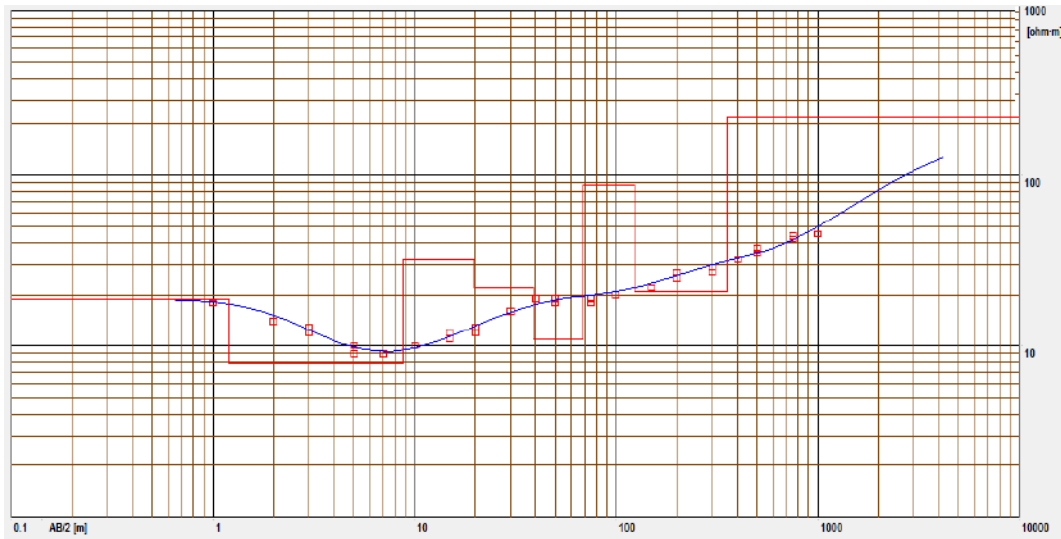


Figure 65. Calibration using borehole J₃₋₄₄

Table 25 Calculation of the Model at borehole J₃₋₄₄

Resistivity (Ohm.m)	Thickness (m)	Depth (m)
19	1,2	
8	7,6	1,2
32	11	8,8
22	19	20
11	30	39
88	55	69
21	233	124
215		357

2.2.2. Calibration using borehole J₄₋₄₅: Standard borehole S2 (Fig.66 Tab 26) drilled 130 m from borehole J3-45 located at UTM 30 coordinates: X= 663.917 km, Y= 3 544.209 km intersected a depth of 158 m :

- a resistant level, with a resistivity of 124 to 268 Ohm.m, 7m thick, corresponding to dry sands.
- A conductive ground, with a resistivity of 28 Ohm.m for a thickness of 8m corresponding to the clays.
- A third level, 111m thick, with a resistivity of 179 to 560 Ohm.m, belongs to the sandstones, with gravel passages that are probably not saturated.
- A fourth horizon of 25 Ohm.m and a thickness of 297m corresponds to the marls.
- A very resistant bedrock with a resistivity of 454 Ohm.m, probably corresponding to limestone
- hard, compact dolomitic rocks of the Upper Jurassic.

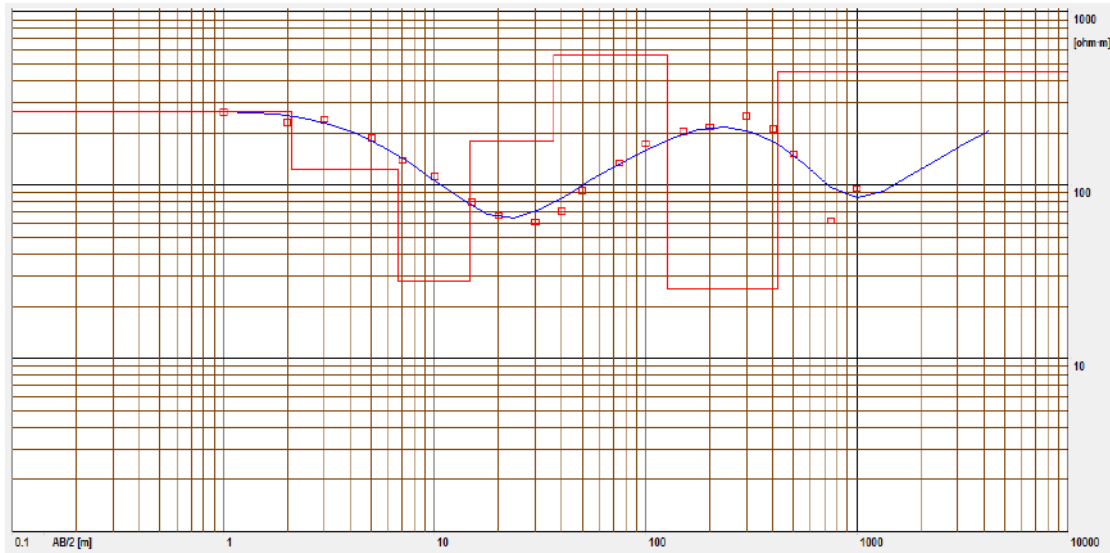


Figure 66. Calibration using borehole J₄₋₄₅

Table 26: Calculation of the Model at borehole J3-45.

Resistivity (Ohm.m)	Thickness (m)	Depth(m)
268	2,1	
124	4,6	2,1
28	8	6,7
179	22	15
560	89	37
25	297	126
454		423

2.2.3. Resistivity scale

Analysis of the results of the electrical surveys shows that electrical resistivities vary widely in the study area:

- The resistivity of the surface formations of alluvium, sand dunes and Reg varies between 4 Ohm.m and 3177 Ohm.m (depending on their water saturation).
- The low resistivity values encountered correspond to clays and sandstone clays (6 Ohm.m to 77 Ohm.m).
- Intermediate values, between 82 Ohm.m and 120 Ohm.m correspond to clayey sandstones, sandy or sandy clays and soft sandstones with clayey cements.
- Resistivity values above 250 Ohm.m are attributable to hard sandstones with gravel and dolomitic limestone passages.

Based on the data from the electrical surveys and the existing boreholes used to calibrate the measurements, we have established the following resistivity scale (**Tab.27**):

Table 27 Scale of resistivities adopted for the study area

Training	Age	Resistivities (Ohm.m)
Alluvium, dunes and Regs	Quaternary	4 à 3177
Clay and marl	Continental Midsole	6 à 28
Sandstone clays		33 à 77
Hard sandstone		250 à 1782
Sandstone, sand		82 à 120
Limestone and limestone	Jurassic	106 à 2480

The results of the geophysical interpretation are expressed in the form of 13 interpretative geoelectric sections, three apparent resistivity maps and a bedrock map.

2.2.4 Interpretation of geoelectric cross-sections: For the purposes of drawing up and interpreting the geoelectric cross-sections (Fig.67 and Fig.68), we agreed to group all the lithological variations into three groups according to the range of resistivities shown in Tab 27

A. Geoelectric sections A, B and C: The north-south oriented geoelectric sections A to C (Fig.67) in western part of the study area show two distinct geoelectric units:

- At the base, the Upper Jurassic, represented by limestone and dolomitic limestone with high resistivities ranging from 247 to 2480 Ohm.m (boreholes B₂, C₄), is relatively flat but with continuous folds with a large radius of curvature (borehole C₂).
- At the top, the Upper Jurassic is overlain by a large detrital deposit of Lower Cretaceous sandstone and clay; the sandy layers are located at boreholes A₃ and B₍₂₎.

B. Geoelectric sections D, E and F: The sections (Fig.67) show the same formations encountered previously, the calcareous-dolomitic Jurassic is resistant with resistivity values between 142 and 1172 Ohm.m, surmounted by the intercalary continental characterised by lateral passages and frequent facies changes marked by sandstones, clayey sands, clays and sandy clays. The predominance of sandstone is clearly seen in boreholes E₄, F₄ and G₃, with resistivities ranging from 97 to 1425 Ohm.m.

C. Geoelectric sections H, I and J: Overall, the same over-cited lithological assemblages can be observed in geoelectric sections H, I and J (Fig.68). However, there is a clear predominance of the clay fraction in all the sections.

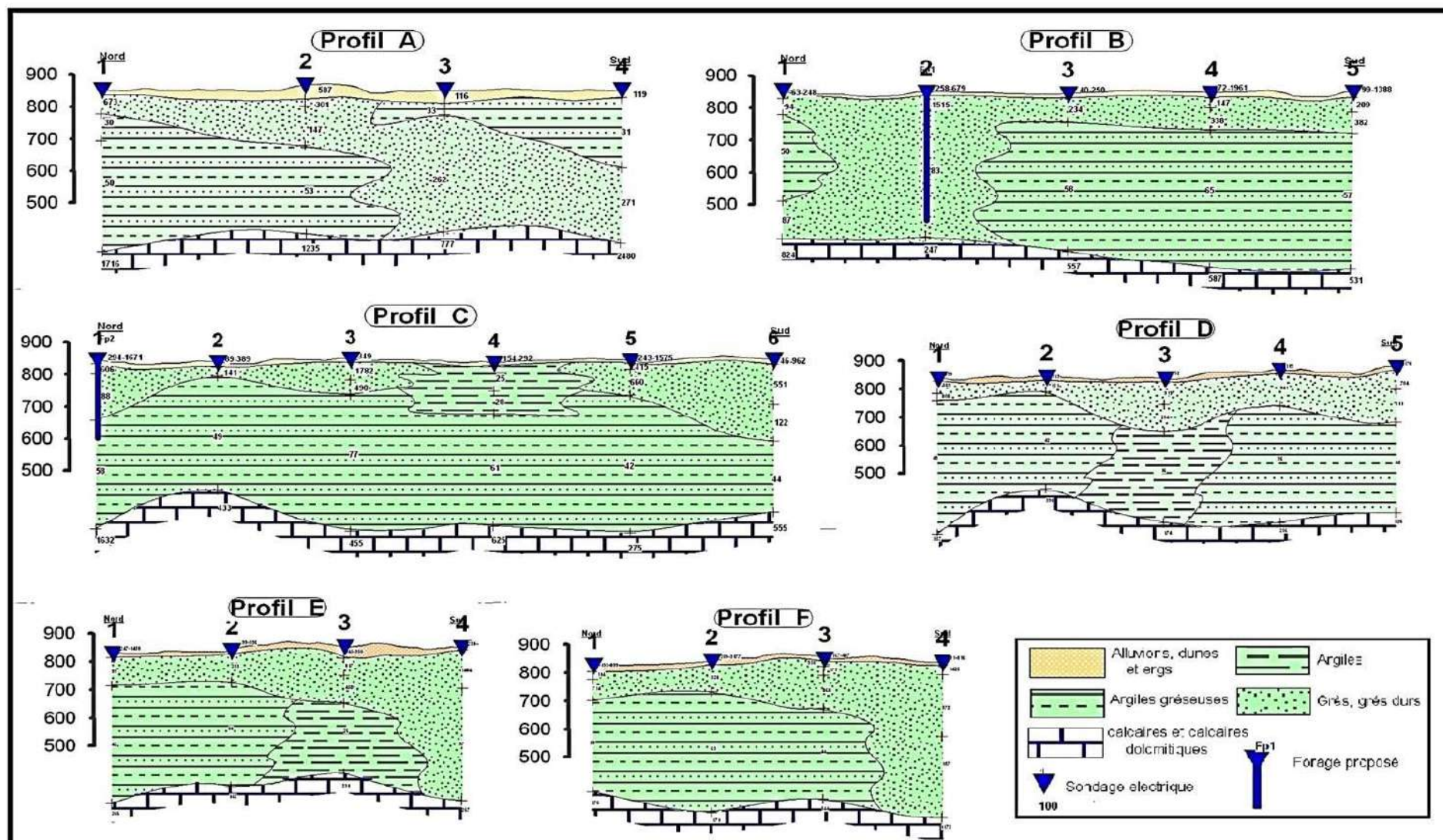


Figure 67: geoelectric cross-sections of the profile A, B, C, E, F.

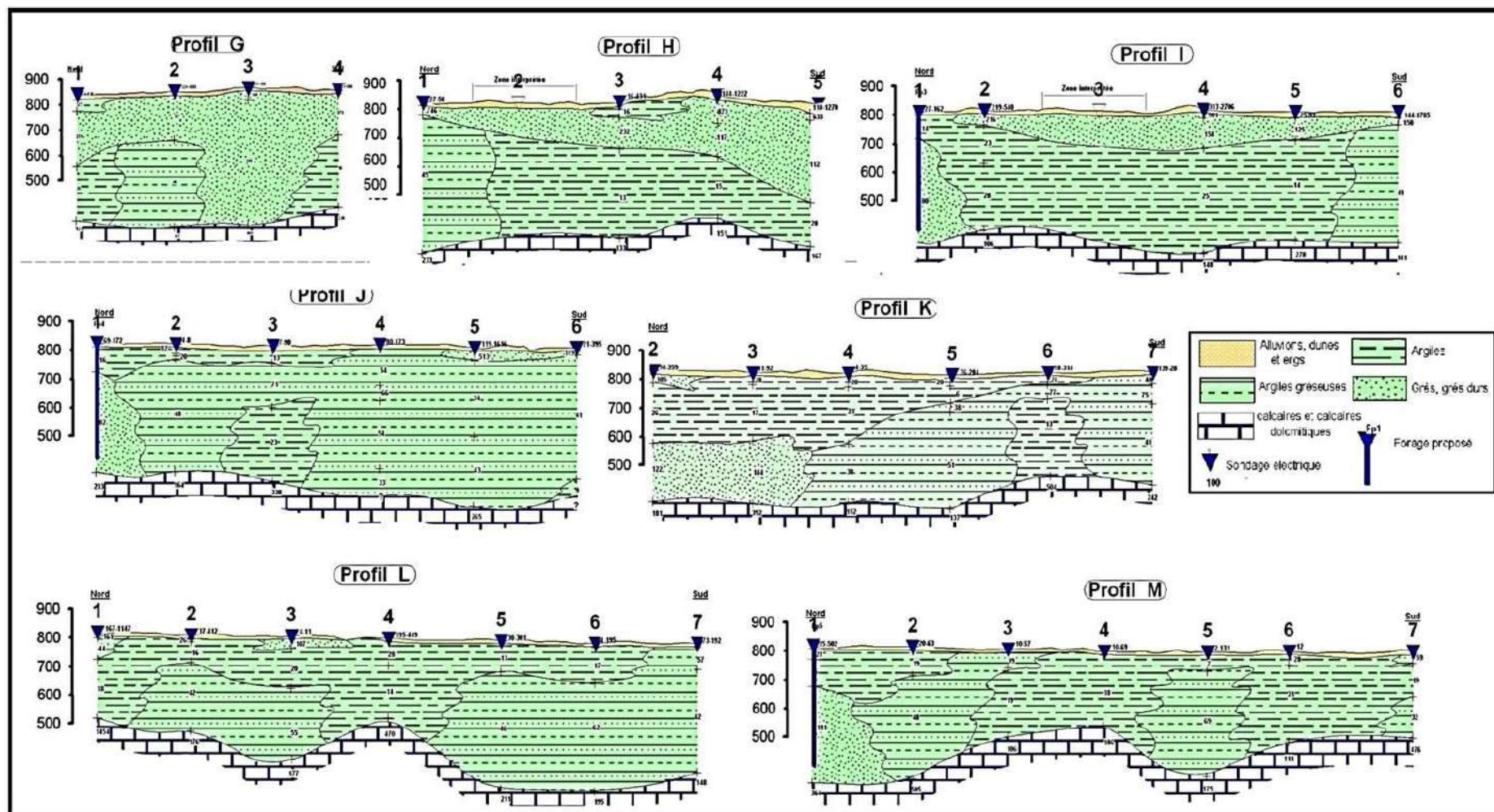


Figure 68. Geoelectrical sections of profiles G, H, I, J, K, L, M.

- In the central and western parts of the study area, apparent resistivities are generally greater than 100 Ohm.m, reflecting the continuity of resistant series corresponding to unsaturated hard sandstones with a low clay fraction.
- On the other hand, the low values (below 60 Ohm.m) are located in the eastern part.

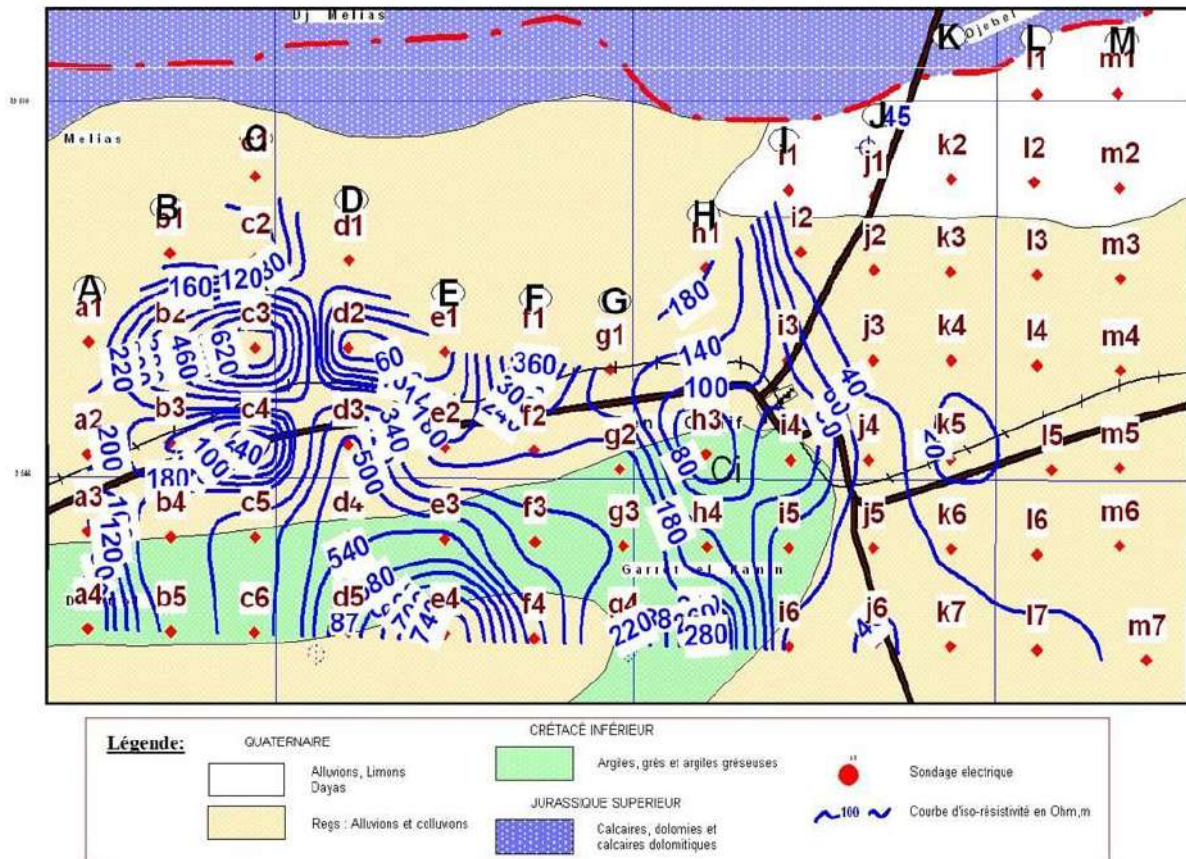


Figure 70. Map of apparent resistivities (AB = 1000 M)

C. Apparent resistivity map (AB = 2000 M): This map (Fig.71) with a depth of investigation of between 300 and 500 metres. The values of the apparent iso-resistivity curves on this map show two ranges of resistivity:

- A beach with resistivities above 100 Ohm.m theoretically corresponds to the resistant bedrock of the Upper Jurassic. This is represented by a carbonate facies made up of limestone and dolomitic limestone.
- A zone to the east beyond profile J where apparent resistivities are less than 60 Ohm.m and which corresponds to more or less sandstone clays of the Intercalary Continental.

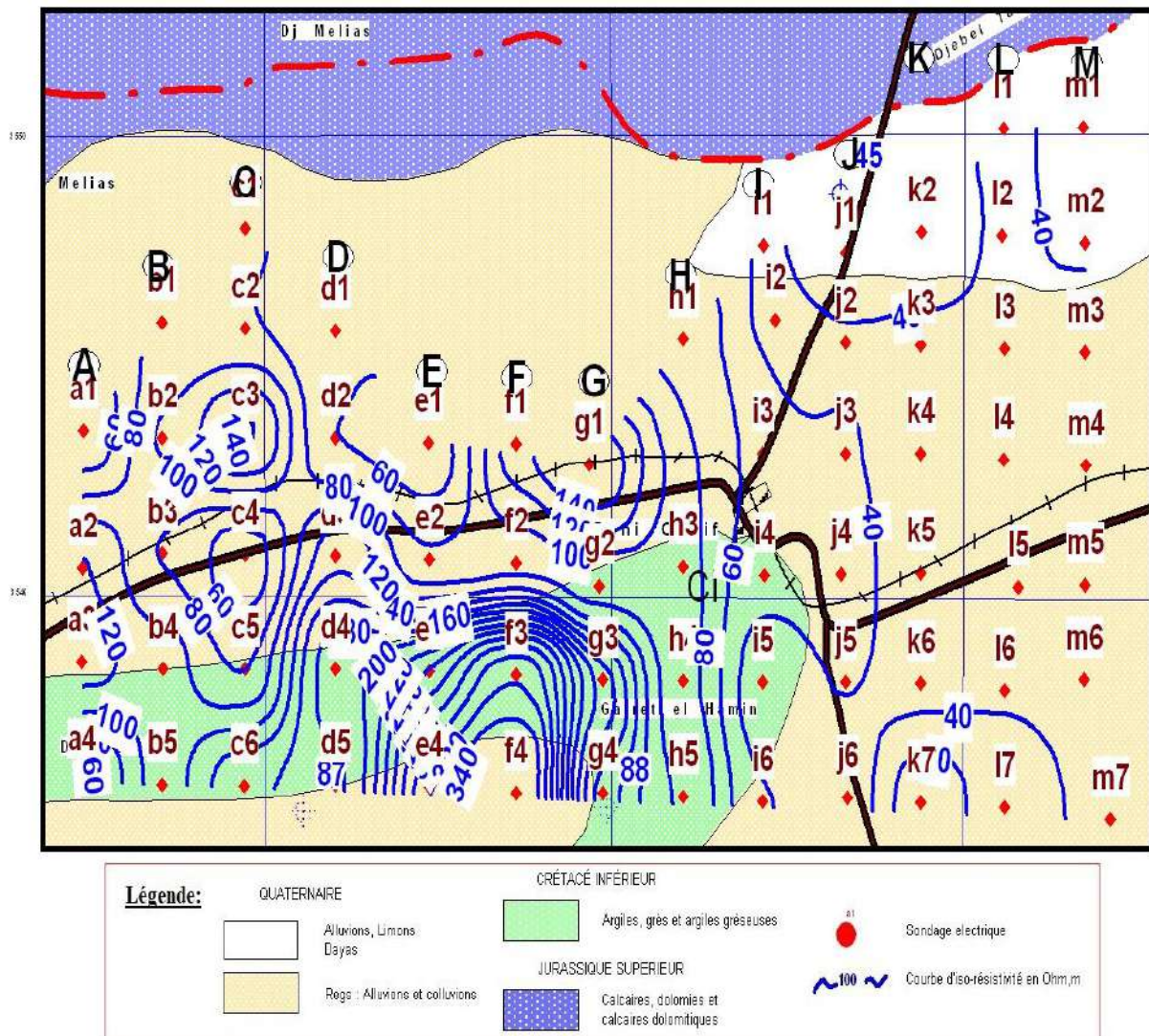


Figure 71: Map of apparent resistivities ($AB = 2000 M$)

2.2.6. Jurassic bedrock top map: The Jurassic bedrock top isobath map (Fig.72) produced in the study area shows that the bedrock is represented by limestone and dolomitic limestone, the surface of which undulates with depths varying between 300m and 380m; there are also a few depressions where the depth can reach 480m towards the east.

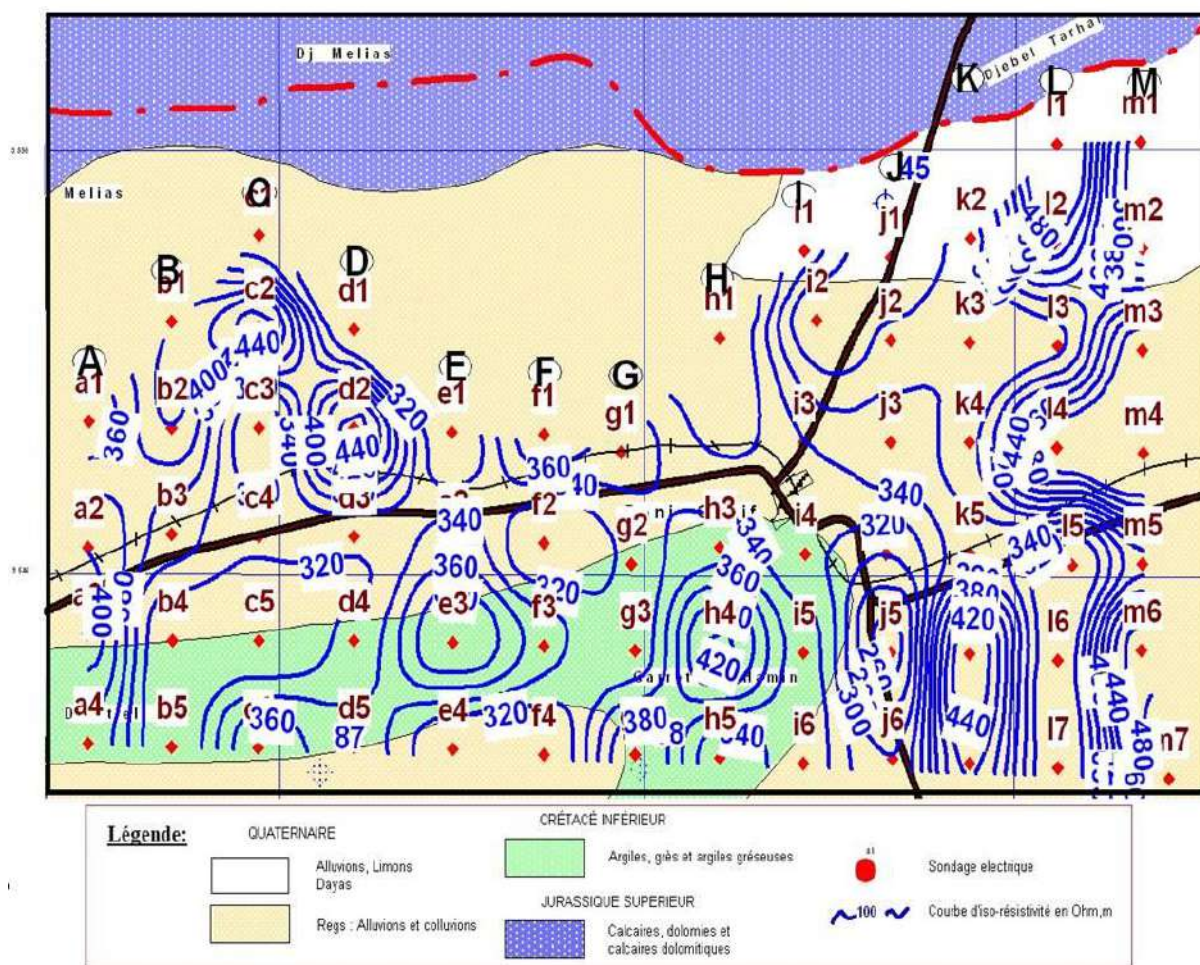


Figure 72: Jurassic bedrock isobath map

2.2.7. Map of proposed drilling locations : By comparing all the geological data and geophysical results we were able to identify several areas suitable for the installation of water wells. These favourable points for hydraulic structures are boreholes B₂, C₁, I₁, J₁, M₄ (Tab2.6 and Fig.73).

Table 28: Proposed hydraulic exploration structures.

	Proposed	Contact		SEV NUMBE	Depth of boreholes
		X	Y		
1	Fp1	658,787	3 547,410	B2	400
2	Fp2	659,747	3 549,229	C1	270
3	Fp3	665,734	3 549,085	I1	400
4	Fp4	666,692	3 549,020	J1	400
5	Fp5	669,432	3 550,104	M4	400

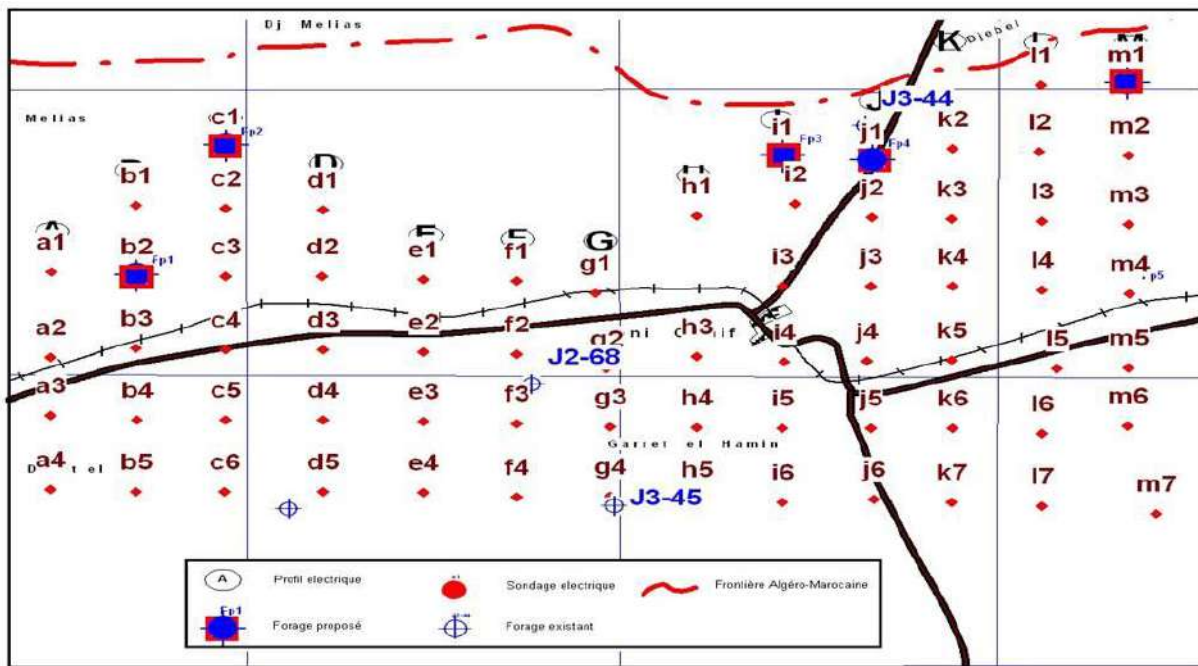


Figure 73: Map of proposed borehole locations

Interpretation of the geophysical results confirmed the litho-stratigraphic diversity of the Lower Cretaceous by :

- The detrital, repetitive nature of the sometimes metric, clayey and sandstone sequences characterising almost all of the formations, which are very difficult to differentiate using the electrical method.
- Lateral facies passages.

The geoelectrical sections (**Fig.74**) show three horizons that are quite distinct from one another:

The resistant horizons, with resistivity values ranging between 300 and 1782 Ohm.m, correspond to hard sandstone with gravel deposits, indicating permeability. The more conductive layers, with resistivity values below 60 Ohm.m, correspond to clays and sandstone clays, which are semi-permeable. Additionally, a resistant bedrock with resistivity values between 106 and 2580 Ohm.m corresponds to the limestones and dolomitic limestones of the Upper Jurassic, which are also permeable.

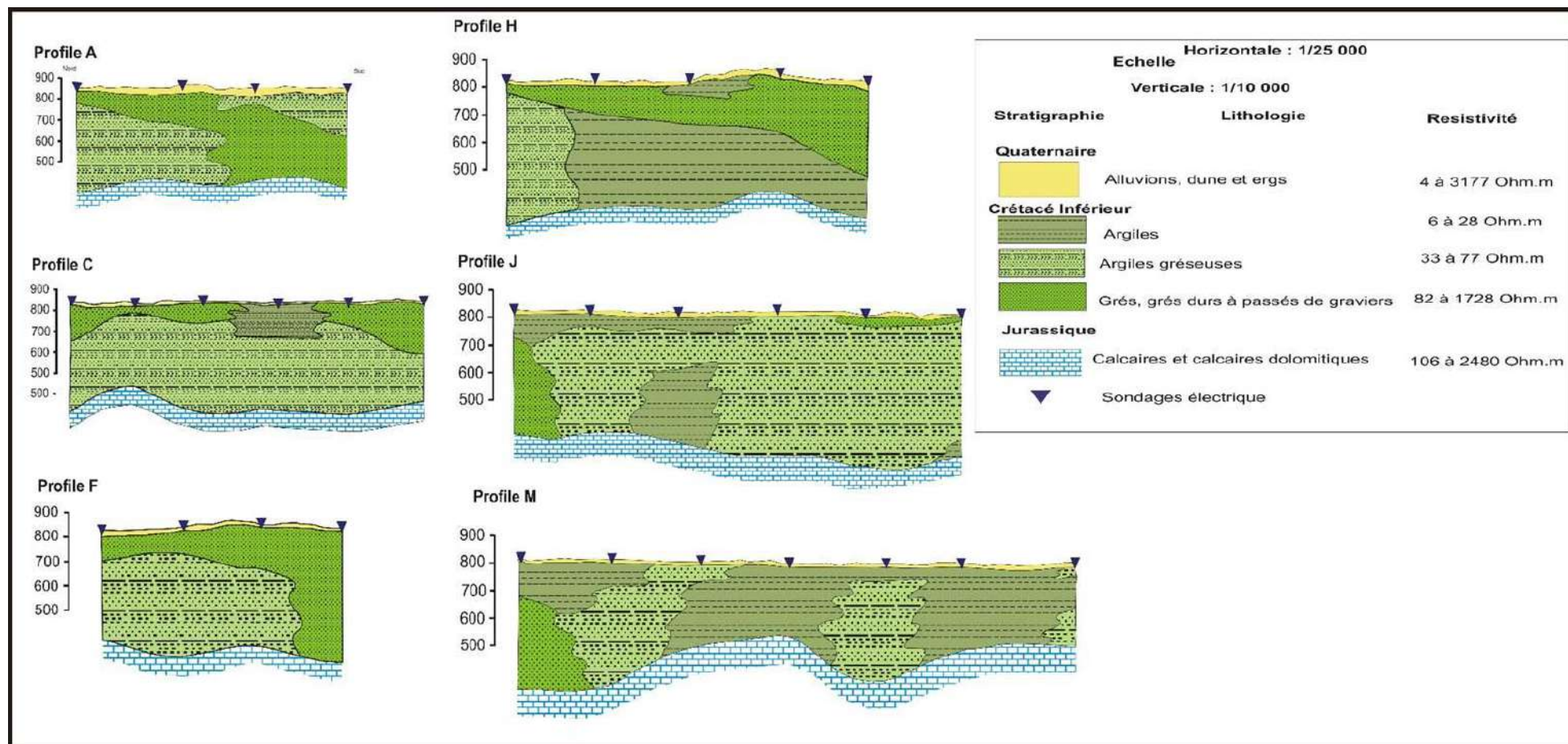


Figure 74: Geoelectric sections of the Beni-Ounif region (ANRH, 2011)

The correlation between the three boreholes F1, F4 and F3 (**Fig.75**) confirms the results of the geophysical study: the sandstone terrain is formed by an intercalation of sandstone and clay.

