DOI 10.7343/as-2023-626

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2023-AS44-626: 53 - 61

Hydrochemical and isotopic characterization of a complex aquifer system

Caratterizzazione idrochimica ed isotopica di un sistema acquifero complesso

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ARTICLE INFO

Ricevuto/*Received*: 11 January 2023
Accettato/*Accepted*: 28 March 2023
Pubblicato online/*Published online*: 30 March 2023

Handling Editor: **Marco Pola**

Citation:
Toumi, F., Hani, S., Bougherira, N., Hani, A., Chaffai, H., Djabri, L. (2023). Hydro chemical and isotopic characterization of a complex aquifer system. Acque Sotterranee - *Italian Journal of Groundwater*, 12(1), 53 - 61 https://doi.org/10.7343/as-2023-626

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Keywords: *piezometry, salinity, oxygen-18; deuterium, flow paths, Algeria.*

Parole chiave: piezometria, salinità, ossigeno-18, deuterio, linee di flusso, Algeria.

Riassunto

In questo lavoro è stata sviluppata una metodologia per analizzare l'assetto idrogeologico di un sistema acquifero complesso utilizzando un numero limitato di dati. Questo approccio è stato applicato al bacino di Tindouf (Algeria sud-occidentale) e ha permesso di identificare aree favorevoli per la costruzione di nuovi pozzi e la presenza di una ricarica recente nel sistema acquifero.

L'analisi delle componenti principali (PCA), il diagramma deuterio – ossigeno-18 e i diagrammi di equilibrio Mg/Na e Ca/Na sono state le tecniche utilizzate per combinare differenti dataset con lo scopo di identificare gruppi chimici ed isotopici che a loro volta sono stati utilizzati per individuare le linee di flusso nell'acquifero. Inoltre, sulla base dell'equilibrio termodinamico, è stato possibile definire l'evoluzione chimica nel sistema acquifero di Tindouf. I risultati di questo studio sono consistenti con il modello concettuale disponibile. La combinazione di differenti approcci metodologici ha permesso di definire e caratterizzare i percorsi di flusso principali dalla zona di ricarica fino alla zona di deflusso del sistema. Questi percorsi di flusso sono definiti da gruppi di acque identificati in base alla salinità e all'origine delle acque.

Questo approccio può essere utilizzato per studiare acquiferi caratterizzati da una mancanza di dati e può essere applicato per lo studio di sistemi acquiferi complessi.

Abstract

A methodology was developed and applied to the Tindouf basin (south-western Algeria) to understand the hydrogeology of a complex aquifer system with a limited number of data, to identify the favorable areas for the design and building of new wells, and to know whether there is still current recharge of these aquifers. The principal components analysis (PCA), diagram of deuterium versus oxygen-18, and equilibrium diagrams Mg/Na and Ca/Na were the techniques used to combine different datasets in order to identify chemical and isotopic groups, which were in turn used to define the groundwater flow paths. In addition, on the basis of thermodynamic equilibrium, it is possible to define the chemical evolution of the Tindouf basin aquifer. The results of this study are consistent with the generally accepted hydrogeological conceptual model. The combination of the different methods made possible to define and and to characterise the main groundwater flow paths from their sources to the discharge zones. These flow paths are defined by water categories, which are represented by salinity and groundwater origin.

This approach can be used to analyze aquifers characterized by a lack of data and can also be useful for studying other complex groundwater basins.

Introduction

The shortage of fresh water has become a crucial problem for many countries. Various anthropogenic factors accompany this and others sources of pollution, especially for near-surface aquifers. Deep groundwater, mostly in confined aquifers, in many arid and semi-arid areas is less exposed to surface pollution (Gleick, 2006; 2009).

Nevertheless, hydrological data in such geological and hydrogeological setting are generally scarce, and exploitation is expensive compared with that of shallow groundwater. However, even with a small database, multidisciplinary studies are needed, such as chemical element distribution and isotopic content and physical properties (Abdi & Williams, 2010; Abou Zakhem et al., 2017; Cloutier et al., 2008), and must be processed simultaneously.

Among the classical methods, the principal component analysis (PCA) method can be applied even to a small dataset showing some hydrogeological aspects of the system (Cloutier et al., 2008). It can also be useful to identify and explain groundwater evolution processes (Al-Charideh, 2012; Al-Charideh & Abou-Zakhem, 2009). The PCA technique has been successfully applied in the investigation of groundwaters hosted in the Nubian formation of the Sinai Peninsula and the Negev Desert and to the deep sandstone aquifers of the Albian formation in the Paris basin (Abd El Samie & Sadek, 2001;Abouelmagd et al., 2012; 2014; Ram et al., 2020).

