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GROUNDWATER OVEREXPLOITATION OF THE CONTINENTAL INTERCALACRY AQUIFER. A CASE STUDY FROM GHARDAIA, ALGERIA

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Abstract: Since the late 1999, extensive groundwater extraction within the Sahara aquifer system has been investigated. In this study we analyze the overexploitation of the thermal groundwater stored in the Continental Intercalary aquifer in the Algerian province of Ghardaia. The Saharan aquifer system is recognized by a large number of over 8800 boreholes and springs, on which 3500 operate the Continental Intercalary series and 5300 operate the Terminal complex. This work describes the groundwater order problem of overexploitation and the flows that exploit this hydrothermal system to be identified and analyzed. We have negative impacts on groundwater in that region due to the practice of certain activities which directly affect the quantity causing the water level of the aquifer to be lowered. Using theoretical context, water quality status can be assessed and recommendations suggested. Results show that we have 387.86 million m^3/yr of flow today which is determined 30 m drawdowns. Measures need to be taken until the effects of the appeal become irreversible and the legal system instruments need practical applicability to prevent this context from extending to other areas.

Key words: Algeria, continental intercalary, drawdown, groundwater, piezometric level

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INTRODUCTION

In Algeria, due to its rarity and interruption of its natural cycle, water occupies a crucial role in economic development, especially for the areas getting closer to the desert, such as the Ghardaia province (86,000 km^2 wide, South of Algeria, located in the northern parts of the Sahara Desert). Agricultural production over the last 50 years and population growth in the Ghardaia province resulted in considerable water demand. Groundwater is the primary source of water supply for several cities, such as Ghardaia City and Sebseb, contributing more than 70 per cent to the water needs of more than 96,000 residents. When groundwater extraction exceeds groundwater recharge in extensive areas over a long period of time such as Ghardaia province, depletion of groundwater may occur (Wada, van Beek, & Bierkens, 2012). The term overexploitation occurs when extraction exceeds both the natural and induces long-term aquifer recharge (Pophar, Lamsoge, Katpatal, & Nawale, 2014). Some widely known examples of researches on groundwater depletion are US High Plains and Central Valley (Scanlon, et al., 2012), North China Plain (Jiang, et al., 2020; Kinzelbach, Wang, Li, Wang, & Li, 2021; Feng, et al., 2022; Zhou, Dai, Wei, & Luo, 2023), southern Europe (Herandez-Mora, Martinez, & Llmas, 2007; Kallioras, Pliakas, & Diamantis, 2010) and Algeria (Amroune, Mihoub, Guastaldi, & Urena-Nieto, 2020; Dekakra, Menani, & Khedidja, 2022).

Ghardaia province is masked by the strong early Quaternary erosion of the river which cut the flat-topped buttes and shaped valleys in its southern part. Two aquifers exist in this region, the Continental Intercalary, and the Terminal complex. Continental intercalary midsole series combines Lower Jurassic and Lower Cretaceous terms. Terminal complex ranges from the Upper Cretaceous to the Paleocene, Eocene, and Miocene, the carbonate formation period. However, due to over-exploitation by unregulated pumping, the piezometric level is gradually lowering (Amroune, Boudoukha, Boumezbeur, Benaabidate, & Guastaldi, 2017). The condition of degradation and decline of water supplies is not only limited to Ghardaia province, but it’s present also in Saudi Arabia and the Gulf States (Mihoub, 2017).

The nomenclature of boreholes and the study of water volumes are taken from the Continental Intercalary deep aquifer, since the extensive extraction of groundwater supplies has greatly affected this aquifer's hydrodynamic functioning. As a result, flow extracted from the Saharan aquifer decreased significantly. The problem is much more pronounced in the world where climate changes have led to a rise in water demand for multiple uses. Groundwater overexploitation is a relatively typical problem in semi-arid, arid or Saharan climate regions as recorded in numerous studies (Changming, Yu, & Kendy, 2001; Salameh, 2008; Pophar, Lamsoge, Katpatal, & Nawale, 2014; Amroune, Boudoukha, Boumezbeur, Benaabidate, & Guastaldi, 2017; Gonzalez, Carreon, Franceschini, Cerca, & Teatini, 2018).

The cumulative pumping rate was quantified at 387.86 million m^3 per year, while the total recharge is zero, in an area where people believes that water is a inexhaustible resource in such aquifers (Mihoub, 2017). This means in not renewable underground water the medium rate of aquifer recharge is very weak, but on the other hand with very important complete reservations (several km^3 often). Then, such a overexploitation consists in a sort of a working of underground water of mining type, when means are not renewed, that implicates a reduction of reservations (Custodio & Llmas, 1976; Columbus, 1992; Margat, 1992). The consequences of this problem, among others, could be at different levels:

Environment: water quality change, due to physico-chemical imbalances caused by excessive drainage of aquifers;

Economic: higher operating costs, for water level depth increasing; drop loss, by wells being dry or producing very low; need to carry water from a distant location.

MATERIALS AND METHODS

Study area

The Ghardaia province extends across the northern part of the Sahara basin. This is bordered by the Grand Erg Occidental to the west, the Grand Erg Oriental to the east, the

Timimoun depression to the south and the Saharan Atlas to the north (Figure 1). It is characterized by an arid climate type, with minimum and maximum air temperatures varying during the summer and winter months from 14°C to 47°C and from 2°C to 37°C respectively. The area is distinguished by 68 mm of annual rainfall on average (Mihoub, 2017). On the other hand, mean annual evapotranspiration, as estimated by empirical formulae such as Thornthwaite, Turc, and Penman, ranges from 2000 to 2800 mm per year (ANRH, 2006).

