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Alternatives for water resources management in the Tindouf Basin (Algeria)

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Abstract

In the Tindouf region, the intense exploitation of the Hamadian and Visean aquifers has cause drainage out of these reservoirs. A new possibility could be found by aquifers of the Lower Devonian and Cambro-Ordovician sandstones, which were confined and slightly exploited. The main problem was to identify the favorable zones for the implantation of wells and to know whether a current recharge of these aquifers still exists. The isotopic study combined with classical hydrochemical and hydrogeological studies have pointed out a recharge of these aquifers and have shown the main flow paths. Based on the thermodynamic equilibrium of systems, the chemical evolution of the groundwater closely follows the underground water circulation reflecting the aquifers aging.

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Introduction

The Paleozoic syncline of Tindouf, still poorly defined in the geometrical point of view, contains several aquifer levels in Hamada's superficial of Cambro-Ordovician sandstones, Lower Devonian sandstones and dolomitic limestones of the lower Visean. The studies conducted in this area (Idrotecno, 1979; Progress Sarl-Annaba, 1999; Hani *et al.*, 2003; Hani, 2003) have shown an evidence of an intensification of surveys at the Visean aquifer, water contamination with evaporite levels and the absence of current groundwater recharge from the surface, with the exception of the Hamidian aquifer.

In addition, hydrological data in the aquifer-hosted basins are generally scarce, and exploitation is expensive compared with that of shallow groundwater. Optimal management of the aquifer may reduce these costs. But even with a small database, multidisciplinary studies are needed, such as chemical element distribution and isotopic and physical properties (Castany, 1967; Fontes, 1976) that must be processed simultaneously.

The main objectives of this study are: (1) to define the recharge areas of the various aquifers in the region; (2) to assess the preferential directions of groundwater flow; (3) to delineate favorable areas to the implementation of new wells to meet the ever-increasing needs of local populations.

From the hydrochemical and isotopic analyzes of some sampling points, we have tried to define the recharge areas of the various aquifers in the region, to assess the preferential directions of groundwater flow and to delineate favorable areas to the implementation of piping water wells. This study of the Tindouf syncline was in fact justified by the necessity to show that the definition of arid and semi-arid climatic regime in hydrogeology did not always correspond to geographical and climatic range.

Material and methods

The geomorphology and climate framework

The Paleozoic Tindouf syncline is located between the Anti-Atlas in the north and the ridge of Reguibat in the south.

To the East, it is bounded, from north to south by the Tafilalt and the chain of Ougarta respectively. To the West, it passes the country of "Mecheurs" then to the Western Sahara where it disappears beneath the Cretaceous and starts showing outcrops within 100km from Tindouf.

The study area is submitted to a Saharan climate with occasional rainfalls. Indeed, the Saharan rainfall, essentially capricious, falls as localized torrential rain, separated by periods of drought to one or many years. The Sahara average rainfall and especially return period are only indicative. In Tindouf, the rainfall between 60 to 70mm was less represented in the region, and almost the basin has received amounts between 10 to 20mm. Indeed, if we refer to isohyets and a work of DUBIEF (1953), almost the entire basin has received 10 to 15 mm and only in Hamada of Tindouf being favored with 30 to 50 mm in its north-western parts.

The temperatures recorded in the study area have showed the persistence of high values that reached 50°C. The frequency and speed of the wind, the relative low humidity and the combined nebulosity with recorded temperatures have favored the high values of evaporation. The majority of watersheds in the study area were spread over large areas; hence it occurred huge flow volume (hundreds of millions of m^3) after a rainstorm (Castany, 1967; Castany, 1968). By traveling hundreds of kilometers, these flows would feed the various aquifers in the Tindouf basin.

The geological and hydrogeological setting

The main aquifers are identifiable as:

- The Hamadian formations are mainly constituted of a clayey sandstone layer at the base and white limestone tuff at the top, with a variable thickness of 20 to 80m. The flow, limited to the western area by lack of surveys, was generally from west to east (Fig. 1A). The supply was most likely by infiltration of rainwater through the formation of the Tindouf's Hamada and by the exceptional water supply that accumulates on surface at the playas.

The outlet of the groundwater was formed by the great Sebkha of Tindouf and the Abdullah Sebkha (Idrotecno, 1979 and Progress 1999). With the exception of the well 50 which has a relatively high value, the specific flow rates were low. The calculated transmissivity was about $6,5.10^{-6}$ m^2/s.