In this research, the PCA is used as a tool to process chemical data in order to study the nature of the Tindouf deep aquifers that have previously been the subject of many research studies (Lamouroux & Hani,2006; Mahia et al., 2017). Whereas, thermodynamic calculations made it possible to identify a chemical evolution in the reservoirs of the Tindouf basin. In this research, the Mg/Na and Ca/Na equilibrium diagrams are used to follow the flow of water from upstream to outflow.

Natural isotopes are used as tracers to know if groundwater is replenishing, where it comes from, how it moves underground, and if it is vulnerable to pollution and changing weather conditions. In this research, the classical diagram deuterium versus oxygen 18 was used to explain the origin of groundwater. Carbon 14 was used to estimate the water age.

The objectives of this research are to develop a hydrogeological conceptual model of the aquifer system hosted in the Tindouf basin, to identify the different outcrops serving as infiltration zones, and to define the main axes of groundwater flow.

Data and Methods

Geomorphological, climatic and geological frameworks

The Tindouf basin is located at the extreme west of the Saharan platform. This basin forms a vast depression oriented east-west, covering a surface of more than 100,000 km^2. Tindouf, the main municipality in the basin, is located 1,460 km south-west of Algiers (Algeria). The study area is bounded by Morocco to the west, the territory of western Sahara to the south-west, and Mauritania to the south.

The Paleozoic syncline (basin) of Tindouf is located between the Anti-Atlas in the north and the Reguibat ridge in the south (about 300 km). To the east, it is delimited, respectively from north to south, by the Tafilalt and the Ougarta chain; to the west, it passes through the Mecheurs country, then to the western Sahara where it disappears under the Cretaceous, which arrives less than 100 km from Tindouf. Due to its morphological aspects, the Tindouf syncline can be subdivided into three major morphological units as follows (Fabre, 1976; Gevin, 1958; 1960):

– *Northern flank*: the first terrains visible by climbing the northern slopes leading to the peaks of the Anti-Atlas belong to the Upper Devonian (sandstone). Above, the Tournaisian is represented by limestone with crinoids and corals. The Visean is represented by fossiliferous limestone. This limestone series gives a characteristic aspect to this flank and constitutes, to the north of Hamada, the crest of Djebel Ourkziz between the Dra plain and the Betana depression.
– *Hamada*: it is a limestone slab. There are levels of conglomerates and gypsum. It covers the often peneplaned Paleozoic. The thickness varies globally from north to south with an average of about 100 meters.
– *Southern flank*: the Hamada being crossed, we find the Paleozoic series resting on the Precambrian of the Reguiba ridge, descending a series of plateaus and cliffs.

Aquifers of the Tindouf basin.

In the study area, four aquifers are distinguished (Figs. 1 and 2):

– The Hamadian aquifer is composed mainly of sandy clays at the base overlain by carbonates. The thickness of this formation varies from 10 m in the Sebkha Abdallah sector to more than 100 m in the Hamada of Tindouf. This aquifer is locally in hydraulic contact with the underlying layers of upper Visean (Figs. 1A and 2A). Groundwater flow is west-east Recharge probably occurs by infiltration of large quantities of rainfall and occasionally water floods on the Hamada of Tindouf. For this aquifer, the outflow occurs through the Sebkha of Tindouf and, to a lower extent, through Sebkha Abdallah. The transmissivity is low; it is of the order of $6.5\ 10^{-6}\ m^2/s$.
– The upper Visean of Tindouf aquifer is composed, from top to the bottom: i) tens of meters of clay with massive gypsum levels, ii) about fifty meters dolomite, iii) limestone, iv) a series of gravel-rich limestone alternating with layers of dolomite and clay, v) ferruginous clay, vi) siltstones with layers of massive anhydrite. Water-table observations carried out in 1998 show a depression around Sebkha Abdallah, thus demonstrating an intense drainage zone of the aquifer (Progress Sarl-Annaba, 1999). The measurements acquired in 1975 also highlighted an inflow starting from the east towards the sebkha (Idrotecno,1979). The aquifer recharge would be governed by rainfall on the Hamadian formations

