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HYDROGEOLOGICAL CHARACTERIZATION AND MANAGEMENT OF THE OUARGLA AQUIFER SYSTEM IN THE ALGERIAN SAHARA

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Abstract

This study, conducted in the arid Ouargla Basin of the Algerian Sahara provides a comprehensive analysis of water resource management, focusing on water quality assessment, field geometry, and hydrodynamics. Through the analysis of lithological stratigraphic characteristics, three major aquifer units have been identified: the Continental Intercalary, the Terminal Complex, and the Quaternary-hosted phreatic aquifer. The Continental Intercalary, characterized by permeable sandy-clay units, serves as the primary water reservoir. The Terminal Complex, with litho-stratigraphic formations separated by impermeable layers, relies on peripheral runoff and Eastern Erg infiltration for replenishment. The Quaternary-hosted phreatic aquifer encircles the basin and captures local infiltration for its shallow domain.

Hydrodynamic parameters (Transmissivity and storage coefficient) were evaluated to assess aquifer capacity in Ouargla, while observational data revealed seasonal and interannual fluctuations in phreatic levels. Notably, factors like variable recharge, delayed flood impacts, and evapotranspiration influence these fluctuations. The findings underscore the critical need for sustainable groundwater management in the region.

Keywords: Aquifer capacity; Groundwater management; Hydrodynamics; Lithological stratigraphy; Ouargla Basin.

Introduction

Over the millennia, humanity has developed empirical knowledge of the search for and use of groundwater. However, the notion of groundwater resources as a modern concept has emerged with the realization that some groundwater catchments show diminishing returns over time or have detrimental effects on natural sources, waterways, and other catchments (Castany, 1991; Viavattene, 2006; Loudière & Gourbesville, 2020).

These effects, often misinterpreted, have led to the idea of "overexploitation," the belief that some exploitation of groundwater resources is excessive. This has generated concerns regarding the management of this resource, which is considered a maximum not to be exceeded or an "income" that must not exhaust "capital." The complementary idea of "safe yield," adapted to the scale of wells, also appeared to assess the viability of exploitation (Lassaube, 2020).

In reality, exploiting groundwater resources means influencing this system according to technically feasible and economically acceptable criteria. The assessment of exploitable groundwater resources aims to find ways to optimize the quantities of water extracted in a given system while respecting present and future constraints (Collignon, 1994; Lavenus et al., 2016; Slimani et *al*., 2017; Slimani et *al*., 2023).

For effective management of this precious resource, it is essential to understand and know the aquifer system of a region. This encompasses all the underground geological formations that contain and transport groundwater. A complete understanding of this system is essential to ensure sustainable water management. This includes determining groundwater availability, identifying recharge and discharge areas, and assessing the impacts of climate change and human activities. With this knowledge, we can ensure water security and environmental sustainability while protecting this essential resource for current and future generations through well-informed decision-making and strategic implementation (Alley et *al*., 2002; Kettab et *al*., 2008; Slimani et *al*., 2017; KC et *al*., 2022).

In the specific context of the Ouargla region, located in the Algerian Sahara, the aquifer system is of capital importance to meet the water needs in this arid zone. To maintain sustainable management of this essential resource, it is crucial to comprehend the flow of deep groundwater in this aquifer system.

Materials and methods

- **Study area**

Ouargla region is part of the Lower Sahara of Algeria. It is a vast depression that encompasses around 750 km^2 (Figure 1). It is found in the Quaternary bed of the Oued Mya low fossil valley (Charikh et *al*., 2022; Slimani et *al*., 2023).