- The Visean limestone layer is represented by ten meters of clay with massive gypsum levels overcoming fifty meters of gravel limestone and dolomitic clay which are deposited on a series of alternating gravelly limestone and dolomitic clay, ferruginous clay siltstones and sandstones and some levels of white massive anhydrite. In the present state of our knowledge, it is very difficult to define the groundwater flow in the limestone of Visean. However, surveys conducted in 1975 have showed water provenance from the east to the Sebkha (Fig. 1 A). The power of the layer is governed by rainfall on Hamadian formations that may be a hydraulic continuity with the limestone over a wide fault oriented west-east (Idrotecno, 1979). It could also come from the contributions of the outcrop areas of the aquifer located in the Atlas (Progress, 1999). Geographically, it was located in the drilling area of Sebkha Abdallah which has the highest values of specific flows; while in the east of the Sebkha Abdallah, the performance of piping water wells have showed a fairly sharp decline.

- The Devonian Lower sandstone rocks correspond to a fine to medium grained sandstone series of white medium to greenish gray color with clayey limestone cement. The top is characterized by a series of alternating siltstone, very fine sandstone grains, with rare intercalations of limestone. The five piezometric surveys carried out show a directed flow northward dipping under layers (Fig. 1B). The only two values have showed relatively very low specific flow rates. Transmissivity was of the order of 9.10^{-5} m^2/s (T7).

- The Cambro-Ordovician sandstone layer is between transgressive formations on antecambrien base and the first levels of the Silurian black Graptolits clays. The basic series consist of clay and quartzite gravel of 0.1 to 1 mm in diameter. The upper series are represented by a bar of sandstone with limestone nodules. In general, the aquifer that could be free in half along the sandstone outcrops, flows from west to east (Fig. 1B). The transmissivity has showed relatively higher values than those of the Devonian. The transmissivity varied between $1,3.10^{-3}$ and $2,6.10^{-4}$ m^2/s. The storage coefficient was 7.10^{-4}.

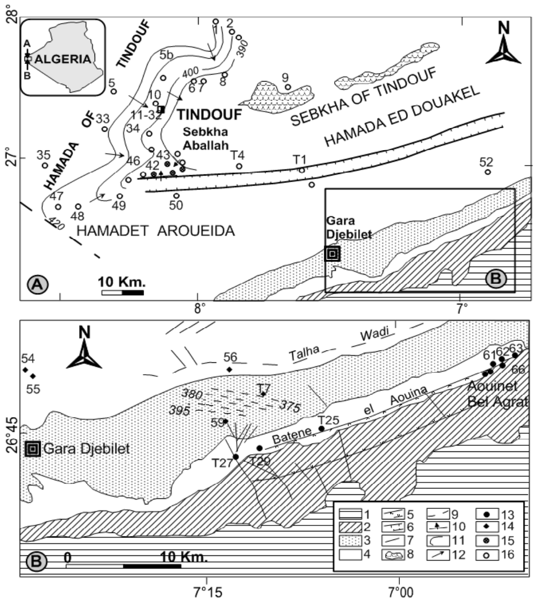

Fig. 1. Water points Location and geological scheme of: A) the Hamadian and the Visean aquifers (after Idrotecno, 1979, modified); B) Devonian and Cambro-Ordivician aquifers (after Idrotecno, 1979, modified). 1: Precambrian; 2: Cambro-Ordovician Sandstone; 3: Devonian sandstone; 4: Cenozoic; 5: Non-confined area of the Cambro-Ordovician aquifer; 6: Area where the Visean is covered by Hamadian; 7: Fault; 8: Sebkha; 9: Piezometric surfaces of the Devonian aquifer; 10: Piezometric surfaces of the Visean aquifer; 11: Piezometric surfaces of the Hamadian aquifer; 12: Strean line; 13: Observation well of the Cambro-Ordocian aquifer; 14: Observation well of the Devonian aquifer; 15: Observation well of the Visean aquifer; 16: Observation well of the Hamadian aquifer.

Results

Hydro-chemical and isotopic data

Hydro-chemical properties

Based on the collected analytical data, it was possible to highlight the following findings (Lamouroux and Hani, 2006).