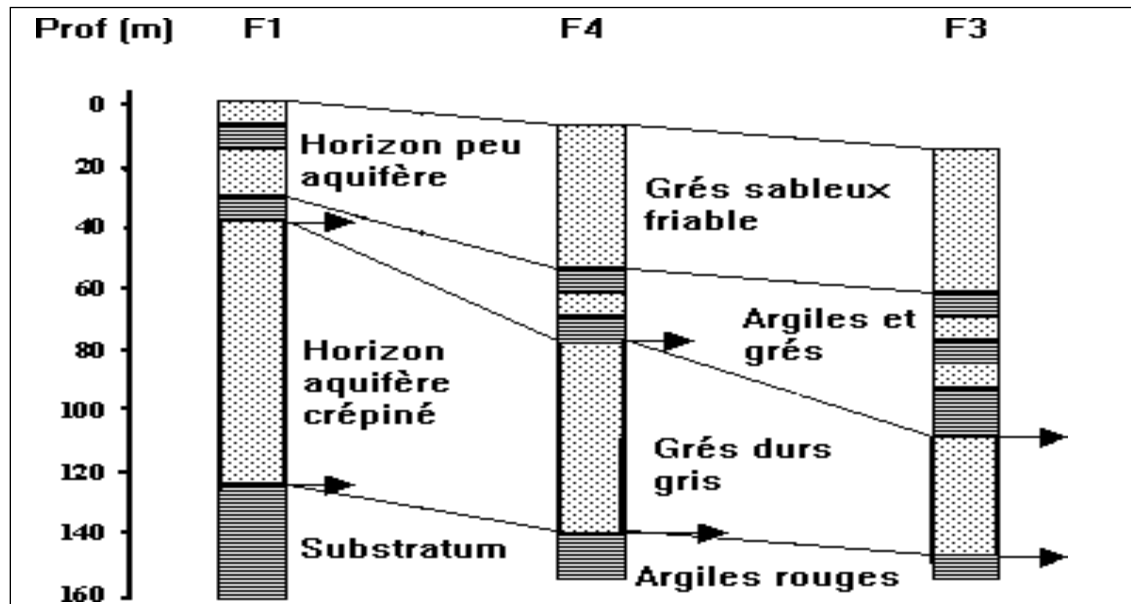


Figure 75: Summary logs of hydraulic boreholes at Béni Ounif.

3. Conclusion

A geophysical survey was conducted using vertical electric boreholes along line AB (2000 m). This covered all the detrital formations of the Intercalary Continental down to a depth of 500 m, as well as the upper part of the Jurassic.

Interpretation of the geophysical results confirmed the lithostratigraphic diversity of the Intercalary Continental Formation.

- the repetitive, sometimes metric, clayey and sandstone sequences that characterise almost all of the formations and which are very difficult to differentiate using the electrical method;
- lateral facies passages.

The geoelectrical sections show two quite distinct horizons:

The resistant horizons, with resistivity values between 300 and 1782 $\Omega \cdot m$, correspond to hard sandstone with gravel layers that are probably unsaturated.

- Conductive ranges below 60 $\Omega \cdot m$ correspond to clays and sandstone clays.

The intermediate ranges, between 80 and 110 $\Omega \cdot m$, correspond to sandstones and less clayey sands with gravel layers. Water accumulates in this type of loose, detrital formation and is sheltered beneath and between the clay levels contained within it, giving the formation the appearance of a charged aquifer.

A resistant bedrock with resistivity values between 106 and 2580 $\Omega\cdot\text{m}$ corresponds to limestone and dolomitic limestone of the Upper Jurassic.

However, it is important to note that the thicknesses of the sandstone-clay complex referred to in this report as 'clayey sandstone' are not entirely sandstone. In reality, it is an alternation of sandstones and clays of varying degrees of sandiness, but predominantly sandstone in terms of the measured electrical resistivities.

Chapter 04:

Hydrochemistry

1. Introduction

The aim of this chapter is to assess the chemical quality of groundwater stored in the Continental Intercalary and Beni Ounif shallow aquifers for potential use for human consumption, irrigation and industrial applications, and to identify the hydrochemical processes that influence the mineralisation of these waters.

The quality of water intended for consumption was assessed using the Water Quality Index (WQI). The WQI is a method widely used throughout the world to assess the quality of surface water and groundwater for various domestic uses ([Bouselsal et al. 2025](#)), by integrating a series of physico-chemical characteristics. This method condenses these details into a single score that can be easily communicated to the public.

To assess the suitability of groundwater for irrigation, factors influencing soil and plant quality were examined, including electrical conductivity (EC), sodium adsorption ratio (SAR), percentage soluble sodium (SSP), permeability index (PI), Kelly ratio (KR), potential salinity (PS) and magnesium adsorption ratio (MAR). These parameters are then integrated to calculate the irrigation water quality index (IWQI) ([Boussaada et al. 2023](#); [Bouselsal and Egbueri 2024](#)). In terms of industrial water use, scaling and corrosion are the most commonly assessed indicators. Corrosion is defined as the physical and chemical interaction between metal and its environment, altering the properties of the metal ([Shahmohammadi et al. 2018](#); [Lakhdari et al, 2025](#)). Scaling, on the other hand, is a multiphase process in which ions react with substances present in the water to form a film deposited on the internal surfaces of pipes. Various indices, such as the Langelier index, the Ryznar index, the Larson-Skold index, the Puckorius index and the aggressiveness index, are used to assess these processes ([Amiri et al. 2021](#); [Egbueri et al. 2021](#); [Kaur et al. 2019](#)).

Groundwater mineralisation processes were identified using hydrogeochemical methods such as Piper, Schoeller and Gibbs diagrams, as well as chemical element ratios.

The results of this study can be used to improve the management of groundwater resources in the region and prevent environmental degradation.

A flow chart illustrating the methodology used to study the groundwater quality assessment and hydrogeochemical characteristics of the continental intercalary aquifer and the Beni Ounif shallow aquifer is shown in Figure 76.

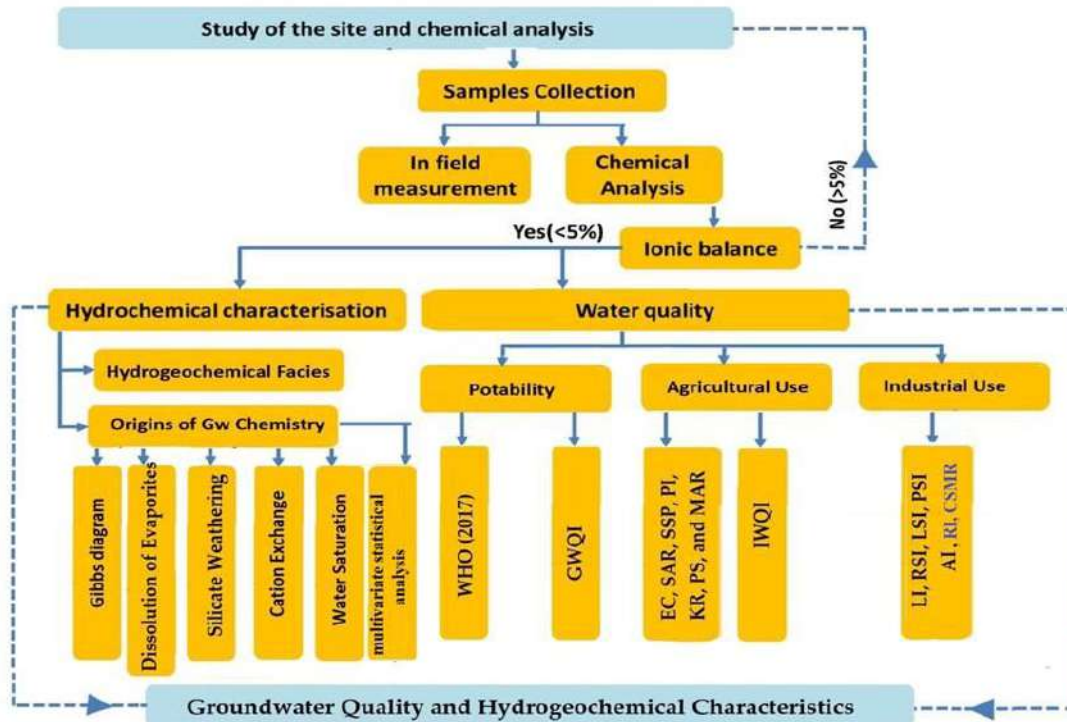


Figure 76. Flow chart of the method adopted.

2. Materials and methods

2.1 Sampling and analysis methods

In this study, 16 water samples were taken from the continental intercalary (CI) aquifer and 30 samples were taken from the shallow Beni Ounif aquifer. Samples from the CI aquifer were distributed across the study area in order to obtain data representative of the spatial variability of groundwater chemistry in the CI aquifer. Samples from the shallow aquifer were taken mainly in the northern part of the study area, near the town of Beni Ounif (Fig.77). Physicochemical parameters such as electrical conductivity (EC), temperature (T), pH and total dissolved solids (TDS) were measured in situ using a portable multimeter. Samples were filtered on site and stored at temperatures below 4°C before being transported to the laboratory for analysis. Analyses of major elements were carried out using standard techniques (Rodier 2005) in the ANRH laboratories in Adrar and Bécharr. Calcium, magnesium, chloride and total hardness were analysed using titration methods, while sodium and potassium were measured using a flame photometer. Other anions, such as sulphate and nitrate, were quantified using a spectrophotometer, and bicarbonate and carbonate were measured using volumetric methods. The ion balance (equation 1) was calculated to assess the reliability of the results. Results are considered acceptable if the percentage error is less than 5%.

$$\text{Ionic balance} = [(\sum \text{cations} - \sum \text{anions}) / (\sum \text{cations} + \sum \text{anions})] * 100 \text{ (equation 1)}$$

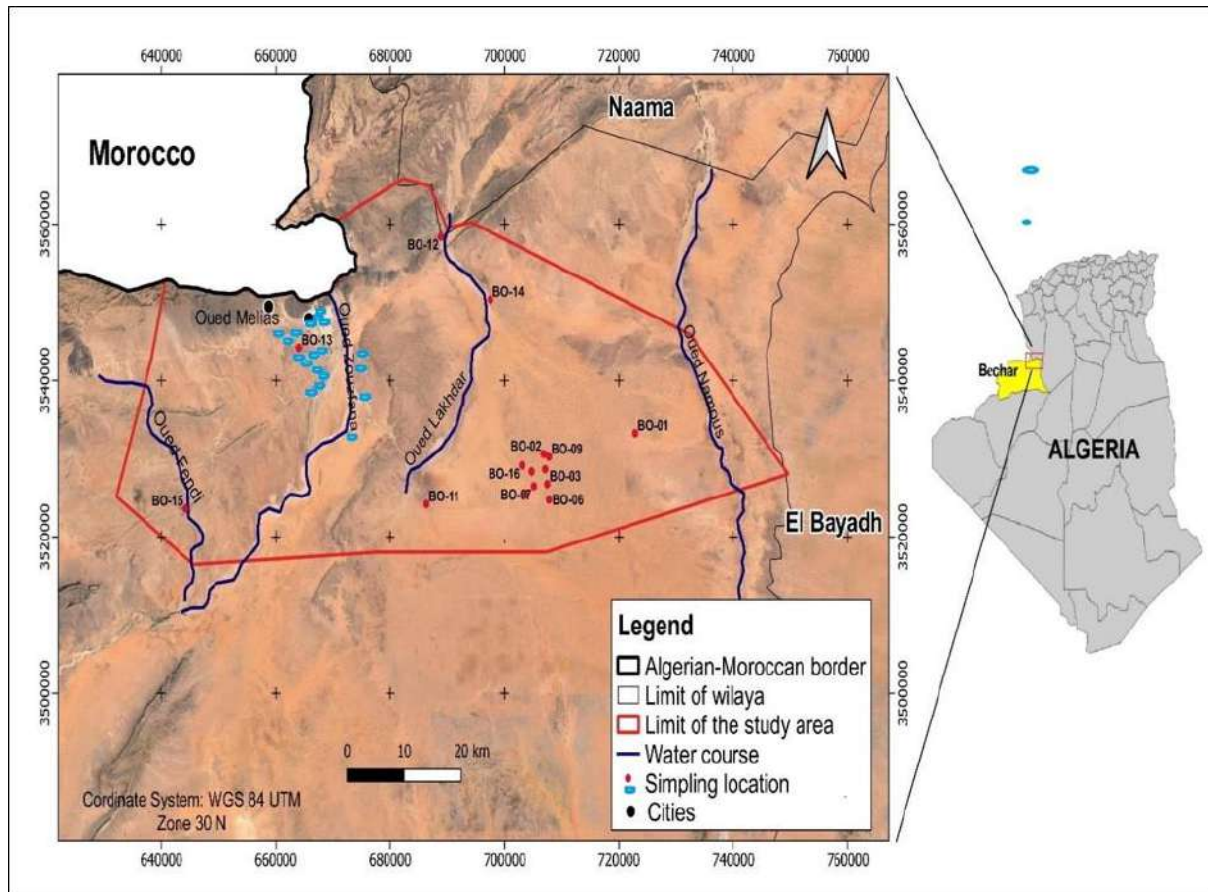


Figure 77. Position of sampled boreholes.

2.2 Water quality for different uses

Water quality was assessed in two stages. Firstly, the sampled water values were compared with the World Health Organization ([WHO 2017](#)) standards for drinking water (Table 3). Next, the Water Quality Index (WQI) was used to assess the potability of the water.

The Water Quality Index (WQI) is a mathematical method that synthesises a large amount of data on water quality into a single number ([Horton, 1965](#); [Brown et al., 1970](#); [Hammad et al., 2023](#); [Ouerakh et al., 2021](#)). This method has been developed to assess the quality of water for consumption, considering several parameters such as pH, conductivity, major elements, nitrates, etc.

In this study, the groundwater quality of the CI aquifer and the shallow Beni Ounif aquifer was assessed using the WQI method ([Nafyad et al. 2018](#); [Houatmia et al. 2016](#); [Liaghat et al. 2013](#)). The chemical data of the analysed water samples were compared to the WHO drinking water standard ([WHO 2017](#)), which was taken into account in the WQI calculation, as shown in Table 29.

The WQI is calculated in three stages (Bouselsal et al. 2025; Touahri et al. 2022). In the first stage, each of the 11 parameters is assigned a weight (w_i) according to its relative importance for the overall quality of the water intended for consumption. These weights are listed in Table 1. The second step is to calculate the relative weight (W_i). The calculated relative weights (W_i) of each parameter are also shown in Table 1. In the third step, a quality scale (q_i) for each parameter is calculated by dividing its concentration in each water sample by its respective standard concentration prescribed by the World Health Organization, and the result is multiplied by 100.

$$WQI = \sum SI_i = \sum W_i q_i = \sum \left[\left(\frac{w_i}{\sum_{i=1}^n w_i} \right) * \left(\frac{C_i}{S_i} * 100 \right) \right] \quad (\text{Equation 2})$$

$$W_i = q_i / \sum_{i=1}^n q_i \quad (\text{Equation 3})$$

With :

C_i : concentration of the parameter measured in the laboratory

S_i : guide value set by the WHO (2017). (Tab. 29)

w_i : parameter weight

q_i : parameter notation (Tab. 1)

W_i : relative weight (equation 3)

SI_i : the sub-index for parameter i . The results obtained for the water quality index (WQI) were classified into five water quality categories: excellent (<50.1), good (50.1 to 100.1), poor (100.1 to 200.1), very poor (200.1 to 300.1) and unfit for consumption (>300.1).

Table 29. Weighting of parameters used in calculating the WQI.

Parameters	(q_i)	(S_i)	(W_i)
pH	4.0	8.50	0.114285
CE	4.0	1000	0.114285
TDS	5.0	500	0.114285
Ca	2.0	75	0.057142
Mg	1.0	50	0.028571
Na	2.0	200	0.057142
K	2.0	12	0.057142
Cl	3.0	250	0.085714
HCO ₃	3.0	300	0.085714
SO ₄	4.0	250	0.114285
NO ₃	5.0	45	0.114285
Total	35.0	-	1.00

The ion content of water influences its suitability for irrigation. Highly mineralised water tends to reduce the water absorption capacity of crops, which can have adverse effects on plant development and overall agricultural production. To assess irrigation water quality, the Irrigation Water Quality Index (IWQI) method was used in this study. The IWQI calculation

incorporates seven parameters, namely electrical conductivity (EC), sodium adsorption rate (SAR), percentage soluble sodium (SSP), permeability index (PI), Kelly ratio (KR), potential salinity (PS) and magnesium adsorption rate (MAR).

The formulae needed to estimate these irrigation parameters are provided by equations 4 to 10 (Kebili et al. 2021; Bouselsal et al, 2024).

$$\text{Sodium Absorption Ratio} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca}+\text{Mg}}{2}}} \text{ (equation 4)}$$

$$\text{Soluble Sodium Percentage} = \frac{\text{Na}^+ + \text{K}^+}{\text{Ca}^{+2} + \text{Mg}^{+2} + \text{Na}^+ + \text{K}^+} \times 100 \text{ (equation 5)}$$

$$\text{Kelly's Ratio} = \frac{\text{Na}^+}{\text{Ca}^{+2} + \text{Mg}^{+2}} \text{ (equation 6)}$$

$$\text{indice de perméabilité} = \frac{\text{Na} + \text{K} + \sqrt{\text{HCO}_3}}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}} \times 100 \text{ (equation 7)}$$

$$\text{Potential Salinity} = \text{Cl}^- + \frac{1}{2} \text{SO}_4 \text{ (equation 8)}$$

$$\text{Magnesium Adsorption Ratio} = \frac{\text{Mg}}{\text{Ca} + \text{Mg}} \times 100 \text{ (equation 9)}$$

The irrigation water quality index (IWQI) is calculated by applying the following equation (Boussaada et al. 2023; Bouselsal and Egbueri 2024):

$$IWQI = \sum \left[\left(\frac{w_p}{\sum_{i=1}^7 w_p} \right) * (Q_i * 100) \right] \text{ (equation 10)}$$

With :

Wi is the relative weight (Tab.2),

wi is the weight of the irrigation parameter,

Qi is the individual score given by the formula

$$Q_i = (C_i / S_i) \times 100,$$

Ci = the value of the parameter calculated by equations 4 to 9,

and Si is the standard for irrigation water (Tab. 30).

The results obtained for the irrigation water quality index (IWQI) were classified into five water quality categories: excellent (<50), good (50 to 100), doubtful (100 to 200), acceptable (200 to 300) and unsuitable for irrigation (>300).

Table 30: Parameters required to calculate the IWQI.

parameters	CE	SAR	SSP	RK	IP	SP	RAM
weight	4.0	5.0	5.0	3.0	3.0	3.0	2.0
Wi	0.160	0.200	0.200	0.120	0.120	0.120	0.080
Standard (Si)	2250	18.0	40.0	2.0	85.0	10.0	50.0

The quality of water intended for industrial use has been assessed using specific indices that address the issues of corrosion and scaling. The indices used include the Langelier Saturation

Index (LI), the Ryznar Stability Index (RI), the Larson-Skold Index (LSI), the Puckorius Scaling Index (PI), the Aggressivity Index (AI), the Revelle Index (RI) and the Chloride-Sulphate Mass Ratio (CSMR). Equations numbered 11 to 23 were used to calculate these indices (Shipra et al. 2020; Egbueri et al. 2021).

Langelier Index (LI)

$LI = pH - pH_s$ (equation 11)

$pH_s = (9.3 + A + B) - (C + D)$ for $pH > 9.3$ (equation 12)

$A = (\log_{10} (TDS) - 1) / 10$ (equation 13)

$B = -13.2 \times \log_{10}(T + 273) + 34.55$ (equation 14)

$C = \log_{10} (Ca^{2+}) - 0.4$ (equation 15)

$D = \log_{10} (Alk)$ (equation 16)

pH_s is the pH in the saturated state of $CaCO_3$

TDS is total dissolved solids (mg/L)

T is the temperature ($^{\circ}C$)

Alk is the alkalinity of $CaCO_3$ (mg/L)

Ryznar Index (RI)

$RI = 2pH_s - pH$ (equation 17)

Larson-Skold Index (LSI)

$LS = (Cl + SO_4^{2-}) / (HCO_3 + CO_3)$ (equation 18).

Puckorius Index (PI)

$PI = RI - 2pH_s$ (Equation 19)

$pH_{eq} = 1.465 \times \log_{10}(T - Alk) + 4.54$ (Equation 20)

Aggressive index (AI)

$AI = pH + \log_{10}(T - Alk \times Ca)^{2+}$ (Equation 21)

T-Alk is the total alkalinity (mg/l $CaCO_3$)

This is the calcium hardness (mg/l $CaCO_3$).

Revelle Index (RI) :

$RI = Cl / HCO_3^{-}$ (equation 22)

Chloride-sulphate mass ratio (CSMR) :

$CSMR = Cl / SO_4^{2-}$ (equation 23)

2.3 Water geochemistry

To characterise the water types, the hydrochemical data were plotted on the Piper (1944) and Schoeller (1965) diagrams. The Gibbs diagram (1970) was used to identify the likely sources of the main elements contributing to water mineralisation. Bivariate diagrams were also used

to estimate the various mineral assemblages dissolved in the water, based on the lithological analysis of the aquifers and the climatic conditions of the study area.

To elucidate the mechanisms by which mineralisation is acquired, PHREEQC software was used to determine the saturation indices of minerals present in aquifer reservoirs, such as calcite, dolomite, gypsum, anhydrite and halite. The level of saturation is indicated by the saturation index (Is), where a value of 0 indicates equilibrium between the water and the mineral, a value below 0 indicates undersaturation, and a value above 0 indicates oversaturation. If a solution is undersaturated in relation to a mineral, it is likely to dissolve. Conversely, an oversaturated solution tends to precipitate the mineral.

3. Results and discussion

3.1 Groundwater chemistry

The analytical results for physicochemical parameters, as well as cation and anion concentrations, are summarised in Table 31, which also includes the guide values for drinking water set by the World Health Organisation (WHO 2017).

Table 31: Summary of statistics on the hydrochemistry of the Beni Ounif subsoil.

Aquifer		Surface aquifer				CI aquifer			
Parameters		Average	Max	Min	S-D	Average	Max	Min	S-D
Ca ²⁺	In mg/l	63	143	33	28	54	67	39	10
Mg ²⁺		45	97	22	20	33	43	15	9
Na ⁺		62	220	10	60	62	80	45	8
K ⁺		5.57	15	1.2	3.75	5.27	7	4	0.82
Cl ⁻		96	295	5	87	98	115	50	16
SO ₄ ²⁻		120	580	13	142	114	183	50	53
HCO ₃ ⁻		245	518	153	78	161	183	148	14
NO ₃ ⁻		31	70	4	14	26	43	19.6	9
TDS		611	1322	320	305	498	590	352	87
TH	In mg/l	346	761	190	146	272	341	172	62
CaCO ₃									
pH	/	7.44	7.77	7.15	0.16	7.31	7.60	7.10	0.15

3.1.1 pH

The pH measures the concentration of hydrogen ions in a given solution, reflecting the stability of the equilibrium between the different forms of carbonic acid. In deep groundwater, pH is influenced by the buffer system of carbonates and bicarbonates, the geological nature of the aquifer and temperature. The pH values observed in the two aquifers in the study area are all alkaline, ranging from 7.15 to 7.77 with an average of 7.44 for the shallow aquifer, and from 7.10 to 7.60 with an average of 7.31 for the intercalary continental (IC) aquifer (Fig. 78). These

measured values comply with the potability standards set by the World Health Organisation (WHO 2017).

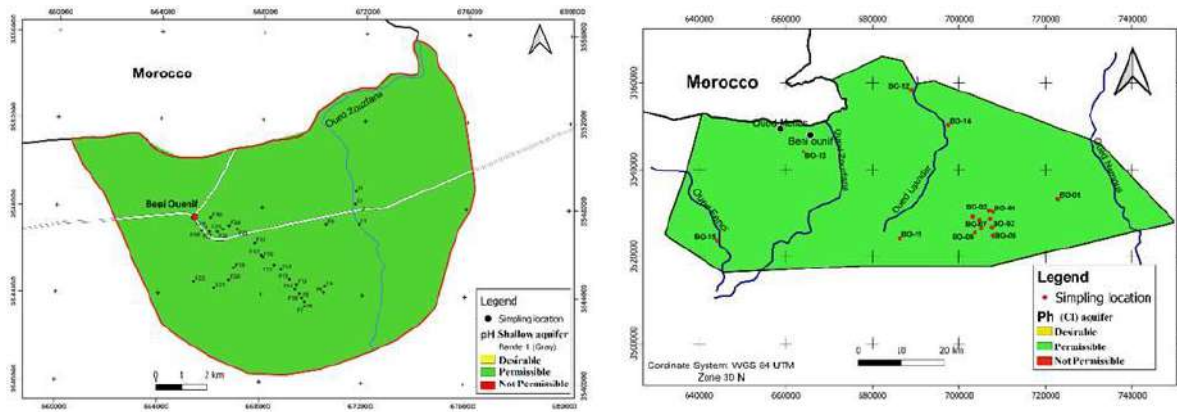


Figure 78. Map of pH variations in groundwater at Beni Ounif

3.1.2. Electrical conductivity (EC)

The term "electrical conductivity" is synonymous with "specific electrical conductance". The standard unit of measurement for conductivity is $\mu\text{S}/\text{cm}$. Electrical conductivity (EC) is commonly used to assess the total ion concentration in natural waters. It is closely related to the sum of cations (or anions) determined by chemical analysis and, as such, correlates well with the total dissolved solids (TDS) content. The World Health Organization (WHO 2017) recommends a threshold value of $1500 \mu\text{S}/\text{cm}$. Surface aquifer waters have EC values ranging from 500 to $2067 \mu\text{S}/\text{cm}$, with an average of $955 \mu\text{S}/\text{cm}$. For water from the Continental Intercalary (CI), electrical conductivities vary between 922 and $550 \mu\text{S}/\text{cm}$, with an average of $779 \mu\text{S}/\text{cm}$ (Fig. 79). The values measured in the study area therefore generally comply with the standards set by the World Health Organisation, with the exception of the boreholes (F18, F21, F23 and F24) tapping the shallow aquifer.

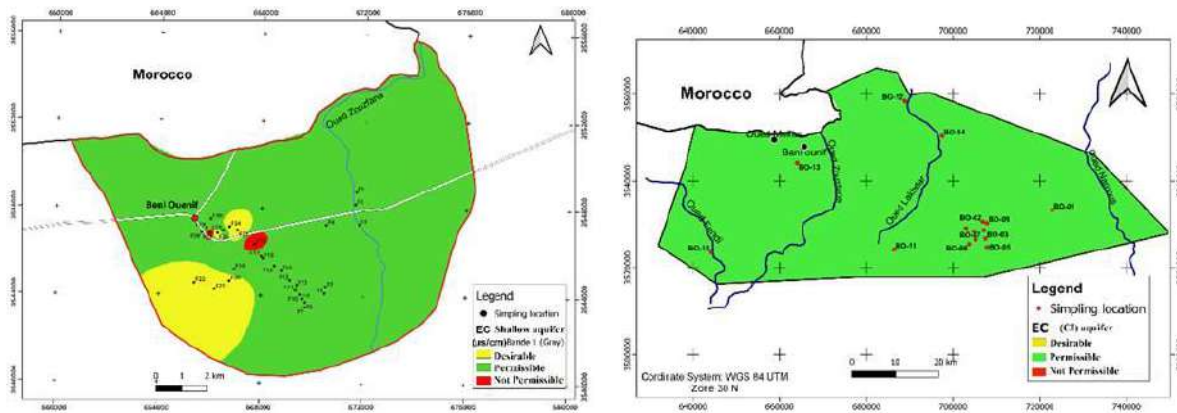


Figure 79. Map of variations in EC in groundwater at Beni Ounif.

3.1.3. Total dissolved solids (TDS)

Total dissolved solids (TDS) include the mineral components dissolved in water. It is measured by evaporating a sample of filtered water and weighing the resulting dry residue. A TDS concentration of less than 500 mg/L is generally considered acceptable for drinking and various industrial uses. Above this threshold, the water may become unfit for consumption. The main sources of TDS in groundwater are bicarbonates, carbonates, sulphates, chlorides and calcium. High concentrations of TDS can alter the taste of water, increase its hardness and enhance its corrosive properties. TDS is essential for assessing water quality because it provides information on the hardness of the water, which is influenced by the lithology of the ground through which it flows and the geological nature of the reservoir.

In the study area, TDS levels vary from 320 to 1322 mg/L with an average of 611 mg/L for the shallow aquifer, and from 352 to 590 mg/L with an average of 498 mg/L for the continental intercalary (CI) aquifer (Fig. 80). The spatial distribution of TDS values follows that of electrical conductivity, indicating homogeneity in the mineralisation of CI waters and heterogeneity in the shallow aquifer. According to water classification criteria (Freeze and Cherry, 1979; Carroll, 1962), CI waters are classified as freshwater, while shallow aquifer waters are mainly fresh (86.67% with TDS < 1000 mg/L) and partially brackish (13.33% with $1000 < \text{TDS} < 10000 \text{ mg/L}$).

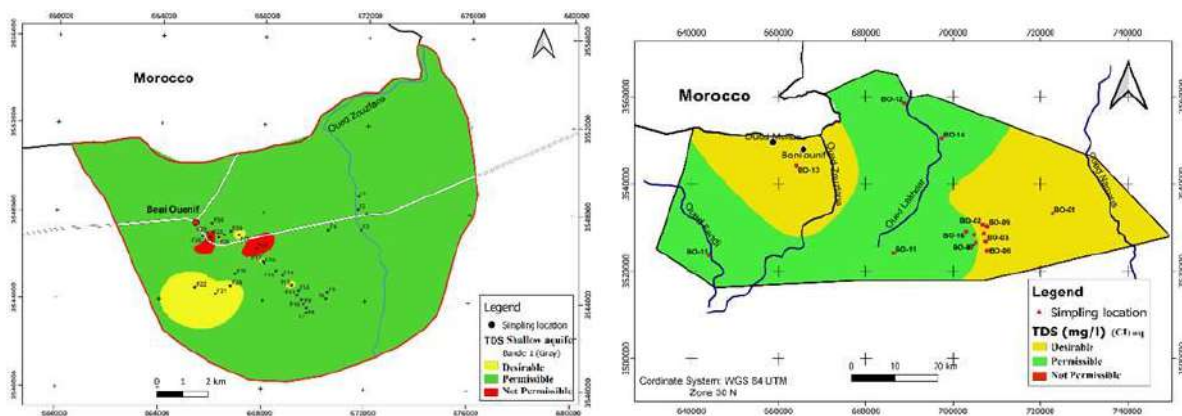


Figure 80. Map of TDS variations in groundwater at Beni Ounif.

3.1.4. Total hardness (TH)

Measuring water hardness is essential for assessing its quality for domestic, agricultural and industrial uses, mainly due to the presence of calcium and magnesium ions. Water hardness is divided into temporary hardness, which can be eliminated by boiling, and permanent hardness, which resists this method. The sum of these constitutes total hardness. This characteristic reflects the interactions of water with the geological formations it passes through. Total

hardness, expressed in mg/L of CaCO_3 , is calculated by adding the concentrations of calcium and magnesium, according to the formula $\text{TH} = [\text{Ca} + \text{Mg (in meq/L)}] * 50$. For drinking water, a maximum total hardness of 500 mg/L is recommended. Above 300 mg/L, it can have an impact on heart and kidney health. According to the [Sawyer and McCarty \(1967\)](#) classification, adopted by the [USEPA in 1994](#), water is considered soft if it contains less than 75 mg/L of CaCO_3 , moderately hard between 75 and 150 mg/L, hard between 150 and 300 mg/L, and very hard above 300 mg/L. In the Beni Ounif region, TH values vary from 190 to 761 mg/L of CaCO_3 , with an average of 346 mg/L of CaCO_3 for the shallow aquifer. For the intercalary continental aquifer (CI), total hardness values vary between 172 and 341 mg/L CaCO_3 with an average of 272 mg/L CaCO_3 (Fig. 81). With the exception of 6 boreholes tapping the shallow aquifer, all the boreholes analysed comply with the WHO drinking water standard ([2017](#)).

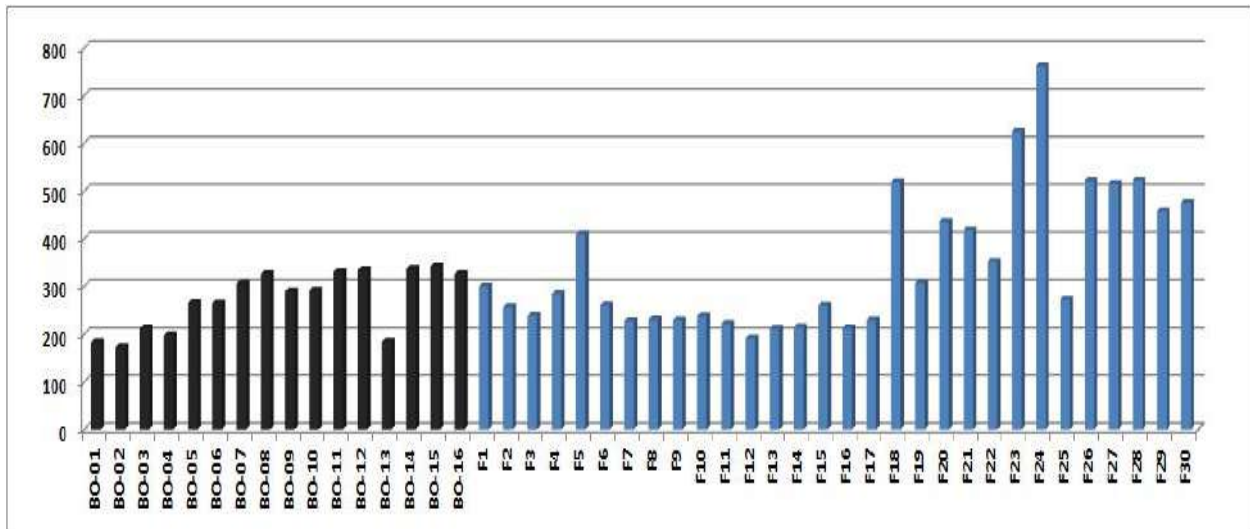


Figure 81. Histogram of TH variations in groundwater at Beni Ounif.

3.1.5. Sulphate

The sulphate ion (SO_4^{2-}) is an oxidised form of sulphur, mainly produced when sulphide minerals undergo alteration in contact with aerated water. This oxidation process also generates a significant quantity of hydrogen ions ([Hem, 1989](#)). Sulphur is widely distributed in its reduced form in magmatic and sedimentary rocks in the form of metal sulphides. Pyrite, in particular, is a major source of sulphate and ferrous iron in groundwater. Soluble calcium sulphate, in the form of gypsum or anhydrite, is a major component of many evaporitic rock sequences. Soluble sodium sulphate forms in some closed basin lakes ([Hem, 1989](#)). Sulphates are currently recycled from the atmosphere and from the dissolution of sulphate minerals in sedimentary rocks, although historically in the hydrosphere most sulphates probably originated from the oxidation of sulphides in magmatic rocks and gases ([Davis and DeWiest, 1966](#)). In gypsum and anhydrite deposits, the concentration of SO_4^{2-} can reach the saturation point of gypsum, which

is around 1,360 mg/L. In the groundwater in the study area, sulphate concentrations range from 13 to 580 mg/L, with an average concentration of 120 mg/L in the shallow aquifer, and from 50 to 183 mg/L, with an average concentration of 114 mg/L in the continental intercalary (CI) aquifer. Only two boreholes (F18 and F24) tapping the shallow aquifer exceed the drinking water standard (Fig. 82).