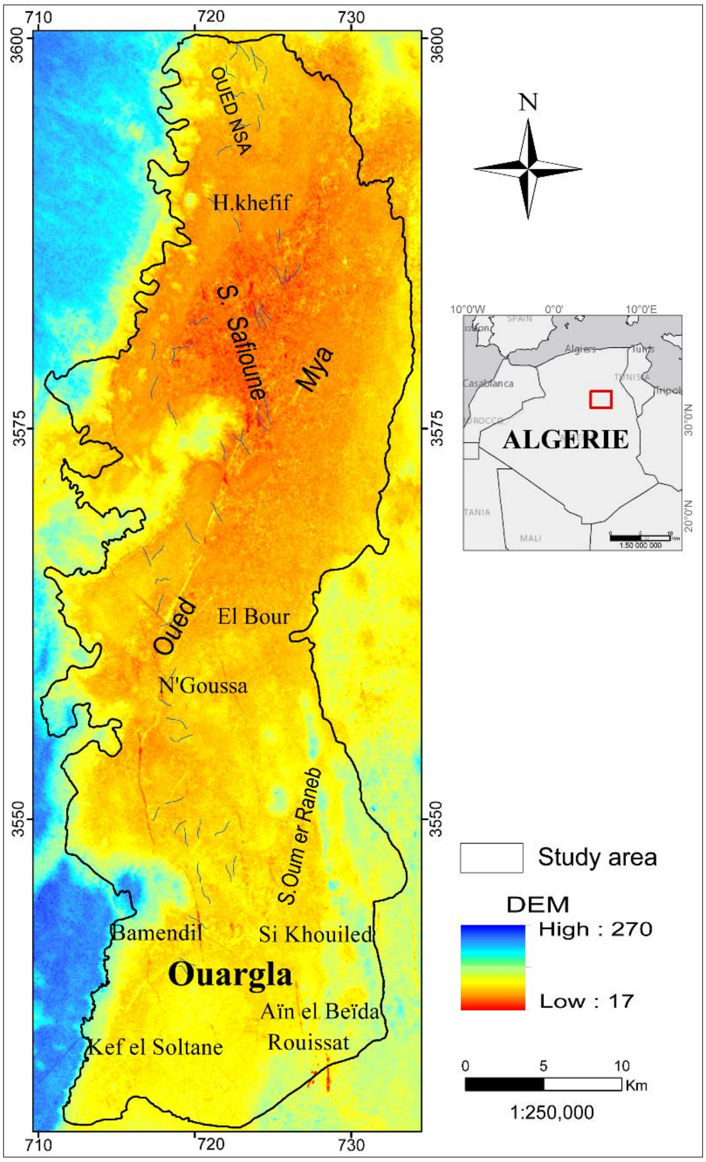

Figure 1: Location of the study area

Climatically, the region falls under to the Mediterranean level of the Saharan type. The investigation of cyclical fluctuations revealed that precipitation is irregular, with an annual average of 44 mm ranging from 0 mm to 90.9 mm. Although the Sahara is often dry, there is a noticeable increase in rainfall in November, December, and January. The average temperature varies from 16 °C in the coldest months (January and February) to 30 °C in the warmest months (July and August). Winds-especially sandstorms-have a special drying effect. The average July relative humidity is low (26%), peaking at 62% in December. With an annual average of 222.78 mm, evaporation increases on average from 83 mm in January to 393 mm in July. Evapotranspiration reaches its highest at 218.2 mm in July, on an annual basis, it is approximately 1114.6 mm.

Wadi N'sa and Wadi M'zab, the two principal wadis of the M'zab basin, drain into the Ouargla basin at Sebkhat Sefioune from a hydrological perspective. There is also a large wadi on Mount Tadmaït, named Wadi Mya, which runs through the Ouargla valley in a southwest/northeast direction (Emsalem, 1955; Lelièvre, 1969; Rouvilois-brigole, 1975). Depending on the industry and the time of year, each of these wadis has a transient flow. Although flows are usually minor, during floods—which replenish the groundwater—they can reach notable values.

The region's geology is defined by sedimentary formations that have accumulated through time in the basin, notably the CI which is composed of a sequence of sandstones. This detrital series is an important aquifer that rests on the impermeable Cenomanian series of anhydrous and clayey strata. The deposition of marl-limestone in the Cenomanian and fissured limestone in the Turonian characterizes the middle and upper Cretaceous. These two strata are critical to the region's morphological landscape. The Miopliocene, which occurs in the Tertiary period, is formed of alternating layers of clay and sand, with two permeable levels separated by a layer of clay. Outcrops of recent alluvial deposits and sandy deposits define the Quaternary (Cornet, 1964; Aumassip et *al*., 1972; Slimani, 2016; Slimani et *al*., 2023).

The geological formations of Ouargla feature two major groups of aquifer formations separated by thick evaporitic or clayey strata. The lower group is known as the CI while the top set is known as the " Terminal Complex (CT)" from the base of the top Cretaceous. "The Phreatic nappe," a third, smaller structure, is added to the preceding two.

- The CI aquifer is composed of sandy and sandy-clay deposits. It spans the Triassic to Lower Cretaceous periods and is commonly referred to as the Albien aquifer after its top level (Cornet, 1964; Aumassip et *al*., 1972). It is a massive reservoir that gets extra water circulation under the southern Oran Hamada and the Western Erg from water infiltration from the Saharan Atlas (Castany, 1982; Cornet, 1964; Castany, 1991). The pressure at the top of wells in this aquifer reaches roughly 30 kg/cm2 in Ouargla, and the largest flow rates are achieved from artesian wells (Lelièvre, 1969; Albient & Margat, 1970; BRL, 1998).

- The CT consists of multiple lithostratigraphic formations, with aquifer formations included within the Upper Cretaceous and Tertiary permeable layers. This complex in Algeria has two separate aquifer formations (Cornet, 1964; Nesson, 1978; Castany, 1982). The first is found in Miopliocene sands, whereas the second is found in Upper Senonian and Lower Eocene (mostly Senonian in Ouargla). These aquifers are predominantly fed by runoff from the basin's perimeter (Mzab ridge's eastern slopes) (UNESCO, 1972;Guendouz et *al*., 2003; Besbes et *al*., 2003), as well as infiltration via the Eastern Erg (Nesson, 1978; Edmunds et *al*., 1997; BRL, 1998).
- The phreatic aquifer is enclosed inside Quaternary rocks, which are mostly made of alluvium from the Oued Mya valley. It encircles the whole Ouargla basin. The aquifer is contained in the Quaternary surface sands, which are formed of fine to medium clayey sands, seldom coarse south of Ouargla, and becoming gypsum-rich as one proceeds north (N'goussa and Sebkhet Safioune), with gypsum dominating at Sebkhet Safioune. Its capillary fringe frequently appears on the ground as little chotts on each side of the city of Ouargla (Bernard & Gardel, 2003).

- **Methodology**

In order to better understand the geometry of the underground reservoir in the region studied, a litho-stratigraphic correlation was carried out based on the information provided by the lithological and stratigraphic sections of water drilling and cores carried out on the entire basin by ENAGEO (1992) and LTPS (1995–2018). The section is oriented from southeast to northwest. Outside the study area, it passes through Rouissat, Aïn el Beïda, Sidi Khouiled, Bour el Haïcha, N'goussa, and Hassi bou Taieb. It refers to drilling data that captures the CI: J10-580, J10-581, J10-583, J10-511, J10-568, and J10-621.