- Water flowing into the Hamadian aquifer were very heterogeneous (Fig. 2a) with 5 from 15 samples of sodium chloride-facies, 4/15 of sulfated magnesium, 4/15 of sulfated calcium, 1/15 of sulfated sodium and 1/15 of chloride-calcium. The dry residue (DR) ranged from 896 mg/l to 5460 mg/l and the highest mineralization was generally recorded in downstream flow due to transit time. The supply was made likely by infiltration from rainwater through the formation of the Tindouf Hamada and by exceptional rainstorms that might accumulate on huge and thick alluvial plains. The outlet of the groundwater is composed of the great Sebkha of Tindouf and to a lesser extent by Abdullah Sebkha.

- The Visean aquifer was characterized by three types of water (Fig. 2b): the sodium chloride (2/4 samples), the calcium sulfate (1/4 samples) and the sulfated sodium (1/4 samples). The dry residue passed from 2348 mg/l (well 43) to 14006 mg/l in Q1 due to the washing of evaporates by the sheet wash process.
- Water of the Devonian age was also of three types (Fig. 2c): 5/8 calc-chlorinated samples, 1/8 chloride-calcite samples and 2/8 sodium sulfated samples. The dry residue ranged from 1264 mg/l (and 55) to 2592 mg/l (T7).
- In the Cambro-Ordovician aquifer, three types of water were distinguished (Fig. 2d): 5/8 the calcium sulfate, 2/8 sodium and 1/8 chlorinated calcite. The dry residue ranged from 694 mg/l (T29) to 4000 mg/l (66).

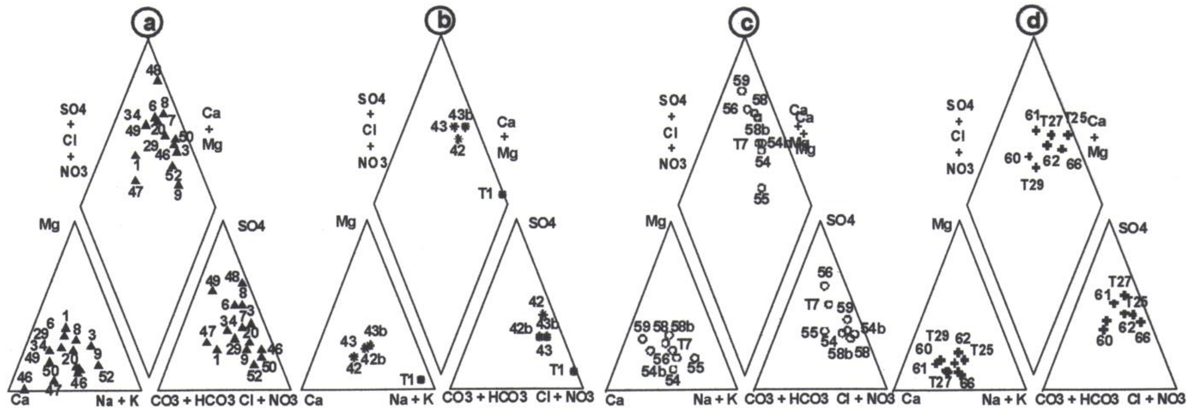

Fig. 2. Piper Diagram of Water in Tindouf aquifers basin: a) Hamadian, b) Visean, c) Devonain, d) Cambro-Ordovician.

Isotopic properties

The oxygen-18 and tritium were measured in all samples, while deuterium and C14 were analyzed only in 11 and 9 samples respectively. The main results were reported as follows (Fontes, 1976; Hani *et al.*, 2003):

- Hamadian aquifer*:* The interpretation of isotopic data, particularly tritium one, has shown a distribution of 3 water families: 1) very recent water (^{3}H > 16,6 UT): samples 34, 48 and 49; 2) relatively new water (8,3 <^{3}H < 16,6 UT): samples 1,3,6,8 and 46; 3) oldest water (^{3}H < 8,3 UT): samples 7, 9, 20, 29, 47, 50 and 52;
- Upper Visean limestone aquifer*:* the tritium values for all considered samples were very low or null. The age of the water ranged between 6700 years (drilling T4) and 8600 years (drilling 42);
- Lower Devonian sandstone aquifer*:* ^{14}C has shown a wide variation in values that have ranged from a current activity to a modern carbon (100‰ drilling 58) highlighted by a ^{13}C (= - 6.9‰) and almost zero activity (1.43% in T7 well), in accordance with a ^{13}C partially exchanged with the matrix (-5.6‰).