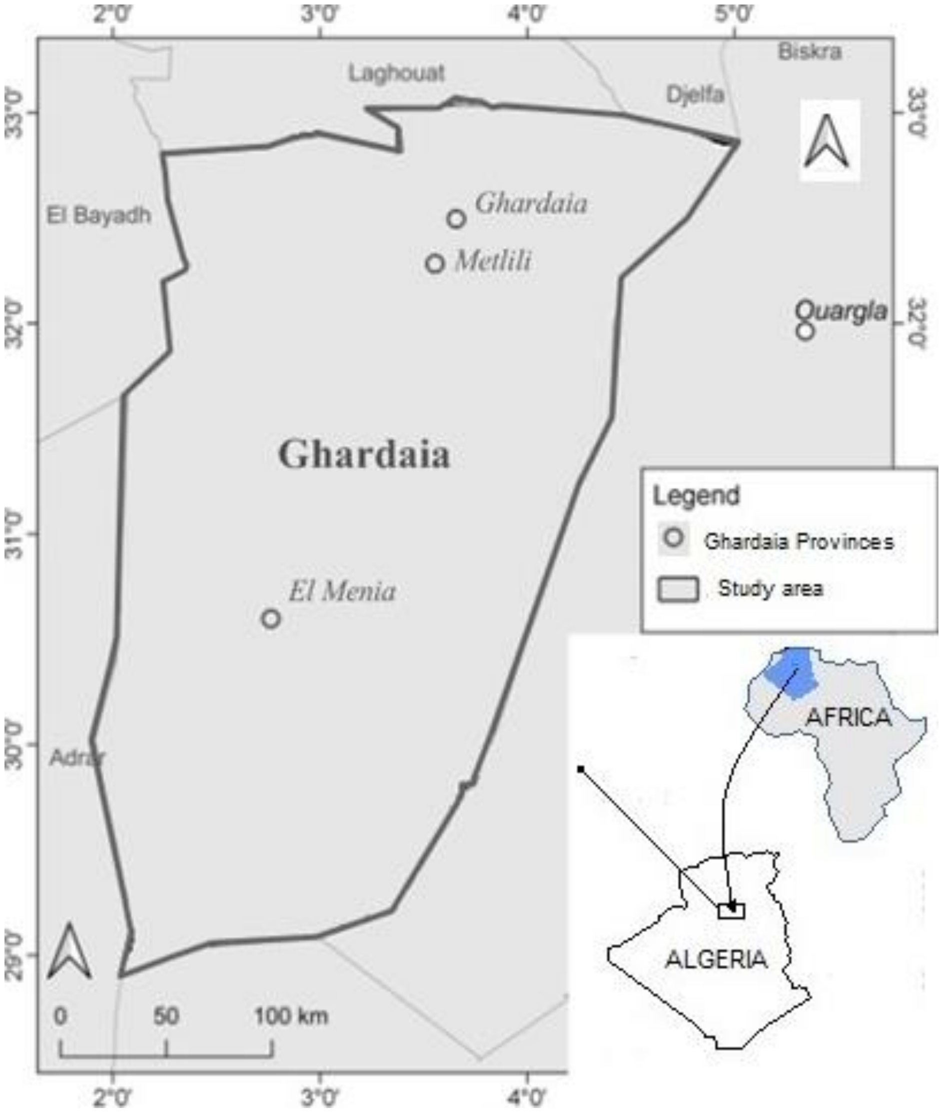


Figure 1. Geographical location of the study area

The extensive drainage network consists of a few ephemeral flows, locally called wadis, which collect surface runoff from the Saharan Atlas to the Timimoun and Oued Mya continental depressions (Mihoub, 2017). The study area pediments, which generally encompass loamy soils rich enough in organic matter, involve eolic or river soils and form the arable land of traditional oases. The plant cover in the oasis consists of almost intact date palm forests (*Phoenix dactylifera L.*), organized into various gardens separated by walls of palm trees.

Geological setting

Ghardaia province presents a succession of geological formations, from the Cenomanian to the Continental Miocene-Pliocene. The Carbonate and Marly Upper Cretaceous formation is gradually thickening and deeping eastward, and is covered by more recent layers of Tertiary period, in particular of Miocene-Pliocene (Mihoub, 2017). The quaternary corresponds to the alluvial recovery sediments (Figure 2).