Based on data from lithological sections from drillings carried out between the years 1898 and 2008, maps of the roof and the walls of the reservoir formation in isobath curves were created. The equal-depth curves of the roof of the formation are determined in relation to the ground surface (Castany, 1982). These maps make it possible to establish the morphology of the impermeable roof of the Miopliocene and Senonian aquifers of the Terminal Complex.

From a hydrodynamic viewpoint, the two key variables that define an aquifer are the storage coefficient, which describes the storage function, and the transmissivity, which is represented in m2/s and characterizes the conductive function of the reservoir. Results of the pumping tests were used for estimating each aquifer's transmissivity and storage coefficient.

We compared the maximum piezometer levels observed during the period 1959-1964 (Lelièvre, 1969)and during the period 1998-2023 (ANRH, 2023) in piezometers P001, P002, P004, P007, P025 and P027 to study the interannual fluctuation of the Phreatic Aquifer in long-term.

Results and Discussion

- **Geometry of reservoirs**

Observation of the litho-stratigraphic section of the study area (Figure 2) shows the presence of the Barremian. It is captured in the clay-sandy lithological formation, arriving at a depth of 2400 m in drilling J10-568. Above this Barremian, the Aptian is present to the northwest; its thickness increases and reaches 310 m in borehole J10-568, but it is absent in boreholes J10-581 and J10-511.

The Albian is found throughout the region, with a thickness varying between 64 and 644 m, hence the importance of the aquifer potential. This thickness decreases towards the southeast between boreholes J10-568 and J10-581. A slight increase in the thickness is recorded at drilling J10-511. Measuring 120 m in thickness, the Vraconian is found exclusively at drill J10-681.

Throughout the region, the Cenomanian is present and takes an anticlinal form. The Turonian tops it. The thickness of the latter is more or less stable at the level of boreholes J10-621 and J10-581, and it is less significant at the level of borehole J10-568, which is the summit of the anticlinal. The Senonian is present throughout the region with a very significant thickness (600 m). The Eocene is thinner in the northwest and nonexistent in the southeast. In the area, the Miopliocene is omnipresent and has a relatively constant thickness. It covers the Senonian immediately at drilling level J10-568.

The depth of the Albian at well J10-511 is 1400 m, and 2144 m at well J10-568. The difference of 744 m allows us to deduce the existence of a fault between the two wells, which caused the collapse of the formations in the vicinity of well J10-568.The Vraconian is only present at the level of drilling J10-681, with a thickness of 120 m.