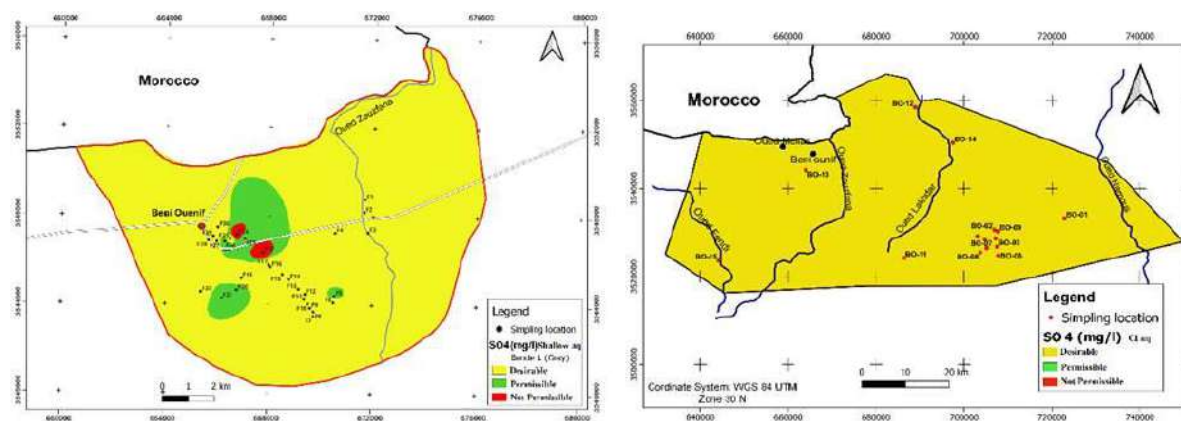


Figure 82. Map of sulphate variations in groundwater at Beni Ounif.

3.1.6. Chloride

Chloride (Cl^-) is the most abundant element among the halogens, which also include fluorine, bromine and iodine. More than three-quarters of the chlorine present in the earth's crust, atmosphere and hydrosphere exists in the form of chloride ions (Cl^-) dissolved in seawater (around 19,000 mg/L). According to the average concentrations of chloride in rocks, only a small proportion of the chloride content of seawater comes from the weathering of rocks (Matthess, 1982). Chloride is found in various types of rock at lower concentrations than all the other major constituents of groundwater. Sedimentary rocks, particularly evaporites, are much more important sources of chloride than magmatic rocks. Chloride also enters the hydrological cycle from liquid and solid waste, fertilisers and road salt. Normal concentrations of chloride in potable groundwater are less than 30 mg/L; higher values generally indicate mixing with mineralised water or anthropogenic pollution (Matthess, 1982). Once dissolved, chloride remains in solution and is often described as a 'conservative' ion, as it does not participate significantly in oxidation or reduction reactions and does not form significant solute complexes with other ions, unless chloride concentrations are extremely high (Hem, 1989). For these reasons, chloride has often been used as a conservative tracer. The concentration of chloride (Cl^-) in groundwater in the study area varies from 5 to 295 mg/L, with a median value of 96 mg/L in the shallow aquifer. It varies between 50 and 115 mg/L, with an average concentration

of 98 mg/L in the intercalated continental aquifer (CI). All the concentrations measured in the Beni Ounif region comply with WHO drinking water standards (Fig. 83).

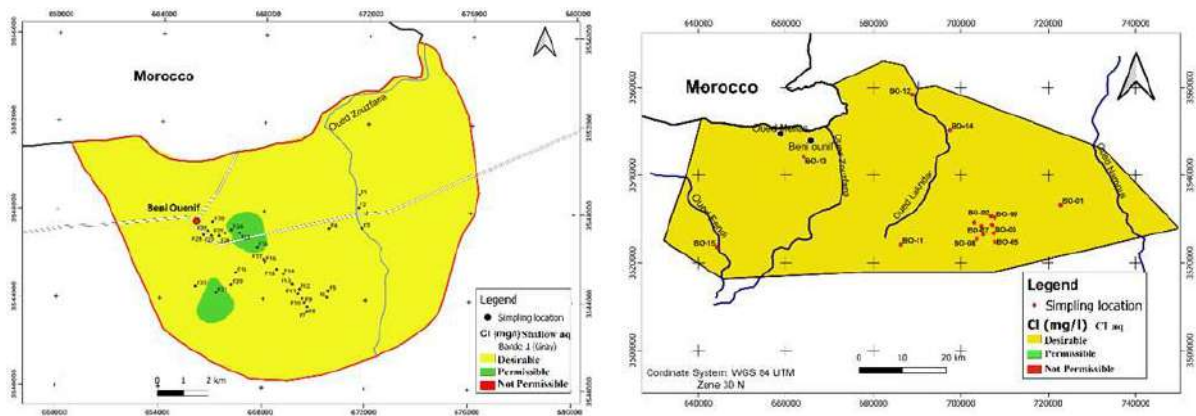


Figure 83. Map of chloride variations in groundwater at Beni Ounif.

3.1.7. Bicarbonate

The bicarbonate ions (HCO_3^-) present in groundwater come mainly from atmospheric and soil CO_2 , as well as from the dissolution of carbonate rocks such as calcium carbonate and calcium magnesium carbonate (dolomite). The term 'alkalinity' is often used as a synonym for measuring the bicarbonate and carbonate content of groundwater. It should be noted, however, that this use of the term 'alkalinity' differs from common chemical usage, according to which only water with a pH above 7.0 is considered alkaline (Davis and DeWiest, 1966). Groundwater generally contains more than 10 mg/L but less than 800 mg/L of bicarbonate, the value usually being between 50 and 400 mg/L. At equilibrium, the pH value of the water indicates the proportions of the different carbonate species. Bicarbonate predominates at a pH between 6 and 8.5. The dissociation of bicarbonate into carbonate begins at a pH of around 8.35, and carbonate dominates in very alkaline water. If the pH is below 5, the solution contains only free CO_2 . Bicarbonate concentrations in groundwater in the study area range from 153 to 518 mg/L, with a median of 245 mg/L for the shallow aquifer, and fluctuate between 148 and 183 mg/L in the CI aquifer. With the exception of well F 27, all the wells sampled met drinking water standards. According to the geological data, the presence of bicarbonate in the region's groundwater is mainly due to the dissolution of carbonate formations.

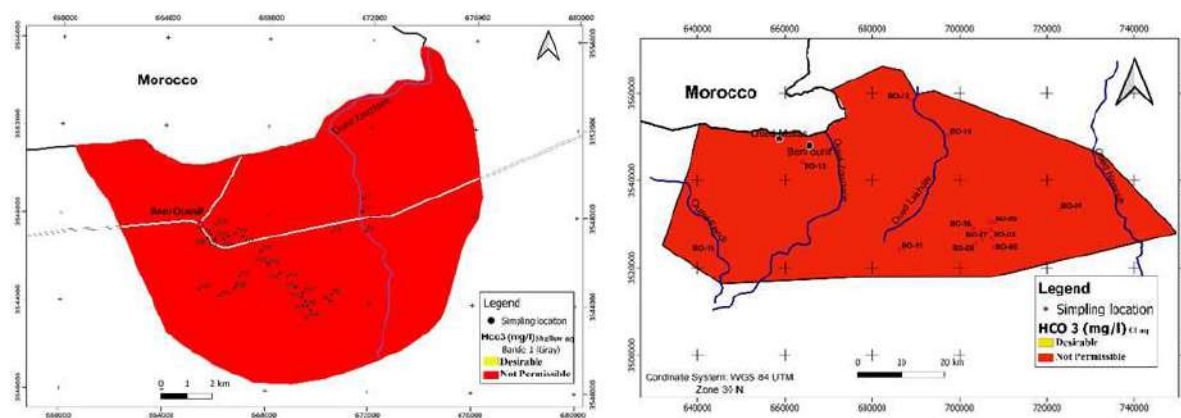


Figure 84. Map of bicarbonate variations in groundwater at Beni Ounif.

3.1.8. Nitrates

The nitrogen present in groundwater comes in various forms: neutral gaseous forms (elemental nitrogen, nitrous oxide, nitric oxide), ammonia (NH_3), nitrite anions (NO_2^-) and nitrate anions (NO_3^-), ammonium cation (NH_4^+), and in various states of oxidation in soluble organic compounds. Other pollutants, such as cyanide (CN^-), may also be present. Nitrates are particularly noteworthy because they migrate easily into groundwater and remain stable under a variety of conditions, unlike nitrites and organic compounds, which are unstable and degrade rapidly, often indicating contamination by sewage or organic waste. The presence of nitrates and ammonium can indicate remote or ancient pollution. The extensive use of nitrogen fertilisers has led to an increase in nitrate levels in many agricultural areas, and nitrogen oxides, produced by the combustion of fossil fuels, contribute to the acidification of rain and the formation of nitrates.

The sources of the various forms of nitrogen in groundwater are mainly linked to the biological activity of plants and micro-organisms, animal waste and various human activities, including agriculture, wastewater treatment and the use of fossil fuels.

In natural groundwater not affected by pollution, nitrate concentrations are generally below 2 mg/L. However, high nitrate concentrations in groundwater generally indicate contamination. According to the WHO (2017), the maximum permissible limit for nitrates in drinking water is set at 45 mg/L. Nevertheless, in the study area, nitrate concentrations vary from 4 to 70 mg/L in the shallow aquifer and from 19 to 43 mg/L in the CI aquifer (Fig. 85). 80.44% of nitrate concentrations exceed 20 mg/L. Levels above 20 mg/L of NO_3^- are attributed to anthropogenic factors (Antonakos et al., 2000; Kharroubi et al, 2023), such as the application of nitrogen-rich fertilisers and agricultural processes that lead to nitrate leaching through porous soil into groundwater in agricultural areas, as well as human waste from septic tanks located beneath urban centres.

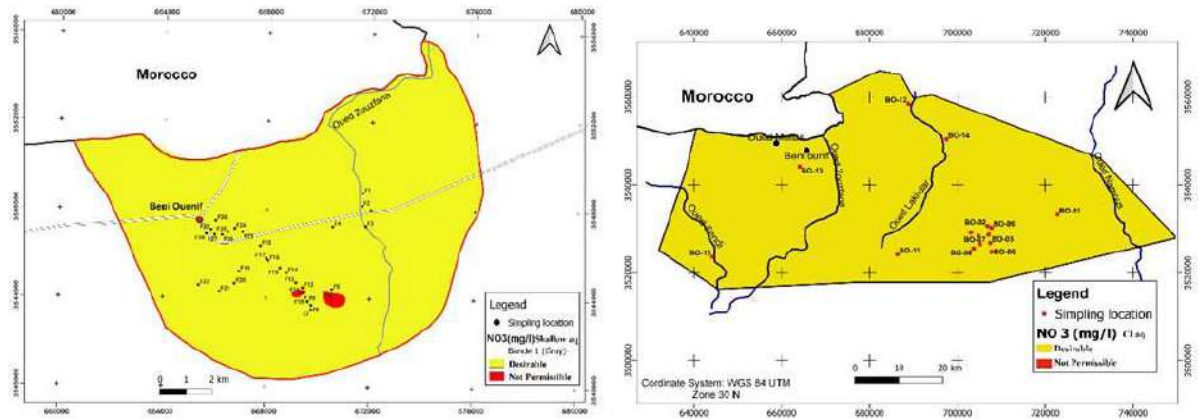


Figure 85. Map of nitrate variations in groundwater at Beni Ounif.

3.1.9. Calcium

Calcium (Ca^{2+}) is the most abundant alkaline earth metal and a major component of many common rock minerals and solutions in natural waters. It exists in only one oxidation state, Ca^{2+} . It is essential for plant and animal life forms. In aquatic systems, its presence is mainly due to the dissolution of more soluble calcium-containing solids and is largely governed by the equilibria between the dissolved and gaseous phases of carbon dioxide. Calcium also plays a role in cation exchange equilibria at the surface of aluminosilicates (clays) and other minerals (Hem, 1989). Although calcium is an essential component of many igneous rock minerals, particularly chain silicates such as pyroxenes and amphiboles, as well as feldspars, its concentration in groundwater from magmatic terrains is generally low.

In this study, analysis of groundwater samples taken in the Beni Ounif region shows that calcium (Ca^{2+}) concentrations in water from the CI aquifer vary between 39 and 67 mg/L, with a median value of 63 mg/L, while Ca^{2+} concentrations in water from the superficial aquifer vary between 33 and 143 mg/L, also with a median value of 63 mg/L (Fig. 86). These measured concentrations comply with drinking water standards. The presence of calcium in the study area results mainly from the dissolution of carbonates and sulphates.

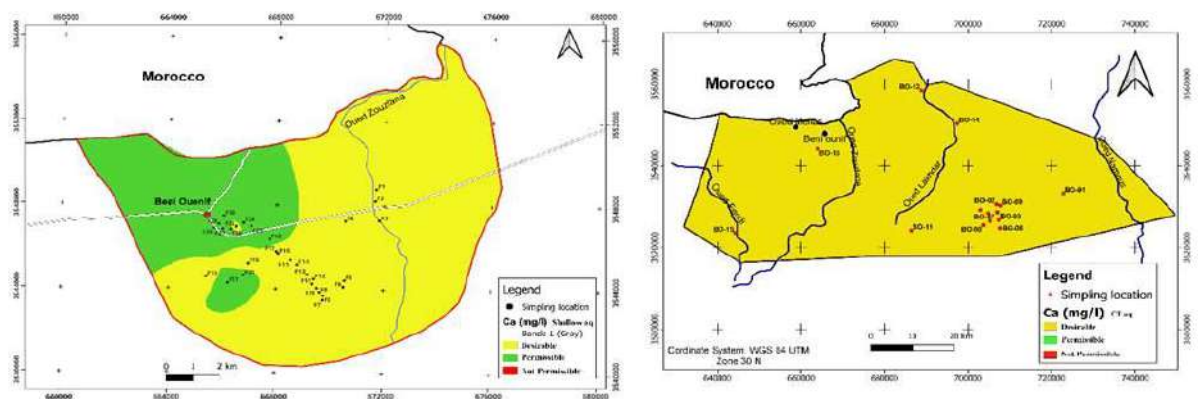


Figure 86. Map of calcium variations in groundwater at Beni Ounif.

3.1.10. Magnesium

Magnesium (Mg^{2+}) is an alkaline-earth element essential for plant and animal nutrition, existing exclusively in the form of Mg^{2+} in aqueous chemistry. Sharing properties with calcium, such as their contribution to water hardness, magnesium is distinguished by the smaller size of its ions compared with those of calcium (Hem, 1989). Present in magmatic rocks as a major component of dark ferromagnesian minerals such as olivine, pyroxenes, amphiboles and dark micas, it is also widespread in minerals such as chlorite and serpentine in metamorphic rocks. Sedimentary rocks contain magnesium carbonate (magnesite), MgCO_3 , and double carbonate of calcium and magnesium (dolomite), $\text{CaMg}(\text{CO}_3)_2$, which, like calcite (CaCO_3), dissolve in the presence of CO_2 dissolved in groundwater. Although magnesite is more soluble in pure water than calcium carbonate, its actual solubility under natural conditions is complicated by the presence of various hydrated forms of magnesium carbonate such as nesquehonite, landsfordite and hydromagnesite. In solution, the magnesium ion, Mg^{2+} , is generally the predominant form of magnesium, while the MgOH^+ complex becomes negligible below a pH of around 10 (Hem, 1989).

In this study, magnesium concentrations (Mg^{2+}) in water from the CI aquifer ranged from 15 to 43 mg/l, with a median value of 33 mg/l. As for the waters of the superficial aquifer, magnesium concentrations vary between 22 and 97 mg/l, with a median of 45 mg/l (Fig. 87). The presence of magnesium in the region studied is mainly attributed to the dissolution of carbonates, particularly dolomite.

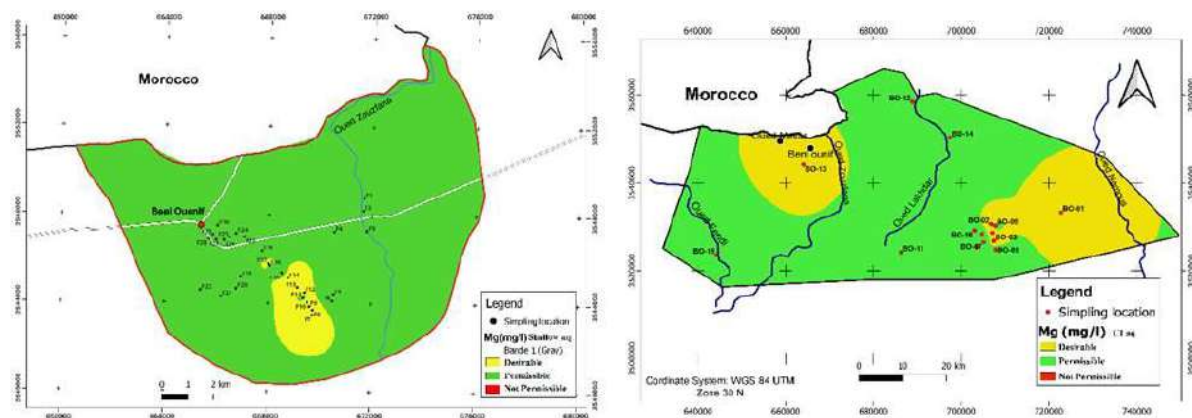


Figure 87. Map of magnesium variations in groundwater at Beni Ounif.

3.1.11. Potassium and sodium

Potassium is slightly less present than sodium in igneous rocks, but more abundant in all sedimentary rocks. However, although its presence in seawater is significant, the concentration of potassium is much lower than that of sodium. In most freshwater aquifers, if the

concentration of sodium exceeds 10 mg/L, the concentration of potassium is generally half or even one tenth of that of sodium (Hem, 1989). In some dilute natural waters where the combined concentration of sodium and potassium is less than 10 mg/L, potassium levels can equal or even exceed those of sodium. These observations highlight the markedly different behaviour of these two alkali metals in natural systems.

Although potassium salts are also highly soluble and potassium is generally as abundant as sodium in rocks, it is rarely found in concentrations equal to those of sodium in natural waters. However, the chemical reactions in water involving potassium are not yet well understood, which makes it difficult to quantify the different behaviour of sodium and potassium. Furthermore, potassium remains one of the most difficult ions to analyse accurately, which is the main reason why sodium and potassium are generally grouped together in the category of the main cationic constituents of groundwater when reporting analysis results.

Sodium tends to remain in solution quite persistently once it has been released from silicate mineral structures. No significant precipitation reaction can maintain low concentrations of sodium in water. Sodium can be retained by adsorption on mineral surfaces, particularly clays, which have a high cation exchange capacity. However, the interactions between surface sites and sodium (a monovalent ion) are much weaker than those with divalent ions such as calcium. Cation exchange processes therefore tend to remove divalent ions from solution and replace them with monovalent ions (such as sodium). It should also be noted that excessive sodium levels in groundwater used for irrigation can damage soil structure, as sodium replaces calcium and magnesium adsorbed on clays and soil colloids. The two main effects of this replacement are a reduction in soil permeability and a hardening of the soil (USSL 1954).

In water from the CI aquifer, sodium levels (Na^+) vary from 45 to 80 mg/L, with a median value of 62 mg/L, while sodium concentrations in the shallow aquifer vary from 10 to 220 mg/L, also with a median of 62 mg/L (Fig. 88). Well F18 is the only water point analysed that recorded a Na level^+ higher than the WHO standard of 220 mg/L.

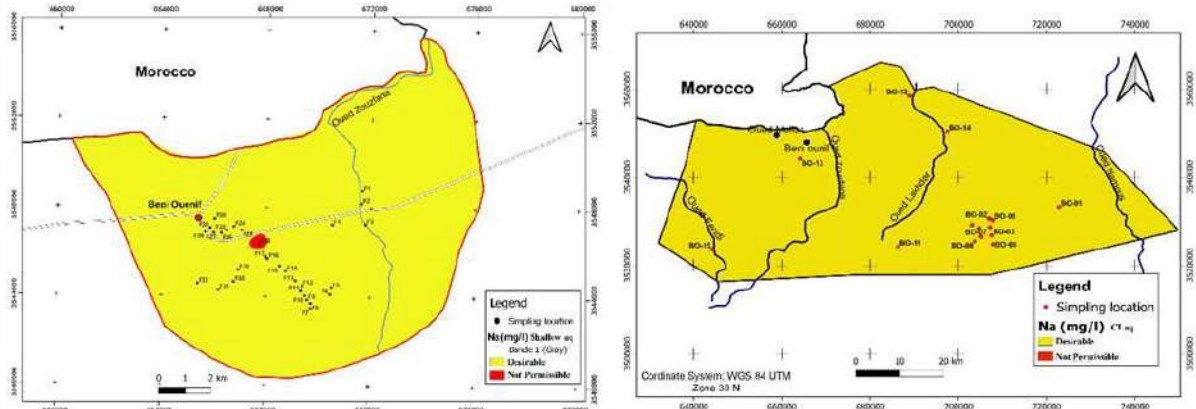


Figure 88. Map of sodium variations in groundwater at Beni Ounif.

Potassium concentrations (K^+) vary from 1.2 mg/L to 15 mg/L, with an average of 5.57 mg/L in the shallow aquifer. In the CI aquifer, potassium levels are between 4 and 7 mg/L, with a median of 5.27 mg/L (Fig. 89). The presence of potassium and sodium in the region is mainly attributed to the dissolution of evaporites and the weathering of silicate minerals.

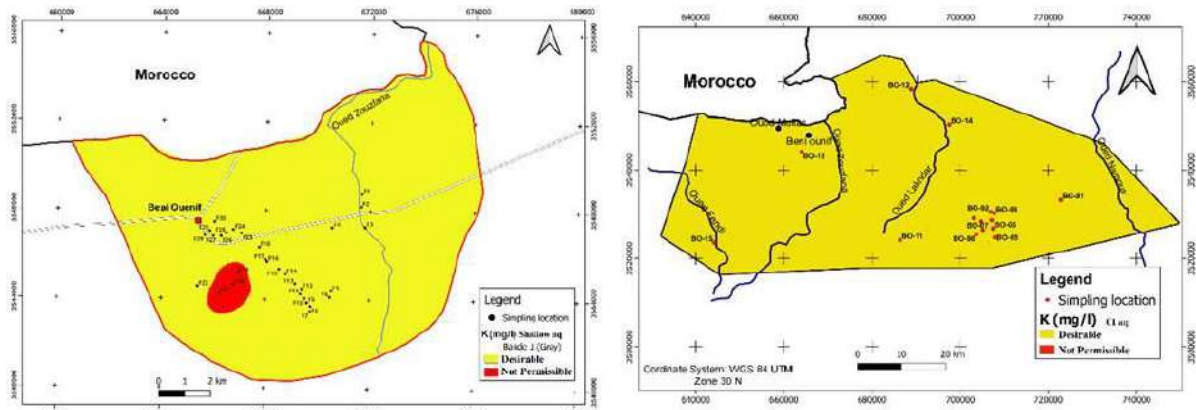


Figure 89. Map of potassium variations in groundwater at Beni Ounif.

3.2. Drinking water quality

The suitability of groundwater in the Beni Ounif area for human consumption was assessed in accordance with the World Health Organization guidelines for drinking water (WHO 2017) (Table 32). This approach is frequently used to determine the potability of water (Boussaada et al. 2023; Bahir et al. 2022; Balamurugan et al. 2022; Li et al. 2021; Mateus et al. 2020) and to identify critical parameters that require treatment prior to water distribution.

Total hardness (TH), a critical parameter for assessing the quality of water for human and domestic use, is calculated by adding the concentrations of calcium and magnesium, expressed in milligrams per litre of $CaCO_3$ (Adimalla and Ajay, 2020). In the aquifers studied, the TH values made it possible to classify the waters of the intercalary continental aquifer as hard (56.25%) and very hard (43.75%).

Water from the shallow aquifer is also predominantly classified as hard (56.67%) and very hard (43.33%) (Sawyer and McMcarty 1967), with the exception of six boreholes representing 20% of the water points analysed, which comply with WHO standards (2017) for total hardness.

Measurements of electrical conductivity (EC) and total dissolved solids (TDS) indicate that four water samples (F18, F21, F23, F24) from the shallow aquifer are not suitable for consumption, with values exceeding the thresholds set by the WHO in 2017. In addition, concentrations of Na^+ (6.67%), K^+ (10%), $\text{SO}_4^{(2-)}$ (6.67%), HCO_3^- (3.33%) and NO_3^- (23.33%) in some samples from this aquifer also exceed the permissible limits according to WHO standards (2017).

Overall, according to the results in Table 4, most of the water samples analysed are deemed suitable for consumption after simple treatment. This treatment mainly involves softening to reduce total hardness and oxidation methods to lower nitrate levels.

Table 32. Suitability of groundwater for consumption.

N°	Joining forces	WHO standard (2017)		Potability CI		Superficial Potability A	
		Desirable limit (DL)	Permissible limit (PL)	Number of samples exceeded PL	of sample exceeding PL	Number of samples exceeded PL	of sample exceeding PL
Ca	mg/l	75	200	00	00	00	00
Mg	mg/l	50	150	00	00	00	00
Na	mg/l	-	200	00	00	02	06.67
K	mg/l	-	12	00	00	03	10
Cl	mg/l	200	600	00	00	00	00
SO₄	mg/l	200	400	00	00	02	06.67
HCO₃	mg/l	300	500	000	00	01	03.33
NO₃	mg/l	-	45	00	00	07	23.33
pH	-	-	6,5 à 8,5	00	00	00	00
TDS	mg/l	500	1000	00	00	04	13.33
CE	µsm/cm	500	1500	00	00	04	13.33
TH	mg/l (CaCO ₃)	100	500	00	00	06	20

The Water Quality Index (WQI) uses various physicochemical characteristics to assess water quality and determine whether it is fit for consumption. This method combines a wide range of water quality parameters into a single score (Shah et al. 2021; Bouselsal and Saibi. 2022; Kharroubi et al. 2022), providing a concise and clear summary of scientific data on water quality in an easily expressed and understandable format. This score represents numerically and consistently the changes in the main characteristics of water, making it easier to compare different water sources. The WQI is a valuable tool for local authorities and water resource managers to make informed decisions about water use.

In the Beni Ounif region, water quality indices (WQIs) were calculated for groundwater samples (Tab. 33). The WQI values for the shallow aquifer water ranged from 46 to 142, with an average of 68 (Fig. 90). These results made it possible to classify the water into three distinct quality categories. The first category, comprising 13.33% of the wells studied and including wells F9, F10, F16 and F17, is considered to be of excellent quality. The second category, representing 80% of the wells analysed, is considered to be of good quality. The last category, representing 6.67% of the wells (F18 and F27), was classified as being of poor quality.

For the waters of the intercalary continental aquifer, the calculated WQI values range from 53 to 74, with an average of 66 (Figure 91). These results place the waters of the CI aquifer in the right category for consumption.

Table 33 :WQI classification scheme and sample categories

Classes	WQI value	CI aquifer		Surface aquifer	
		N ^{ber} Samples	of samples	N ^{ber} Samples	of samples
Excellent	<50	00	00	04	13.33
Good	50 - 100	16	100	24	80
Poor	100 - 200	00	00	02	06.67
Very low	200 - 300	00	00	00	00
Unsuitable	>300	00	00	00	00

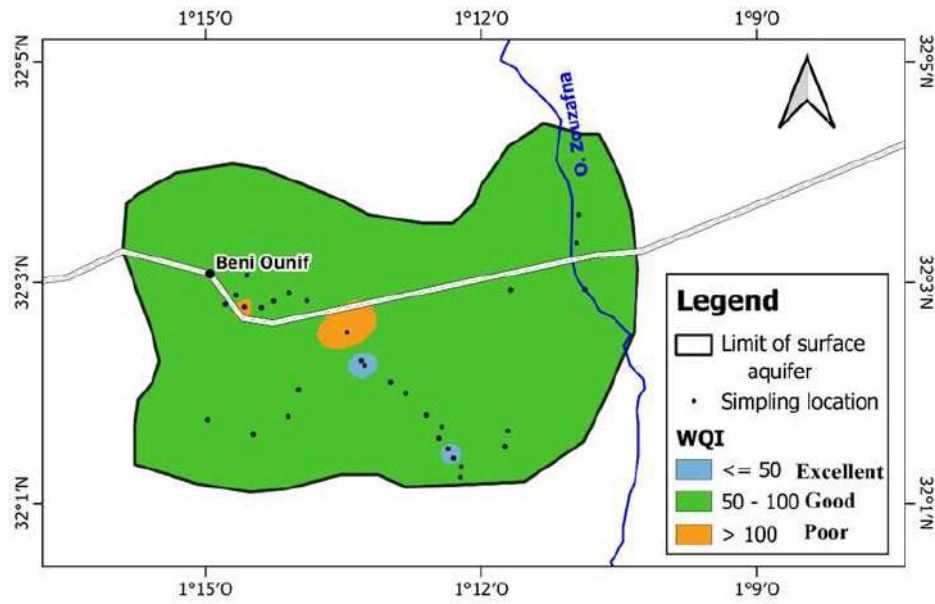


Figure 90. Variation in the WQI in shallow aquifers.

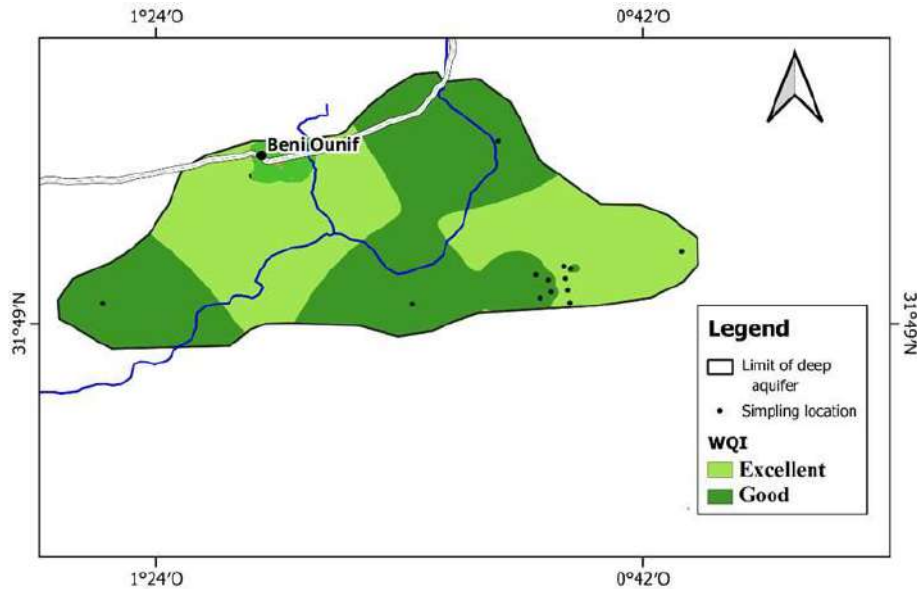


Figure 91. Variation in the WQI in the waters of the intercalary continental aquifer.

3.3. Suitability of water for agricultural use

High concentrations of chemical ions in groundwater can have adverse effects on soil and vegetation, hindering plant development and disrupting osmotic and metabolic processes. These concentrations also have an impact on soil permeability and aeration, which has a direct influence on plant growth (Bengal and Aznarul, 2021; Eldaw et al. 2021). It is therefore essential to monitor water quality parameters for irrigation, such as EC, SAR, SSP, PI, KR, PS and MAR, to ensure healthy and sustainable plant growth.

Water salinity is mainly associated with total dissolved solids (TDS) and electrical conductivity (EC) (Ayers and Westcott, 1985; Todd, 1959). A common method for estimating TDS in mg/l

or ppm is to multiply the EC (in $\mu\text{S}/\text{cm}$) by 0.64, depending on the types of salts present. High levels of TDS and EC can increase soil salinity, which is detrimental to plant growth and has an impact on soil structure, permeability and aeration. An increase in dissolved solids can also make it more difficult for roots to absorb water and nutrients, leading to stunted growth, reduced yield, discolouration and leaf burn. EC measurements in shallow aquifer water range from 500 $\mu\text{S}/\text{cm}$ to 2,067 $\mu\text{S}/\text{cm}$. According to the Wilcox classification (Wilcox 1955) (Table 6), the waters of this aquifer are classified into three salinity risk categories: low (20%), medium (53.33%) and high (26.67%), while those of the CI aquifer are classified into two risk categories: medium (37.5%) and high (62.5%).

SAR, introduced by Richards (1954), assesses the tendency of Na^+ ions to accumulate in the soil, calculated using equation 4. High SAR levels in irrigation water can increase Na^+ accumulation in the soil, reducing water infiltration due to the dispersion of soil particles. Excessive SAR can also promote crusting and reduce soil aeration (Aravinthasamy et al. 2021). High sodium concentration (SAR) can also lead to soil alkalinisation. According to Richards (1954) (Table 35), groundwater quality at Beni Ounif for irrigation is considered excellent.

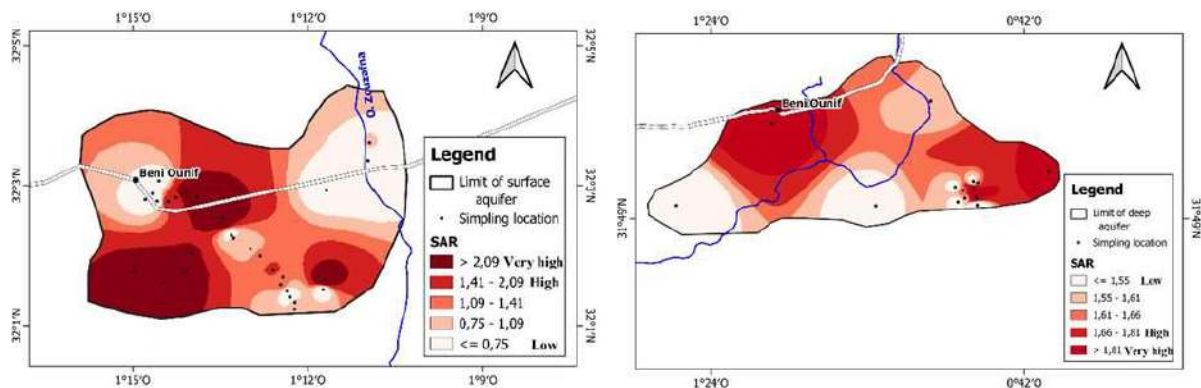


Figure 92. Variation in SAR in groundwater in the study area.

The USSL (1954) diagram (Fig. 93a) shows that all the groundwater samples from the study area belong to the S1 category, characterised by a low sodium content. These waters are suitable for irrigation of most soil types, with minimal risk of accumulation of harmful exchangeable sodium. However, it is important to note that sodium-sensitive crops, such as stone fruits and avocados, can accumulate harmful levels of sodium.

In terms of salinity, the waters of Beni Ounif are classified as follows:

Class C1: representing 20% of the boreholes analysed in the shallow aquifer. This low-salinity water is suitable for irrigating most crops and soils, with a low risk of soil salinisation. Some

leaching is necessary, but this is generally provided by normal irrigation practices, except in extremely low permeability soils.

Class C2: includes 53.33% of boreholes in the shallow aquifer and 37.5% in the CI aquifer. These moderately saline waters can be used provided adequate leaching takes place. Crops with moderate salt tolerance can generally be grown without special salinity management practices.

Class C3: includes 26.67% of boreholes in the shallow aquifer and 62.5% in the CI aquifer. These high salinity waters are not suitable for soils with limited drainage. Even with good drainage, specific salinity management strategies may be required, and it is advisable to select salt-tolerant crops (Bouselsal et al 2014b).

The Wilcox classification, which takes into account the electrical conductivity and sodium content of the water, classifies the groundwater at Beni Ounif as excellent to good quality, as shown by the distribution of samples on the diagram (Fig. 93b).