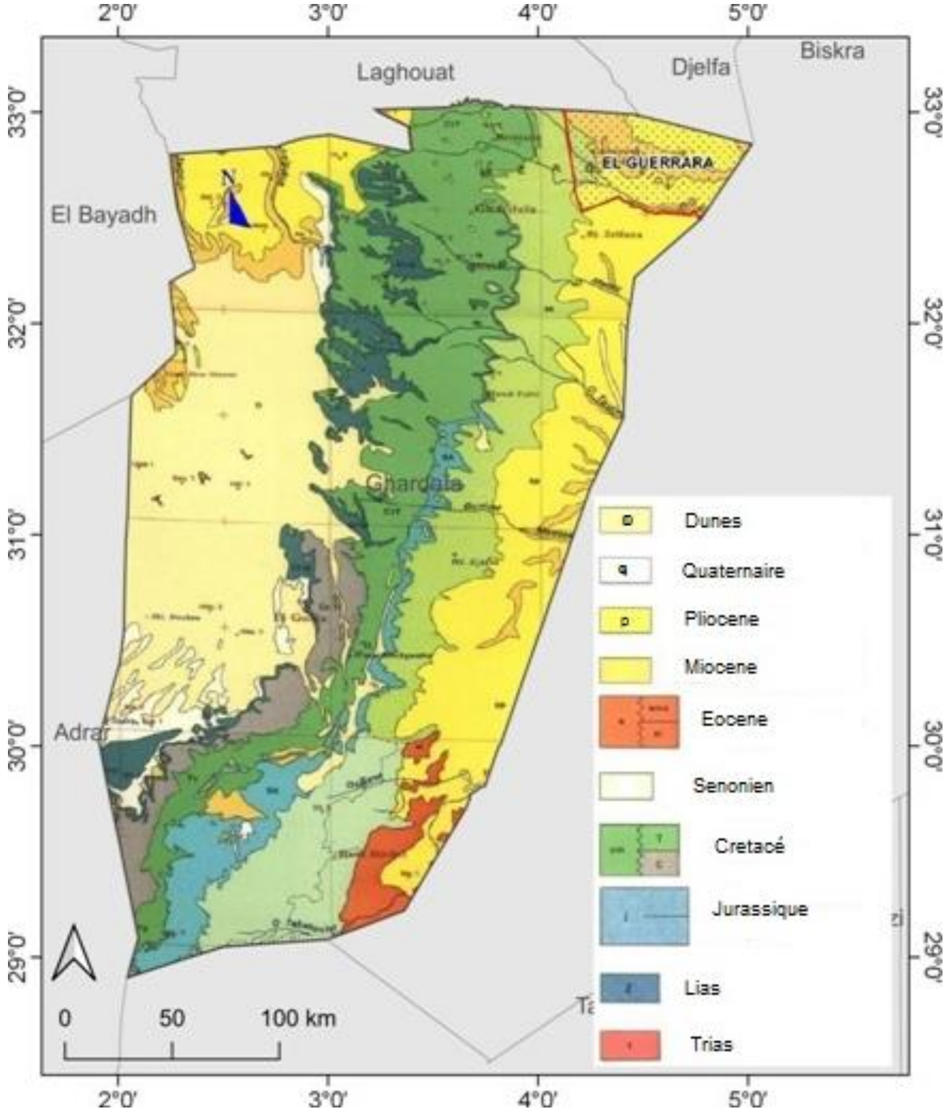


Figure 2. Geological map of the study area; SASS

The geology study also revealed the presence of large-depth formations (3,641–3,732 m) that can present significant geothermal potential. Hence, lithological observation enables the continental clay formations of the Lower Cretaceous to be defined (Neocomian, Barremian and Albian). This geological data will be associated with the thermal data and used to create digital models for understanding positive and negative thermal anomalies and their spatial behaviors.

Hydrogeological conditions

From a hydrogeological point of view, the three different aquifer systems being used are as follows (Figure 3):