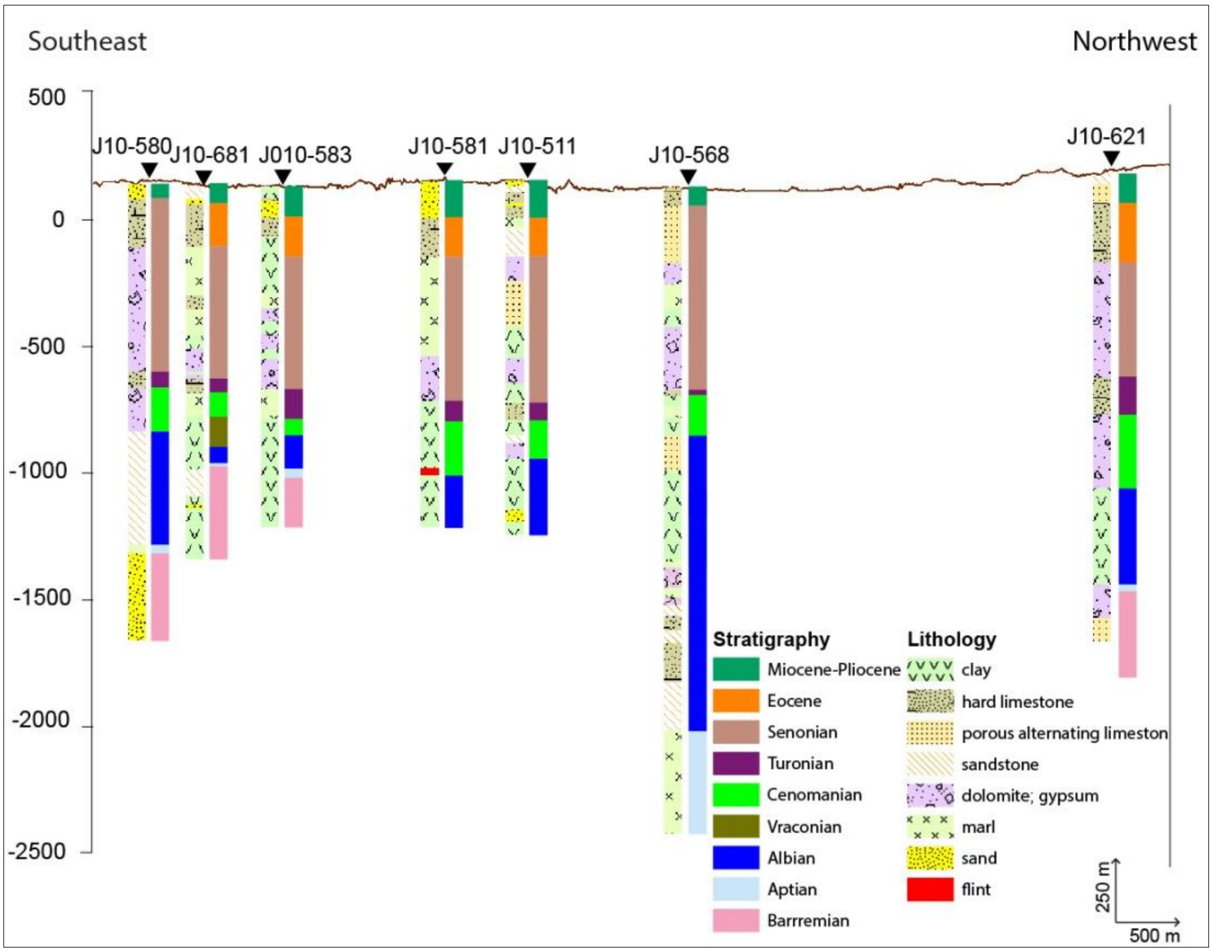

Figure 2: Litho-stratigraphic cross section of Ouargla.

- **Aquifer Formation's**

Figure (3) shows that for the CI, we only have five boreholes, so it is impossible to map the roof. According to the data from these drillings, the roof of this aquifer is located -850 m from sea level and -1000 m from the ground; the thickness of this reservoir is 800 m in total.
The Miopliocene roof map for the CT indicates shallow depths in the southern region that don't go below 40 meters. At Sebkhet Safioune, the depth rises to 90 meters as one moves north.
The national water resources agency's (ANRH) 2018 inventory of drilling data for the Senonian aquifer only includes data from the southern portion of the research region; the roof's depth increases from southeast to northwest.

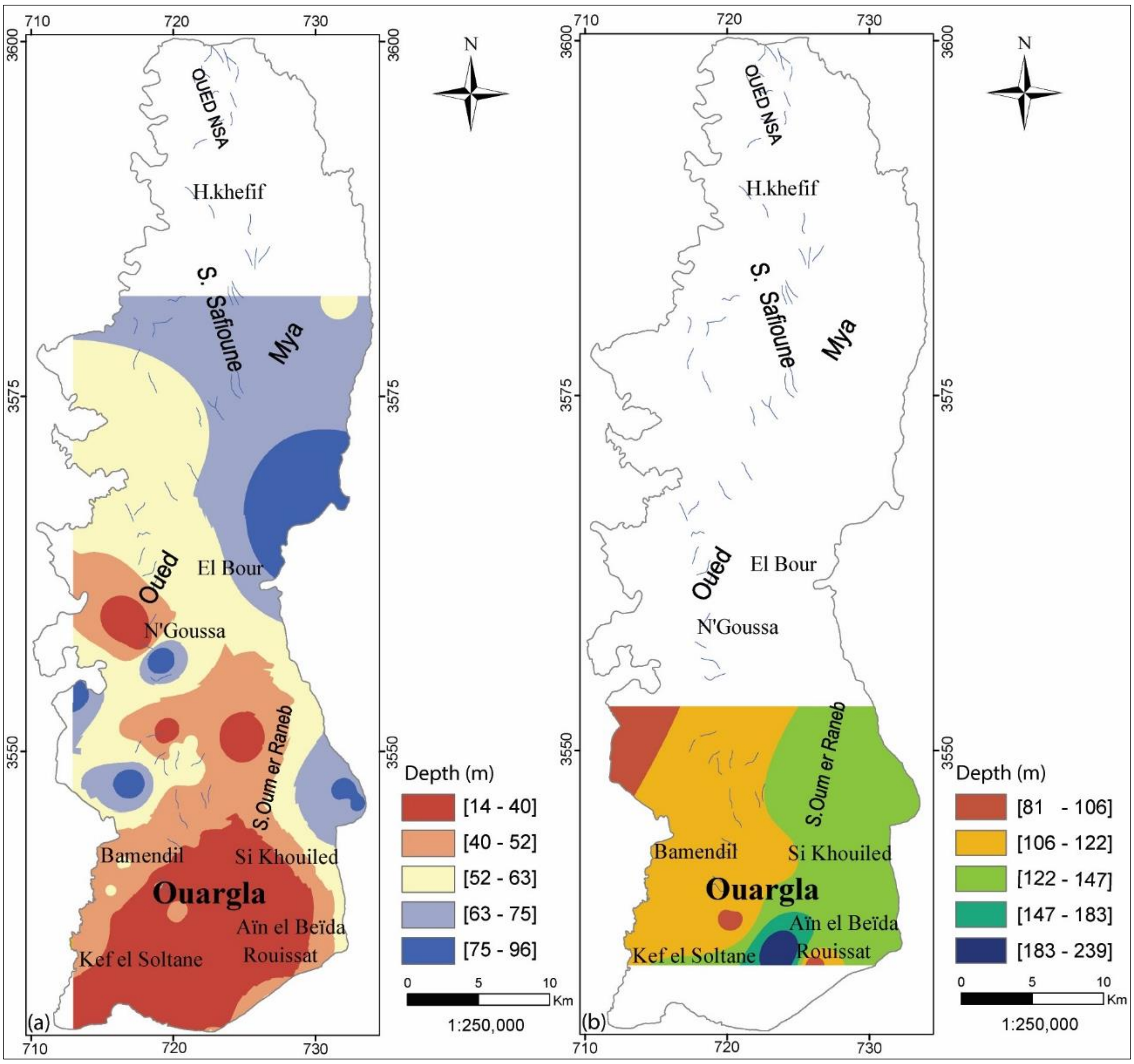

Figure 3: Map of the roof of the CT aquifer, Miopliocene (a) and Senonian (b).