The tritium has also highlighted the existence of current water (samples 58 and 59) with values in the range of 20 UT corresponding to a current age and the oldest waters with null values (drilling T7) and whose age would be 28000 years;

- The Cambro-ordovician sandstone aquifer*:* the tritium levels have shown less current water supply on the major part of the aquifer except in areas affected by faults; while the radiocarbon has indicated variable ages between a minimum of 660 years drilling T27 and a maximum of 11,000 years related to well T25.

Interpretation

- The Hamadian aquifer**:** by analyzing the isotopic values of the samples relative to their geographical distribution, we could deduce that the oldest water represents the natural evolution of the aquifer. Indeed, the high salinity values corresponded to low tritium content. The youngest water volumes were induced by local conditions, such as the washing of evaporates that has increased the salinity or has shown the influence of evaporation during the accumulation of rainwater in the spreading plains.

- Upper Visean limestone aquifer**:** according to the Visean aquifer, the graphic $\delta^{18}O‰$ - $\delta\ ^2H‰$ of Fig. 3 has shown that the point 43 and 42 were adjusted to the right side of evaporation while the drilling T1 is located to the right middle part of rainfall indicating the absence of evaporation. This situation has shown that the difference in chemical composition between points 42 and 43, and point T1, located in the same geological setting, was mainly due to the presence of evaporates at the last drilling well.

- Lower Devonian sandstone aquifer**:** the right equation $\delta‰H_2 = 4.95\ \delta‰\ O_{18} - 24,94$ has shown quite well the effect of evaporation on the aquifer (Fig. 3).

- Cambro-Ordovician sandstone aquifer**:** all points were arranged along the evaporation line (Fig. 3). The differences in behavior between the hydrochemical drilling T27 and T25 were mainly due to more recent water flows in areas where the aquifer was affected by faults.

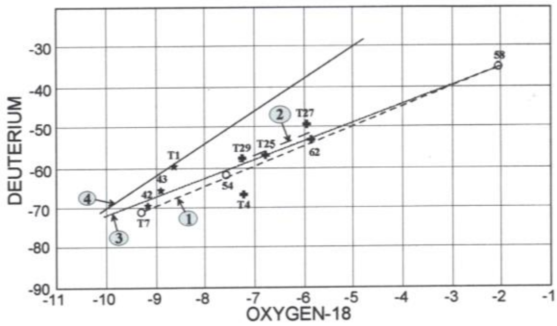

Fig. 3. Relationship between δ^2H (⁰/₀₀) - $\delta^{18}O$ (‰) in the ground waters.

The comparison of the results outlined above with those provided by the lithological and structural setting has allowed highlighting the following statements:

1- The spatial distribution of hydro chemical facies in Hamadian aquifer did not establish any zoning for various reasons; the effect of evaporation in the capillary zone, heterogeneity of the lithological formations and time of stay. In sum, the wells with highly mineralized water were probably supplied in part by interflow in Quaternary formations undergoing high evaporation. Besides the spread plain that would receive rainstorms that could accumulate on huge thicknesses, generating sufficient charge; and therefore a supply of deep groundwater;

2- Hydraulic continuity between points 42 and 43, taking in the Visean limestone aquifer, was very evident. However, a significant difference between the physical and chemical behavior of these two points and T1 drilling well was highlighted. This difference might be largely explained by the presence of evaporites reported by lithological section of the T1 drilling well and to a lesser degree by the transit time of water during flows;

3- The water stay time in the aquifer, local supply and evaporation might also explain the differences between the analytical data of the set of points 54 and 59 and point T7 related to the aquifer lower Devonian sandstone.

4- In the Cambro-Ordovician aquifer, the hydrochemical evolution was essentially governed by the direction of flow, directed from west to east. However, some exceptions to this rule were found in areas where the groundwater supply through fractures was possible (T29 drilling explo.).

Discriminant factorial analysis

The discriminant factorial analysis used in this study was to learn the role of a qualitative variable (space, time) in addition to quantitative variables (Davis, 1984; Deverel 1989; Melloul and Colin, 1991; Melloul, 1992; Melloul, 1995).