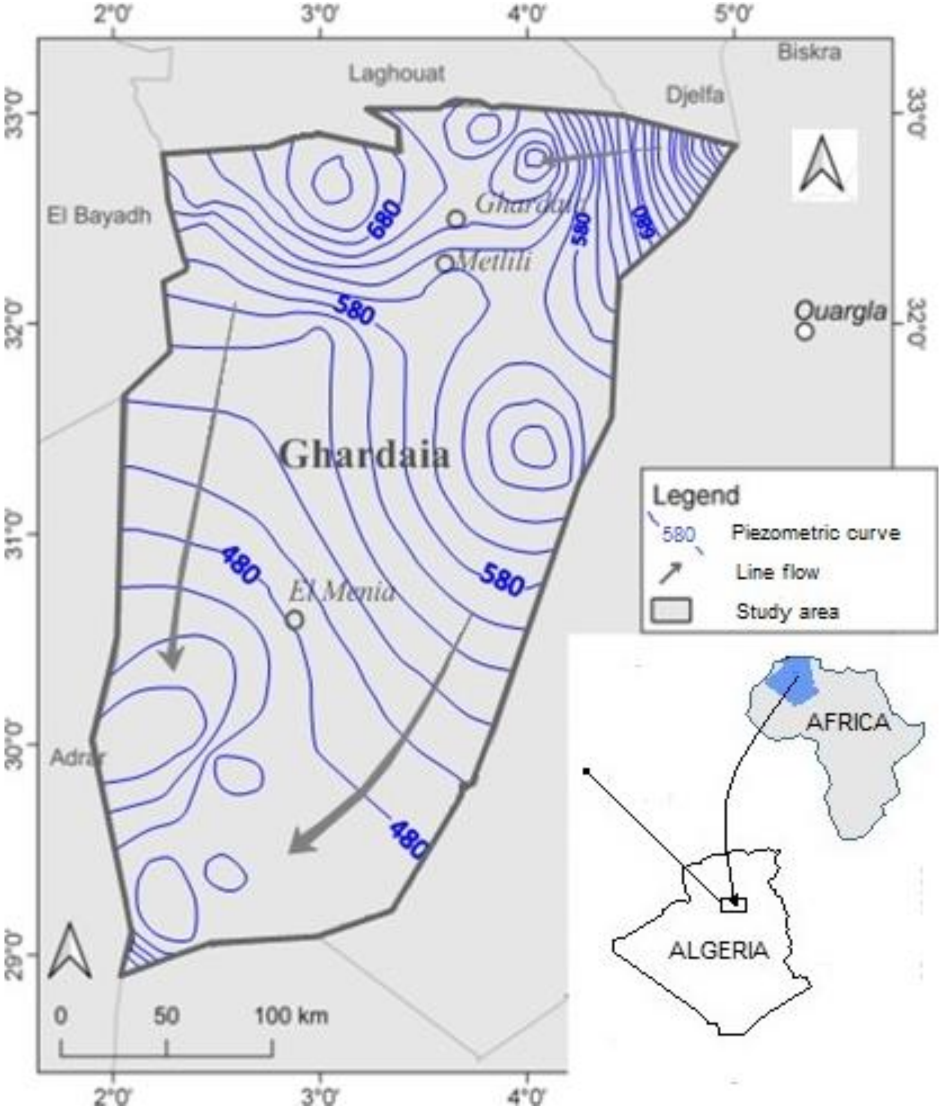


Figure 3. Hydrogeological cross-section of the Saharan basin

At the base, the Continental Intercalary aquifer (CI) is confined deep into the Lower Cretaceous formations. It is found in a complex sequence of Mesozoic age clastic sediments with a significant lateral variability in thickness and lithology. Its depth reaches 500 m locally (Bel & Demargne, 1966). The flow rates of the study region's boreholes range from 100 to 200 l/s.

The middle aquifer is composed by very heterogeneous formations of the Terminal Complex (TC). It represents the permeable Senonian limestone bases, as well as the Mio-Pliocene clay sands and sandstones. This aquifer has a depth of between 100 and 600 m and averages 300 m. It is contained within the boundaries of the region studied (Bel & Demargne, 1966; Bel & Cuche, 1970; Bel, Cuche, Schoute, & Lefort, 1970; UNESCO, 1972). The direction of flow of the aquifer as established on the scale of the entire study area (UNESCO, 1972; OSS, 2002) shows that the main flow proceeds from the north-west (recharge zone: Saharan Atlas) towards the south-east (discharge zone: Zelfana, El Guerrara and El Golia) (Figure 3). Mio-Pliocene formations on the surface contain the phreatic waters. It consists mainly of medium pink sand, rounded to subangular, passing locally to poorly consolidated white sandstone and white calcareous levels. It is exploited through more than a thousand wells dug by farmers. This aquifer's mean permeability is approximately 10^{-4} m/s (Guendouz, Moulla, & Reghis, 1993). Estimations of its horizontal transmissivity and storage coefficient were 10^{-2} m^2/s and 2.10^{-1} m^2/s respectively (Lavassor, 1978).

RESULTS AND DISCUSSIONS

Nomenclature of flows extracted from water points

The nomenclature referred to 565 boreholes exploited by CI aquifer, 426 of which are in operation providing a flow of approximately 387.86 Hm^3/year and 92 functional drilling capable of generating a volume of 85.65 million m^3 in addition, an inventory of illegal boring for their potential sealing was also taken out in the area of El Menia and Hassi el Fahel in the south of Ghardaia. The area has experienced a rapid change in the number of boreholes falling off the Continental Intercalary (Figure 4).

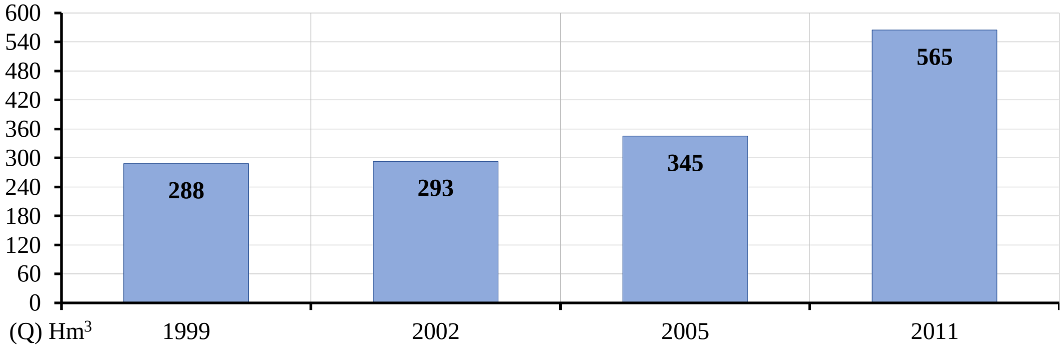


Figure 4. Mobilized flows in the period 1999 to 2011 (Mihoub, 2017)

This change is mainly due to the introduction of programs for agricultural growing in the territory (Figure 5), as well as to meet the increasing population's water needs. Table 1 and Table 2 show the CI operating volumes for the main three users in the main localities of the area (AEP: drinking water supply; IRR: irrigation and AEI: industrial water supply).

Table 1. Number of boreholes, exploitation volumes, water destinations
Data source: (Mihoub, 2017)

Municipality	**Total**	**Exploited**	**No Exploited**	**Average flow** (l/s)	**Extracted volume** (hm^3/year)	**Depth** (m)	**Destination**
Bounoura	18	13	3	30^{p}	7.73	500	AEP+IRR+ AEI
El Atteuf	21	16	3	25^{p}	6.70	500	AEP + IRR
Ghardaia	41	27	7	30^{p}	14.90	500	AEP+IRR+ AEI
Daya bendahoua	20	9	8	20^{p}	2.48	500	AEP + IRR
Berriane	22	12	6	30^{p}	7.59	500	AEP+IRR+ AEI
Metlili	39	25	12	80^{a}	13.42	1000	AEP + IRR
Sebseb	14	10	4	60^{a}	4.00	450	AEP + IRR
Mansourah	21	16	5	45^{p}	13.23	450	AEP + IRR
Hassi F'hel	40	33	6	$20\text{-}70^{a+p}$	59.47	250	AEP+IRR+ AEI
El Meniaa HG	262	209	34	30^{p}	178.07	500	AEP+IRR+ AEI