The map of the wall of the deep Miopliocene and Senonian layers of the study region presents the same appearance as that of the roof of the same formation (Figure 4).

The wall of the Miopliocene aquifer reaches depths greater than 200 m in the southeast, and the lowest depths are encountered in the southeast of the region as well as in downtown Ouargla and the northwest of N'goussa. As we move towards the north, the depth increases significantly, reaching a value of 120 m at El Bour and 175 m at Hassi El Khafif.

The Senonian aquifer wall's depth descends from west to east, reaching depths of almost 300 meters north of Aïn el Beïda and reaching its lowest points west of Kef El Soltane.

Recent formations contain the phreatic aquifer. Between one and five meters lie beneath the city and the principal palm groves; this thickness, which is known to be permeable (soft sand and sandstone), gradually diminishes to the southwest of Mekhadema and to the east of Chott and Sidi Kouiled.

The continuity of the marl, clay, or compact limestone formations thought to make up the superficial aquifer's impermeable bedrock is uncertain, and it is impossible to completely rule out the possibility of exchanges between the phreatic aquifer and the Miopliocene aquifer due to either the bedrock's local absence or drainage through it.

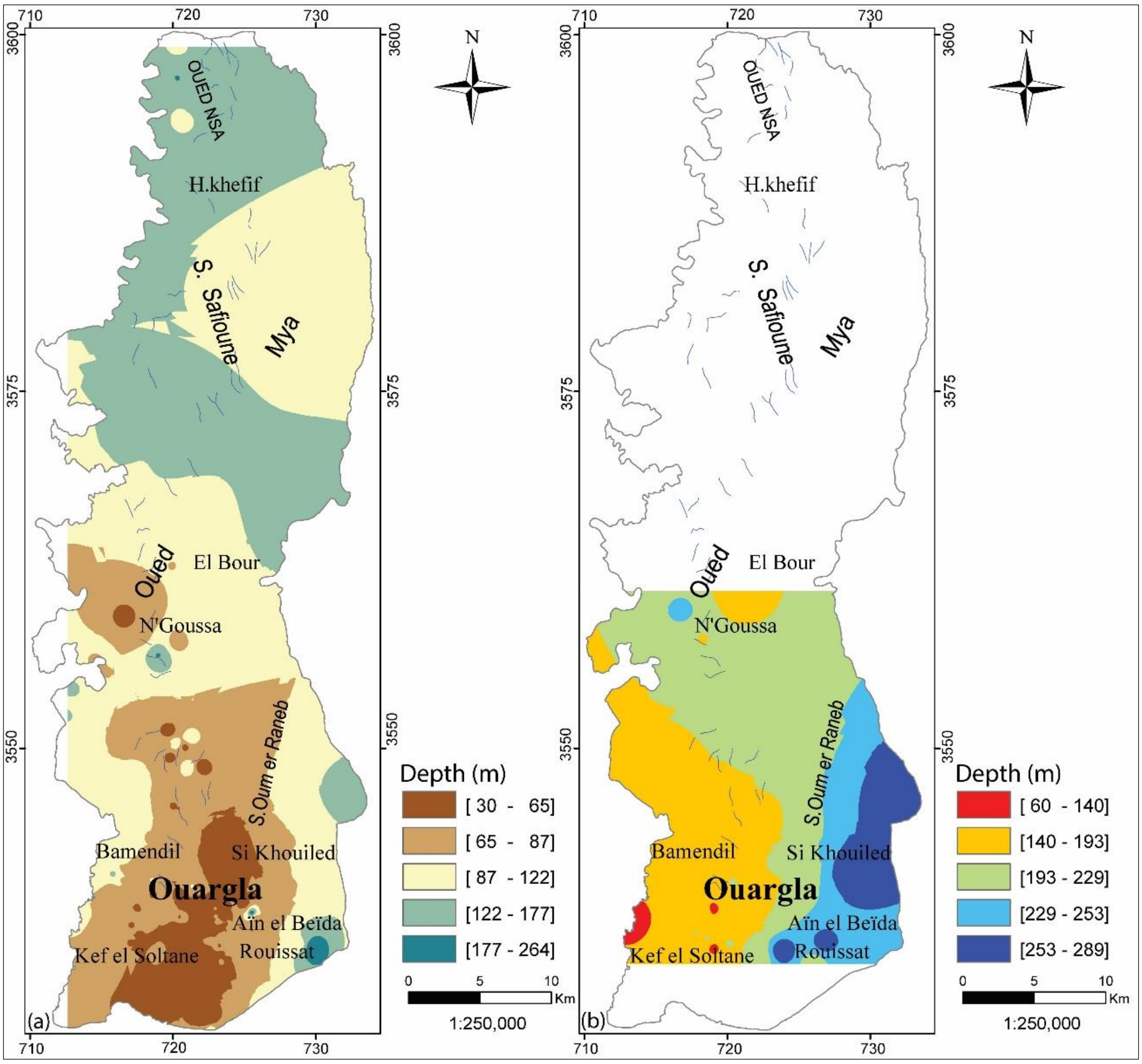

Figure 4: Map of the Terminal Complex's table wall, Miopliocene (a) and Senonian (b).

- **Hydrodynamic Aquifer Characterization**

Transmissivity governs the flow of water that flows per unit width of an aquifer under the effect of a unit hydraulic gradient. It is equal to the product of permeability and the thickness of the aquifer.