Using a quantitative variable within a population of individuals to a partition of the population, each individual was assigned to a set called group. The discrimination of groups was to maximize the variance between the centers of gravity and might then highlight the properties that might distinguish them from each other's.

If the individual was reassigned to its group, it said "well classified" if it was reassigned to another group, it said "misplaced".

The four aquifers were in the same watershed and have a different mineralization. In order to study the behavior of these aquifers in space (system), we could divide the population into four groups (Hamadian aquifer, Visean limestone aquifer, Lower Devonian aquifer and Cambro-Ordovician sandstones aquifer).

Axis I was determined by the elements of the mineralization and ^3H which were opposed to oxygen-18, it was an axis of mineralization. It has opposed the water of the Devonian sandstone aquifer, Cambro-Ordovicien and limestone Visean to those of hamadian aquifer (Fig. 4a). Axis II was characterized by a contrast between the pCO_2 and pH that has reflected the balancing of water by highlighting the time of stay of water in aquifers. In terms of individuals (Fig. 4b), the axis II has opposed the Cambro-Ordovician sandstone aquifer to those of Devonian and limestones of upper Visean. In Hamadian aquifer, the points have evolved younger aquifer water (tritium> 30 UT) to the most chemically advanced and the oldest aquifer water ($1.3 < {}^3H < 4.2$ UT) according to an isotopic aspect.

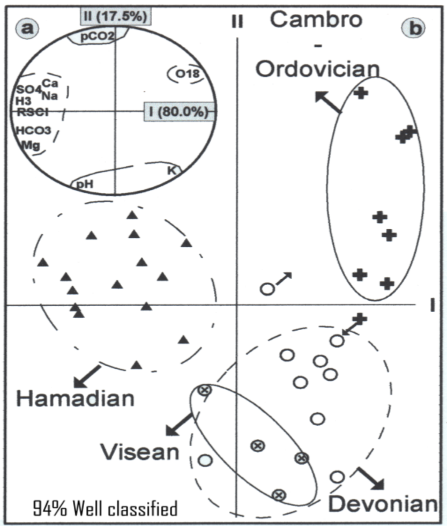

Fig. 4. Results of discriminant factorial analysis.

Stretching of envelopes containing points of the Devonian parallel to axis II could translate the passage of recharge areas water to the outlets according to the flow direction (W-E).

The ranking results have given 93.8% of well classified elements. The hamadian and Visean aquifer were completely separate (100% well classified). Devonian and Cambro-Ordovician were also distinct with low exchange of individuals (one for each aquifer).

The different aquifers were autonomous and have a chemical nature dependent on lithology. The individual exchange between the Devonian and Cambro-Ordovician sandstones, which have the same chemistry have highlighted an axis of drainage between the two aquifers at the favor of the numerous faults that have affected these two formations. Based on thermodynamic equilibrium, it was possible to define a chemical evolution in the reservoirs of the Tindouf basin (Fig. 5a, b, c, d and 6a, b, c, d). In the hamadien aquifer, water has shown an evolution of the points the less chemical developed elements (34,49 and 48) to the most ripest and developed points (50, 52). The first family corresponded to the most recent waters with values of tritium of 50.7 UT for the sample 34; 30.1 for sample 49 and 35.7 for sample 48. However, for the second group, the tritium levels were very low.

The waters of the confined Visean limestone aquifer, samples T1, 42, 43 and 43a have shown a more advanced and mature chemical phenomenon and have displayed an age of about 8600 years. The envelope of 8 samples taken in December 1998 was superimposed on that of points 42 and 43; and therefore might support the idea that the Visean area did not receive any recent contribution.

Devonian waters were divided into two groups; the first has represented by points 58 and 59, very less developed whose actual age 340± 100 years for point 54. Water drilling T7 has shown a highly developed and mature chemical situation and has displayed a much older age (about 28,000 years). The distribution of the Cambro-Ordovician water on the stability diagram Ca/Na has shown an evolution of the least chemical mature points (T25, T27 and T29) to the most developed ones (61, 62, 63 and 66) with an evolution in flow direction from west to east.

The age of the first three points have ranged from 11,000 years at T25, 660 years at T27 to 2270 years at T29; however, for the second group the age would be about 7100 years (62).