Guerrara	43	36	4	35^p	49.06	450	AEP + IRR
Zelfana	24	20	0	80^a	31.22	1000	AEP+IRR+ AEI
Total	**565**	**426**	**92**	-	**387,86**	-	-

Note: ^{p}: Pumping; ^{a}: Artesian, IRR: Irrigation, AEP: Drinking water supply, AEI: Industrial water supply

Table 2. Number of boreholes, exploitation volumes, water destinations
Data source: (Mihoub, 2017)

Municipality	**Boreholes**		**IRR Drilling**		**AEI Drilling**		**Total of drilling**	**Volumes extracted** (m^3/year)
	Number of boreholes	**Q** (hm^3/an)	**Number of boreholes**	**Q** (hm^3/an)	**Number of boreholes**	**Q** (hm^3/an)		
Bounoura	7	5.09	3	1.33	2	1.31	17	7.73
El Atteuf	8	2.45	6	1.26	2	0.51	21	6.70
Ghardaia	22	13.97	3	0.63	2	0.30	42	14.90
Daya bendahoua	4	1.30	4	1.02	1	0.16	20	2.48
Berriane	7	5.55	5	2.04	0	0.00	22	7.59
Metlili	11	7.27	10	4.03	1	0.26	39	13.42
Sebseb	1	0.79	7	3.41	0	0.00	14	4.00
Mansourah	2	1.05	11	10.10	0	0.00	21	13.23
Hassi F'hel	4	4.42	29	53.16	0	0.00	40	59.47
El Meniaa HG	18	10.30	184	163.88	5	3.13	262	178.07
Guerrara	7	6.53	26	40.98	0	0.00	43	49.06
Zelfana	5	10.00	11	20.18	4	1.04	24	31.22
Totals	99	68,71	299	302,02	17	6,71	565	387,86$^{(*)}$

Note: *Not including the volume of illicit boring (116 boring) in the valley of El Menia, which total a volume of water extracted 19,30 m^3/ year, which is 0,612 m^3 /s (Mihoub, 2017)

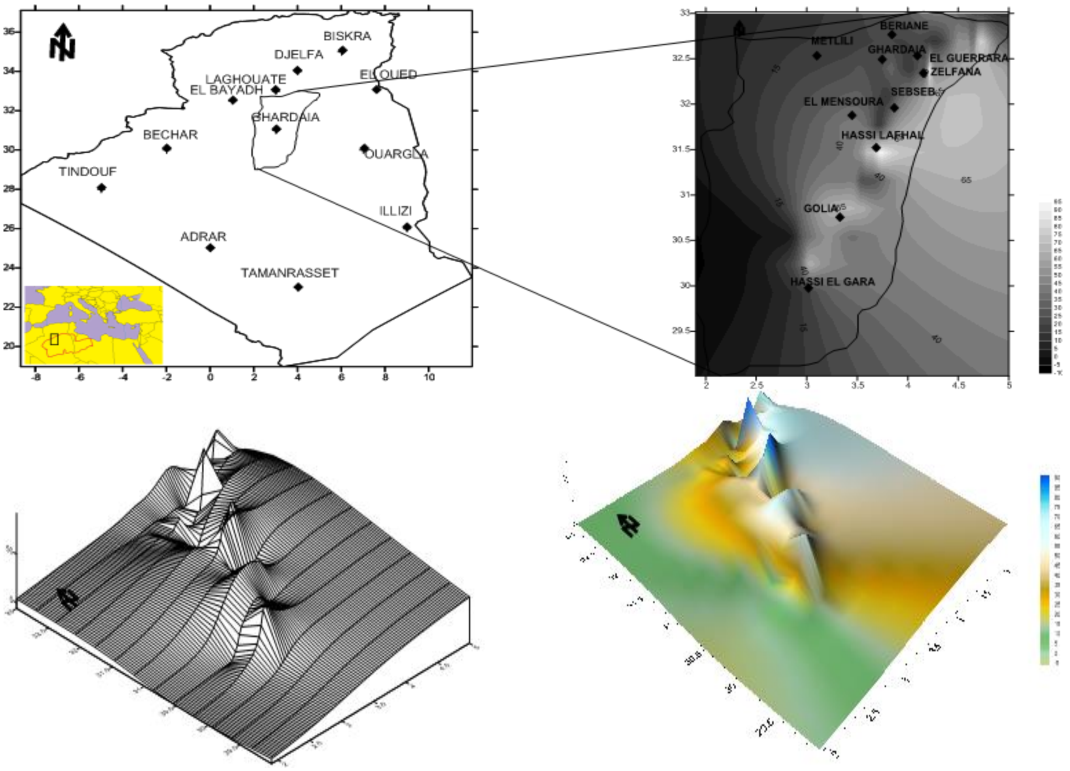


Figure 5. Flows extracted (l.s^{1-})

In this time (1999–2005–2011), the volumes exploited for the 3 applications AEP, IRR and AEI exceeded 179 million m^3/year in 1999 to 214 million m^3/year in 2005, compared to 388 million m^3/year in 2011 (Figure 6).