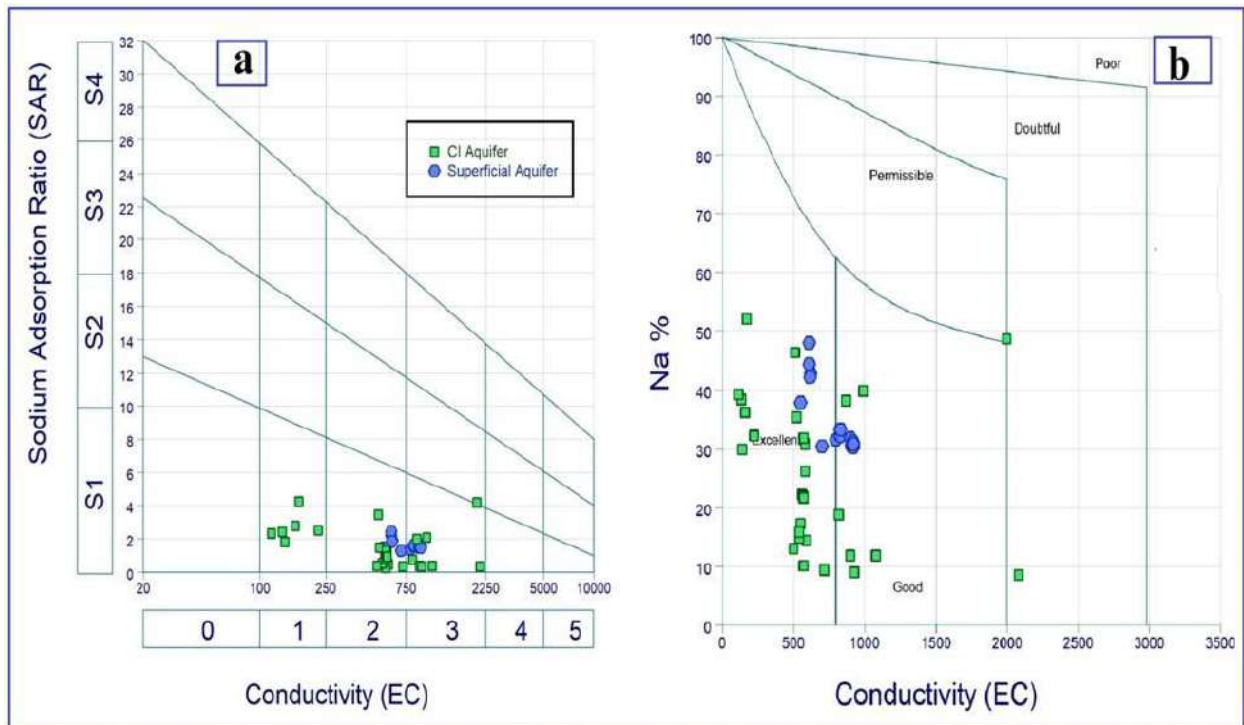


Figure 93. USSL and Wilcox diagram for groundwater at Beni Ounif.

The percentage of soluble sodium (PSS) is an essential parameter for assessing the quality of irrigation water and estimating the risk associated with sodium. The PSS is calculated as the ratio between sodium and the sum of cations, including calcium and magnesium, multiplied by 100 (equation 5). A high percentage of sodium can promote the exchange of sodium with calcium and magnesium in clay particles, reducing soil permeability, which can lead to poor internal drainage and soil hardening, degrading soil quality and crop emergence (Kshitindra Kr

et al. 2020). High sodium levels can also cause soil salinity and alkalinity, hindering plant growth and productivity. Todd (1959) classified irrigation water quality into five categories based on SSP (Tab. 6 and Fig. 19): excellent (>20), good (20 to 40), fair (40 to 80) and poor (<80). According to this study, for surface aquifer water, 40% of samples fall into the "excellent" category, 50% into the "good" category and 10% of wells analysed fall into the "authorised" category. For water from the CI aquifer, 75% of samples are in the "good" category and 25% of wells analysed are in the "authorised" category.

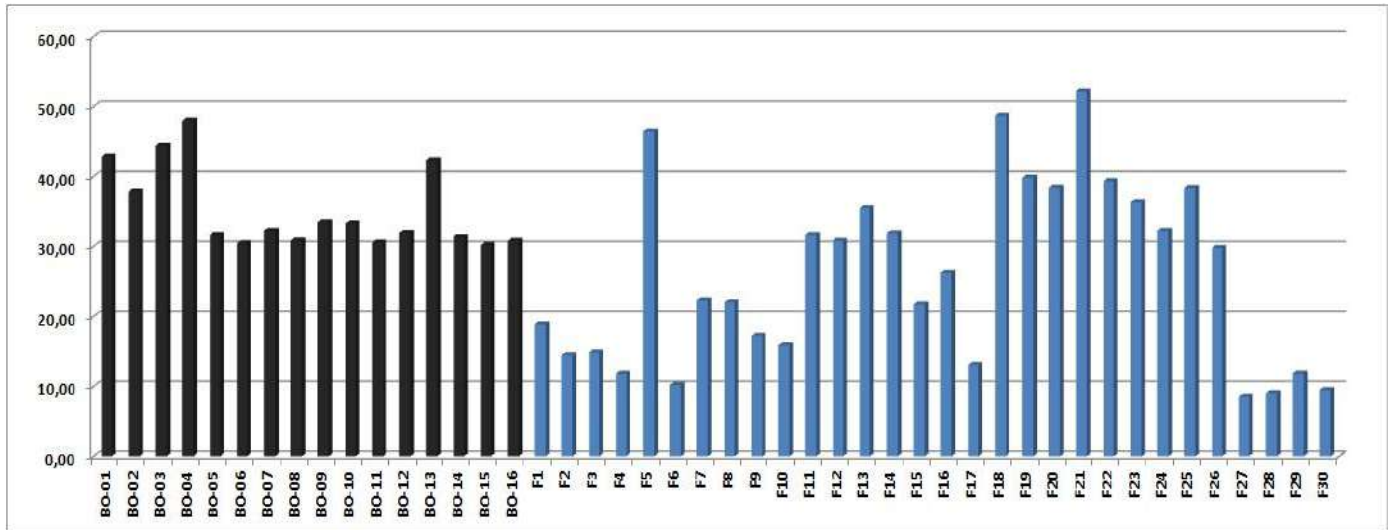


Figure 94. Variation in SSP in groundwater in the study area.

The Kelly ratio is a crucial indicator for assessing water quality for agricultural purposes. It compares the concentration of sodium with that of calcium and magnesium in the water (calculated using equation 5) (Kelly, 1940). A Kelly ratio greater than 2 indicates an excess of sodium, making the water unsuitable for irrigation. A ratio between 1 and 2 indicates poor water quality for irrigation, while a ratio below 1 indicates that the water is suitable for irrigation. In the study area (Tab. 35), all the wells are of good quality for irrigation with the exception of well F21, which is classified as doubtful for irrigation (Fig. 95).

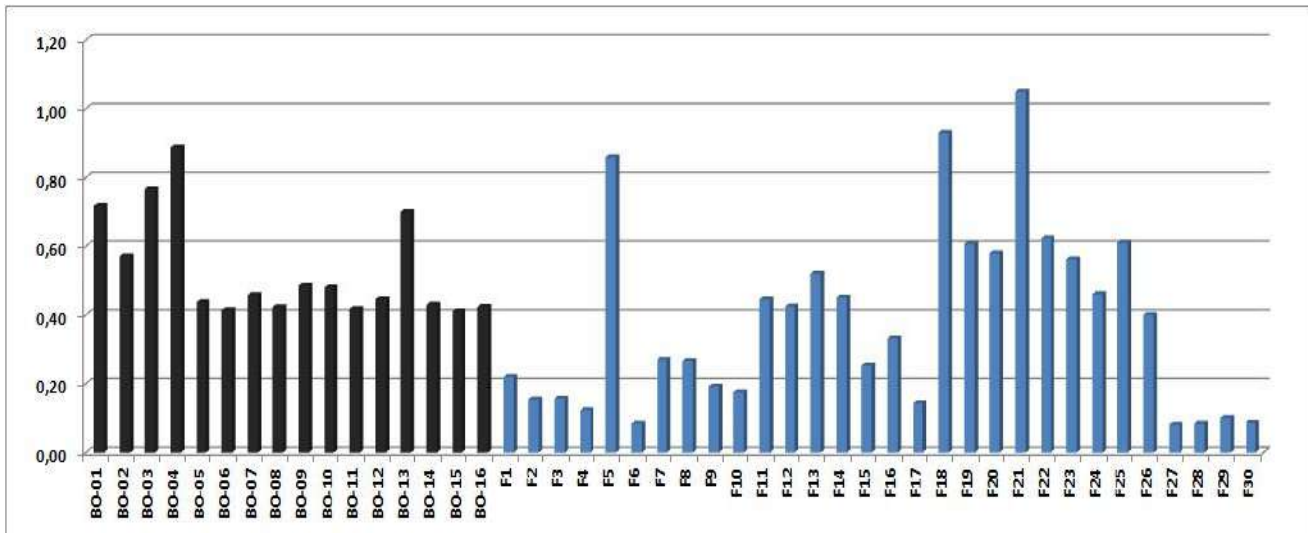


Figure 95: Variation in KR in groundwater in the study area.

The infiltration capacity of groundwater is largely influenced by soil permeability. To assess the suitability of groundwater for irrigation, the permeability index (PI) is calculated using the concentrations of Na^+ , Ca^{2+} , Mg^{2+} and HCO_3^- as specified in equation 7. According to Doneen's (1964) classification (Tab.6), PI values are classified into three groups: Class 1 for excellent values, Class 2 for good values, and Class 3 for inadequate values. Groundwater in Classes 1 and 2 is considered good for irrigation, with a potential permeability of 75% or more, while water in Class 3, with a maximum permeability of only 25%, is considered unsuitable. In the study area, the permeability indices indicate that all the groundwater samples are suitable for irrigation, with a permeability of 75% or more (Fig. 96).

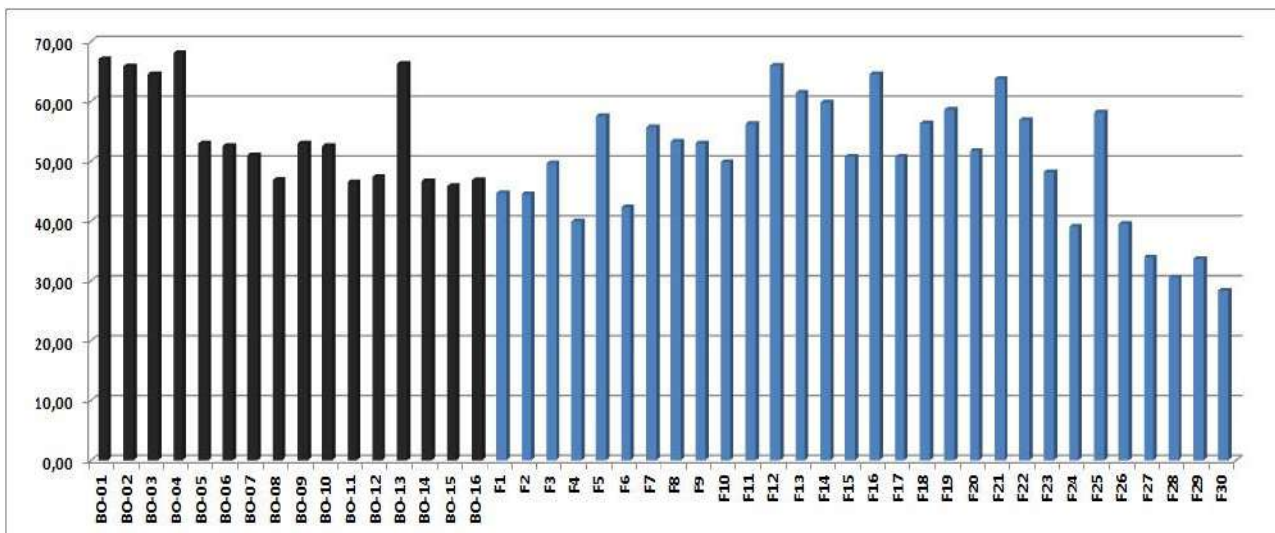


Figure 96: Variation in PI in groundwater in the study area.

Salinity potential (SP) is an essential parameter for assessing the quality of water used for irrigation. It is determined as a function of the sulphate and chloride concentrations in the water,

as shown in equation 8. The formation of insoluble salts in irrigation water can lead to their precipitation and accumulation in the soil after each crop cycle, which has a negative impact on crop yields. Therefore, maintaining an optimum PS is essential for sustainable water use and the long-term viability of irrigated land. The classification of irrigation water according to PS is detailed in Table 6. Groundwater samples taken in the study area show PS values ranging from 0.43 to 12.80 meq/l, with an average of 3.98 meq/l for shallow aquifer waters, and from 2.49 to 1.34 meq/l, with an average of 1.68 meq/l for IC aquifer waters (Fig. 97). These measurements make it possible to classify the waters of the shallow aquifer into two categories: good to detrimental (86.67%) and detrimental to unsatisfactory (13.33%). In addition, all the water in the CI aquifer is classified as good to detrimental for irrigation.

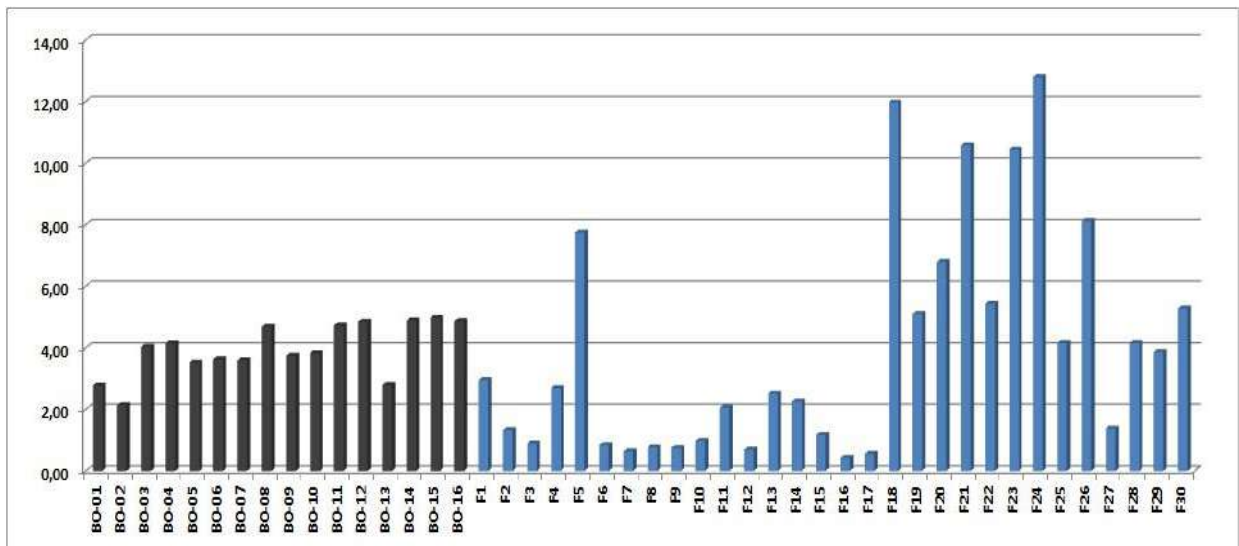


Figure 97. Variation in SP in groundwater in the study area.

The suitability of water for irrigation is also influenced by magnesium and calcium concentrations. Magnesium has a greater impact on groundwater quality than calcium. To assess this, the magnesium adsorption ratio (MAR) is used to measure the ratio of magnesium to calcium in water, as shown in equation 9. According to Ragunath (1987), a MAR of less than 50 indicates that the water is suitable for irrigation. Conversely, a MAR above 50 makes the water unsuitable for irrigation and can reduce crop yields by increasing soil alkalinity and promoting sodium adsorption, which can reduce soil permeability (Kshitindra Kr et al. 2020). According to the data in Table 35 and Figure 23, 80% of the groundwater samples from the shallow aquifer and 37.5% from the CI aquifer are considered suitable for irrigation, while the remaining groundwater samples are not suitable for this purpose.

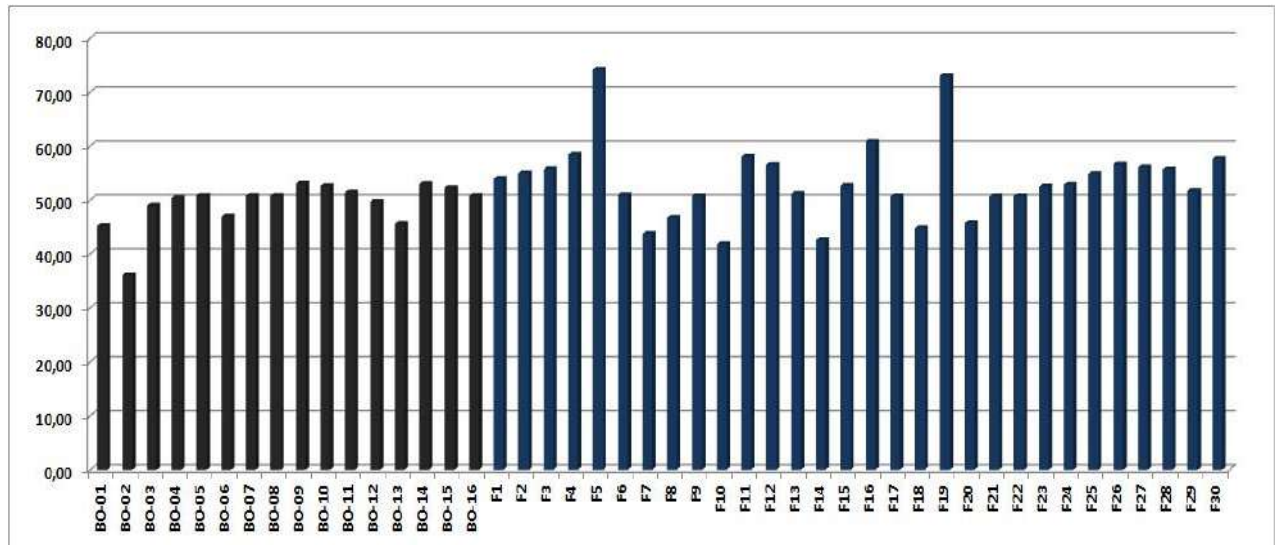


Figure 98. Variation in MAH in groundwater in the study area.

The quality of water for agricultural use can be assessed using the Irrigation Water Quality Index (IWQI), which combines seven predetermined water quality parameters into a single value that indicates the suitability of the water for irrigation purposes. In the Beni Ounif region, the IWQI values for the waters of the continental intercalary (CI) aquifer range from 51 to 64, as shown in Table 35 and Figure 99. For the shallow aquifer, IWQI values vary between 40 and 88.

Approximately 63.33% of groundwater samples from the shallow aquifer and 100% of samples from the CI aquifer are classified as "good", while 36.67% of samples from the shallow aquifer are classified as "excellent". The lower IWQI values are attributed to the relatively modest mineralisation of the groundwater in relation to the arid climatic conditions prevailing in the study area. The reduction in concentr.

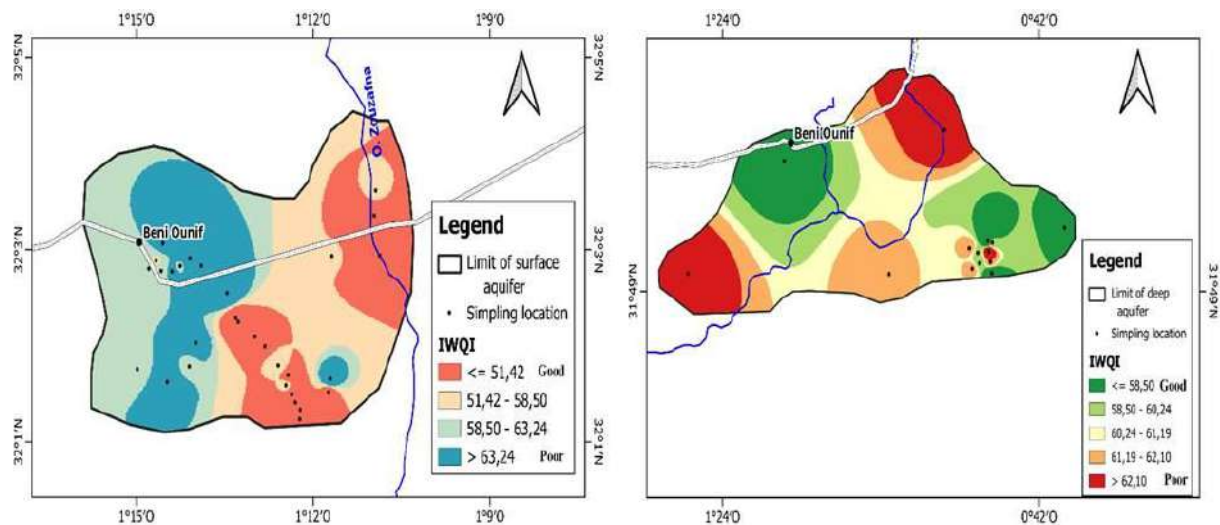


Figure 99. Variation in IWQI in groundwater in the study area.

Table 34 : Classification of groundwater samples for irrigation.

Parameters	Scale	Groundwater classes	CI aquifer		Surface aquifer	
			No, the sample.	of the sample.	No, the sample.	of the sample.
EC ($\mu\text{S}/\text{cm}$) (Wilcox 1955)	<250	low (good)	00	00	06	20
	250-750	medium (moderate)	06	37.5	16	53.33
	750-2250	high (low)	10	62.5	08	26.67
	>2250	very high (very low)	00	00	00	00
SAR (meq/l) (Richards 1954)	0-10	Excellent	16	100	30	100
	10-18	GOOD	00	00	00	00
	18-26	Doubtful	00	00	00	00
	> 26	Inappropriate	00	00	00	00
SSP (Todd 1959)	0-20	Excellent	00	00	12	40
	20-40	GOOD	12	75	15	50
	40-60	Permits	04	25	03	10
	60-80	Doubtful	00	00	00	00
	> 80	Inappropriate	00	00	00	00
RK (Kelley 1963)	< 1	Good	16	100	29	96.67
	1-2	Doubtful	00	00	01	3.33
	> 2	Inappropriate	00	00	00	00
PI (%) (Doneen 1964)	> 75	Max. Permeability (100%)	00	00	00	00
	75-25	75% of maximum permeability	16	100	16	100
	< 25	25% of maximum permeability	00	00	00	00

SP (Doneen 1954)	> 5	Excellent to good	16	100	26	86.67
	5-10	Good for pests	00	00	04	13.33
	< 10	Detrimental to unsatisfactory	00	00	00	00
MAR (%) (Ragunath 1987)	< 50%	Appropriate	06	37.5	24	80
	> 50%	Inappropriate	10	62.5	06	20
IWQI	0-50	Excellent	00	00	11	36.67
	50-100	Good	16	100	19	63.33
	100-200	Permits	00	00	00	00
	200-300	Doubtful	00	00	00	00
	> 300	Inappropriate	00	00	00	00

3.4. Water quality parameters for industrial use

The use of groundwater in the industrial sector worldwide is confronted with various water quality problems. The two most important water quality problems encountered by industries are corrosion and scaling (Kaur et al. 2019; Amiri et al. 2021; Shankar et al. 2014). These phenomena are influenced by several factors, including pH, temperature, alkalinity, TDS, Cl^- , SO_4^{2-} and Ca^{2+} ions. In this study, the Langelier Index (LI), Ryznar Index (RI), Larson-Skold Index (LSI), Puckorius Scale Index (PI), Aggressivity Index (AI), Revelle Index (RI) and Chloride-Sulphate Mass Ratio (CSMR) are used to assess water quality for industrial use. The results of these assessments are presented in Table 34.

3.4.1. Langelier Index (LI)

The Langelier saturation index is used to assess the potential for scale formation or corrosion by agents present in water (Egbueri et al. 2021). This index determines whether the water tends to dissolve or precipitate calcium carbonate. Equations 11 to 16 are used to calculate the Langelier index (LI), whose values are classified into three categories, as shown in Table 34. In our study, LI values for groundwater samples from the superficial aquifer ranged from -0.20 to 0.96, with an average of 0.33. For the CI aquifer, LI varied from -0.39 to 0.33, with an average of -0.03 for the water samples (Fig. 100). Of these samples, 43.75% of the shallow aquifer and 93.34% of the CI aquifer are classified as supersaturated, indicating a tendency for calcium carbonate (CaCO_3) to precipitate. Conversely, 56.25% of samples from the shallow

aquifer and 6.66% from the CI aquifer were classified as undersaturated, indicating a tendency for calcium carbonate (CaCO_3) to dissolve.

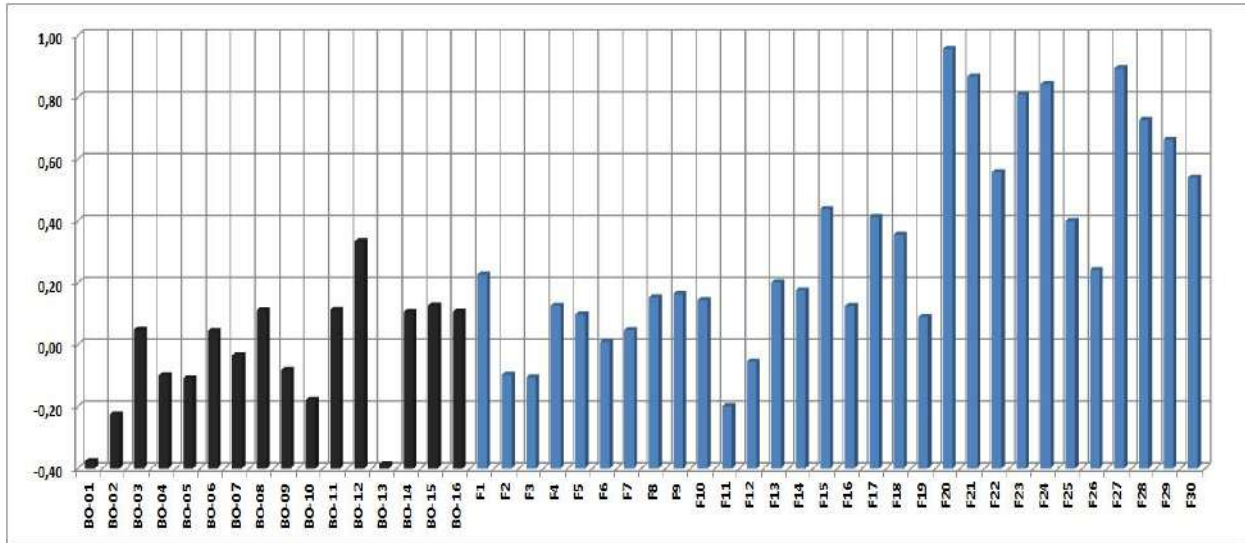


Figure 100. Variation in LI in waters in the study area.

3.4.2. Ryznar Index (RI)

The Ryznar Index is a modified version of the Langelier Index (LI), proposed by Ryznar, which uses pH and alkalinity values to more accurately quantify the scaling properties and corrosive tendencies of water. While IR is specific to flow systems, IL is more suited to assessing water storage systems in reservoirs. Water samples are classified into three Ryznar Index levels (Shipra et al. 2020): $\text{RI} < 6$ (highly saturated, prone to CaCO_3 precipitation), $6 \leq \text{RI} \leq 7$ (saturated, CaCO_3 in equilibrium), and $\text{RI} > 7$ (undersaturated, corrosion potential). In the study area, RI values for water samples from the CI aquifer ranged from 6.93 to 7.87, while for the shallow aquifer RI values ranged from 5.75 to 7.69 (Fig. 26). According to Table 34 :

In the superficial aquifer, 30% of the samples were balanced with no tendency towards scaling, 20% were supersaturated with a tendency towards precipitation of calcium carbonate (CaCO_3), and 50% showed a corrosive tendency. Conversely, in the CI aquifer, 93.75% of the samples were balanced with no tendency for scaling, while 6.25% showed a corrosive potential.

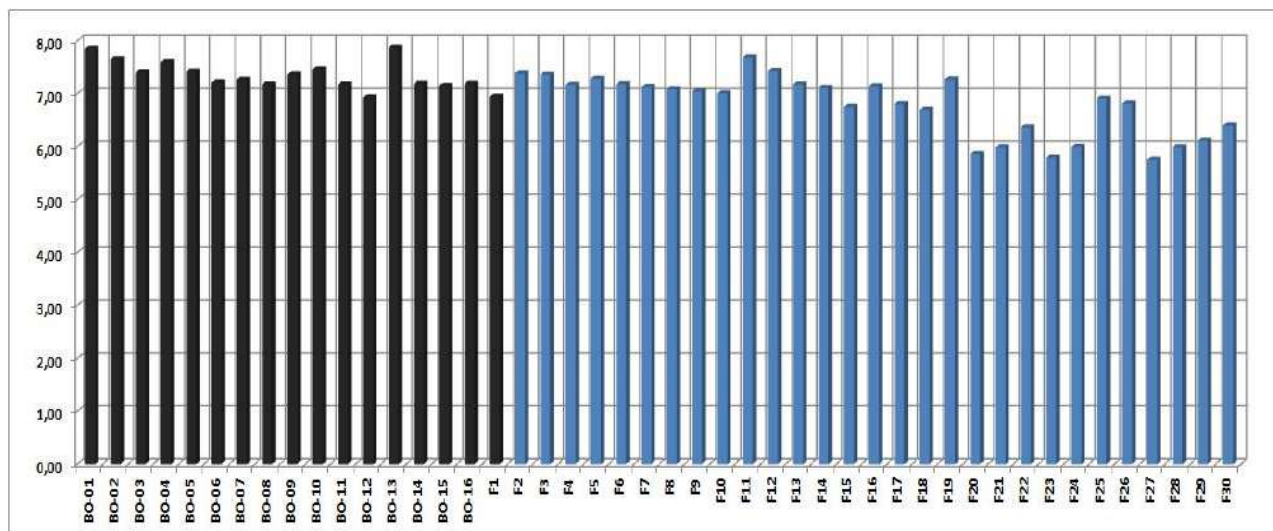


Figure 101. Variation in IR in the waters of the study area.

3.4.3 Larson-Skold Index (LSI)

The Larson-Skold index was developed to assess the corrosiveness of water, taking into account the impact of Cl^- and SO_4^{2-} ions (Larson and Skold 1958). The value of the Larson-Skold index is calculated using equation 19, and the value thresholds and their significance are presented in Table 35 (Shipra et al. 2020). Langelier Saturation Index (LSI) values for samples from the study area range from 2.30 to 0.95 in the CI aquifer, while Ryznar Index (RI) values for the shallow aquifer range from 5.95 to 0.10 (Fig. 27). According to the results in Table 35:

In the shallow aquifer, 66.67% of the samples show a potential for scale deposition, 6.66% have a corrosive tendency and 26.67% are very corrosive. Conversely, in the CI aquifer, 37.5% of samples have a corrosive tendency and 62.5% are very corrosive.

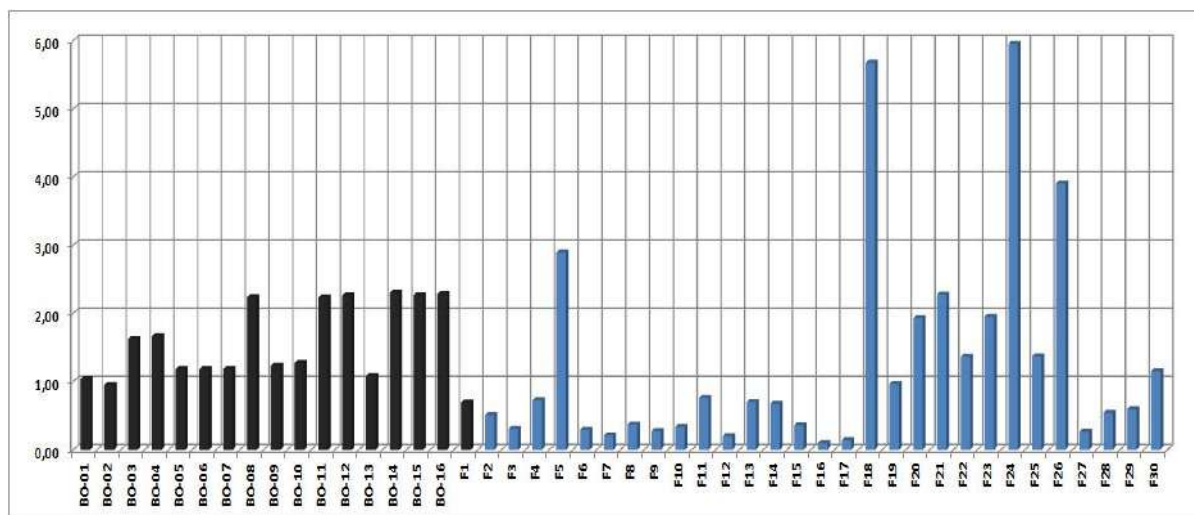


Figure 102. Variation in SLI in the waters of the study area.

3.4.4 Puckorius Index (PI)

The Puckorius scale index is based on assessing the pH and alkalinity of water in order to analyse its buffering capacity and precipitation properties. This index uses the equilibrium pH rather than the actual pH of the water. According to the PI classification, water samples can be classified as slightly corrosive ($PI < 6$), slightly corrosive ($6 < PI < 7$), prone to scaling ($PI > 7$) or highly prone to scaling (Shipra et al. 2020). The results of this study show that: In the shallow aquifer, 26.67% of the samples show a potential for scale formation, 10% of the samples are balanced and 63.33% show a high corrosive tendency. Conversely, in the CI aquifer, 68.75% of samples were balanced and 31.25% showed a corrosive tendency.

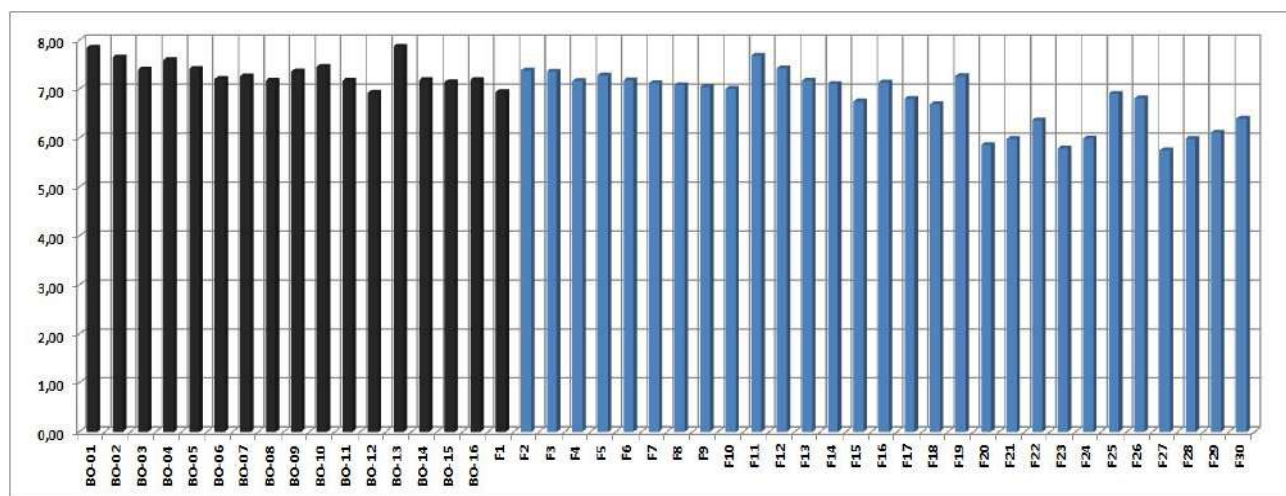


Figure 103. Variation in PI in the waters of the study area.