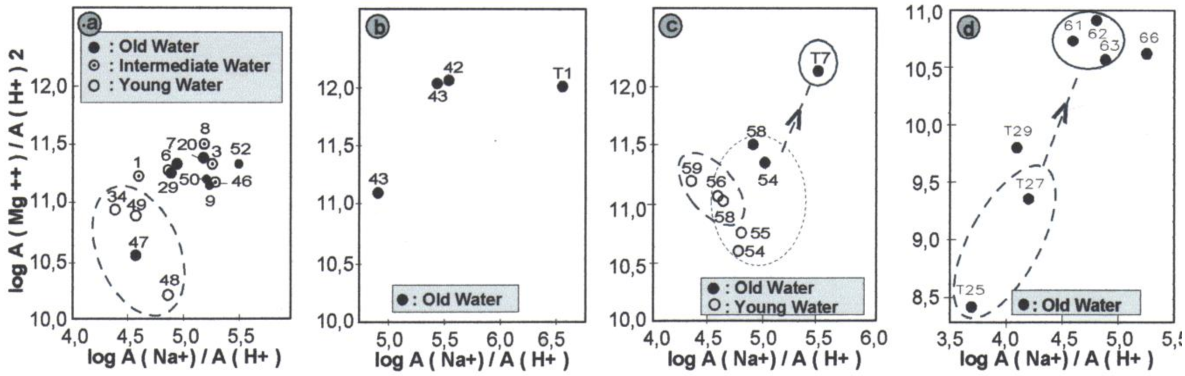

Fig. 5. Mg/Na Stability Diagrams.

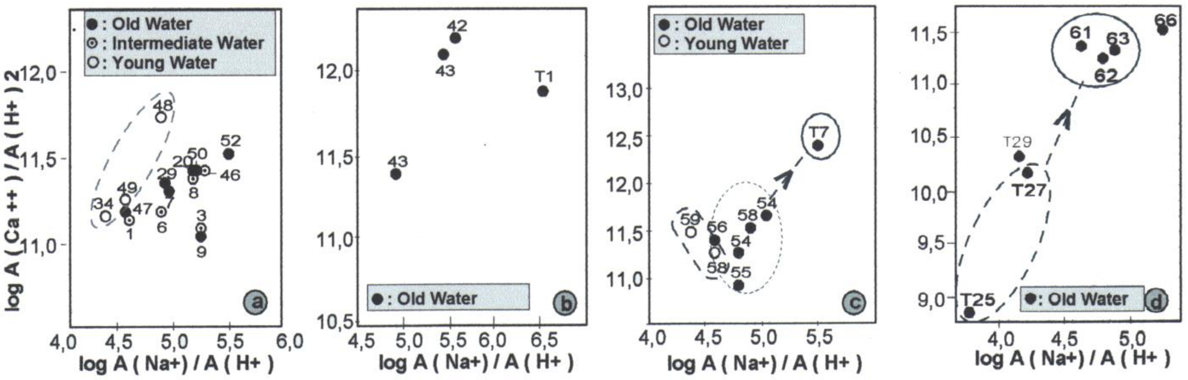

Fig. 6. Ca/Na Stability Diagrams.

Discussion

Alternatives for water resources management

Four aquifer systems were identified (Fig. 7):

- The hamadian aquifer was characterized by a perched position that did not allow it to be recharged except at its base. Currently, it has undergone a drip of inherited reserves of the last Quaternary humid period. The supply was essentially made by the waters of exceptional floods that have accumulated on the enormous and thick spreading plains. The outlet of the aquifer was made mainly by the great Sebkha of Tindouf and the Abdullah's Sebkha.

Considering the lithology and its extension, the reserves of this aquifer were still very limited. However, the most favorable sites for exploitation by shallow drilling would be at the end of the old Hamada. The water was not suitable for human consumption. RS might vary depending on the sampling position relative to recharging areas.

- Visean aquifer, which was the main aquifer of exploitation in this recent period, has presented favorable hydrological conditions particularly in the area of Sebkha Abdullah. Indeed, studies have allowed the identification of a system that has shown, by place, three very productive horizons. The aquifer consisting essentially of limestone and dolomites has undergone intense fracturing, confirming the importance of the reservoir. An additional exploitation could, without modelling, cause an imbalance of the overall balance and therefore the contamination of the aquifer by very salty waters of the Sebkha or by loads coming from the east sector.