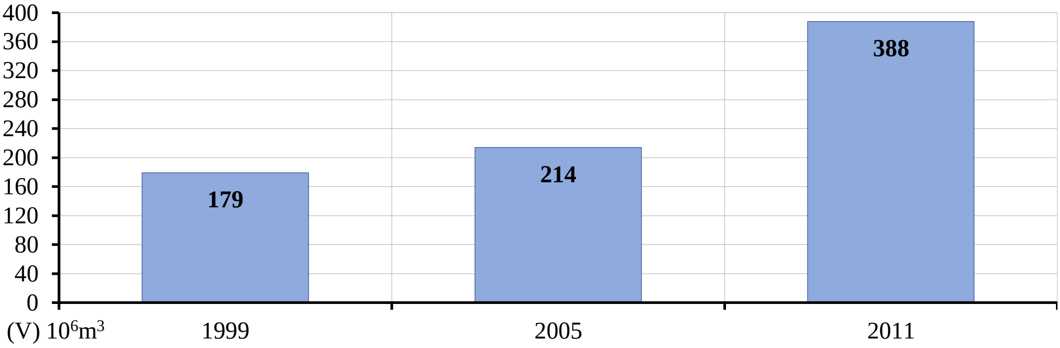


Figure 6. Evolution of the volumes of water taken out of the aquifer during the period (1999-2005-2011)

299 boreholes are intended for agricultural use on the 426 drilling operated throughout the territory. This means that the total volume of water in the agricultural sector is 302 million m^3/year of total mobilized water (Figure 7).

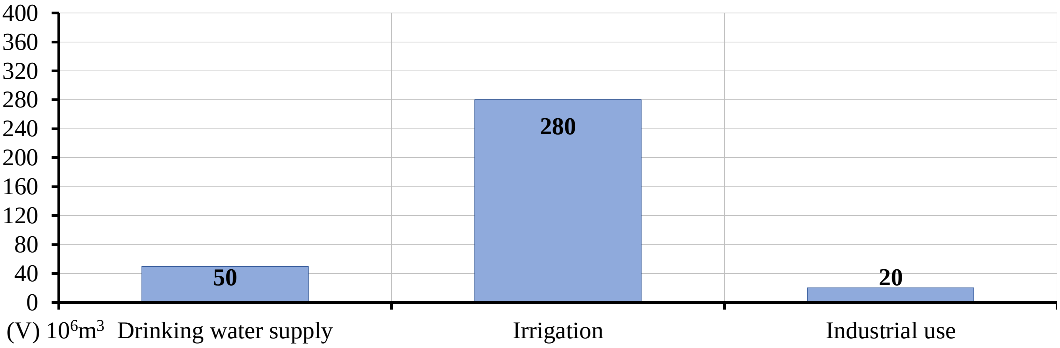


Figure 7. Volumes of water elevated by uses

The entire debit side collected by the CI is 387, 86 million m^3/year (Figure 8), which is 12, 30 m^3/s by 426 exploited boring.

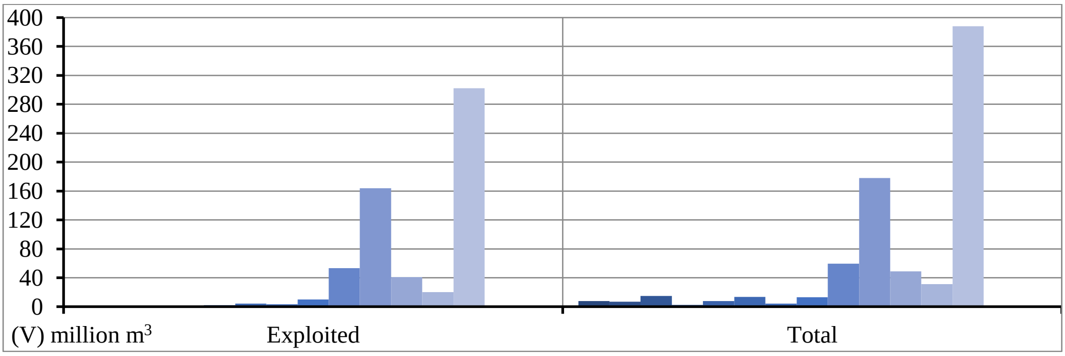


Figure 8. Exploited and total water

Such overuse most frequently causes long-term transient hydrodynamic conditions and disrupts the hydraulic interconnection between aquifer systems. It can contribute to adverse changes in water quality. Overexploitation just meets the required reload. It cannot even cause an immediate decrease in the hydraulic head because the relation in the water-bearing adjacent enables the requirement to be fulfilled (Andres & Egger, 1985).

Illegal boreholes problems

The plain is relatively urbanised and irrigated for agriculture purposes by means of very poor quality water, mainly coming from 500 m depth (Figure 9); it has decreased stagnant or local levels.