3.4.5. Aggression Index (AI)

The aggressivity index is used to assess the corrosive capacity of water and the potential damage that aggressive water can cause to equipment and pipework. This index is calculated using equation 19. An Aggressivity Index (AI) of less than 10 indicates that the water is highly corrosive. An AI between 10 and 12 indicates that the water is moderately corrosive. An AI greater than 12 implies that the water has a tendency to form calcareous deposits and is considered non-corrosive (Mirzabeygi et al. 2016).

The Aggressivity Index (AI) values of the CI aquifer samples range from 11.18 to 11.92, while the AI values of the shallow aquifer range from 11.37 to 12.52 (Fig. 104). According to the data in Table 35, all the water points in the CI aquifer and 66.67% of the samples in the shallow aquifer are classified as moderately aggressive, and 33.33% of the samples in the shallow aquifer are classified as non-aggressive but tend to form calcareous deposits.

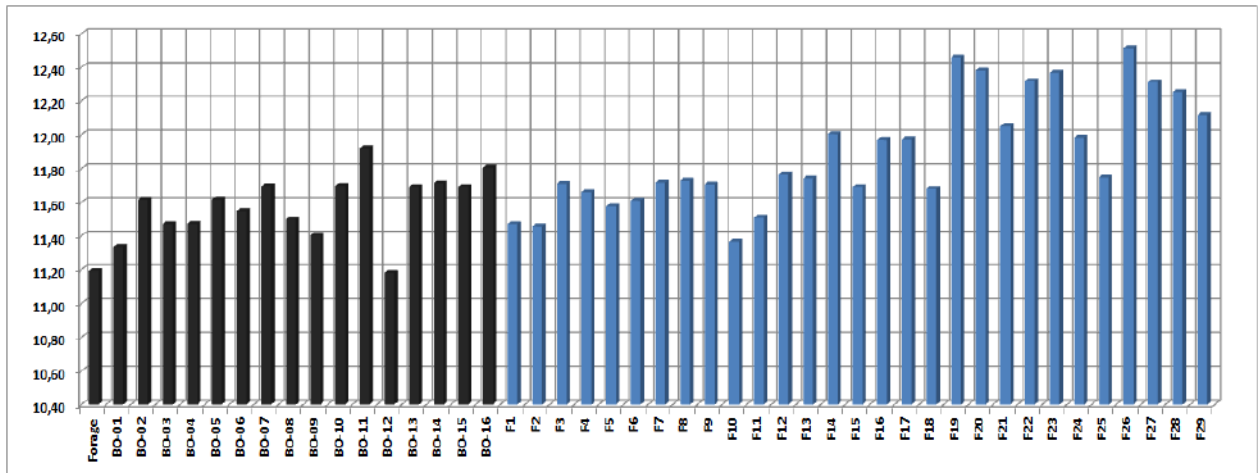


Figure 104. Variation in AI in the waters of the study area.

3.4.6 Revelle Index (RI)

Groundwater samples taken in the study area were subjected to Revelle Index (RI) assessment to describe the potential impact of salinisation on the chemical composition of the water and the risks of corrosion and scale formation. It is calculated by equation 23. The RI values in this study range from 0.02 to 1.51, with an average of 0.44 for the shallow aquifer. The Revelle index in the CI aquifer ranged from 0.32 to 0.78, with an average of 0.61 (Figure 30). The results indicate that 93.75% of the samples from the CI aquifer and 33.33% of the samples from the shallow aquifer are slightly affected by salinisation, while the other samples show no impact from salinisation (Table 35) (Egbueri et al., 2021).

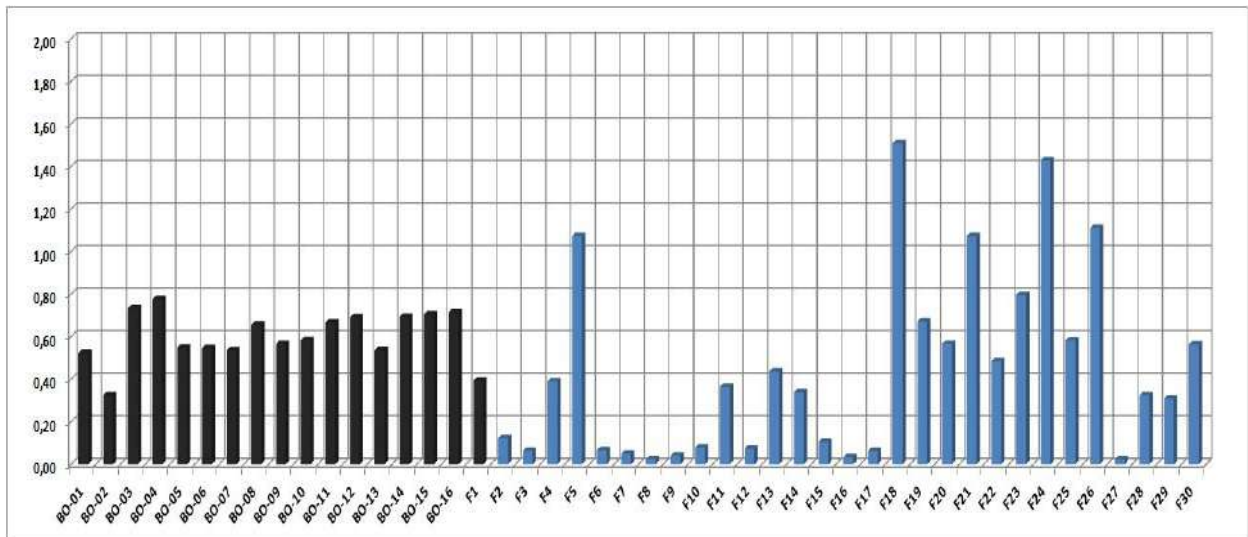


Figure 105. Variation in IR in the waters of the study area.

3.4.7. Chloride-sulphate mass ratio (CSMR)

Regarding the chloride-sulphate mass ratio (CSMR), values below 0.5, as recommended by Nguyen et al. (2011) and Stets et al. (2017), indicate that water installations do not promote galvanic corrosion of lead fittings in water distribution channels. In this study, all samples

analysed for the CI aquifer are aggressive; however, only 33.33% of samples from the shallow aquifer are aggressive (Table 35 and Figure 106).

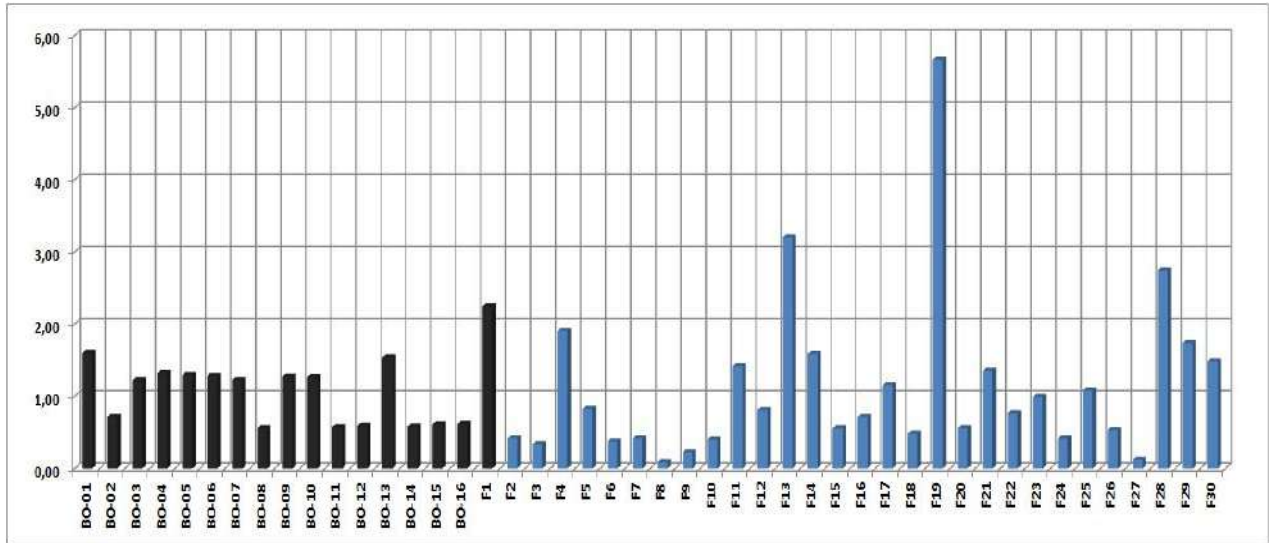


Figure 106. Variation in CSMR in the waters of the study area.

Table 35. Variations in water quality indices for industry.

Parameters	Interval	Indication	Surface aquifer		CI aquifer	
			Sample number	of sample	Sample number	of sample
Langelier Index (LI)	< 0	Under-saturated, tends to dissolve solid CaCO_3 .	09	56.25	02	6.66
	0	Saturated, the CaCO_3 is in equilibrium.	00	00	00	00
	> 0	In the event of over-saturation, a tendency to precipitate CaCO_3	07	43.75	28	93.34
Ryznar Index (RSI)	< 6	In the event of over-saturation, a tendency for CaCO_3 to precipitate	00	00	06	20
	6-7	Saturated, the CaCO_3 is in equilibrium.	01	06.25	09	30
	> 7	Under-saturated; Corrosion potential	15	93.75	15	50
	< 0,8	Scalability potential	00	00	20	66.67
	0,8-1,2	Corrosion potential	06	37.5	02	06.66

Larson-Skold Index (LSI)	> 1.2	High corrosion rates	10	62.5	08	26.67
Puckorius Index (PSI)	< 6	Scalability potential	00	00	08	26.67
	6-7	Water in balance	11	68.75	03	10
	> 7	High corrosion potential	05	31.25	19	63.33
Aggressive index (AI)	AI < 10	Corrosion potential	00	00	00	00
	10 < AI < 12	Moderately corrosive	16	100	20	66.67
	AI < 12	Evolutionary and non-aggressive potential	00	00	10	33.33
Revelle Index (RI)	> 0,5	Insensitive to salinisation	01	06.25	20	66.67
	0,5 à 6,6	Slightly affected by salinisation	15	93.75	10	33.33
	< 6.6	Heavily affected by salinisation	00	00	00	00
Chloride-sulphate mass ratio (CSMR)	> 0,5	Aggressive	16	100	10	33.33
	< 0,5	non-aggressive	00	00	20	66.67

3.5. Hydrogeochemical facies

3.5.1. Piper diagram

The Piper diagram (1944), developed from a similar model by Hill (1940), is a graphical tool used to illustrate the chemical equilibrium between cations and anions in water. It consists of two triangles representing the percentage of equivalent anions and cations in milliequivalents. The rhomboidal squares obtained by the intersection of the two triangles indicate the chemical facies of the sample. This diagram is used to classify the hydrochemical facies of groundwater. In the Piper diagram shown in Figure 107, the groundwater samples taken in the study area are classified as follows:

For the intercalary continental aquifer (CI): all the CI water samples from Beni Ounif belong to the Ca-Mg-Cl category. In terms of cations, alkaline-earth metals outweigh alkalis, and strong acids outweigh weak acids. In terms of anions, there is a dominance of strong acids over weak acids, and SO₄ and Cl have a greater influence than sodium (Venkatramanan et al., 2015).

This type of water highlights the complexity of the hydrogeochemical processes governing the mineralisation of IC waters in the study area. CI waters are influenced by recharge processes by infiltration of surface aquifer waters and by the regional flow of deep waters from the Saharan Atlas.

For the shallow aquifer: the water samples analysed are grouped into three types, namely Ca-HCO₃ representing 43.33% of the samples, Ca-Mg-Cl representing 46.67% of the samples, and Ca-Cl representing 10% of the samples. The types of water found in the shallow aquifer indicate different origins of the water, such as direct recharge by precipitation, drainage from wadis and interaction between water and rock during groundwater flow.

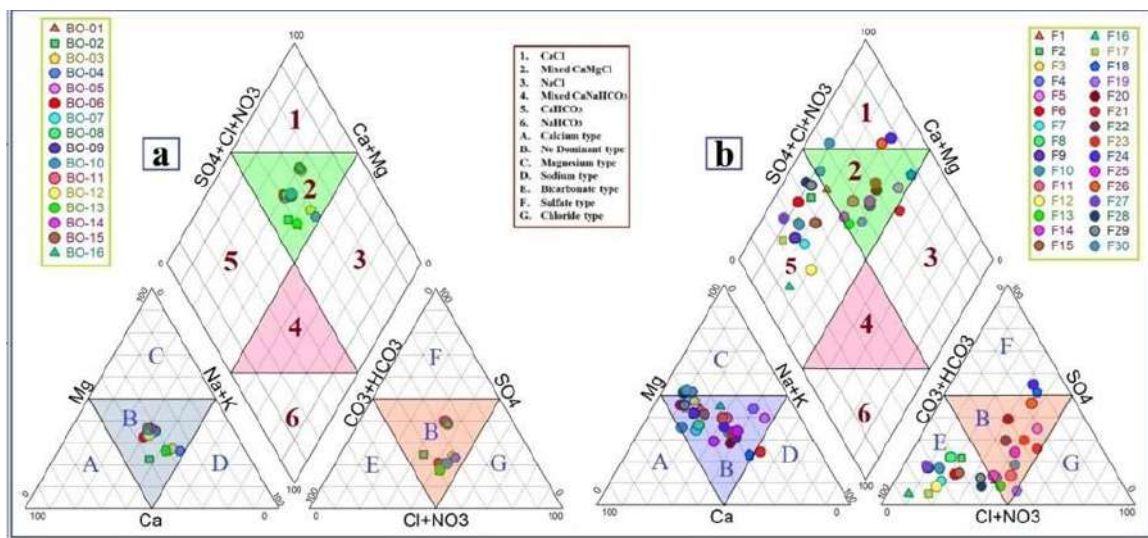


Figure 107. Piper diagram a) Intercalary aquifer (CI), b) Shallow aquifer.

3.5.2. Schoeller Berkaloﬀ diagram

The Schoeller-Berkaloﬀ diagram is used to represent the chemical facies of several water samples. Each sample is represented by a broken line, where the concentration of each chemical element is represented by a vertical line on a logarithmic scale. The broken line is formed by connecting all the points representing the different chemical elements. A group of waters with variable mineralisation but constant proportions of dissolved elements will produce a family of parallel broken lines. Where the lines cross, a change in chemical facies is evident.

The diagram confirms the dominance of the calcium chloride facies, indicating that mineralisation of the water is mainly linked to Cl⁻ and Ca²⁺ ions. Two other facies are then observed: calcium sulphate and sodium chloride.

Plotting the results of the chemical analysis of the CI aquifer on the Schoeller diagram (Figure 108) revealed that the groundwater samples from the study area have very similar concentrations, with a trend towards increasing and decreasing concentrations of major ions

indicating the same water source. Overall, the relative concentrations of ions appear in the following order: $Mg > Ca > Na+K$ and $HCO_3 > SO_4 > Cl$. These results are consistent with those of the Piper diagram. However, the total hardness of groundwater samples is the main concern for drinking water.

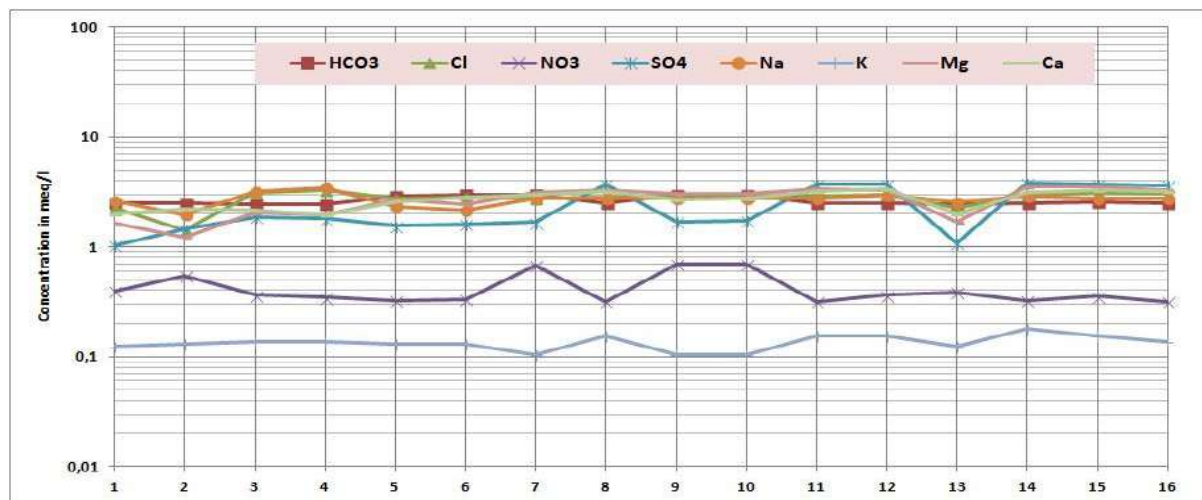


Figure 108. Schoeller diagram of water in the Beni Ounif aquifer.

Plotting the results of the chemical analysis of the shallow aquifer on the Schoeller diagram revealed that the groundwater samples in the study area have varying concentrations and different chemical facies. This is reflected on the Schoeller diagram (Fig. 109) by broken lines that overlap at several points. These results are consistent with observations from the Piper diagram. In general, the following facies can be distinguished: i) calcium bicarbonate facies, ii) magnesium bicarbonate facies and iii) sodium chloride facies.

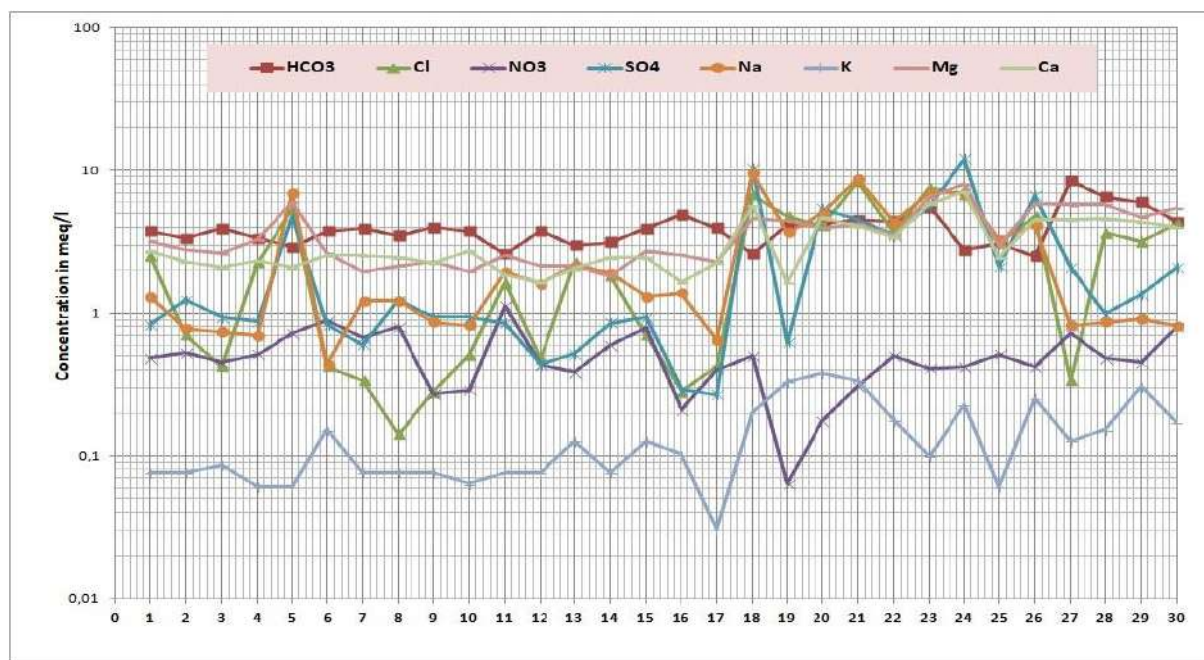


Figure 109. Schoeller diagram of the waters of the shallow Beni Ounif aquifer.

3.6. Origins of groundwater chemistry

The Gibbs diagram (1970) is a tool used to characterise some of the fundamental processes that influence water chemistry. Originally developed to analyse the processes governing the chemical composition of surface water, it has since been adapted to interpret the key processes influencing the chemistry of most groundwater systems. In fact, up to two-thirds of the flow in the world's rivers comes from delayed groundwater sources, which means that even surface water has a component derived in part from groundwater that has reached the watercourse.

In 1970, Gibbs established a relationship between the chemical composition of water and the lithology of the aquifer. In the Gibbs diagram, the y-axis represents the total dissolved solids concentration (TDS), the x-axis represents the $\text{Na}/(\text{Na}+\text{Ca})$ ratio for cations, and the $\text{Cl}/(\text{Cl}+\text{HCO}_3)$ ratio for anions. This graphical representation allows groundwater to be divided into three distinct areas. The first area corresponds to water whose chemical composition is mainly influenced by interactions between water and rocks. The second area covers water whose chemical composition is mainly affected by evaporation processes. Finally, the third area covers waters whose chemical composition is mainly influenced by precipitation processes.

Referring to Figure 110, it is clear that groundwater mineralisation in the Beni Ounif region is mainly due to interactions between water and rocks.

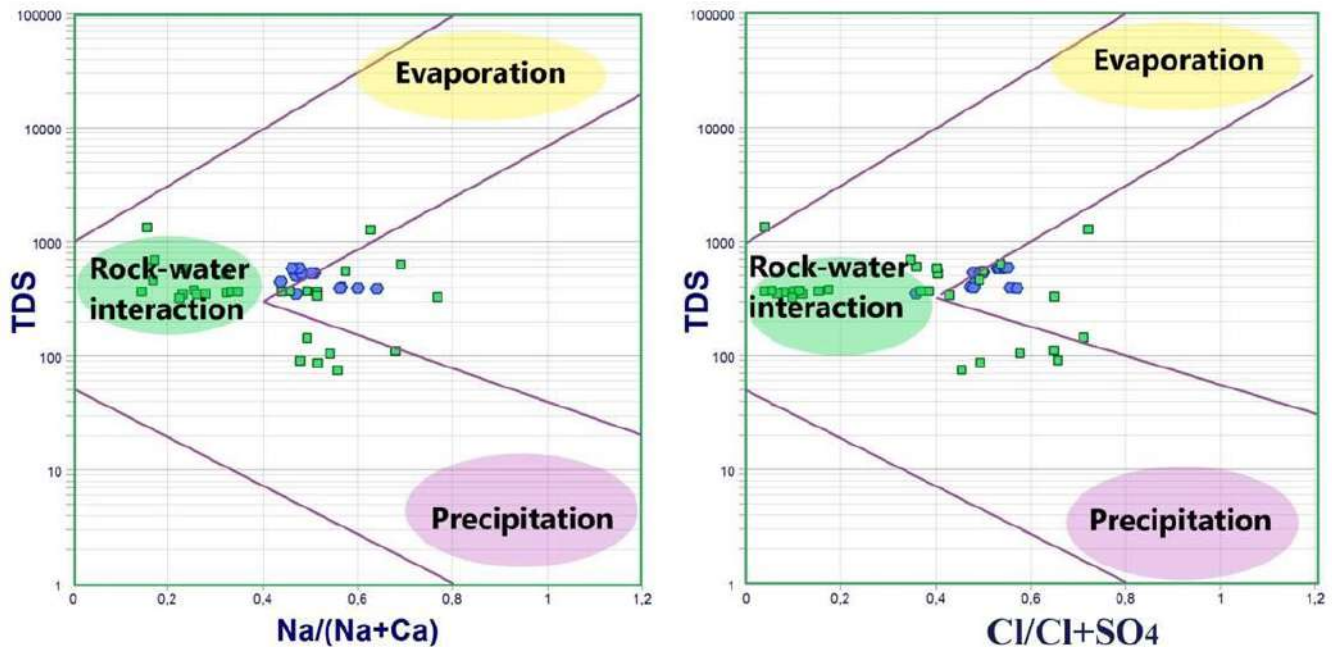


Figure 110. Gibbs diagram of groundwater at Beni Ounif.

The Mg versus Ca and HCO_3 versus Ca dispersion diagrams normalised to Na, proposed by Gaillardet et al. in 1999, are commonly used to identify the rocks involved in groundwater mineralisation. These tools are effective in determining the sources of chemical ions, namely

the dissolution of evaporites, the alteration of silicates and the dissolution of carbonate rocks (Ouarekh et al, 2024). From Figure 111, groundwater samples from the shallow aquifer in the study area are located in the silicate alteration domain and are slightly removed from the evaporite dissolution domain. This observation suggests that processes such as dissolution, precipitation and cation exchange control the water chemistry of this aquifer. These results confirm the conclusions drawn from the Gibbs diagram (Figure 35).

For the intercalated continental aquifer (CI), the diagram shows that water mineralisation is mainly controlled by the interaction between water and rock.

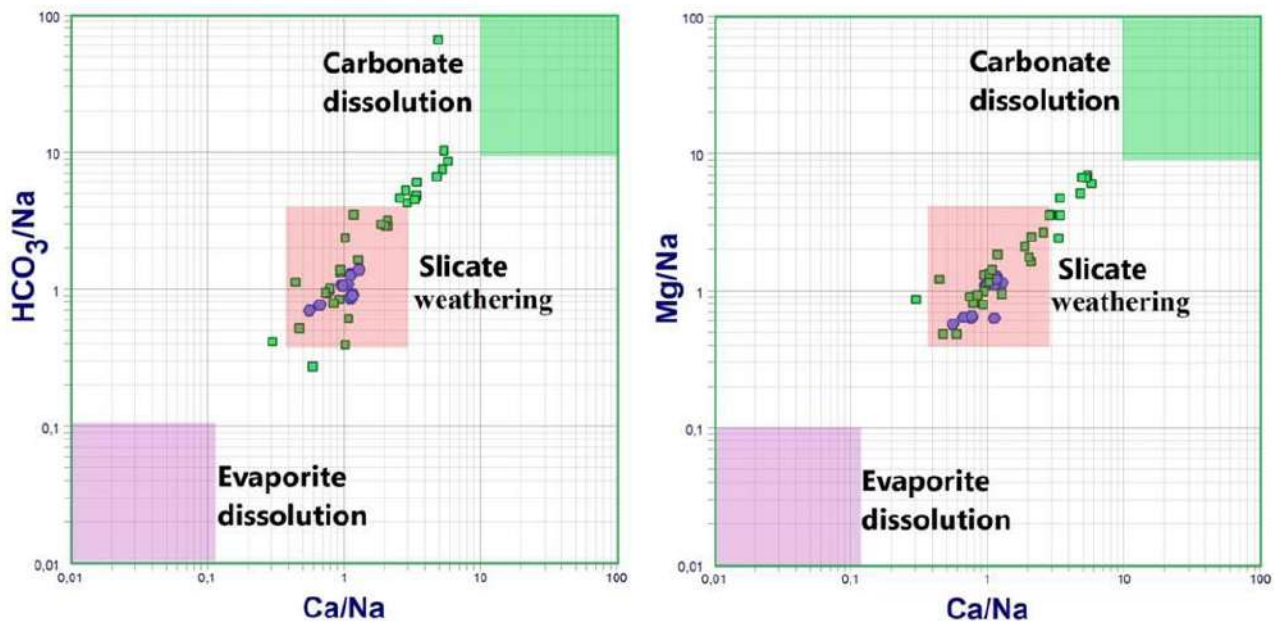


Figure 111. Bivariate plots of Ca/Na vs HCO_3^-/Na and Ca/Na vs Mg/Na.

4.4 Salt charge acquisition mechanism

The concentration of dissolved ions in groundwater is generally controlled by lithology (Schoeller 1962), groundwater flow, natural geochemical reactions, human activities and mixing with water from deep aquifers (CT and CI).

The fundamental hydrochemical mechanisms that influence groundwater mineralisation include ion exchange reactions with surrounding rocks, dissolution of saline minerals, acid-base interactions, ion exchange and human activities. The chemical composition of groundwater is often analysed using bivariate diagrams based on compound concentrations in meq/l (Hao et al., 2022; Kharroubi et al., 2022). The selection of these diagrams follows an examination of the lithological composition of the aquifer and the establishment of correlation links between the different chemical compounds present in the water.

A study of the correlations established between the concentrations of major elements (Ca^{2+} , SO_4^{2-} , Na^+ , and Cl^-) and the total dissolved solids (TDS) (Fig. 112) has made it possible to trace the origin of the mineralisation of the water. The presence of a positive correlation between these ions and TDS reflects their contribution to the saline charge of groundwater and indicates the presence of a common source of mineralisation, which can only be the dissolution of evaporites such as halite and gypsum (Abid et al., 2009; Farid et al., 2012; Appelo et al., 1994).

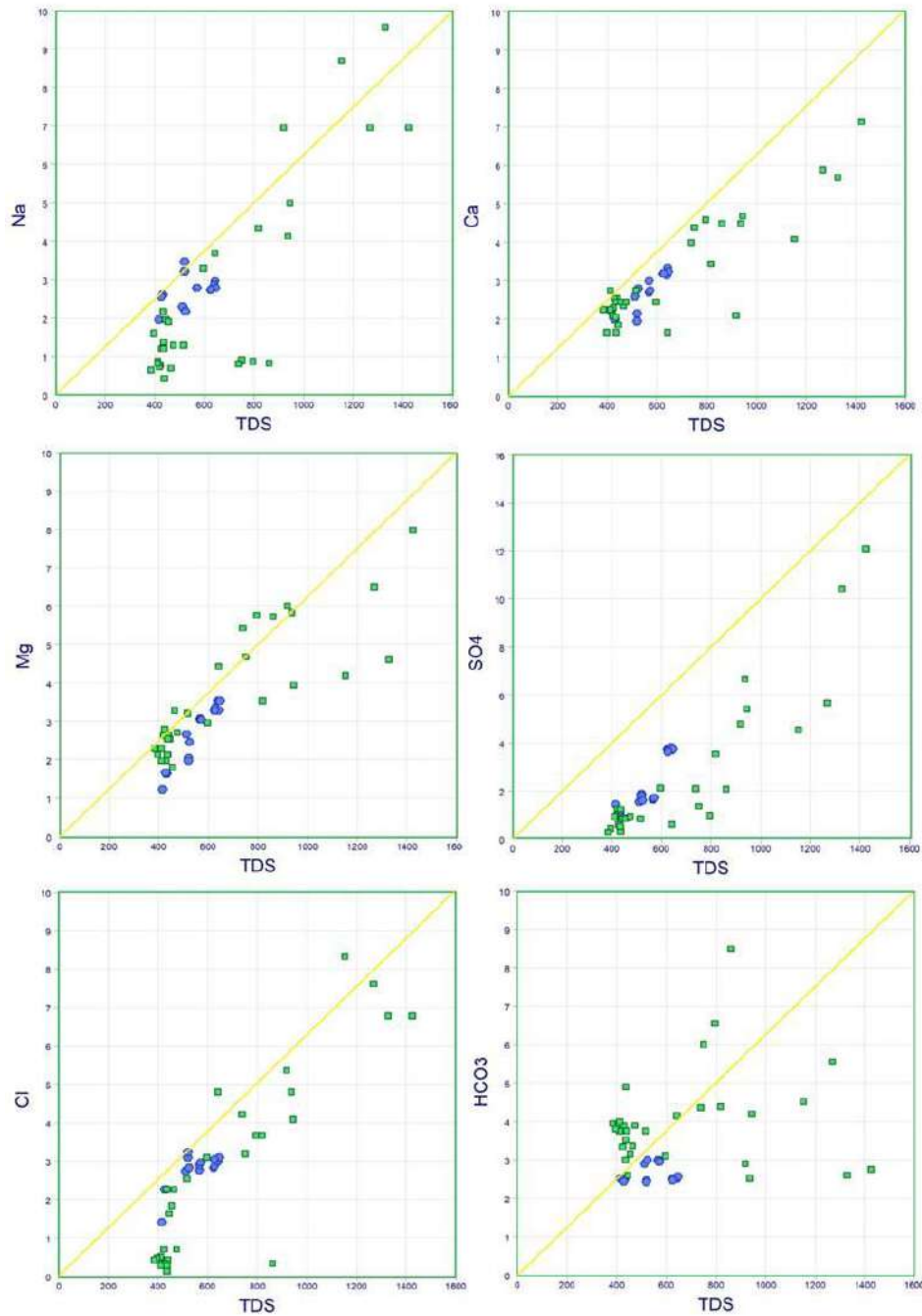


Figure 112. Changes in major chemical elements with water mineralisation.

3.6.2. Alteration of silicates

Silicate transformation is a crucial geochemical process that shapes the chemical composition of groundwater (Gopinath et al., 2019; Garrels and Mackenzie 1967). Silicates, the most abundant minerals in the Earth's crust, dissolve slowly in water, releasing ions that can react with other elements present in the water. This process accounts for around 45% of the total dissolved load in rivers around the world and has a significant impact on water quality. In addition, the transformation of silicates constitutes an important reservoir of carbon dioxide (CO₂) in the global CO₂ cycle. When silicates dissolve, they release bicarbonate into the water, which can react with cations such as calcium and magnesium to form carbonates (Roy et al., 2023).

However, quantitative assessment of silicate weathering products is difficult, as silicate weathering produces multiple solid phases (Zhang et al., 2022; Vinnarasi et al., 2021; Gaillardet et al., 1999; Freeze and Cherrey, 1979). In this study, the ratios of Na +K⁺⁺ and Ca +Mg²⁺²⁺ to total cations (Fig. 38) were used to confirm the silicate weathering process responsible for the release of Na⁺, K⁺, Ca²⁺ and Mg²⁺ ions into groundwater (Roy et al., 2023). Equivalent ratios (Na +K⁺⁺)/total cations are generally less than 0.5, suggesting that silicate weathering was the main source of sodium and potassium. The equivalent ratio (Ca +Mg²⁺²⁺)/total cations varies from 0.5 to 1, indicating that, in addition to silicate weathering, the dissolution of sulphate and carbonate minerals can also contribute to the enrichment of waters in Ca⁽²⁺⁾ and Mg²⁺, as shown in equations 24, 25 and 26 (Hao et al., 2020).

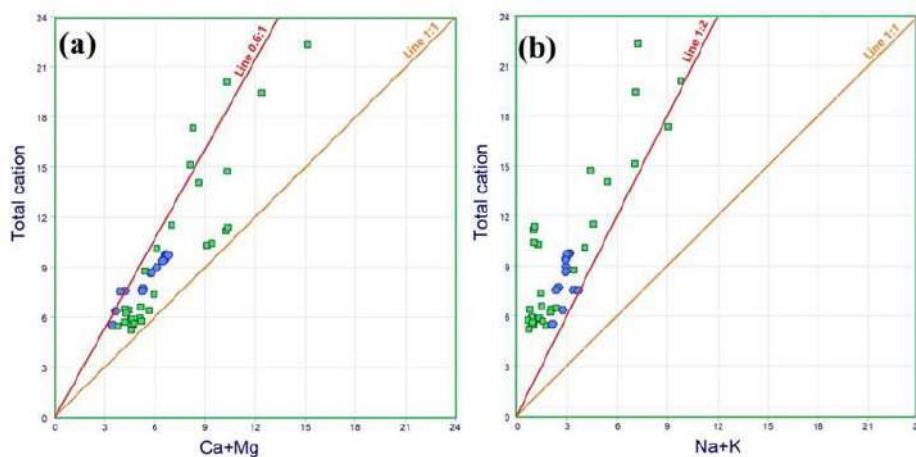
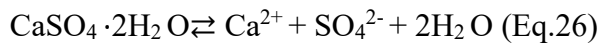
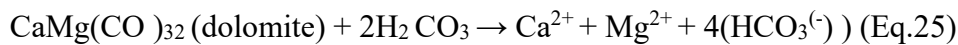
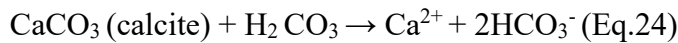


Figure 113. Diagrams showing silicate alteration: (a) total cation as a function of Na+K, and (d) total cation as a function of Ca+Mg.