In Ouargla, the CI aquifer has a transmissivity of 8.10^{-3} m^2/s. For the CT aquifer, the values range from 8.10^{-3} to 9.10^{-2} m^2/s, whereas for the groundwater table, they range from $9.37.10^{-3}$ to $1.86.10^{-2}$ m^2/s.

The storage coefficient S, without dimension, expresses the ratio of the volume of water released per unit of surface area of the aquifer and per unit of variation of the hydraulic head. For a phreatic aquifer, this parameter is equivalent to the effective porosity; it is expressed in %. For a confined aquifer, it is much smaller.

The values of the average storage coefficient calculated for the captive aquifers are 10^{-3} m^2/s for the CI and between 5.10^{-3} and 3.10^{-2} m^2/s for the Terminal Complex. At the level of the free aquifer of the phreatic, the values of S vary between 10^{-2} and 2.10^{-1} m^2/s.

- **Aquifers Exploitation**

For the Albian, a first reconnaissance survey was carried out in 1956, and it was stopped for technical reasons at a depth of 893 m in the Cenomanian. A second borehole, located 350 m west of Bordj Chandez at an altitude of 137.5 m, was immediately started and reached the aquifer levels in the same year, and water gushed out with a flow rate of 258 l/min. At the wellhead, the pressure is 22 kg/cm2, and the piezometric height is 405 m. In 1961–1962, two more wells were drilled: one in Trois Pitons, a previously deserted area east of Erg Touil, and the other in El Hadeb, southeast of Rouissat.

In order to guarantee the Ouargla region's access to drinking water, two boreholes have been erected in Rouissat: El Hedeb I drilling, which has a depth of 1335 m and a flow rate of 141 l/s, and El Hedeb II drilling, which has a depth of 1400 m and a flow rate of 68 l/s.

The Ouargla Miopliocene aquifer has been exploited since a very long time ago (Moulias, 1927). Because it was crucial in the creation of the oasis and made it prosperous, this tablecloth has come to be known by its mythical reputation. Its piezometric level was once greater because Ain Sfa in Sedrata, which is 8 km upstream, gushed at a height of almost 145 meters. Beni Sissine West and Beni Brahim, two of the historic palm grove's wells, spouted at 133 and 134 meters above sea level (Bel, 1966). This level has decreased due to the centuries-long increase in drilling. It is now impossible to say whether or not the resources compensate for current exploitation; according to the ANRH inventory (2023), more than 900 drillings have been listed. Prudence imposes a limit of use beyond which the phreatic table could risk flooding.

For the Senonien, a 315 m-deep survey well was completed in 1953. Up until 1969, the flow rate never went above 540 l/min; it stayed at 480 l/min with a piezometric level no higher than 136 m and artesianism of less than 1 km/cm2. Since then, a 420 l/min pump has been installed. The low yield of this well has long led to neglect of the exploitation of the Senonian aquifer. In 1965, a borehole was carried out to the northwest of the Beni Thour palm grove, and in 1969, two other boreholes were carried out, intended to supply the city with drinking water and to irrigate an extension of Mekhadma, Garet Chenia, bringing the water table flow to 2485 l/min. Currently, 73 wells are spread among the Ouargla, Rouissat, Hassi Ben Abdallah, Sidi Khouiled, An el Beda, and N'goussa districts (ANRH, 2022).

- **Phreatic aquifer piezometry**

The "Evacuation and drainage of water from the Ouargla basin" project included the installation of a phreatic aquifer monitoring network in Ouargla. ENAGEO installed 160 piezometers in 1991. Subsequently, in 1992, 2001, and 2003, a supplemental program was introduced; over 200 piezometers are included in this program (ANRH, 2004–2023). As of 2023, the ANRH inventory reveals a very striking decline in the network's state, with only 85 piezometers remaining.

The piezometric observations carried out periodically allowed us to establish five (05) piezometric maps corresponding to: November 1998, April 2001, June 2003, November 2007, and June-November 2018 (Figure 5).

The appearance of the piezometric map of the phreatic aquifer established in 2023 (Figure 6) does not differ too much from what it was in previous years (Figure 5). Underground flows generally follow the local topography with a slope towards the east and west sebkhas, but with a considerable piezometric dome under the agglomeration, swelling that even extends upstream in areas with low urbanization and without current water.