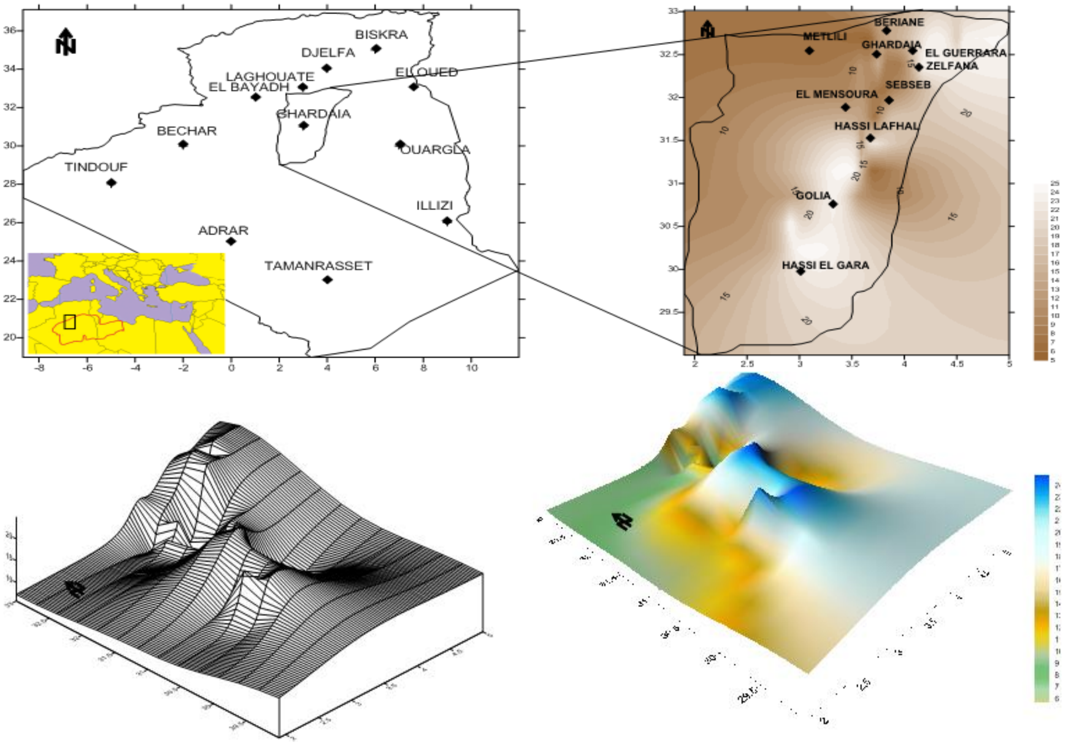


Figure 9. Frequency pumping time (l/day)

The El Meniaa valley has experienced a significant proliferation of illegal boreholes these last years, drilled by percussion, with an average depth of 75 m, touching the upper part of CI. The area has more than 116 illegal wells, with an average pace of up to 12 l/s of artesian discharge at Hassi el Gara. The 116 illegal drillings totaled a volume of extracted water of 19.30 million m^3/year, or 0,612 m^3/s, representing 24% of the total output of authorized Ghardaia boreholes.

Drawdowns at the CI

In the Ghardaia region, drawdowns of around 15 m have been recorded (Figure 10). Further south, at Ouargla, the drop is 66 m and it is 46 m at Hassi Messaoud and 10 m at El Golea (OSS, 2002).

Subsequently, all the hydrogeological synthesis and fundamental data relating to the CI were enriched and supplemented by important studies and in particular the simulation models developed during the last 30 years. Finally, it should be remembered that Besbes and Zammouri (1988) and Zammouri (1990) provided a first comprehensive modeling of the Saharan Continental Intercalary, at the Algerian-Tunisian-Libyan scale.

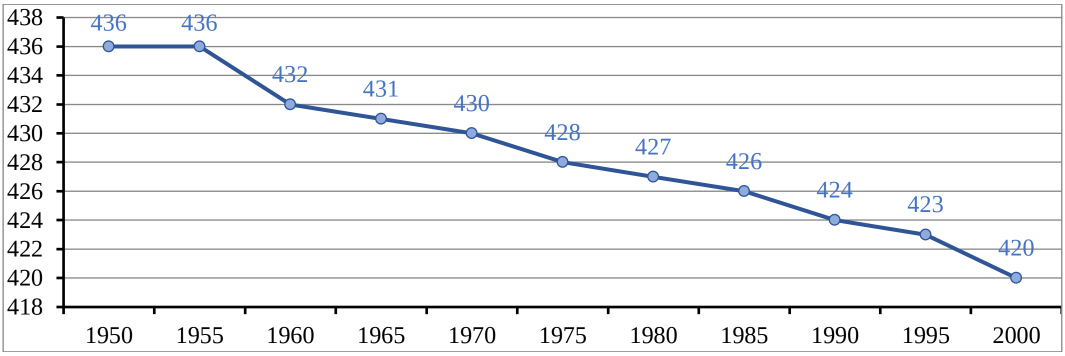
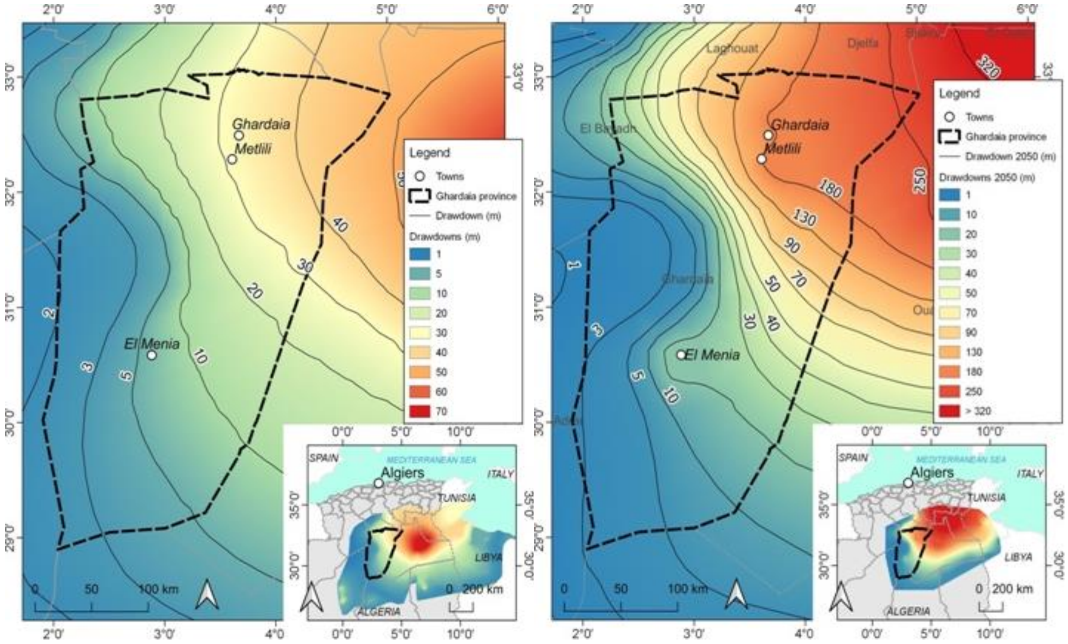