3.6.2. Dissolution of carbonates

Theoretically, the main components of calcium, magnesium and bicarbonates in groundwater result from the alteration of carbonates by the dissolution of calcite (equation 24) and dolomite (equation 25). Under these conditions, the Ca/HCO_3 ratio should be equal to 1, and the $\text{Ca}+\text{Mg}/\text{HCO}_3$ ratio should theoretically balance out at 2. Thus, for the bivariate analyses carried out on the samples from the study area, the Ca/HCO_3 ratio varies between 0.4 and 3, while the $\text{Ca}+\text{Mg}/\text{HCO}_3$ ratio varies between 1 and 3 (Fig. 114). These variations indicate that, in addition to carbonates, calcium and magnesium have other sources, probably the dissolution of gypsum.

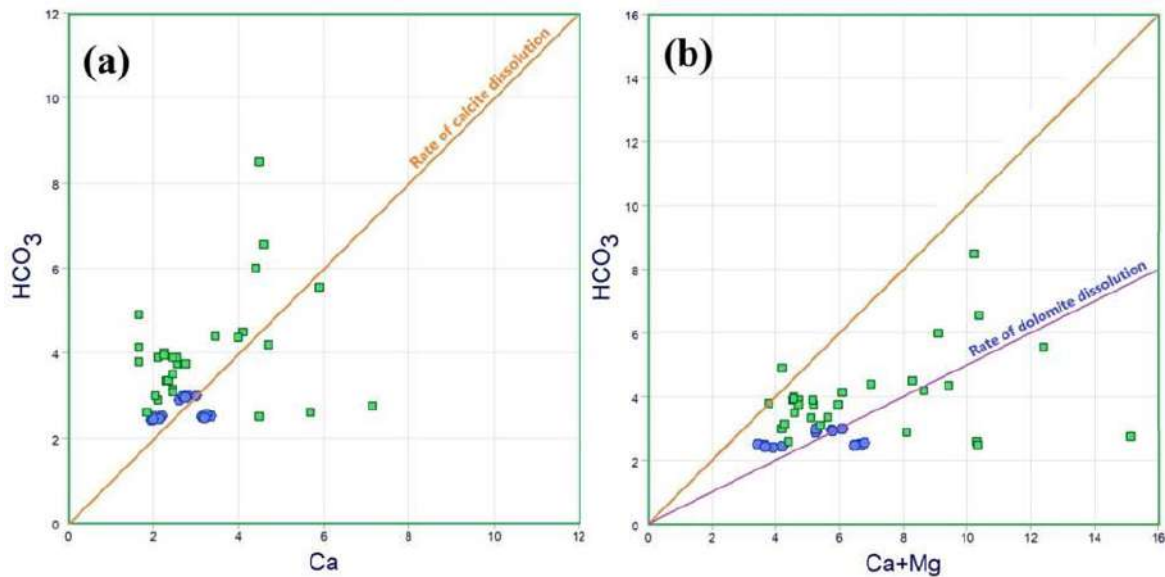
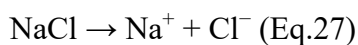


Figure 114. Carbonate dissolution diagrams: (a) Ca vs. HCO_3 and (d) Mg vs. HCO_3 .

3.6.1. Dissolution of evaporites

To determine the sources of mineralisation present in groundwater, it is common to plot the ratio between the concentrations of Na^+ and Cl^- . If halite is the main source of these ions in the water, the Na/Cl ratio should line up with 1:1 (Ouarekh et al, 2023). However, if the Na/Cl ratio deviates from this line, this may indicate silicate alteration and/or ion exchange processes. In one study, the sodium to chloride variation diagram was used to analyse several groundwater sampling points. The results show that some sampled water points do align with slope line 1 (Fig.115a), suggesting a common source of sodium and chloride, mainly due to halite dissolution (as indicated by equation 27) (He et al., 2022; Hao et al., 2020). However, other points show an excess of chlorine, which may indicate either an additional source of chloride ions (such as chloride-rich salts) or the removal of sodium from groundwater by ion exchange. The excess sodium observed in the study area could be attributed to silicate weathering.



The graph showing the variation of calcium in relation to sulphate obtained from the analysis of the samples shows a dispersion on either side of the 1:1 line (Fig. 40b). In fact, some of the water wells analysed show a deficit in calcium in relation to sulphate, while others show the opposite case. Although dissolution of gypsum (as indicated by Equation 26) present in CI aquifer materials is the most likely source of sulphate and calcium in groundwater (Hao et al., 2020; Bouselsal and Belksier 2018), the calcium deficit can be attributed to several factors, such as calcite precipitation and cation exchange. In this case, clays can adsorb calcium ions from groundwater in exchange for sodium and/or potassium ions. Conversely, based on the geology of the aquifer, it is assumed that other sulphate salts are involved in the groundwater mineralisation process in the study area (mirabilite, thenardite, epsomite, etc.).

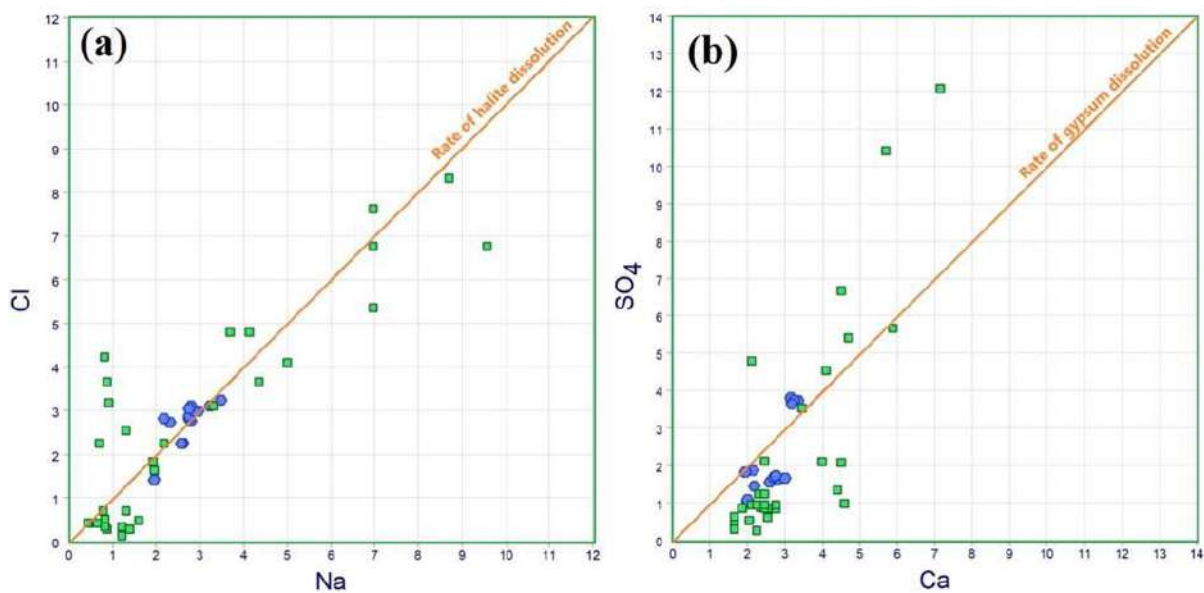


Figure 115. Diagrams showing the dissolution processes of evaporite: (a) Na vs. Cl and (b) Ca vs. SO₄.

3.6.3. Cation exchange

Base or cation exchange is a crucial process in groundwater mineralisation, particularly where clay minerals are abundant in the aquifer system. In general, these clay minerals tend to balance their electrostatic charge by binding monovalent cations, such as Na⁺ and K⁺, and releasing divalent cations, such as Ca²⁺ and Mg²⁺, or vice versa. The ion exchange process involves a reversible mass transfer between adsorbed ions and free ions in solution (Appelo and Postma, 2005). This mass transfer occurs between ions of the same charge, in proportion to their charge. Materials that facilitate this exchange are sometimes called ion exchangers, while the ions involved in this process are called adsorbed. Hydrogeologists also consider ion exchange to be a mass transfer between groundwater and the materials that make up the aquifer. Mineralogists

and physical chemists, on the other hand, recognise that this process can also occur in the formation of surface complexes or even in crystalline structures, particularly in the case of clay minerals.

The bivariate plot of $\text{Ca} + \text{Mg}^{2+2+}$ versus $\text{HCO}_3^- + \text{SO}_4^{2-}$ was used to determine the dominance of direct or reverse ion exchange along the 1:1 mixing line (Fig. 41) (Zhang et al., 2022).

Consequently, 40% of samples from the shallow aquifer and 18.75% of samples from the CI aquifer are positioned below the 1:1 line, indicating an excess of bicarbonate and sulphate, and a deficiency of calcium and magnesium. The excess of HCO_3^- and SO_4^{2-} could be explained by the dissolution of sulphates and carbonates present in the CI aquifer materials, while the deficiency of Ca^{2+} and Mg^{2+} could be attributed to ion exchange (Houari et al, 2024). Conversely, 60% of samples from the shallow aquifer and 71.25% of samples from the CI aquifer tend to be positioned above the 1:1 line, indicating an excess of calcium and magnesium and a deficit of bicarbonate and sulphate. The excess Ca^{2+} and Mg^{2+} could result from reverse ion exchange and/or silicate weathering.

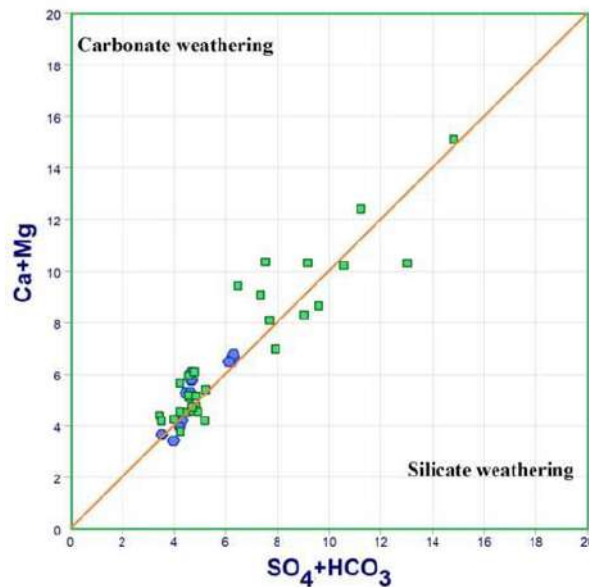


Figure 116. Bivariate diagram $\text{Ca} + \text{Mg}$ vs. $\text{SO}_4 + \text{HCO}_3$.

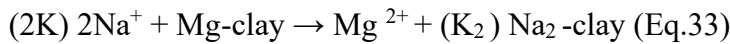
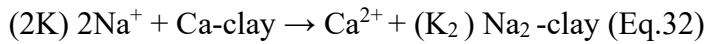
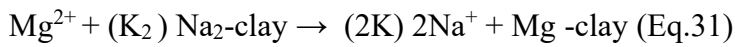
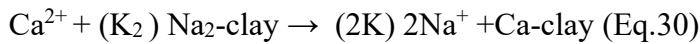
The chloro-alkaline indices (CAI-1 and CAI-2), introduced by Schoeller (1965), provide comprehensive information on cation exchanges between groundwater and aquifer materials, which have a significant impact on water mineralisation and its evolution. These indices are determined by equations 28 and 29 :

$$\text{CAI} - 1 = \frac{\text{Cl}^- - (\text{Na}^+ + \text{K}^+)}{\text{Cl}^-} \quad (\text{Eq.28})$$

$$\text{CAI} - 2 = \frac{\text{Cl}^- - (\text{Na}^+ + \text{K}^+)}{\text{HCO}_3^- + \text{SO}_4^{2-} + \text{CO}_3^{2-} + \text{NO}_3^-} \quad (\text{Eq.29})$$

When ion concentrations are expressed in meq/l

According to Schoeller (1977), negative values of CAI-1 and CAI-2 indicate a cation exchange process, while positive values represent a reverse cation exchange process (Appelo and Postma, 2005; Schoeller 1965; Kharroubi et al. 2024). This highlights that in a geochemical environment, when CAI-1 and CAI-2 have negative values, the calcium and magnesium present in the water are exchanged for Na^+ and K^+ from the aquifer materials (Eq.30 and Eq.31). When CAI is positive, replacement of Na^+ and K^+ in groundwater by calcium and magnesium from aquifer materials occurs, indicating direct or normal cation exchange in this case (Eq. 32 and Eq. 33) (Zhang et al. 2022; Hao et al. 2020).



In this study, CAI-1 and CAI-2 values are both negative in 73.33% of the shallow aquifer samples and in 56.25% of the CI aquifer samples, indicating an exchange of Ca^{2+} and Mg^{2+} ions in the water with Na^+ and K^+ ions from the aquifer materials. Conversely, CAI-1 and CAI-2 values are positive in 26.67% of samples from the shallow aquifer and in 37.50% of samples from the CI aquifer (Figure 42a), indicating an exchange of Na^+ and K^+ ions with Ca^{2+} and Mg^{2+} ions from the aquifer materials. Two water points in the CI aquifer are located close to the point of origin (0.0), indicating the absence of cation exchange processes.

The calcium deficiency observed in the Ca vs SO_4 diagram (Fig.40) can be attributed to the phenomenon of base exchange, where Ca^{2+} is adsorbed on the surface of clay minerals in exchange for Na^+ . This base exchange between groundwater and the sandy-clay and sandy-clay formations of the aquifer is highlighted by the relationship $[(\text{Mg}^{2+} + \text{Ca}^{2+}) - (\text{SO} + \text{HCO}_3^{2-})] \text{ vs. } (\text{Na} + \text{K} - \text{Cl}^{++})$ (Fig.42b) (Garcia et al. 2001 ; Bouselsal and Zouari 2022). This relationship makes it possible to exclude ions potentially resulting from the dissolution of halite, anhydrite and gypsum, which are particularly abundant in the reservoirs of the aquifers studied. In the absence of base exchange, all the water points sampled should cluster near the point of origin (Mc Lean et al. 2000).

Figure 117b confirms the conclusions drawn from the previous figure and clearly demonstrates that the cation exchange process also contributes to groundwater mineralisation in the Beni Ounif region.

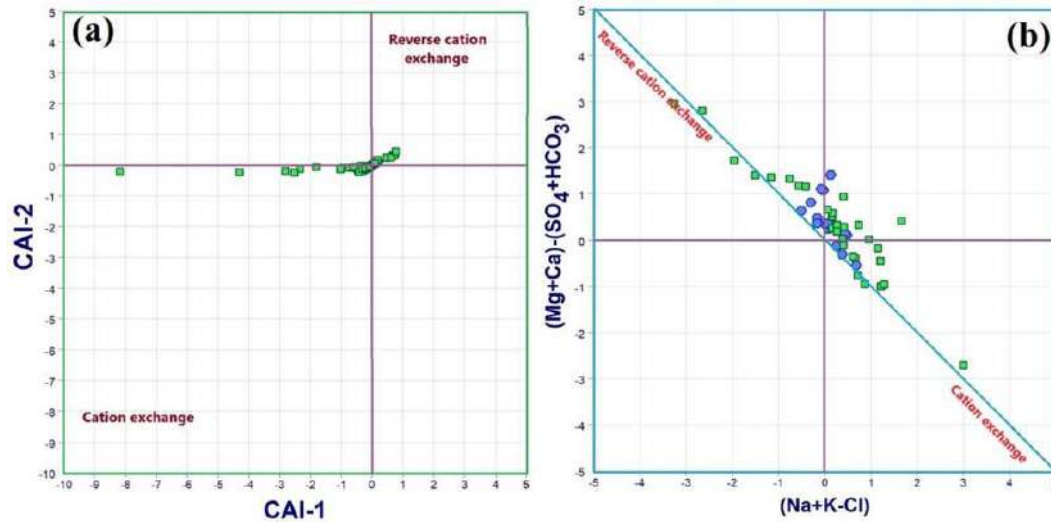


Figure 117. Bivariate diagrams illustrating cation exchange processes in the study area: (a) CAI-1 vs. CAI-2 (b) $(Mg + Ca) - (SO_4 + HCO_3)$ vs. $(Na + K - Cl)$.

3.6.4. Water saturation

The saturation index (SI) is a measure used to assess whether minerals are likely to dissolve or precipitate in water. It indicates supersaturation ($SI > 0$), equilibrium ($SI = 0$) or undersaturation ($SI < 0$). Using PHREEQC software, researchers can determine the SI of essential minerals in the aquifer, providing valuable information about hydrogeochemical processes that impact groundwater quality (Zhang et al., 2022; Bouselsal, 2016; Parkhurst and Appelo, 2013). Figure 118 shows that, in 60% of the wells analysed, carbonate minerals such as calcite, dolomite and aragonite have SI values greater than zero, suggesting a tendency for these minerals to precipitate (Karmakar et al., 2021; Hao et al., 2020; Bouselsal, 2016). Conversely, gypsum, anhydrite and halite systematically show negative saturation indices in all the groundwater samples tested, indicating their dissolution in the area studied.

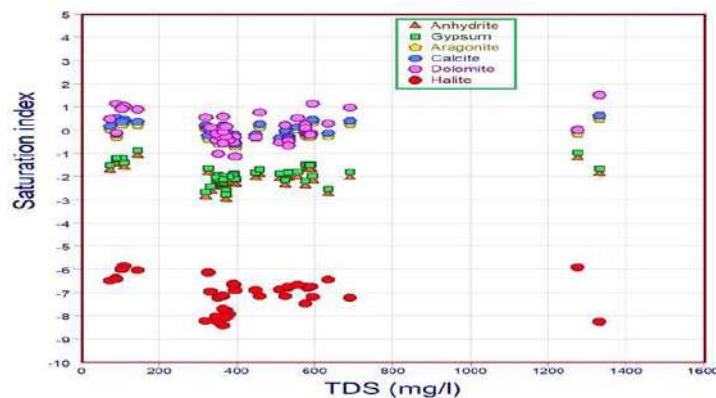


Figure 118. Variation in saturation indices in the study area.

4. Conclusion

In the Beni Ounif region, groundwater is mainly used to meet domestic, agricultural and industrial needs. This chapter focuses on the hydrochemical characterisation of these waters,

assessing their quality for various applications and examining the mechanisms of mineralisation. Hydrochemical data from 16 boreholes tapping the intercalary continental aquifer (CI) and 30 boreholes accessing the shallow aquifer were analysed.

The water's suitability for consumption was assessed by comparing it with WHO standards. Most of the water was classified as hard to very hard, with only 6 boreholes in the shallow aquifer showing non-compliance in terms of total hardness. In addition, only 4 samples of water from the shallow aquifer were deemed unfit for consumption due to high values of electrical conductivity and total dissolved solids. In addition, seven boreholes in the shallow aquifer exceeded WHO drinking water standards for nitrates, requiring treatment before distribution for consumption.

Application of the Water Quality Index (WQI) method revealed that the water in the shallow aquifer was classified into three quality categories: poor (6.67%), good (80%) and excellent (13.33%). The WQI scores also indicated that the CI aquifer water was of good quality for drinking.

The quality of water for agricultural use was assessed using the Irrigation Water Quality Index (IWQI). The results showed that the majority of groundwater samples were classified as "good" and "excellent", due to the low concentrations of sodium and chloride.

For industrial uses, the water was assessed on the basis of its corrosive potential and its capacity for scaling. Some samples showed a tendency towards corrosion or scaling, requiring treatment to ensure compliance with industrial standards.

In addition, analyses of Piper, Schoeller and Gibbs diagrams, binary diagrams and the calculation of saturation indices for the main minerals indicated that the mineralisation of the aquifers studied is associated with the alteration of silicates and carbonates, the dissolution of evaporites, cation exchange and anthropogenic inputs, which mainly affect the water chemistry in these aquifers.

Chapter 05:

Water resource management

Water resource management in the Beni Ounif region

Water resources are mainly used to supply drinking water (AEP), irrigation water (AEI) and to meet the water needs of industry (AEI) in the regions of Bénéounif and Béchar (**Fig.119**) for the present and future.

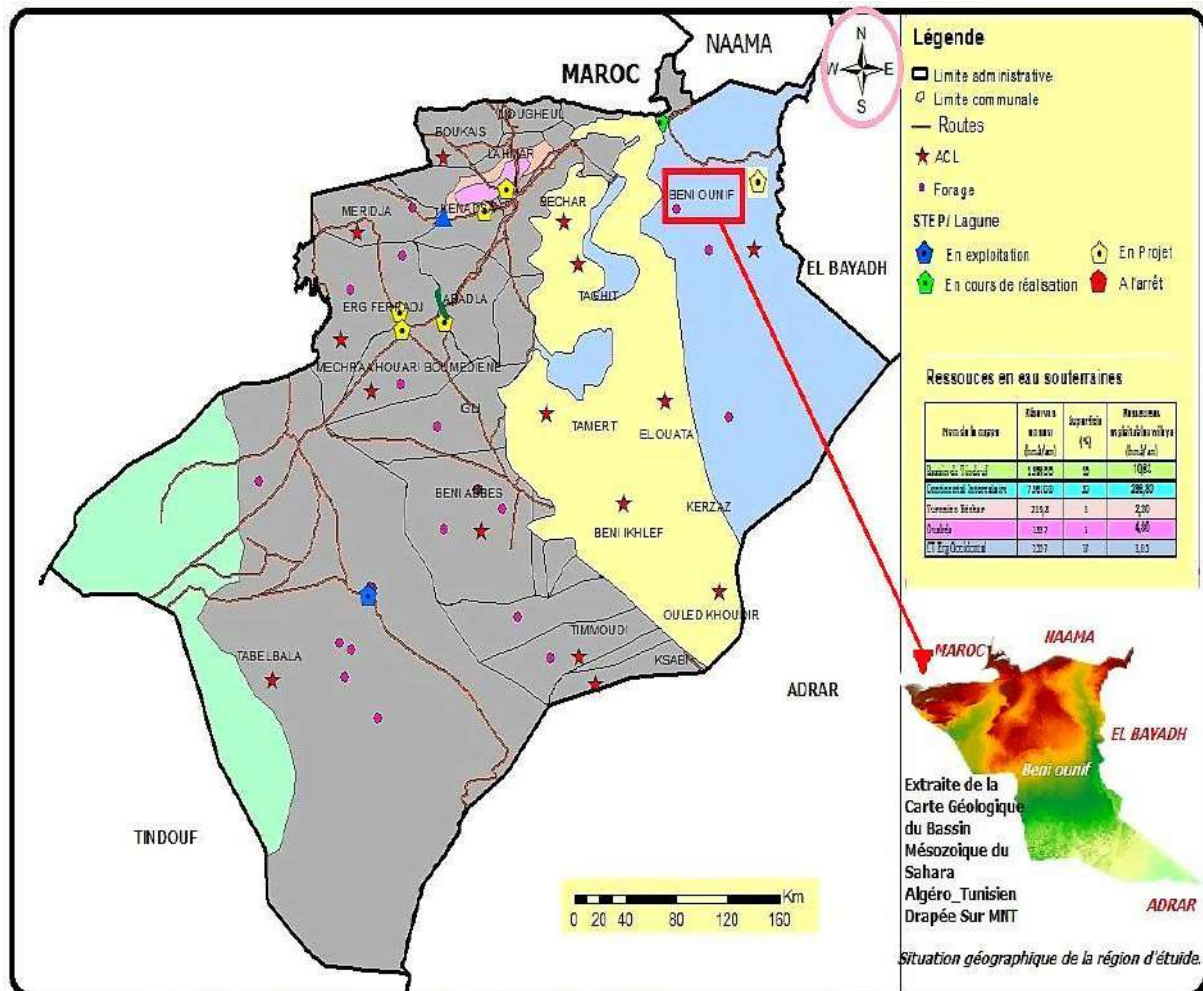


Figure 1119: Map of water resources in the wilaya of Béchar.

These needs are assessed globally according to the average daily demand for water per inhabitant, without taking into account the specific needs of each user. Two parameters are taken into account:

- The evolution of the population over time.
- Average water supply.

With regard to the unit allocations, we have chosen allocations in descending order according to the size of the agglomeration. These allocations are based on current water resources, assimilating them with the allocations of J. Bonin, 1962.

3.1 Evolution of the total population of the wilayas of Béchar and by horizon.

The demographic evaluation of the agglomerations for the Commune of Beni ounif is based on the population census carried out by the ONS in 2008, and the growth rate of the PNE study (2010) as indicated in the following formula: $P_{\text{projected}} = P_{2008} (1 + T)^n$

- $P_{\text{projected}}$: Estimated population for the horizon
- P_{2008} : Population censused in 2008.
- T : Growth rate.
- n : number of years between the horizon in question and the year 2008.

According to the 2008 RGPH, the population of the 10 wilayas in the South is 3,741,621 (Fig.120) and (Tab.37), rising to 4,093,894 in 2012 and 5,694,606 by 2030.

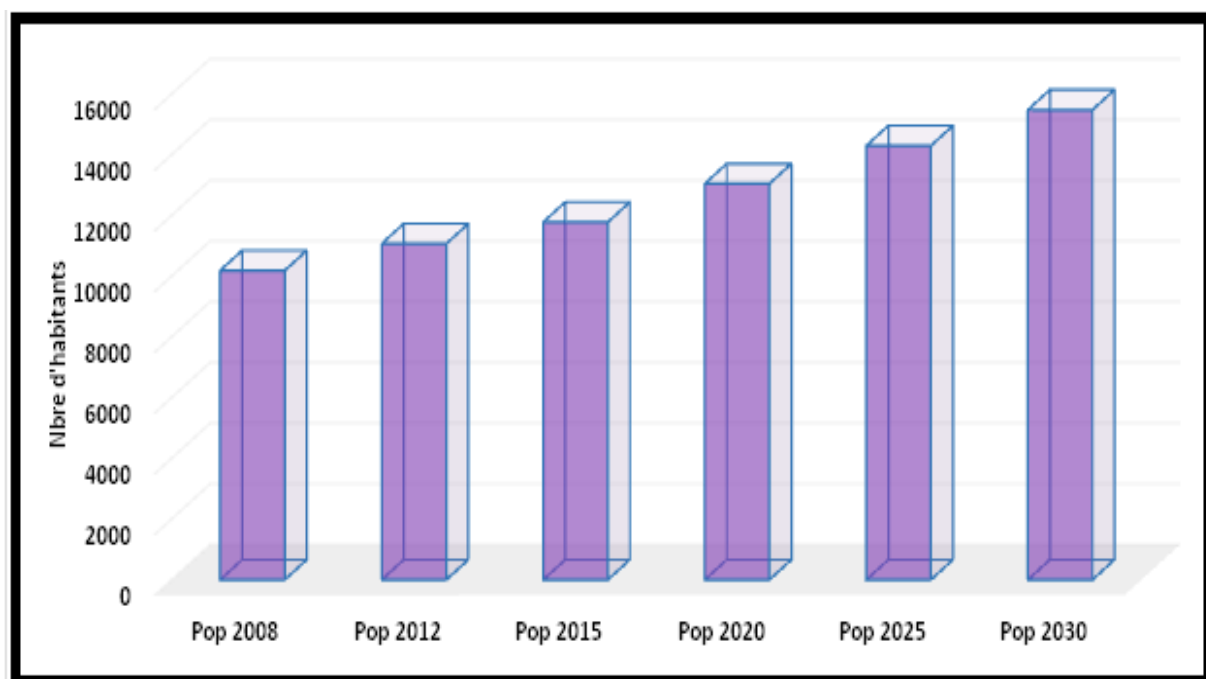


Figure 120: Prospects for population growth in the commune of Beni ounif.

Table 36: Total population of the wilayas of Béchar and by horizon.

Municipality	Conurbation	2008	2012	2015	2020	2025	2030
Bechar	Bechar	165241	179565	191116	211629	231943	251102
Beni Ounif	Beni Ounif	10183	11066	11778	13042	14294	15474
Erg Ferradj	Erg Ferradj	1922	2089	2223	2462	2698	2921
	Guir Lotfi	1530	1663	1770	1960	2148	2325
	Hassi Menounet	768	835	888	984	1078	1167
En'Mer	En'Mer	453	492	524	580	636	688
	Ouled Rfaa	1717	1866	1986	2199	2410	2609
	Ouled khoudir	1359	1477	1572	1741	1908	2065
	Khebeb El K	722	785	835	925	1013	1097
Meridja	Meridja	592	643	685	758	831	900
	Boutarfaya	656	713	759	840	921	997
	Timoudi Ksar	1597	1735	1847	2045	2242	2427
Lahmar	Lahmar	1691	1838	1956	2166	2374	2570

Beni-Abbes	Beni-Abbes	9965	10829	11525	12762	13988	15143
	Ougarta	371	403	429	475	521	564
	Zeghamra	549	597	635	703	771	834
Beni Ikhlef	Beni Ikhlef	1651	1794	1910	2114	2317	2509
	Guerzim	802	872	928	1027	1126	1219
Mechraa H.Boumediene	Mechraa H.B	1747	1898	2021	2237	2452	2655
	Djorf el Barda	1337	1453	1546	1712	1877	2032
Kenadsa	Kenadsa	13205	14350	15273	16912	18535	20066
Igli	Igli	5405	5874	6251	6922	7587	8213
	Mazer	1263	1372	1461	1618	1773	1919
Tabelbala	Tabelbala	2181	2370	2523	2793	3061	3314
	Cheraya	1389	1509	1607	1779	1950	2111
	Zaouia Sidi Zekri	931	1012	1077	1192	1307	1415
Taghit	Taghit	2295	2494	2654	2939	3221	3488
	Barrebi Ksar	1515	1646	1752	1940	2127	2302
	Zaouia Fougania	837	910	968	1072	1175	1272
	Zaouia Tahtania	738	802	854	945	1036	1121
	Bakht	636	691	736	815	893	966
	Brelka	293	318	339	375	411	445
El Ouata	El Ouata	1567	1703	1812	2007	2200	2381
	Ammes	1644	1787	1901	2106	2308	2498
	Aguedal	1291	1403	1493	1653	1812	1962
	Amefid	1005	1092	1162	1287	1411	1527
	Bayadha	680	739	786	871	954	1033
	El Ouata centre	504	548	583	645	707	766
Boukais	Boukais	970	1054	1122	1242	1362	1474
Mogheul	Mogheul	628	682	726	804	882	954
Abadla	Abadla	13544	14718	15665	17346	19011	20582
Kerzaz	Kerzaz	845	918	977	1082	1186	1284
	Ksar Kerzaz	2699	2933	3122	3457	3788	4101
	Zaouia el Kebira	1294	1406	1497	1657	1816	1966
	sparse area	187	203	216	239	262	284
Ksabi	Ksabi	1631	1772	1886	2089	2289	2478
Tamtert	Tamtert	497	540	575	637	698	755

(Source ABH Régional Ouargla).

3.2 Assessment of the demand for drinking water in the commune of Beni ounif

The data used to calculate water requirements are those from the PDARE study in 2018. The results of the calculations are summarised in **Table 37**.

Table 37 Situation of the use of water resources in the wilayade of Béchar (ONS).

General data	Indicator	Value
	Surface area	162 200 km ²
	Number of communes	21
	Nombre de daïras	12
	Number of agglomerations	68
	Population (2014)	313 207 inhabitants
	Agglomerated population	313 207 inhabitants
	Rainfall (mm/year)	30 – 70
	SAU (ha)	52 912 ha (in 2013)
Alimentation en Eau Potable	Drinking water supply Water demand (m ³ /d)	46981
	Supply (l/d/inhab)	150
	Production (m ³ /d)	42956
	Average coverage rate (%)	91 %
	Storage capacity (m ³)	53070
	ADE management	07 communes sur 21
Indicateurs de Distribution	Continuous distribution	5 % de la population
	Daily distribution	30 % de la population
	Distribution every other day	65 % de la population
	Distribution every third day or more	0 %
Secteur Hydro-Agricole	Area equipped with GPI	5 400 ha
	Area irrigated with PMH (ha)	22 466 ha (en 2013)
	PMH water requirements (Hm ³ /year)	157 (en 2013)

Information relating to the distribution and treatment of domestic water in the wilaya of Béchar is summarised in Figure 45. According to the figure, the commune of Beni Ounif has an AEP distribution network that supplies the population every day, but the commune does not have a STEP, i.e. domestic wastewater is discharged directly into watercourses.

The data used to calculate domestic water requirements are those from the PDARE study in 2012 and the ABH report. The formula used to calculate drinking water requirements is as follows:

$$Q_{AEP} = \text{Pop} * T_{\text{racc}} * [(\text{Dot} * (1 + ((M_{\text{aci}} + M_{\text{tour}})/100)) / ((100 - P_{\text{AEP}})/100)]$$

Q_{AEP} : Demand for AEP water , Dot: Domestic water supply (l/d/capita).

Pop: Number of populations. ; P_{AEP} : Water loss from the AEP network (estimated at 40%).

M_{tour} : Grossing-up coefficient for tourist activities (15%). ; M_{aci} : Surcharge coefficient for assimilated users. ; T_{racc} : Rate of connection to the water supply network (taken from the AGIRE geodatabase explanatory note).

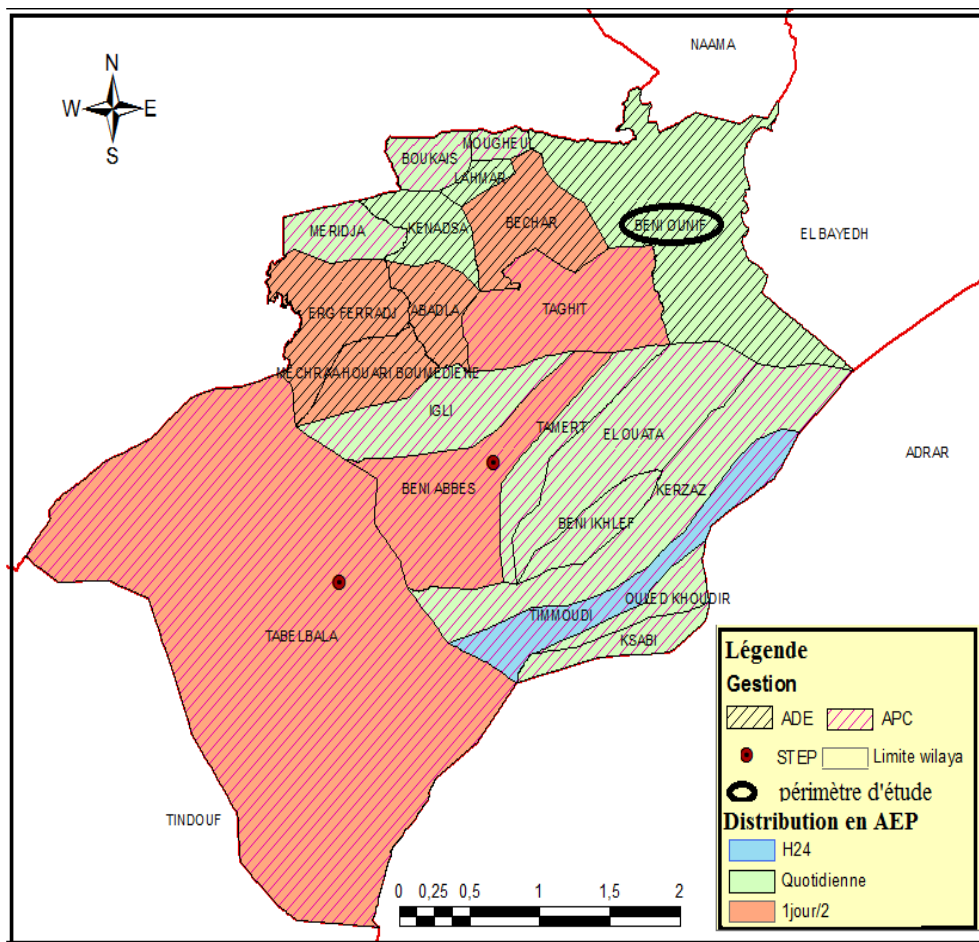


Figure 121: Situation of water supply in the Beni Ounif region in the wilaya of Béchar

Water requirements in the commune of Beni Ounif are estimated at 0.98 hm³/year in 2015, rising to 1.08 hm³/year in 2020 and will be of the order of 1.18 hm³/year (Tab 38). For the commune of Bechar supplied by the Beni Ounif catchment field, demand rises from 28.95 hm³/year in 2015 to 31.96 hm³/year in 2020, reaching 37.92 hm³/year in 2030.