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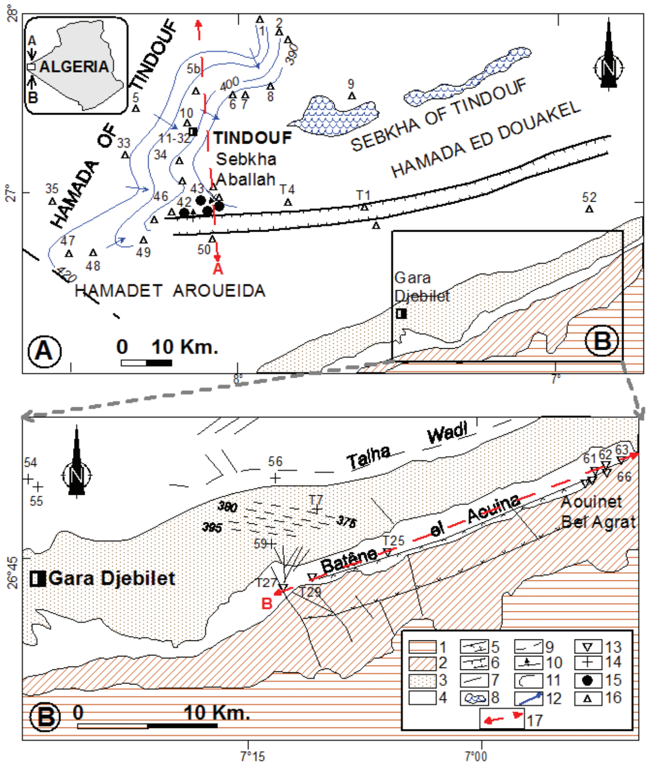

Fig. 1 - (A) Location and hydrogeological settings of Hamada and Visean aquifers; modified from Idrotecno (1979). (B) Location and hydrogeological settings (included in (a)) of Devonian and Cambro-Ordovician aquifers; modified from Idrotecno (1979). Legend: (1) Precambrian; (2) Cambro-Ordovician sandstone; (3) Devonian sandstone; (4) Cenozoic; (5) unconfined sector of Cambro-Ordovician aquifer; (6) sector where Visean is covered by Hamadian formation; (7) fault; (8) sebkha; (9) potentiometric surface of the Devonian aquifer; (10) potentiometric surface in the Visean aquifer; (11) potentiometric surface of the Hamadian aquifer; (12) cross-section (Fig. 2a); (13) observation well of the Cambro-Ordovician aquifer; (14) observation well in the Devonian aquifer; (15) observation well in the Visean aquifer; (16) observation well in the Hamadian aquifer; (17) cross section (Fig. 2b).

Fig. 1 - (A) Ubicazione e assetto idrogeologico degli acquiferi di Hamada e del Viseano (mappa modificata da Idrotecno, 1979). (B) Ubicazione e assetto idrogeologico degli acquiferi del Devoniano e Cambro-Ordoviciano (mappa modificata da Idrotecno, 1979). Legenda: (1) Precambriano; (2) Cambro-Ordoviciano; (3) arenarie del Devoniano; (4) Cenozoico; (5) parte freatica dell'acquifero del Cambro-Ordoviciano; (6) settore dove il Viseano è coperto dalla formazione di Hamada; (7) faglia; (8) sebka; (9) superficie potenziometrica dell'acquifero del Devoniano; (10) superficie potenziometrica dell'acquifero del Viseano; (11) superficie potenziometrica dell'acquifero di Hamada; (12) traccia della sezione (Fig. 2a); (13) pozzo nell'acquifero del Cambro-Ordoviciano; (14) pozzo nell'acquifero del Devoniano; (15) pozzo nell'acquifero del Viseano; (16) pozzo nell'acquifero di Hamada; (17) traccia della sezione (Fig. 2b).

through the hydraulic E-W-directed continuity with limestones and the contribution of the Atlasian aquifers in northern part of the studied area. The transmissivities vary from 8 10^{-4} to 3.1 10^{-2} m^2/s. The storage coefficient calculated (Well 43) is around 5 10^{-4}, which characterizes a confined aquifer.

- The Devonian aquifer is composed of a fine-to medium-grained sandstone series with clay-limestone cement. This formation is overlain by siltstones alternating with very fine-grained sandstone, and rare limestone layers. The total thickness of the whole formation is approximately 120 m. The five piezometric surveys performed in the aquifer indicate that the groundwater flow is mainly towards the north following the dip of the strata. From the hydrogeological point of view, the data provided by the wells drilled in the sandstones show a transmissivity of 9 10^{-5} m^2/s in well T7. Everywhere else, tests on large-diameter wells and on the T10 gave very low flow rates for fairly excessive drawdowns
- The Cambro-Ordovician aquifer is transgressive over Precambrian and is limited in the upper part by the Silurian graptolites-rich black-clays. This formation consists of three distinct units: i) the lower unit is composed of clays and fine-grained felspathic quartzites, ii) the intermediate unit consists of sandy clays containing clastic elements, iii) the upper unit is represented by fine-grained massive sandstones layers containing often limestone nodules. The transmissivities, calculated from the interpretation of data from three pumping tests, show very heterogeneous values with a maximum of 1.3 10^{-3} m^2/s at well T29 and a minimum of 2.6 10^{-4} m^2/s at wells T25 and T27. Generally, the aquifer is partly unconfined and the global flow is West-East directed (Figs. 1B and 2B).