Another possibility was to recover operating losses through evaporation at the Abdullah Sebkha.

The design of watershed development, unsuited to this type of aquifers containing evaporate levels, and inadequate quality of execution of drilling could cause low flow rates provided by the capture and the high salinity waters in some areas;

- The aquifer of lower Devonian has shown outcrops in the extreme south of the study area. Due to its structural arrangement, it might contain probably modest reserves with good quality. This aquifer was fed in some places by superficial water and the contribution of the underlying aquifers (Cambro-Ordovician) in favor of intense fracturing, which was probably the origin of Oued Talha. In the context of this hypothesis, the aquifer would be exploitable by drilling over the most part of this wadi's valley.

- The Cambro-Ordovician aquifer, located further south of the previous aquifer, has formed the southern boundary of the study area and the Tindouf Basin. This aquifer, very affected by cracking especially in its central part, has the advantage to benefit from an abundant supply of the fracture origin. The weak performance observed at almost all drilling wells (except T29) was due, probably, to the poor conception of drilling. In general, the water quality has remained from good to acceptable. A further exploitation of the aquifer could be possible in the area of T27 and T29 wells which would be seen in Fig. 7 with the intersection of faults.

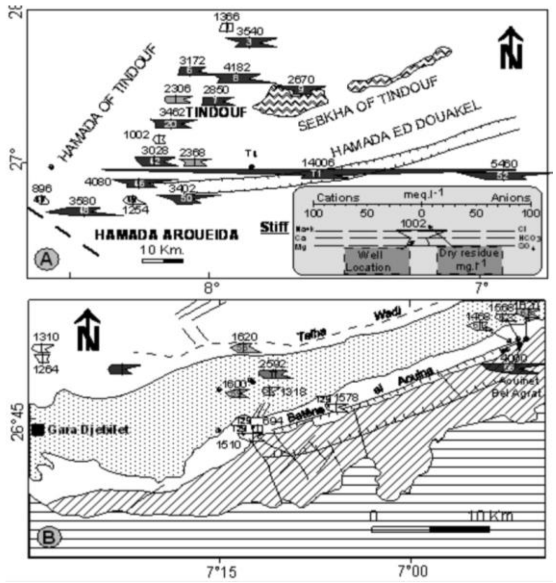

Fig. 7 Groundwater Stiff diagrams of the Tindouf Basin aquifer. A- Hamada Visean aquifer; B- Devonian and Cambro-Ordovician aquifers.

Conclusions

The geochemical study of aquifers of Tindouf basin has allowed highlighting the following statements:

- A current water recharge at the Devonian and Cambro-Ordovician outcrops in the cracked areas.

- The independence of the various aquifers (No marked drainage except perhaps between the Cambro -Ordovician and Devonian age).

The existence of an ancient recharge into Hamadian and Visean aquifers:

The directions of groundwater flow are generally: i) formations of Hamada of Tindouf especially receiving torrential rains to the great Sebkha of Tindouf and Abdallah Sebkha; ii) the visean aquifer supply would be ensured by rainfall on hamadian formations and by contributions from outcrop areas of the aquifer located in the Atlas; iii) In the aquifer of the lower Devonian sandstone, the flow was directed from south to north; iiii) Finally, in the aquifer of the Cambro-Ordovician sandstone, the flow is from west to east. The practical conclusion of this study has shown: the most favorable sites for exploitation by shallow drilling wells in the hamadian aquifer would be located at the foot of the old Hamada where water was not proper for human use.

The Visean aquifer, which is the main aquifer in operation today, presents exceptionally favorable hydrogeological conditions particularly in the area of Abdullah's Sebkha. An additional operation could cause an imbalance of the overall balance and therefore, the contamination of the aquifer by very salty waters of the Sebkha or by flows coming from the east area of the drilling well. Due to its structural aspect, Lower Devonian aquifer has contained probably modest reserves with good quality. The aquifer would be exploitable by drilling over most of the valley of Wadi Talha. A further exploitation of the aquifer of the Cambro-Ordovician could be possible in the area of T27 and T29 wells which would be located along traverses where they were intersections of faults. In general, the water quality remains from good to acceptable.

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