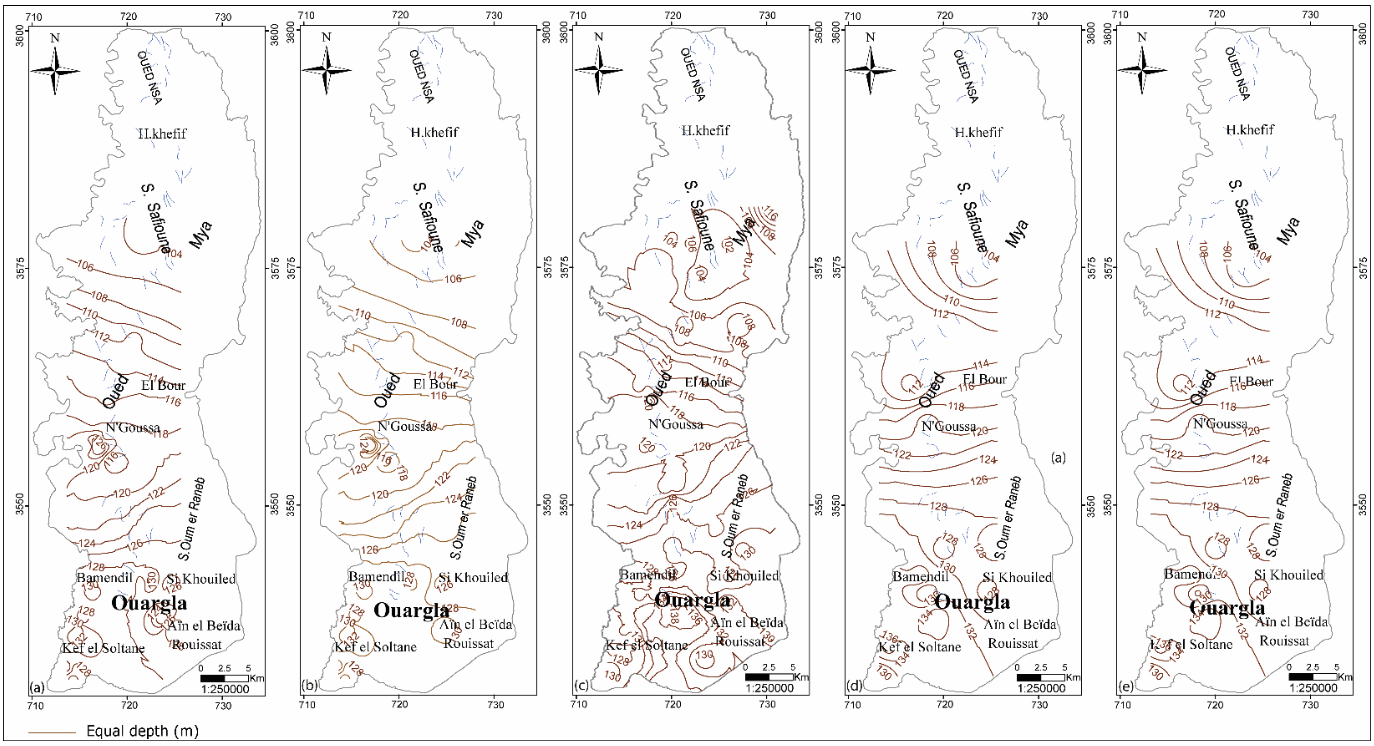

Figure 5: The piezometric maps for: November 1998 (a), April 2001(b), June 2003 (c), June 2007 (d) and June 2018(e).

We see the same phenomenon for N'Goussa, with circular swelling around the palm grove, more significant upstream than downstream. The piezometric dome in the Chotts region corresponds to a significant supply area where we notice a narrowing of the piezometric curves.

The maps established show that the general flow of the water table takes place from south to north, following the slope of the valley, and they confirm the existence of two distinct zones, separated by a dividing line located to the south of Bour El Haicha. The first zone extends from Bour el Haicha in the south to Sebkhet Sefioune in the north. The second corresponds to the southern part of the basin and includes Rouissat, Ain El Baida, and the surrounding chotts.

- **Seasonal fluctuation of phreatic aquifer**

The piezometric levels show seasonal fluctuations; the origin of these fluctuations can, a priori, be threefold: Fluctuations due to seasonal variations in intake; Fluctuations due to the propagation of flood and recession waves from the Chott (either by the water table or by the drains); Fluctuations due to seasonal variations in evaporation.

In order to research by zone of preponderant influence of these three actions, we divided the study region into three clearly individualized zones. The first zone brings together the Chott of Ain el Bieda, the palm groves bordering the Chott (east, southwest, south, and southeast), the palm groves of Rouissat, and the palm groves of Oum Raneb. The second brings together the cities of Ouargla, Bamendil, and N'Goussa, and the third presents the rest of the basin up to Sebkhet Safioune.

- Zone I study: The motor pumps that move water from the Said-Otba canal into the Oum Raneb discharge zone have stopped working, which has resulted in an increase in the aquifer's water level in the Chott. The level fluctuations of the chotts only influence the piezometric levels of the water table in the immediate vicinity of the latter and that the piezometric fluctuations observed, in phase with those of the chott, are due to the combined influence of drains and variations in evapotranspiration in palm groves.
- Zone II study: The supply is stronger in summer (52.1 $l.s^{-1}$) than in winter (37.5 $l.s^{-1}$) and the influence of the chott cannot be felt there (distance chott city of about 2 km and absence of drains). Evaporation is less strong in this area than in the rest of the basin. The summer maximum proved that the seasonal variation in food very roughly outweighs the seasonal variation in evaporation.
- Zone III study: The supply is practically constant during the year, with a drop in the static level, which is often less than 1 meter from the ground surface. These zones are subject to significant evaporation, especially in the regions of Sebkhet Sefioune and Sebkhet Bamendil.