Table 38: Water demand for drinking water supply in Beni ounif and Bechar (in hm³/year)

<i>commune</i>	<i>Pop 2015</i>	<i>AEP 2015</i>	<i>Pop 2020</i>	<i>AEP 2020</i>	<i>Pop 2025</i>	<i>AEP 2025</i>	<i>Pop 2030</i>	<i>AEP 2030</i>
Beni Ounif	11778	0.98	13042	1.08	14294	1.18	15474	1.28
Bechar	165241	28,85	191116	31,96	211629	35,03	251102	37,92

(Source ABH Régional Ouargla).

3.3 Assessment of irrigation water demand in the Beni ounif commune

For the 10 wilayas of the South, the irrigated area was 326,929 hectares in 2013, increasing by 17% to 382,506 hectares by 2030. The wilaya of Biskra accounts for more than 32%, or 104,990 hectares, of the total irrigated area of the ten southern wilayas.

Table 39: Irrigated area by wilaya and by horizon.

Wilaya	Irrigated area (ha) 2013	Projected irrigated surface area (ha)			
		2015	2020	2025	2030
Adrar	32 783	33 439	35 078	36 717	38 356
Laghouat	32 710	33 364	35 000	36 635	38 271
Biskra	104 990	107 089	112 339	117 588	122 838
Béchar	22 466	22915	24039	25162	26285
Tamanrasset	11 338	11 565	12 132	12 699	13 265
Ouargla	31 182	31 806	33 365	34 924	36 483
Illizi	2 119	2 161	2 267	2 373	2 479
Tindouf	721	735	771	808	844
El Oued	68 179	69 542	72 951	76 360	79 769
Ghardaïa	20441	20 850	21 872	22 894	23 916
Total	326 929	333 466	349 814	366 160	382 506

The water requirements of the 10 wilayas for the agricultural sector were approximately 3 121 hm³ in 2013, rising to 3 624 hm³ by 2030. The following table shows the breakdown of demand by wilaya and by time horizon.

Table 40: Irrigation water demand by wilaya and by horizon.

Wilaya	Demand (hm ³ /year) 2013	Projected demand (hm ³ /year)			
		2015	2020	2025	2030
Adrar	358,59	365,76	383,69	401,62	419,55
Laghouat	195,23	199,13	208,89	218,66	228,42
Biskra	930,45	949,06	995,58	1 042,11	1 088,63
Béchar	157,28	160,43	168,29	176,16	184,02
Tamanrasset	135,32	138,03	144,79	151,56	158,32
Ouargla	392,60	400,46	420,09	439,72	459,35
Illizi	15,54	15,85	16,63	17,41	18,18
Tindouf	4,68	4,77	5,00	5,24	5,47
El Oued	732,83	747,49	784,13	820,77	857,42
Ghardaïa	175,49	178,99	187,77	196,54	205,32
Total	3 121,77	3 193,75	3 349,83	3469,79	2624,68

The wilaya of Bechar has 22,466 hectares of irrigated land out of the total surface area of the 16 wilayas of the South its water supply is average, at around 8,000 (m³/ha/year). Demand for irrigation water in the wilaya of Bechar will be around 168.29 hm³ in 2020.

The Beni ounif area uses gravity-fed irrigation as the dominant system, and the area irrigated by this method was around 994 hectares in 2018, or 63% of the total area. Drip irrigation accounts for 26% and sprinkler irrigation for 11%.

Table 41: Methods of irrigation used in the Béni ounif commune

Mode	S.Gravit	S.Asper	S.Goutte	Total surface	%S. Gravit	%S. Asper	%S. drop
B.O	487	10	497	994	0.49	0.01	0.50
SOL	Sand	sand	sand	Area	sand	Sand	sand

Coef_{IRR}: Technical coefficient of irrigation water in Beniounif (owing to formula (Model of

	Year and irrigated area (ha)					Year and Water demand				
Municipal	2013	2015	2020	2025	2030	2013	2015	2020	2025	2030
Beni ounif	994	1014	1064	1113	1163	6.90	7.04	7.38	7.73	8.07

ABH): $\text{Coef}_{IRR} = (S_{\text{grav}}/\text{Sup_Irrigee}) + 0,25 * (S_{\text{asper}}/\text{Sup_Irrigee}) + 0,75 * (S_{\text{gout}}/\text{Sup_Irrigee})$

S_{gravity} : Area irrigated by gravity.

S_{sprinklers}: Area irrigated by sprinklers.

S_{drip irrigation}: Area irrigated by drip irrigation.

Sup_Irrigee: Total irrigated area, which changes depending on the horizon (we have taken 2013 as the reference year).

Table 43: Demand for irrigation water in the wilaya of Bechar in (hm³/year).

Municipality	Application 2013	2015	2020	2025	2030
Igli	7.60	7.75	8.13	8.51	8.89
Lahmar	9.41	9.60	10.07	10.54	11.01
Mogheul	7.01	7.15	7.50	7.85	8.20
Boukais	4.59	4.68	4.91	5.14	5.37
Taghit	17.21	17.55	18.41	19.27	20.13
Machraa	2.06	2.10	2.20	2.30	2.41
Abadla	3.80	3.88	4.07	4.26	4.45
Erg Faradj	7.54	7.69	8.07	8.45	8.83
Beni ounif	6.90	7.04	7.38	7.73	8.07
Tabalbala	12.05	12.29	12.89	13.49	14.10
Meridja	4.72	4.81	5.05	5.28	5.52
Kenadsa	6.94	7.07	7.42	7.77	8.12
Timoudi	5.30	5.40	5.67	5.93	6.20
Ksabi	10.47	10.68	11.20	11.72	12.25
Ouled Khoudir	7.33	7.47	7.84	8.21	8.57
Beni ikhlef	5.56	5.67	5.95	6.23	6.51
Kerzaz	5.55	5.66	5.94	6.21	6.49
Beni Abbes	3.69	3.76	3.95	4.13	4.31
Tamtert	4.26	4.34	4.56	4.77	4.98
El Ouata	8.97	9.15	9.60	10.05	10.49
Bechar	16.34	16.67	17.49	18.31	19.12
Total	157.28	160.43	168.29	176.16	184.02

(Source ABH Régional Ouargla).

For the Commune of Beni ounif, the irrigated area was 994 hectares in 2013, increasing by 17% by 2030, i.e. over 10,000 hectares, especially with the new catchment field project.

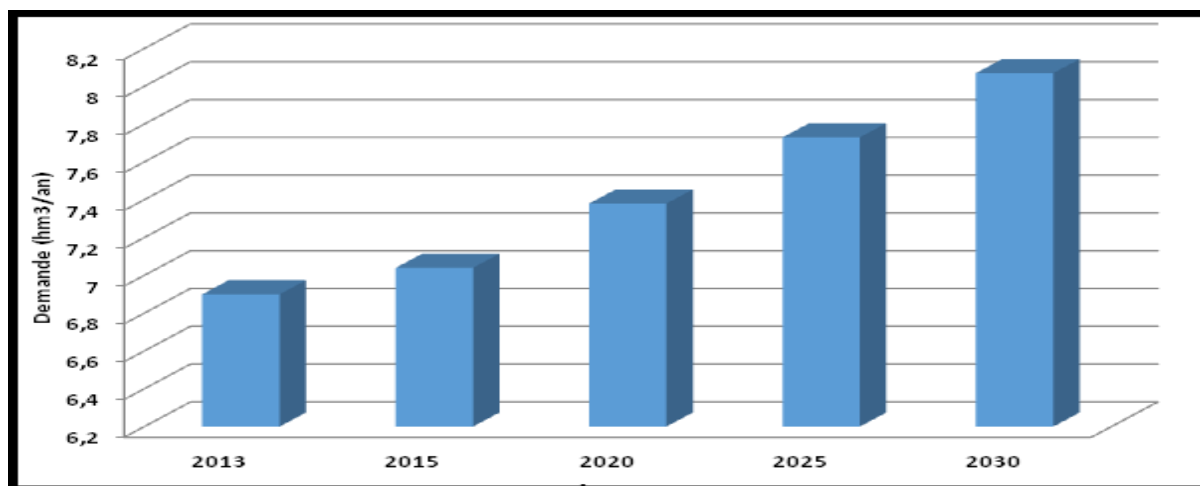


Figure 122: Outlook for irrigation water demand between 2013-2030.

3.4. Assessment of water demand for industry in the Beni ounif commune

Water demand for industry in southern Algeria is still low due to the absence of large industrial units. The total volume consumed in the wilaya of Bechar is around 34,000 m³ by 2020.

Table 44: Industrial water demand in the wilaya of Bechar (en hm³/year).

Year	2011	2012	2015	2020	2025	2030
Béchar	0.03	0.03	0.032	0.034	0.037	0.04

(Source ABH Régional Ouargla).

The Beni ounif region, with its small industrial fabric, mobilises between 10 and 30m³ per day. The evaluation of the industrial water demand of the commune of Béni ounif and different uses such as Hammam, Shower, Sauna, etc..

3.5. The hydraulic transfer project

The shortage of water in certain communes of Béchar has prompted the State and the government to carry out a major hydraulic project in these regions to meet water needs.

The large-scale hydraulic project to transfer Albian water from the catchment area in the Béni-Ounif region to *five* communes in the wilaya - Bechar, Kenadza, Abadla, Mechraa Houari-Boumediene and Erg Farradj - will be completed and put into service at the end of April 2019. The project was preceded by a hydrogeological study carried out by the Agence Nationale des Ressources Hydriques (ANRH), as part of a programme to mobilise the wilaya's underground water resources to meet the drinking water needs of the region's populations, stressed the member of the government.

To this end, an emergency budget of DA9.5 billion has been allocated to the project, to enable the daily transfer of 30,000 m³ of water from ten (10) boreholes varying in depth from 400 to 500 metres, all located in the Béni-Ounif region, explained the Director General of the National Agency for Dams and Hydraulic Transfers (ANBT). The work in progress on this major project,

entrusted to national companies, will enable 190 km of pipes, three (3) pumping stations and two large reservoirs of 15,000 and 20,000 m³, which will be supplied from the aforementioned boreholes, to be completed by the end of April 2019. The work in progress on this major project, entrusted to national companies, will enable 190 km of pipes to be completed by the end of July 2019.



Figure 123: The hydraulic project for transferring CI water from Béni-Ounif to Béchar.

4. Flood risk assessment Beni ounif (Wilaya of Béchar)

The type of geological formations that outcrop in catchment areas has an influence on the distribution of surface run-off. A catchment formed of highly permeable materials with little vegetation cover will generally have a low drainage density, ensuring better infiltration of surface water. On the other hand, a catchment made up of impermeable but loose rock that is not resistant to erosion, such as marl and clay, often has a high drainage density, which favours surface water run-off at the expense of infiltration.

The main wadi running through the town is the Oued Béchar, and a major tributary (the Oued Tighenine) joins the wadi in the eastern part of the town. The Oued Béchar rises in the slopes of the Djebel Antar and Horreit and, after 150 km, silts up at Dhait Tiour, without reaching the Oued Guir. The Oued Béchar is formed from the watershed of the Oued Saoura as shown in the following diagram (Bureau DALI DJAAFAR, 2012).



Fig 124: The most flooded wadis in the Bechar region .

Oued Béchar: its length extends over 17 km within the urban fabric. The easement corridor varies according to the morphology and location of the wadi bed, ranging from 25 m to 270 m, surrounded by buildings erected by private individuals on land previously used for agricultural purposes. It extends to the end in the area known as "Dayate tyor" near Abadla. The catchment area (approximately 5,800 km²) is bounded to the north by the southern slopes of the djebel Grouz, to the west by the djebels Antar and Horreait and to the east by the djebel Béchar and the Ben Zireg anticline. It receives numerous tributaries from the djebels, the most important of which is the oued Sfeiah.

Oued Zouzfana: this tributary of the Guir descends from the Saharan Atlas where it rises at an altitude of 1,600 m at the western end of the Ksour mountains. Its catchment area covers 16,600 km². The Oued Zouzfana runs for 360 km. Its main tributary is the oued Zoubia. Downstream, the highly degraded watercourse functions as a diversion canal.

Oued Guir: the largest river in the Saoura basin, 450 km long. It rises at an altitude of 2,200 m in the Djebel Aichi (on the southern slopes of the Moroccan Atlas mountains). The Guir drains a basin with a surface area of around 27,000 km². The water is completely lost in the desert areas, where it causes flooding and sometimes damage to palm groves. To better manage this water and develop the agricultural sector.

In 1969, a dam was built at Djorf Torba, 50km upstream of Abadla, to serve the Saoura Valley's industrial and energy needs.

Oued Saoura: the wadi begins at Igli, at the confluence of the Guir, Béchar and Zousfana rivers, descending respectively from the Moroccan High Atlas and the Saharan Atlas. The flooding of the Oued Saoura helps to maintain the quality of the water and soil. At Béni Abbès, some chaabats join the Saoura. The run-off generally caused by rainfall in the upper basin flows more or less far downstream, passing through the Béni Abbès region where the wadi bed has become wider, to reach a closed basin, the Sebkha el Mellah, via the Es Souireg wadi which descends towards the north-west at the exit of the Foug el Kheneg.

According to the document "**Plan d'intervention. Flooding**" of the Civil Protection. The flows for the wadis are as follows:

Table 45: Flows for the most flooded wadis in the region.

OUED	Precipitation (T=100)	Flow rate (T=100)
Oued Guir (upstream of the Djorf-Torba dam)	100 mm	7,857 m ³ /s
Oued Zousfana Beni ounif	99 mm	6,026 m³/s
Oued Béchar	86 mm	5,391 m ³ /s

1 It is very important to mention in this paragraph that it was groundwater that enabled the population to settle in the region and develop a specific form of agriculture. The most important aquifers are as follows:

2 Ouakda Turonian aquifer: The Turonian limestones represent an important aquifer in terms of its surface area of 2018 km², despite its relatively low thickness of 25 to 45 metres. The catchment area for this aquifer is located at Ouakda and comprises 5 boreholes.

3 Ouakda Quaternary aquifer: The lithology of the Quaternary contains an aquifer fed by its impluvium and by the Oued Béchar. It is currently exploited by 211 water points, including 186 wells and 25 boreholes.

4 Mougheul Jurassic aquifer: The Mougheul wellfield, located to the north 70km from the town of Béchar, consists of four boreholes varying in depth from 45 to 95 metres.

The water in the city of Béchar's water supply network (737 km) comes mainly from the Djorf Torba dam (80%) and secondarily from the Ouakda Turonian aquifer (20%) .

4.1 Flooding and damage

When rainfall exceeds a very low threshold (5-10 mm), the soil cannot absorb the water and the drainage network begins to function. As we have seen, the geological materials have a very low permeability and the layer of organic matter for water retention is non-existent. Almost all the rain that falls runs off into the main beds. When the flow exceeds the capacity of their beds, flooding occurs in neighbouring areas.

This phenomenon can be observed in all the rivers flowing from the Atlas region and the surrounding hills, heading south to end up in the Saharan ergs. Result of rainfall.

torrential, flooding of the Guir, Béchar, Zousfana and Saoura wadis is frequent, unpredictable and spectacular, with floodwaters frequently overflowing the banks of the wadis and the terraces of these valleys, which are often wide and splayed.

This situation is undoubtedly linked to the amount of rainfall on the heights of the Moroccan Atlas and the K'sour mountains, the steepness of the wadis and the speed of their waters, which results in flooding and the overflowing of water, creating meanders, oxbows, anastomosing beds and fluvial islands.

The other major factor that increases damage is solid transport in catchment areas. Because of the lack of vegetation and the steepness of the slope, there are no obstacles to the movement of loose elements. These elements can range from fine sand to large stones over 50 centimetres in size.

During the field trip, our experts visited several areas in the wilaya to see the damage caused by the recent floods of November 2014 and those of 2008. The sites visited were the towns of Béchar, Taghit and Igli.

Classification of hazard levels associated with hydraulic phenomena or flooding, based on two key parameters: **flow velocity** (m/s) and **water height** (m). These two variables are used to assess the degree of danger or potential impact of a hydrological event. The classification distinguishes three levels of hazard: low, medium and high.

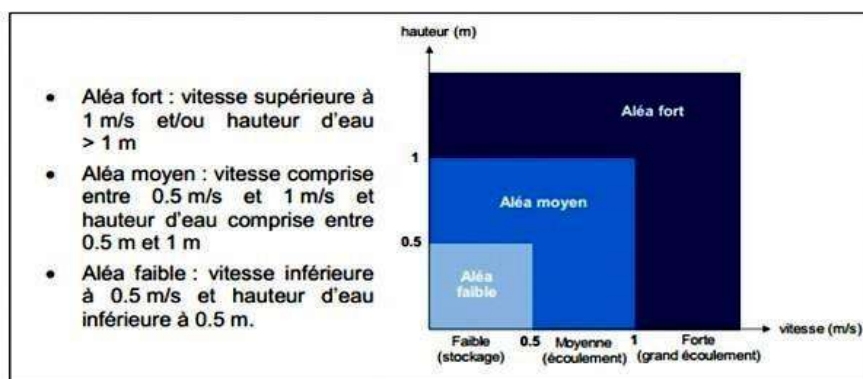


Fig 125. Map showing hazard classes .

The chart axes are defined as follows: The X-axis (horizontal) represents the speed of the flow, measured in meters per second (m/s), and is categorized into three levels: low (storage) for speeds below 0.5 m/s, average (flow) for speeds between 0.5 m/s and 1 m/s, and strong (large flow) for speeds exceeding 1 m/s. The Y-axis (vertical) corresponds to the water height, measured in meters (m), and is divided into three thresholds: less than 0.5 m, between 0.5 m and 1 m, and greater than 1 m.

The combination of these two factors determines the hazard levels. A low-risk level is characterized by a flow speed below 0.5 m/s and a water depth of less than 0.5 m. This scenario poses minimal danger, as the water remains mostly stagnant, with little threat to individuals or infrastructure. A medium-risk level occurs when the flow speed ranges between 0.5 m/s and 1 m/s, and the water height falls between 0.5 m and 1 m. This level presents a moderate hazard, as the flow intensity and water depth can lead to structural damage and potential safety risks. Finally, a high-risk level is defined by a flow speed greater than 1 m/s and/or a water height exceeding 1 m, indicating a significant threat due to the strong current and increased water volume.

• **Interpretation:**

This level indicates a high hazard, characterised by considerable hydraulic force. It can cause serious damage to infrastructure and represents a major risk to human life.

This classification is used in various contexts:

- **Risk analysis:** Used to assess areas at risk of flooding and anticipate potential impacts.
 - **Urban planning:** Facilitates the implementation of preventive measures such as the construction of dykes, the development of flood-prone areas or the organisation of the evacuation of populations at risk.
 - **Crisis management:** Used to prioritise interventions according to hazard levels and to inform vulnerable populations; This section discusses the results of simulations conducted using the Flood Propagation Simulation Model (FPM) to identify areas prone to inundation, providing insight into the extent and impact of flooding.
- The flood propagation simulation model plays a crucial role in identifying areas at risk of inundation during flooding events. Its primary objective is to provide precise information on the extent of flood impact and the distribution of water across the surrounding land. In the case of centennial floods in Beni Wanef municipality, which are extreme flooding events occurring with a probability of once every 100 years, simulations have revealed significant inundation and expansion across large areas of the municipality. The projected total area affected by these centennial floods is estimated to be approximately 241.35 hectares. This figure underscores the

substantial impact of such events and highlights the necessity of effective planning and mitigation measures to manage flood risks.

4.2 The importance of the study:

This simulation shows the extent of the potential expansion of centennial floods, which helps in developing risk management strategies and optimising urban planning in threatened areas. This tool is essential to minimise the negative impacts of floods on people and infrastructure.

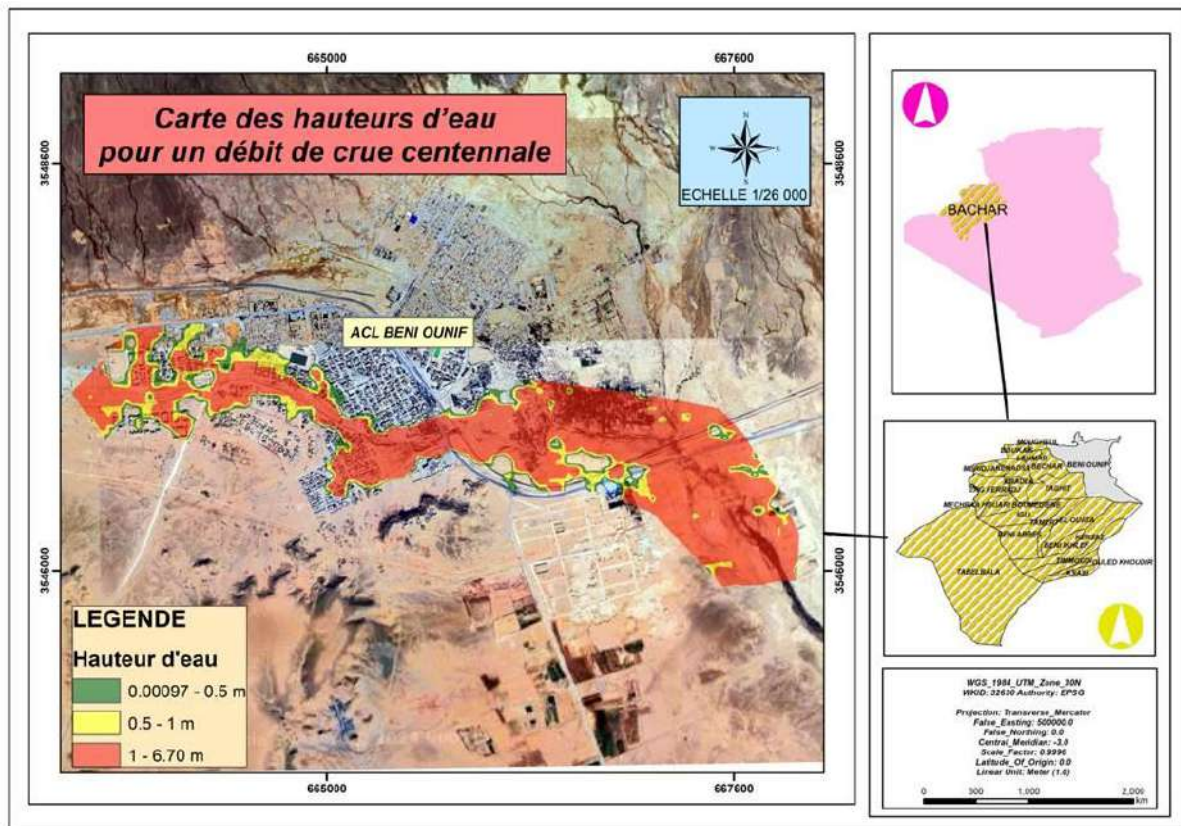


Fig 126 . Distribution of flooded areas by water level class .

Table 46 :Flood risk water level class (m) .

Water height class(m)	Surface area (ha)	Percentage of coverage
Low (0 - 0.5)	21.91	9.08 %
Medium (0.5 - 1)	30.12	12.48 %
Strong (> 1)	189.32	78.44 %
Total	241.35	100 %

Distribution of flow speeds by class:

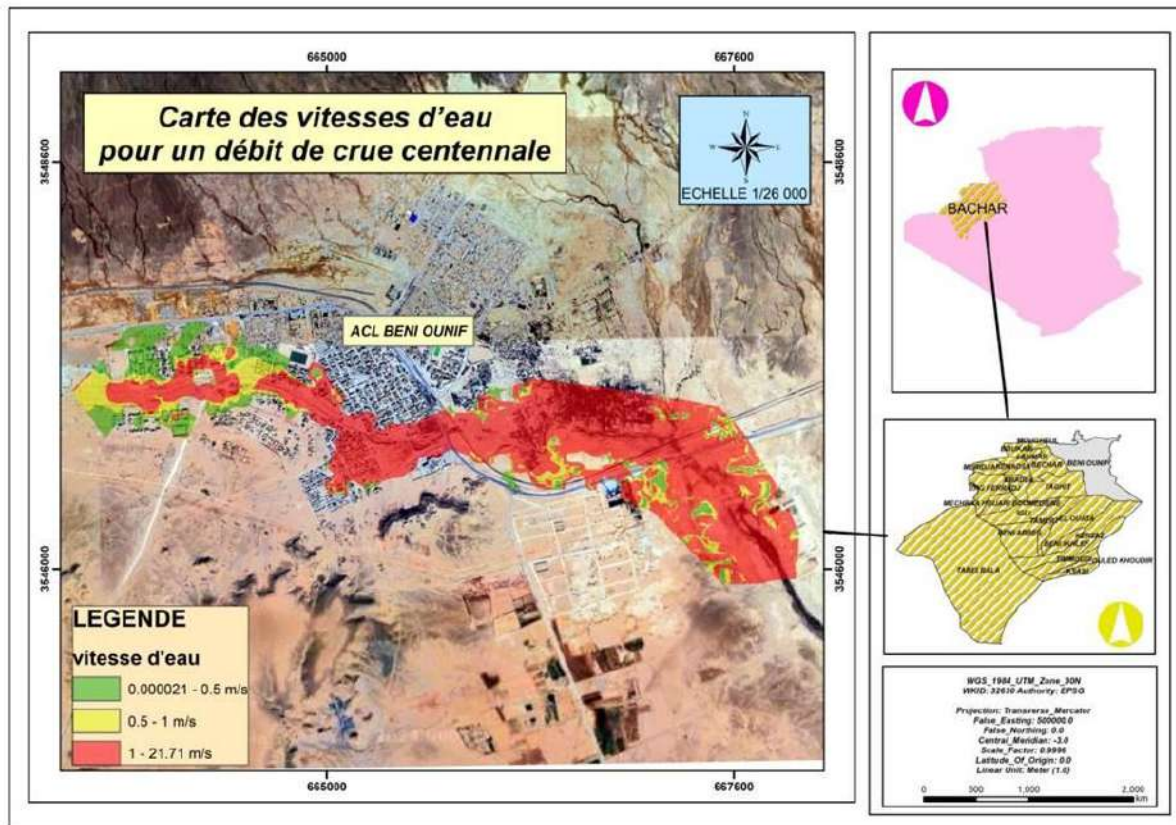


Fig 127. Map of water velocities for a 100-year flood.

Table : 47 Speed class (m/s) .

Speed class (m/s)	Surface area (ha)	Percentage of coverage
Low (0 - 0.5)	31.57	13.08 %
Medium (0.5 - 1)	30.49	12.63 %
Strong (> 1)	179.28	74.28 %
Total	241.35	100 %

The definition and mapping of the hazard is based on these principles. The aim is to delimit the flood zone and, within it, to differentiate between low, medium and high hazard zones. These principles are based on a person's ability to move around in a flooded area.

The flooded area shows that 6% of flooded areas are classified as low or medium risk, while 93.6% are classified as high risk.

The grid used to qualify the reference hazards is based on three (03) hazard classes to delimit the flood zone and differentiate the hazard zones from the weakest to the medium to the strongest.

This section deals with the identification and categorisation of the risks associated with areas at risk of flooding. The process is based on clear principles that aim to map the areas at risk of inundation and identify the levels of risk within these areas. The aim is to divide inundated areas into three levels of risk: Low, Medium and High.

Explain the text in detail:

1. Risk identification and mapping:

- Risk identification and mapping is based on principles related to the ability of people to navigate submerged areas ; The main objective is to identify areas that may be subject to inundation and then categorise them according to the severity of the risk.

2. Categorising submerged areas:

- Data indicates that only 6% of submerged areas are classified as low or medium risk.
- On the other hand, 93.6% of submerged areas are categorised as high risk, showing the importance of taking this category seriously.

3. Risk categorisation grid:

- The reference risk categorisation grid used is based on dividing the submerged area into three categories: Low risk , Medium risk ,High risk ; This categorisation aims to guide preventive efforts and identify appropriate interventions according to the degree of risk in each area.

Tab 48: Hazard class according to flood surface .

Risk	Surface area (ha)	Percentage of coverage
Low	9.74	3.07 %
Medium	5.7	2.36 %
Fort	225.91	93.6 %
Total	241.35	100 %

Importance of the study:

This method reflects an accurate scientific approach to risk identification and flood management planning. It helps the competent authorities to develop proactive plans to protect people and property from the negative effects of floods, especially in high-risk areas.

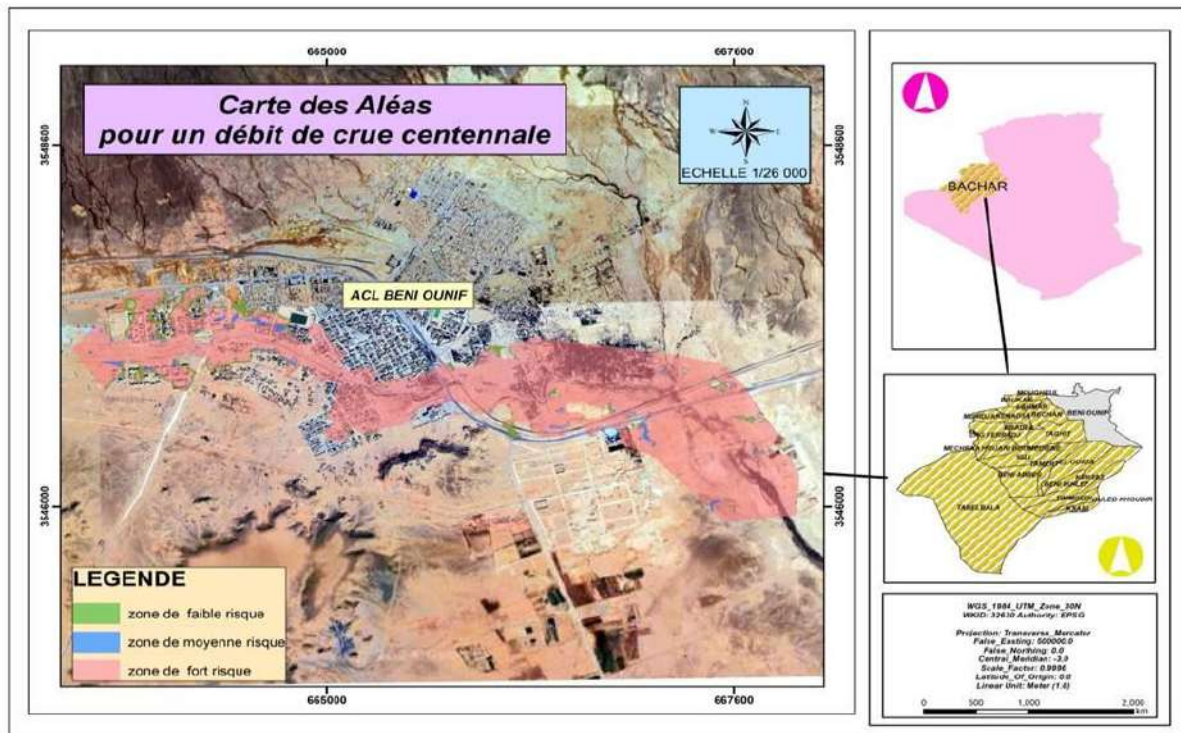


Fig 128. Hazard map for a 100-year flood flow in the Beni ounif region.

We note that Beni Ounif is located in the path of two wadis that carry the risk of flooding throughout the rainy season. The study shows that the flow velocity is very high in the study area, leading to unbearable consequences for the population in the area.

5. Conclusion

The assessment of water needs in the commune of Béni Ounif and Bechar in 2019 and by 2020 total water demand will reach 8.46 hm³ in Beni Ounif and 238 hm³ in the Saoura-Bechar region. It is broken down as follows:

- Béni ounif : 8.46 hm³ of which (AEP = 1.08 hm³, IRR = 7.38 hm³, IND = 0.001hm³)

To meet the growing demand for water in the wilaya of Béchar and the other commune. the body responsible for the state is committed to the large-scale hydraulic project to transfer Albian water from the catchment area in the Béni-Ounif region to five communes in the wilaya, namely Bechar, Kenadsa, Abadla, Mechraa Houari-Boumediene and Erg Farradj. The 1st part of the project, which aims to ensure a regular supply of drinking water, will be handed over and put into service at the end of April 2019.

This classification represents a methodical and rigorous approach to assessing flood risk, based on two key physical parameters. It plays a vital role in the development of prevention, management, and adaptation strategies in response to natural hazards, thereby contributing to the protection of the Beni Ounif region against flooding.

General conclusion

The study area, Beni Ounif, is located in the Wilaya of Bechar in southwestern Algeria, bordering Morocco over an area of 42,730 km². With a population estimated at 13,000 in 2017,

the region is geologically integrated into the vast Saharan platform of the North African Craton, where the rugged Precambrian basement is overlain by thick sedimentary layers, including Paleozoic and Mesozoic formations up to 10 km thick. The climate is Saharan, characterized by warm winters, annual precipitation not exceeding 32 mm, and an average annual temperature of 27.37°C, with extremes of 38.83°C in July and 12.94°C in January. The region has a water deficit due to low rainfall and high evapotranspiration, making aquifer recharge from precipitation negligible and water reserves unexploitable throughout the year.

The hydrogeological study of the Beni Ounif region includes a complex aquifer system comprising three overlaid aquifers. The Continental Intercalary aquifer, dating from the Lower Cretaceous, consists of alternating sandy-clayey-sandstone layers with thickness varying between 100 m and 300 m. Piezometric analyses reveal that in the Oued Namous basin, water flow from this aquifer moves from northwest to southeast. Above, lies the Terminal Complex aquifer of Turonian age, composed of dolomitic limestone 50 m thick, resting on an impermeable clayey-gypsum base and Cenomanian gypsum marl (thickness 60 m).

The shallow free aquifer, composed of Quaternary alluvium, varies in thickness between 300 m and 380 m. It is primarily fed by winter and spring floods from wadis. Geophysical studies of this aquifer indicate a composition of sands, clays, sandy clays with sandstone passages, while the substrate consists of limestones and dolomitic limestones. The surface of this aquifer is undulating, with depths varying between 300 m and 380 m, and depressions reaching up to 480 m towards the east.

The hydrochemical study of the groundwater in the Beni Ounif region was conducted to assess its quality and identify the mineralization processes affecting these vital resources. The region predominantly uses groundwater for domestic, agricultural, and industrial needs, with 16 boreholes exploiting the Continental Intercalary (CI) aquifer and 30 boreholes accessing the shallow aquifer.

To determine water potability, compliance with WHO standards was verified. Most water samples were classified from hard to very hard. Moreover, water from seven boreholes in the shallow aquifer exceeded WHO standards for nitrates, requiring treatment before distribution. The application of the Water Quality Index (WQI) revealed that waters from the shallow aquifer were categorized into three quality levels: 6.67% poor, 80% good, and 13.33% excellent. Waters from the CI aquifer were generally of good quality for consumption. For agricultural use, the evaluation using the Irrigation Water Quality Index (IWQI) indicated that the majority

of samples were classified as "good" and "excellent," mainly due to low concentrations of sodium and chloride. For industrial use, waters were evaluated for their corrosive potential and scaling capacity, with some samples requiring treatment to meet industrial standards.