Figure 10. General evolution of piezometric level at CI in Ghardaia from 1950 to 2000

This simulation constitutes the critical guideline (OSS, 2002). The drawdowns are determined by utilizing the piezometric amounts restored by the system in 2000 (Figure 11).



a b

Figure 11. Drawdowns at the Continental Intercalary; 11a: 2000 to 2050 and 11b: in 2050

The simple continuation of current withdrawals is expected to lead to major drawbacks more than 40 m (measured by 2000 water levels) by 2050 across the Algerian Lower Sahara.

CI Water chemistry

A hydrochemical survey was carried out during the year 2011 to demonstrate the degradation of chemical quality due to overexploitation of CI aquifer. This study showed two very distinct facies.

As shown in Figure 12, the CI waters in the northern part of the area are characterized by a calcium sulfate chemical facies (PT01). They are from sulfated to sodium chlorides (PT03, PT04) in the southern part with a SO_4/Cl ratio indicating an enrichment of chloride to the east (PT19). Water becomes more salty in high-exploitation households (PT13, PT23). This salinity rise was most likely caused by mixing with deeper and saltier levels. The salinity is of evaporative non-marine origin. But it remains to examine the sources of dissolved NaCl (Figure 12).

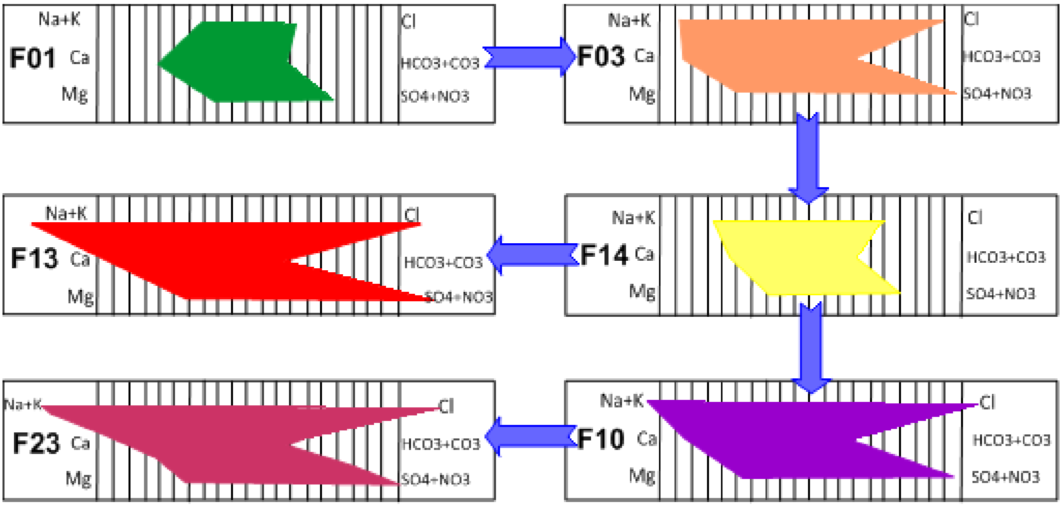


Figure 12. Evolution of the CI hydrochemistry
Source: (Hakimi, Orban, Chettih, & Brouyerre, 2019)

With regard to the salinity of the CI waters at Ghardaia, we note that 80% of water points have a salinity of less than 2 g/l; and 92%lower than 3 g/l salinity.

The waters towards the north of the area produce salinities below 1 g/l. (Hakimi, Orban, Deschamps, & Brouyere, 2021). This is not the case in the southern portion, where the salinities oscillate between 2 and 4 g/l. The salinity of 39% of water points varies from 2 to 3 g/l (Hakimi, Orban, Chettih, & Brouyerre, 2019)

CONCLUSION

The groundwater coming from CI aquifer is of considerable importance for central Algeria's Saharan oases, which share this resource used for drinking and irrigation purposes sharing it with other North African countries. However, this precious resource is threatened by the effects of increased overexploitation and flood irrigation activities, and can be seriously stressed if not properly controlled, as already witnessed by decreasing water levels and deterioration of water quality. This study indicated that overexploitation is really huge and influences the characteristics of groundwater flow and quality, which consequently affects the possibility of properly using it as a resource.

The amount derived from these illegal boreholes mainly involves two municipalities' total production, i.e. the cities of Ghardaia and Sebseb. The overexploitation impacts and human activities have had the following consequences:

Artesian's absence in some areas, and a large decline in pumping fields.

Furthermore, toxic irrigation has affected water quality by encouraging saltwater contamination of the water table.

The key effect of the extraction of non-renewed aquifers is the steady reduction of hydrostatic pressure and thus the water level, which has led to significant consequences.

Deepening of water levels in oasis, palm groves and crop areas.

Drainage of draining galleries, reduction of flow rates up to drying up of springs.

Reduction in water levels at the drilling head in places where the water table is deep in the captive aquifer, with a gradual drop in the Artesian level requiring deeper and deeper pumping, accompanied by a fall in the soil due to hydrostatic pressure that has become lower.

Aknowlegments

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