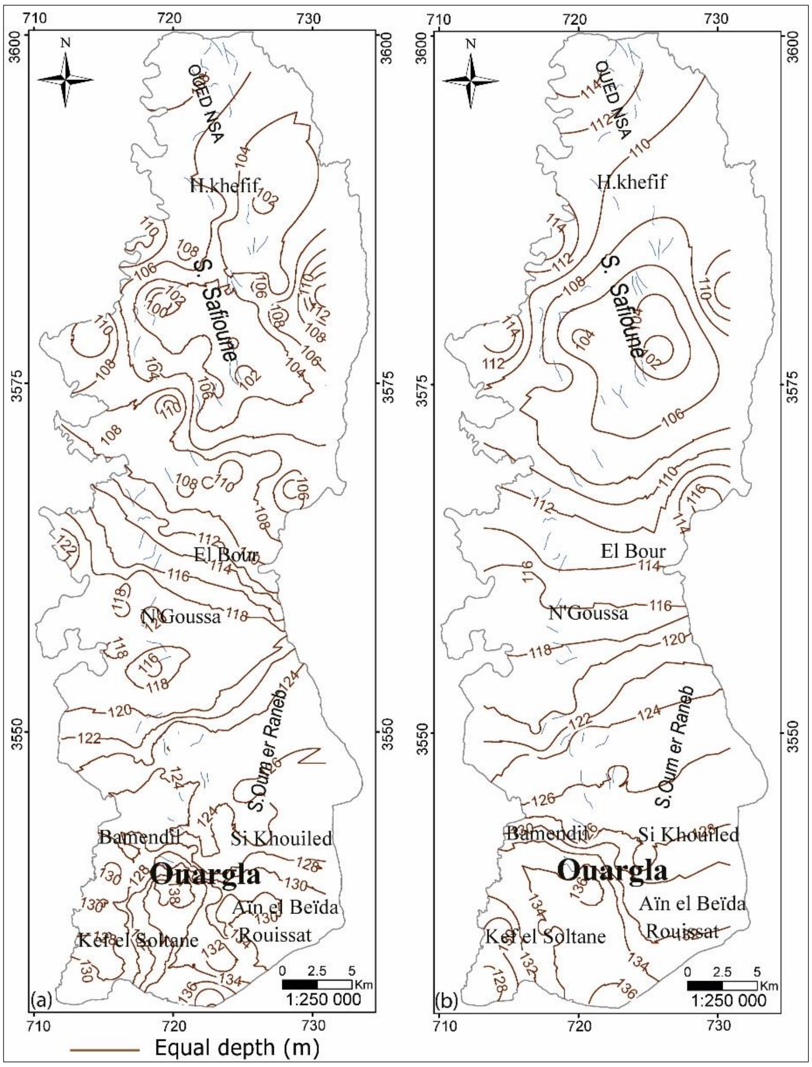

Figure 6: Seasonal fluctuation between two low-water periods in June (a) and high-water periods in November 2023 (b).

- **Long-term interannual fluctuation of the Phreatic Aquifer**

Table 1: Maximum Piezometric Levels Observed Between 1959 and 1964 and 1998 and 2023.

Piezometer / Period	P001	P002	P004	P007	P025	P027
1959-1964	130,30	132,15	133,55	130,90	127,65	128,50
1998-2010	130,93	132,13	133,76	132,10	127,82	128,48

The data suggests the water table is spread out in two piezometers, P002 and P027, where it has risen by 20 cm in two others, P004 and P025, by 60 cm in another P001, and by 1.20 m in the last P007. This indicates that the water table is continually increasing and is not in interannual balance. It is worth mentioning that a general average increase in the water table of 20 cm over ten years amounts to a storage of roughly 6 million cubic meters of water, which translates to an excess stored flow of around 20 l/s when equally divided over ten years (Lelièvre, 1969).

Additionally, we observe from the analysis of the piezometric map created in 2023 the existence of a remarkable rise in the piezometric surface compared to the years 1998–2010. Indeed, comparison of the current levels of the water table with those of 1998–2010 shows that the water table has risen by several meters and that the rise is greater than 5 meters in the southeast sector north of the city.

Conclusion

The establishment of a hydrogeological section based on information provided by the lithology and stratigraphy of water boreholes made it possible to understand the geometry of the underground reservoir.

Detailed analysis of the Ouargla basin's lithology and stratigraphy unearthed a three-tiered aquifer system. At its core lies the Continental Intercalary, a robust reservoir housed within the Lower Cretaceous continental formations. Atop this rests the TC Aquifer, a mosaic of smaller units nestled within Senonian and Eocene carbonates, or Miopliocene sands. Finally, the Quaternary's permeable sand-gypsum deposits cradle the shallow phreatic aquifer, completing the picture of Ouargla's vital water resources. This intricate layering underlines the importance of understanding each aquifer's unique characteristics and vulnerabilities as we seek to manage this precious resource sustainably.

The structural maps of the deep aquifers show that the thickness of the CI aquifer is 800 m in total, that of the Miopliocene is around 95 m, and that of the Senonian is around 140 m.

However, intensive exploitation of aquifers, particularly that of the Miopliocene, has led to major challenges such as decreasing water levels, increasing salinity, and abandonment of agricultural land. Sustainable management of this resource therefore becomes imperative to preserve water quality and maintain the stability of local ecosystems.

The knowledge of hydrodynamic parameters, such as transmissivity and storage coefficient, provided crucial insights to assess the capacity of aquifers to meet demand while maintaining ecological balance. The phreatic aquifer is characterized by seasonal and annual fluctuations. An average decrease in the static level of around 16 cm was noted between 1992 and 1995. On the other hand, in 1998, the variations reached 1 m to 1.5 m. In 2023, they do not exceed 30 cm, a consequence of the importance of contributions from different origins.

Thus, the conclusion drawn from this study highlights the urgency of integrated and sustainable management of groundwater resources in Ouargla. Conservation measures, more efficient agricultural practices, and increased awareness are necessary to ensure the long-term preservation of this crucial resource in the context of climate change and increasing human activities.

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