Furthermore, analysis of Piper, Schoeller, and Gibbs diagrams, as well as binary diagrams and the calculation of saturation indices for major minerals showed that the mineralization of the studied aquifers is associated with the weathering of silicates and carbonates, the dissolution of evaporites, cation exchange, and anthropogenic inputs, which primarily affect the water chemistry in these aquifers.

In terms of water management, the annual demand for drinking and agricultural water in the Beni Ounif region is estimated at 8.46 hm³. To meet this growing demand, a major water transfer project from the Albien aquifers was carried out, aimed at channeling water from Beni-Ounif to five municipalities of the Bechar province. The project enables the daily transfer of 30,000 m³ of water from ten boreholes with depths varying between 400 and 500 meters; The Beni Ounif region in Béchar faces significant flood risks due to its geographical and climatic conditions, which contribute to sudden and intense flooding. Centennial flood simulations indicate extensive inundation, with affected areas reaching approximately 241.35 hectares. These floods pose severe threats to infrastructure, agriculture, and the safety of the local population.

To mitigate these risks, a comprehensive flood management strategy is essential. Key recommendations include: improving early warning systems to enhance preparedness and response; reinforcing flood defense structures, such as levees and drainage systems, to reduce water overflow; implementing strict urban planning regulations to prevent construction in high-risk zones; promoting community awareness and emergency preparedness programs; and integrating sustainable water management solutions, including reforestation and watershed protection, to reduce surface runoff and soil erosion.

Proactive measures and strategic planning are critical to safeguarding the residents of Beni Ounif and minimizing flood-related damages.

References

1. Abbasnia A, Yousefi N, Mahvi Ah, Nabizadeh R, Radfard M, Yousefi M, Alimohammadi M 2019. "Evaluation Of Groundwater Quality Using Water Quality Index And Its

- Suitability For Assessing Water For Drinking And Irrigation Purposes: Case Study Of Sistan And Baluchistan Province, Iran." *Human Ecology Risk Assessment: An International Journal*, Vol. 25, Pp. 988-1005. Doi: <https://doi.org/10.1080/10807039.2018.1458596>.
2. Abid K, Trabelsi R, Zouari K, Abidi B 2009. "Hydrologic And Geologic Factors Controlling Groundwater Geochemistry In The Turonian Aquifer, Southern Tunisia." *Hydrogeology Journal*. Doi: <https://doi.org/10.1007/s10040-010-0668-z>.
 3. Adimalla N, Ajay Kt 2020. "Hydrogeochemical Investigation Of Groundwater Quality In The Hard Rock Terrain Of South India Using Geographic Information System Gis And Groundwater Quality Index Gwqi Techniques." *Groundwater For Sustainable Development*, Vol. 10, Article 100288. Doi: <https://doi.org/10.1016/j.gsd.2019.100288>.
 4. Allia Z (2018). *Le Système Aquifère Mio-Pliocène Du Bassin De Chott Melrhir - Zab Chergui : Caractérisation, Géométrie Et Hydrochimie*. Doctoral Thesis, Université Mohamed Khider Biskra.
 5. Amiri V, Bhattacharya P, Nakhaei M 2021. "The Hydrogeochemical Evaluation Of Groundwater Resources And Their Suitability For Agricultural And Industrial Uses In An Arid Area Of Iran." *Groundwater For Sustainable Development*, Vol. 12, Article 100527. Doi: <https://doi.org/10.1016/j.gsd.2020.100527>.
 6. Antonakos A, Nicolaos L 2000. "Hydrodynamic Characteristics And Nitrate Propagation In The Sparta Aquifer." *Water Research*, Vol. 34, No. 16. Doi: [https://doi.org/10.1016/S0043-1354\(00\)00160-3](https://doi.org/10.1016/S0043-1354(00)00160-3).
 7. Appelo Caj, Postma D 1994. "Geochemistry, Groundwater And Pollution." A.A. Balkema, Rotterdam, The Netherlands.
 8. Appelo Caj, Postma D 2005. "Geochemistry, Groundwater And Pollution." 2nd Edition. Balkema, Rotterdam.
 9. Aravinthasamy P, Karunanidhi D, Subramani T, Priyadarsi Dr 2021. "Demarcation Of Groundwater Quality Domains Using Gis For Best Agricultural Practices In The Drought-Prone Shanmuganadhi River Basin Of South India." *Environmental Science And Pollution Research*, Vol. 28, No. 15, Pp. 18423-18435. Doi: <https://doi.org/10.1007/s11356-020-08518-5>.
 10. Arfa A, Bouselsal B, Zeddouri A, Kebili M 2022. "Groundwater Geochemical And Quality Of The Continental Intercalary Aquifer In Béni Ounif, Southwest Algeria." *Journal Of Ecological Engineering*, Vol. 23, No. 9, Pp. 1-12. Doi: <https://doi.org/10.12911/22998993/151070>.

11. Ayers Rs, Westcott Dw 1985. "Water Quality For Agriculture." Food And Agriculture Organization Of The United Nations, Rome, Italy, No. 29.
12. Bahir M, Otman E, Hicham E 2022. "Hydrogeochemical And Isotopic Assessment For Characterizing Groundwater Quality And Recharge Processes In The Essaouira Basin, Northwestern Morocco." *Arabian Journal Of Geosciences*. Doi: <https://doi.org/10.1007/S12517-022-09817-6>.
13. Balamurugan P, Kirubakaran M, Maciej T 2022. "An Integrated Approach To Explore The Suitability Of Nitrate Contaminated Groundwater For Drinking Purposes In A Semiarid Region Of India." *Environmental Geochemistry And Health*. Doi: <https://doi.org/10.1007/S10653-022-01237-5>.
14. Bassoulet B., 1973. Contribution À L'étude Stratigraphique Du Mésozoïque De L'atlas Saharien Occidental (Algérie). Thèse. Sci. Nat, Univ-Paris Vi, 2 Tomes.
15. Bekhedda B. 1992. Contribution À L'étude Hydrogéologique Du Synclinal De Béni-Ounif (Algérie) Monts Des Ksours (Atlas Saharien Occidental). Mémoire D'ingéniorat. Université D'oran.
16. Bekhedda B. 2016. Contribution À L'étude Hydrogéologique Des Eaux Souterraines De Béni- Ounif (Wilaya Béchar –Sud-Ouest Algérien). Mémoire De Master, Université De Tahri Mohammed-Béchar-.
17. Benest M. 1985. Evolution De La Plateforme De L'ouest Algérien Et Nord Est Marocain Au Cours Du Jurassique Supérieur Et Du Crétacé Inférieur. Stratigraphie, Milieu De Dépôt Et Dynamique Sédimentaire. Docum.Lab. Géol. Lyon, 95, 1 – 2, 581 P, 145 Fig, 23 Pl.
18. Bengal W, Aznarul I 2021. "Assessing The Suitability Of Groundwater For Irrigation In The Light Of Natural Forcing And Anthropogenic Influx: A Study In The Gangetic." *Environmental Earth Sciences*, Vol. 80, No. 24, Pp. 1-19. Doi: <https://doi.org/10.1007/S12665-021-10087-W>.
19. Beta-Consults (2011). Rapport Technique Société
20. Boualem B, Egbueri J.C (2024) Graphical, Statistical And Index-Based Techniques Integrated For Identifying The Hydrochemical Fingerprints And Groundwater Quality Of In Salah, Algerian Sahara. *Environ Geochem Health* 46, 158. <https://doi.org/10.1007/S10653-024-01931-6>
21. Bouselsal B 2016. "Etude Hydrogéologique Et Hydrochimique De L'aquifère Libre D'el Oued Souf, Se Algérie." Phd Thesis, University Of Annaba, Algeria, P. 204.

22. Bouselsal B, Belksier Ms 2018. "Caractérisation Géochimique De L'aquifère De Complexe Terminal De El-Oued, Se Algérie." *Journal International Sciences Et Technique De L'eau Et De L'environnement*, Vol. Iii, No. 1, April, Pp. 74-80.
23. Bouselsal B, Saibi S 2022. "Evaluation Of Groundwater Quality And Hydrochemical Characteristics In The Shallow Aquifer Of El-Oued Region, Algerian Sahara." *Groundwater For Sustainable Development*, Vol. 17, Article 100747. Doi: <https://doi.org/10.1016/j.gsd.2022.100747>.
24. Bouselsal B, Zouari K 2022. "Identification Of Groundwater Quality And Hydrogeochemical Processes In The Shallow Aquifer Of El-Oued, Algerian Sahara." *New Prospects In Environmental Geosciences And Hydrogeosciences*, Springer International Publishing. Doi: 10.1007/978-3-030-72543-3_130.
25. Bouselsal B, Satouh A, Egbueri J, Hashim M, Arafat A, Paramasivam P, Alzaed A, Hussein E. 2025. Groundwater For Drinking And Sustainable Agriculture And Public Health Hazards Of Nitrate: Developmental And Sustainability Implications For An Arid Aquifer System. *Results In Engineering* Vol, 25, March 2025, 104160. <https://doi.org/10.1016/j.rineng.2025.104160>
26. Bouselsal B. 2017. Groundwater Quality In Arid Regions: The Case Of Hassi Messaoud Region (Se Algeria). *J. Fundam. Appl. Sci.*, 2017, 9(1), 528-541. <http://dx.doi.org/10.4314/jfas.v9i1.30>.
27. Bouselsal B., Kherici N., Hadj-Said S. (2015). Vulnérabilité Et Risque De Pollution De La Nappe Libre D'el-Oued (Se Algérie) : Application De La Méthode Drastic. *Bulletin Du Service Géologique National.*, Vol. 26, N° 1.
28. Bouselsal, B., Satouh, A. & Egbueri, J.C. 2024. Evaluating Water Quality, Mineralization Mechanisms, And Potential Health Risks Of Nitrate Contamination In The Continental Intercalaire Aquifer Of Reggane, Algeria. *Environ Earth Sci* 83, 539 (2024). <https://doi.org/10.1007/s12665-024-11844-3>.
29. Bouselsal, B et Kherici, N. (2014 a). Effets de la remontée des eaux de la nappe phréatique sur l'homme et l'environnement : cas de la région d'El-Oued (Sud-Est Algérie). *Afrique Science*, Vol.10, N°3, 1 septembre 2014.
30. Bouselsal B., Kherici N., Hadj-Said S., Belksier M.S. (2014 b) Qualité des eaux des aquifères de Sahara septentrionale cas des eaux des aquifères d'el-oued (SE Algérie). *International Journal for Environment & Global Climate Change*. Vol 2, Issue 3, 2014. P 21-31.

31. Boussaada N, Bouselsal B, Benhamida Sa, Hammad N, Kharroubi M 2023. "Geochemistry And Water Quality Assessment Of Continental Intercalary Aquifer In Ouargla Region, Sahara, Algeria." *Journal Of Ecological Engineering*, Vol. 24, No. 2, Pp. 279-294. Doi: <https://doi.org/10.12911/22998993/156832>.
32. Brown Rm, McClelland Ni, Deininger Ra, Tozer Rg 1970. "A Water Quality Index—Do We Dare?" *Water And Sewage Works*, Vol. 117, Pp. 339-343.
33. Carroll D 1962. "Rainwater As A Chemical Agent Of Geologic Processes: A Review." In *USGS Water Supply Paper*, P. 1535.
34. Chavaillon N. 1964, Note Sur Quelques Dates Intéressant La Préhistoire Du Sahara Nord-Occidental, *Bulletin De La Société Préhistorique Française Année 1964* 61-4 Pp. 88-91
35. Cheylan G. 1952. Création De Deux Points D'eau Dans Les Régions Des Dayas De Mrérirès Et D'el Aouedj Tahtani ; Teritoire D'ain Sefra. Poste De Béni-Ounif. Rapport Pout Le S.C.H, P 5.
36. Cornet A. 1947. Observations Géologiques Dans L'atlas Saharien Sud Oranais. *Bull. Soc. Hist. Nat, Afrique Du Nord*.
37. Davis Sn, Dewiest Rj 1966. "Hydrogeology." Wiley, New York.
38. Deleau P., Mm. Lauradoux. 1933. Etude Géologique De La Région Frontière Algéro-Marocaine Au Nord-Ouest De C. Béchar. *Travaux Récent Des Collaborateurs. Fascicule Ii*, P141.
39. Despois, J. 1959. L'atlas Saharien Occidental D'algérie : « Ksouriens » Et Pasteurs. *Cahiers De Géographie Du Québec*, 3(6), 403–415.
40. Doneen Ld 1964. "Notes On Water Quality In Agriculture." Department Of Water Science And Engineering, University Of California, Davis, Ca, Usa.
41. Douihasni M. 1976. Etude Géologique De Aïn Ouarka –Boussemghoun. Analyse Structurale (Partie Centrale Des Monts Des Ksour, Atlas Saharien, Algérie). Thèse 3ème Cycle, Univ – Oran.
42. Dubief, J. 1963. Le Climat Du Sahara, Tome Ii. Fascicule I. Univers. Alger, Inst. Rech. Sahar. , Publication C.N.R.S, Paris, 275 P.
43. Egbueri Jc, Ezugwu Ck, Unigwe Co, Onwuka Os, Onyemesili Oc, Mgbenu Cn 2021. "Multidimensional Analysis Of The Contamination Status, Corrosivity And Hydrogeochemistry Of Groundwater From Parts Of The Anambra Basin, Nigeria." *Analytical Letters*, Vol. 54, Pp. 2126-2156. Doi: <https://doi.org/10.1080/00032719.2020.1843049>.

44. Eldaw E, Tao H, Adam K, Yahaya M 2021. "Classification Of Groundwater Suitability For Irrigation Purposes Using A Comprehensive Approach Based On The Ahp And Gis Techniques In North Kurdufan Province, Sudan." *Applied Water Science*, 2021, Pp. 1-19. Doi: <https://doi.org/10.1007/S13201-021-01443-Z>.
45. Fabre J. (2005) : *Géologie Du Sahara Occidental Et Central*, Musée Royal De L’afrique Centrale – Belgique
46. Farid I, Zouari K, Kallali A 2012. "Origine De La Salinité Des Eaux Du Bassin Chougafiya, Tunisie." *Revue Des Sciences De L’eau*, Vol. 25, No. 3, Pp. 255-274.
47. Flamand G.B.M. 1911. *Recherches Géologique Et Géographiques Dans Les Haut Pays De L’oranie Et Le Sahara*, Thèse De Doctorat .Lyon .P.587.610.
48. Freeze Ra, Cherry Ja 1979. "Groundwater." Prentice-Hall: Englewood Cliffs, New Jersey, Usa, 1979.
49. Gaillardet J, Dupre B, Louvat P, Allegre Cj 1999. "Global Silicate Weathering And Co2 Consumption Rates Deduced From The Chemistry Of Large Rivers." *Chemical Geology*, 1999, Vol. 159, Pp. 3-30.
50. Galmier D. 1970. *Photogéologie De La Région De Aïn Séfra (Atlas Saharien, Algérie)*. Thèse Doctorat D’état. Fasc. Sc. De Paris. 320 P, 9 Cartes.
51. Galmier D. 1970. *Photogéologie De La Région De Aïn Séfra (Atlas Saharien, Algérie)*. Thèse Doctorat D’état. Fasc. Sc. De Paris. 320 P, 9 Cartes.
52. Galmier D. 1971. *Etude Photo Géologique De La Structure De L’atlas Saharien Occidental*. Thèse De Doctorat, Paris.
53. Galmier D. 1971. *Etude Photo Géologique De La Structure De L’atlas Saharien Occidental*. Thèse De Doctorat, Paris.
54. Garcia Mg, De Hidalgo M, Blesa Ma 2001. "Geochemistry Of Groundwater In The Alluvial Plain Of Tucuman Province Argentina." *Journal Of Hydrology*, Vol. 9, Pp. 597-610.
55. Garrels Rm, Mackenzie Ft 1967. "Origin Of The Chemical Composition Of Some Springs And Lakes." In: Stumm W, Ed., *Equilibrium Concepts In Natural Water Systems*, American Chemical Society, Washington Dc, Chapter 10, Pp. 222-242. Doi: <http://dx.doi.org/10.1021/Ba-1967-0067.Ch010>.
56. Gibbs Rj 1970. "Mechanisms Controlling World Water Chemistry." *Science*, 1970, Vol. 170, Pp. 1088-1090.
57. Gopinath S, Srinivasamoorthy K, Saravanan K, Prakash R 2019. "Tracing Groundwater Salinization Using Geochemical And Isotopic Signature In Southeastern Coastal

- Tamilnadu, India." *Chemosphere*, 2019. Doi: <https://doi.org/10.1016/j.chemosphere.2019.07.036>.
58. Hammad N, Bouselsal B, Boussaada N, Satouh A, Lakhdari A.S. 2023. Application Of Water Quality Index To Assess The Potability Of The Phreatic Aquifer In Ouargla (Algeria). *Journal Of Ecological Engineering* 2023 24(5), 36–45 Doi: [Doi: 10.12912/27197050/163122](https://doi.org/10.12912/27197050/163122).
 59. Hao C, Jiading W, Fei Zhang, Yaxing Z, Chunying X 2022. "Hydrochemical Characteristics And Formation Mechanisms Of Groundwater In West Zoucheng City, Shandong Province, China." *Environmental Monitoring And Assessment*, 2022, Pp. 1-17. Doi: <https://doi.org/10.1007/s10661-022-10136-2>.
 60. Hao Q, Xiao Y, Chen K, Zhu Y, Li J 2020. "Comprehensive Understanding Of Groundwater Geochemistry And Suitability For Sustainable Drinking Purposes In Confined Aquifers Of The Wuyi Region, Central North China Plain." *Water*, 2020, Vol. 12, Article 3052. Doi: <https://doi.org/10.3390/w12113052>.
 61. He X, Peiyue L, Jing N, Song H, Ningning Y 2022. "Geochemical Processes During Hydraulic Fracturing In A Tight Sandstone Reservoir Revealed By Field And Laboratory Experiments." *Journal Of Hydrology*, 2022, Vol. 612, Article 128292. Doi: <https://doi.org/10.1016/j.jhydrol.2022.128292>.
 62. Hem Jd 1989. "Study And Interpretation Of The Chemical Characteristics Of Natural Water," 3rd Edition. United States Geological Survey Water Supply Paper 2254.
 63. Hill Ra 1940. "Geochemical Patterns In Coachella Valley." *Transactions Of The American Geophysical Union*, 1940, Vol. 21, Pp. 46-53.
 64. Horton Rk 1965. "An Index Number System For Rating Water Quality." *Journal Of The Water Pollution Control Federation*, 1965, Vol. 37, Pp. 300-306.
 65. Houari I.M, Bouselsal B, Lakhdari A.S. 2024. Evaluating Groundwater Potability And Health Risks From Nitrates In The Semi-Arid Region Of Algeria. *Ecological Engineering & Environmental Technology* 2024, 25(6), 222–236. <https://doi.org/10.12912/27197050/186954>
 66. Houatmia F, Azouzi R, Charef A, Bédir M 2016. "Assessment Of Groundwater Quality For Irrigation And Drinking Purposes And Identification Of Hydrogeochemical Mechanisms Evolution In Northeastern Tunisia." *Environmental Earth Sciences*, 2016, Vol. 75, Article 746. Doi: <https://doi.org/10.1007/s12665-016-5441-8>.
 67. Jacob, C. E. 1947 -Draw-Down Test To Determine Effective Radius Of Artesian Well. *Transactions. American Society Of Civil Enginess*, 112: 1047-1070.

68. Karmakar B, Singh Mk, Choudhary Bk, Singh Sk, Egbueri Jc, Gautam S, Rawat Sk 2021. "Investigation Of The Hydrogeochemistry, Groundwater Quality And Associated Health Risks In Industrialized Regions Of Tripura, Northeast India." *Environmental Forensics*. Doi: <https://doi.org/10.1080/15275922.2021.2006363>.
69. Kaur L, Rishi Ms, Sharma S, Sharma B, Lata R, Singh G 2019. "Hydrogeochemical Characterization Of Groundwater In Alluvial Plains Of River Yamuna In Northern India: An Insight Into Controlling Processes." *Journal Of King Saud University - Science*, 2019, Vol. 31, Pp. 1245–1253. Doi: <https://doi.org/10.1016/J.Jksus.2019.01.005>.
70. Kebili M, Bouselsal B, Gouaidia L 2021. "Hydrochemical Characterization And Water Quality Of The Continental Intercalare Aquifer In The Ghardaïa Region, Algerian Sahara." *Journal Of Ecological Engineering*, 2021, Vol. 22, No. 10, Pp. 152–162. Doi: <https://doi.org/10.12911/22998993/142041>.
71. Kelley Wp 1963. "Use Of Saline Irrigation Water." *Soil Science*, 1963, Vol. 95, Pp. 355–391.
72. Kharroubi M, Bouselsal B, Ouarekh M, Benaabidate L, Khadri R 2022. "Water Quality Assessment And Hydrogeochemical Characterization Of The Ouargla Complex Terminal Aquifer, Algerian Sahara." *Arabian Journal Of Geosciences*, 2022. Doi: <https://doi.org/10.1007/S12517-022-09438-Z>.
73. Kharroubi M., Bouselsal B., Said S.H., Zeddouri A., Ouarekh M. (2023). Mineralization Mechanisms and Water Quality of the Complex Terminal Aquifer in Algerian Desert (Ouargla). In: Kallel, A., et al. *Selected Studies in Environmental Geosciences and Hydrogeosciences*. CAJG 2020. *Advances in Science, Technology & Innovation*. Springer, Cham. https://doi.org/10.1007/978-3-031-43803-5_42
74. Kharroubi M., Bouselsal B., Sudhir K.S. 2024. Groundwater Quality And Non-Carcinogenic Element Health Risks Assessment Using Multi-Technical Models: A Case Of The Deep Aquifer Of The Complex Terminal In Ouargla City (Southeastern Algeria). *Groundwater For Sustainable Development* 25 (2024) 101140. <https://doi.org/10.1016/J.Gsd.2024.101140>.
75. Kshitindra Ks, Geeta T, Suresh K 2020. "Evaluation Of Groundwater Quality For Suitability Of Irrigation Purposes: A Case Study In The Udham Singh Nagar, Uttarakhand." *Journal Of Chemistry*, 2020. Doi: <https://doi.org/10.1155/2020/6924026>.
76. Lakhdari, A.S., Bouselsal, B., Saibi, H. Ouarekh M. (2025). Assessment of groundwater quality and hydrogeochemical properties in the adrar continental intercalaire aquifer of

- the Algerian Sahara. *Appl Water Sci* 15, 175 (2025). <https://doi.org/10.1007/s13201-025-02552-9>
77. Lakhdari As, Bouselsal B. (2024). Investigation Of The Quality Of The Groundwater And The Nitrate Pollution Hazards To Human Health In The Desert Region Of Algeria. *Ecological Questions* 35(2024)4. [Http://Dx.Doi.Org/10.12775/eq.2024.053](http://Dx.Doi.Org/10.12775/eq.2024.053)
 78. Liaghat S, Khosravi K, Ebrahimian M 2013. "Groundwater Quality Assessment Using The Water Quality Index And Gis In Saveh-Nobaran Aquifer, Iran." *Environmental Earth Sciences*, 2013. Doi: <https://doi.org/10.1007/s12665-013-2770-8>.
 79. Mansour H. 2007. *Hydrologie De Continental Intercalaire Et Du Complexe Terminal En Domaine Aride .Exemple Des Mouts Des Ksour (Atlas Saharien Occidental)*. Thèse Doctorat D'état. Uni. Es Senia Algérie.
 80. Mansour H. 2007. *Hydrologie De Continental Intercalaire Et Du Complexe Terminal En Domaine Aride .Exemple Des Mouts Des Ksour (Atlas Saharien Occidental)*. Thèse Doctorat D'état. Uni. Es Senia Algérie
 81. Mansour H., Verdeil P. 1992. *Hydrogéologie De La Source De Béni-Abbes : Son Alimentation Et Son Captage (Sahara Nord Occidental)*. Fenêtre Ouverte Sur La Science Au Désert. Adrar.
 82. Mateus S 2020. "Characteristics And Impacts On The Groundwater Of The Guriri." *Environmental Development And Sustainability*, 2020. Doi: <https://doi.org/10.1007/s10668-020-01074-5>.
 83. Matthes G 1982. "The Properties Of Ground Water." John Wiley And Sons, New York.
 84. Mc Lean J, Jankowski W, Lavitt N 2000. "Groundwater Quality And Sustainability In Alluvial Aquifer, Australia." In: Sililo Et Al., Eds. *Groundwater, Past Achievement And Future Challenges*. Rotterdam: Balkema., Pp. 567–573.
 85. Meddi H & Meddi M (1998) : *Etude De La Persistance De La Sécheresse Au Niveau De Sept Plaines Algériennes Par Utilisation Des Chaines De Markov (1930-2003)*. *Courrier Du Savoir* – N°09, Mars 2009, Pp.39-48
 86. Mekahli L. 1995. *Hettangien – Bajocien Supérieur Dans Les Monts Des Ksour. Biostratigraphie, Évolution Paléogéographique Et Stratigraphie Séquentielle (Atlas Saharien Occidental)*. Thèse D'état, Univ – Oran – Algérie.
 87. Merzougui f.Z., Makhloufi A., Merzougui T. 2020. "Etude hydrogéologique, hydrochimique et microbiologique des eaux souterraines dans le synclinal du Crétacé inférieur de la région de Béni Ounif (Le revers méridional de l'Atlas Saharien occidental, Algérie) , p.52.

88. Merzougui f.Z., Makhloufi A., Merzougui T. 2019. Hydro-chemical and
89. microbiological characterization of Lower Cretaceous waters in a semi-arid zone Beni-Ounif syncline, South-West of Algeria. *Journal of Water and Land Development*. No. 40 (I–III) p. 67–80. DOI: 10.2478/jwld-2019-0007
90. Mirzabeygi M, Mozhgan N, Nader Y, Mahmoud S, Amir Hm 2016. "Evaluation Of Corrosion And Scaling Tendency Indices In Water Distribution System: A Case Study Of Torbat Heydariye, Iran." *Desalination And Water Treatment*, 2016, Vol. 3994, April. Doi: <https://doi.org/10.1080/19443994.2016.1162206>.
91. Nafyad S, Shankar K 2018. "Groundwater Quality Assessment Using Water Quality Index And Gis Technique In Modjo River Basin, Central Ethiopia." *Journal Of African Earth Sciences*, 2018, Vol. 147, June, Pp. 300–311. Doi: <https://doi.org/10.1016/j.jafrearsci.2018.06.034>.
92. Nezli Imed Eddine (2009) . *Approche Hydrogéochimique A L'étude Des Aquifères De La Basse Vallée De L'oued M'ya (Ouargla)*. Thèse De Doctorat, Université Mohamed Kheider, Biskra.
93. Nguyen Tt, Akira K, Thanh Nt, Naoko N, Hideo A, Romeo G 2015. "Hydrogeochemical Assessment Of Groundwater Quality During Dry And Rainy Seasons For The Two Main Aquifers In Hanoi, Vietnam." *Environmental Earth Sciences*, 2015, Vol. 73, No. 8, Pp. 4287–4303.
94. Doi: <https://doi.org/10.1007/S12665-014-3713-8>.
95. Oss (Observatoire Sahara Et Sahel) (2003) *Système Aquifère Du Sahara Septentrional: Gestion Commune D'un Bassin Transfrontière. Rapport De Synthèse*, Oss, Tunisie.
96. Ouarekh M, Bouselsal B, Belksier Ms, Benaabidate L 2021. "Water Quality Assessment And Hydrogeochemical Characterization Of The Complex Terminal Aquifer In Souf Valley, Algeria." *Arabian Journal Of Geosciences*, 2021, Vol. 14, No. 2239. Doi: <https://doi.org/10.1007/S12517-021-08498-X>.
97. Ouarekh, M., Bouselsal, B., Belksier, M.S., Kharroubi, M. (2023). Hydrogeochemical and Groundwater Flow Studies in El Oued Region (Southeast Algeria). In: Kallel, A., et al. *Selected Studies in Environmental Geosciences and Hydrogeosciences*. CAJG 2020. *Advances in Science, Technology & Innovation*. Springer, Cham. https://doi.org/10.1007/978-3-031-43803-5_40.
98. Ouarekh M, Bouselsal B, Benaabidate L, Belksier M.S, Chellat S, Satouh A (2024). *Geochemical Evaluation Of Fluoride Enrichment In The Complexe Terminal*

- Aquifer And Its Implications For Human Health In Oued Souf, Algerian Sahara. *Sustain. Water Resour. Manag.* 10, 163 (2024). <https://doi.org/10.1007/S40899-024-01148-6>.
99. Ould Baba Sy 2005 : Ould Baba Sm (2005) Recharge Et Paléorecharge Du Système Aquifère Du Sahara Septentrional. Thèse De Doctorat En Géologie, Tunisie, 277p.
 100. Parkhurst DL, Appelo CAJ 2013. "Description Of Input And Examples For Phreeqc Version 3: A Computer Program For Speciation, Batch-Reaction, One-Dimensional Transport, And Inverse Geochemical Calculations." *US Geological Survey, Reston, Va, Usa, Report No. 2328-7055*.
 101. Piper AM 1944. "A Graphic Procedure In The Geochemical Interpretation Of Water Analyses." *Eos, Transactions American Geophysical Union*, 1944, Vol. 25, Pp. 914–928. [Doi: https://doi.org/10.1029/Tr025i006p00914](https://doi.org/10.1029/Tr025i006p00914).
 102. Raghunath HM 1987. "Groundwater Pollution And Legislation." *Groundwater*, 2nd Ed.; Taylor And Francis: Abingdon, UK, 1987, P. 31.
 103. Richards LA 1954. "Determination Of The Properties Of Saline And Alkali Soils." In *Diagnosis And Improvement Of Saline And Alkali Soils, Agriculture Handbook No. 60*; United States Department Of Agriculture: Washington, DC, USA, 1954, Pp. 7–53.
 104. Roy B, Pramanik M, Manna AK 2023. "Hydrogeochemistry And Quality Evaluation Of Groundwater And Its Impact On Human Health In North Tripura, India." *Environmental Monitoring And Assessment*, 2023, Vol. 195, Pp. 39. [Doi: https://doi.org/10.1007/S10661-022-10642-3](https://doi.org/10.1007/S10661-022-10642-3).
 105. Salah HA 2018. "Application Of Traditional Method And Water Quality Index To Assess Suitability Of Groundwater Quality For Drinking And Irrigation Purposes In South-Western Region Of Libya." *Water Conservation Management*, 2018, Vol. 2, No. 2, Pp. 20–32.
 106. Salhi A. 2002. *Evolution Paléogéographique Et Dynamique De La Bordure Méridionale Du Sillon Atlasique Au Cours Du Lias Et Du Dogger (Région De Béni Ounif, Atlas Saharien Occidental, Algérie)*. Thèse Magister, Univ – Oran.
 107. Satouh A., Bouselsal B., Chellat, S., Benaabidate L. 2021. Determination Of Groundwater Vulnerability Using The Drastic Method In Ouargla Shallow Aquifer (Algerian Sahara). *Journal Of Ecological Engineering*, 22(6), 1–8. <https://doi.org/10.12911/22998993/137680>
 108. Sawyer GN, MCMCARTLY DL 1967. "Chemistry For Sanitary Engineers," 2nd Ed., P. 518. New York: McGraw Hill.

109. Schoeller H 1962. "Les Eaux Souterraines : Hydrologie Dynamique Et Chimique. Recherche, Exploitation Et Évaluation Des Ressources." Masson Et Cie. Editions, 642p.
110. Schoeller H 1965. "Qualitative Evaluation Of Groundwater Resources." In *Methods And Techniques Of Groundwater Investigations And Development*; Unesco: Paris, France, 1965; Volume 54–83.
111. Schoeller H 1977. "Geochemistry Of Groundwater." In: *Groundwater Studies—An International Guide For Research And Practice*, Vol. 15. Unesco, Paris, Pp. 1–18.
112. Sghara N. 2013. *Protection De La Ville De Béni-Ounif (Béchar) Contre Les Inondations: Application Du Logiciels Hec-Hms Et Hec-Ras. Mémoire De Magistère, Université De Mohammed Boudiaf, Oran. P 8-24.*
113. Shah Ia, Ashwani Ks, Nawal K, Dalchand J 2021. "Evaluation Of Groundwater Quality In Jampali Coal Mine, Raigarh, Chhattisgarh, India." *Environmental Quality Management*, 2021, Pp. 1-9. Doi: 10.1002/Tqem.21767.
114. Shahmohammadi S, Noori A, Karami S, Amini A, Shahmoradi B 2018. "A Study On Corrosion And Scaling Potential Of Drinking Water Supply Resources In Rural Areas Of Sarvabad, West Of Iran." *Journal Of Advanced Environmental Health Research*, 2018, Vol. 6, Pp. 52-60. Doi: <https://doi.org/10.22102/Jaehr.2018.98342.1037>.
115. Shankar Bs 2014. "Determination Of Scaling And Corrosion Tendencies Of Water Through The Use Of Langelier And Ryznar Indices." *Scholars Journal Of Engineering And Technology*, 2014, Vol. 2, No. 2a, Pp. 123–127.
116. Shipra T, Kiranmay S 2020. "Qualitative Assessment, Geochemical Characterization And Corrosion-Scaling Potential Of Groundwater Resources In Ghaziabad District Of Uttar Pradesh, India." *Groundwater For Sustainable Development*, 2020, Vol. 10, March, Article 100370. Doi: <https://doi.org/10.1016/J.Gsd.2020.100370>.
117. Todd Dk 1959. "Groundwater Hydrology." Wiley: New York, Ny, Usa, 1959.
118. Touahri M, Belksier Ms, Boualem B, Kebili M 2022. "Groundwater Quality Assessment Of Hassi Messaoud Region, Algerian Sahara." *Journal Of Ecological Engineering*, 2022, Vol. 23, No. 11, Pp. 165–178. Doi: <https://doi.org/10.12911/22998993/153396>.
119. Unesco, 1972) : Unesco, 1972. *Study Of Water Resources In The Northern Sahara.* Unesco, Paris, France.
120. Usepa 1994. "Short-Term Methods For Estimating The Chronic Toxicity Of Effluents And Receiving Waters To Freshwater Organisms," 3rd Ed. Epa/600/4-91/002. Usepa, Environmental Monitoring Systems Laboratory, Cincinnati, Oh, Usa.

121. Ussl 1954. "Diagnosis And Improvement Of Saline And Alkali Soils." United States Salinity Laboratory, Us Department Of Agriculture: Washington, Dc, Usa, 1954.
122. Vinnarasi F, Srinivasamoorthy K, Saravanan K, Gopinath S, Prakash R, Ponnumani G, Babu C 2020. "Chemical Weathering And Atmospheric Carbon Dioxide (Co₂) Consumption In Shanmuganadhi, South India: Evidences From Groundwater Geochemistry." *Environmental Geochemistry And Health*, 2020, Vol. 43, Pp. 771–790. Doi: <https://doi.org/10.1007/s10653-020-00540-3>.
123. Wec2007.Rapports Inédits. Sonatrach P 489.
124. Who 2017. "Guidelines For Drinking-Water Quality, 4th Ed.; Incorporating First Addendum." World Health Organization: Geneva, Switzerland, 2017; Available Online: <https://www.who.int/publications/i/item/9789241549950> Accessed 14.01.2021 .
125. Wilcox Lv 1955. "Classification And Use Of Irrigation Water." Usda Circular No. 969: Washington, Dc, Usa, 1955; Pp. 1–19.
126. Zhang X, Rong Z, Xiong W 2022. "Hydrogeochemistry, Identification Of Hydrogeochemical Evolution Mechanisms, And Assessment Of Groundwater Quality In The Southwestern Ordos Basin, China." *Environmental Science And Pollution Research*, 2022, Pp. 901–921. Doi: <https://doi.org/10.1007/s11356-022-20041-7>.