The study area is subject to an essentially Saharan climate, characterized by occasional rainfall. According to (Progress Sarl-Annaba, 1999), almost the entire basin received 10 to 15 mm, only the Hamada of Tindouf being more favored with 30 to 50 mm in its northwestern parts. The temperatures recorded in the study area show the persistence of heat which reaches very high absolute values (50°C).

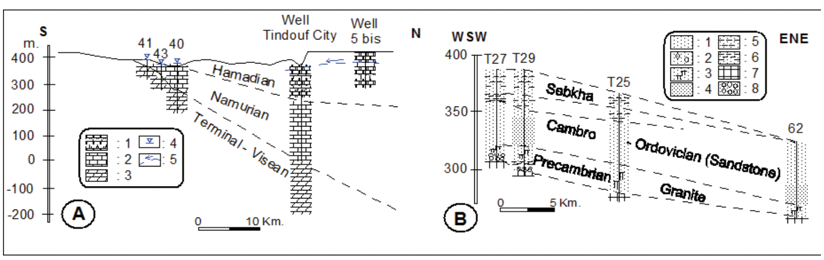

Fig. 2 - Hydrogeological cross-section (modified from Idrotecno, 1979) of the A) Hamadian and Visean aquifers (Legend: (1) sandy clays and carbonates; (2) carbonates; (3) gypsum, dolomite-limestone, dolomite and clay, ferruginous clay, siltstones with anhydrite; (4) potentiometric surface of the Hamadian aquifer; (5) potentiometric surface of the Visean aquifer) and B) of Devonian and Cambro-Ordovician aquifers. (Legend: (1) clay; (2) chalk; (3) dolomite; (4) sandstone; (5) gypsum; (6) anhydrite; (7) conglomerate; (8) marl).

Fig. 2 - Sezione idrogeologica (modificata da Idrotecno, 1979) degli acquiferi A) di Hamada e del Viseano (Legenda: (1) argillite e carbonati; (2) carbonati; (3) gesso, carbonati, siltite con gesso, argillite ferrifera; (4) superficie potenziometrica dell'acquifero di Hamada; (5) superficie potenziometrica dell'acquifero del Viseano), e B) del Devoniano e Cambro-Ordoviciano Viseano (Legenda: (1) argilla; (2) chalk; (3) dolomite; (4) arenaria; (5) gesso; (6) anidrite; (7) conglomerato; (8) marna).

Methodology

There are four steps in the proposed methodology to develop a conceptual model of the aquifer system hosted in the Tindouf basin.

The first step is based on collecting the published and unpublished data (geological maps, complete description of the lithologies and the structural features of the aquifers and any information obtained from the existing observation wells: calcium, magnesium, sodium, deuterium, oxygen 18, tritium, water levels...) (Idrotecno, 1979; Progress Sarl-Annaba, 1999).

The second step consists of collecting, analyzing and identifying the relationships between chemical and physical data in the different sectors of the Tindouf aquifer. PCA (Di Curzio, 2019; Meggiorin et al., 2022) is used to process the available chemical datasets obtained from each of the observation wells. In the case of isotopic variables with incomplete sets of available data, diagram deuterium versus oxygen 18 was used to explain origin of groundwater. Carbon 14 was used to estimate the water age. The use of Ca/Na and Mg/Na thermodynamic diagrams allow to assess the evolution of water from upstream to downstream of each of the aquifers. Information from hydrologic and geologic maps were used in the final stages of this methodology to augment the existing data.

In the third step, groundwater categories are simultaneously defined by their quality and origin. The quality of a given groundwater is affected by changes in chemical constituents due to the processes that can occur in the aquifer (water-rock interaction, evaporation, and interaction between waters with different origin and evolution). Isotopic variables can define the origin of water and differentiate between older water that was recharged during cooler climates and water that was recharged during a more recent warmer period. Groundwater-quality groups obtained from major chemical ionic data and water groups of different origin determined by isotopic properties are graphically combined to show water categories.

The lithological and structural data obtained from geological maps, and the combination of water samples from observation wells depicted in PCA groups are very helpful in defining various aquifer zones of the basin. For instance, low-salinity and relatively recent water that can be determined by the PCA and isotopic properties respectively, are of importance in defining the recharge areas. Similarly, PCA groups of saline and old water, obtained from relatively deep wells in the same aquifer, contribute to the identification of the discharge or transition zones that are little affected by recent groundwater recharge. In the final step, the data and their interpretation help develop a hydrogeological conceptual model of groundwater flow. This consists of an interpretation of groundwater flow patterns in relation to various zones of the aquifer.

Assuming that there is a relationship between the water coming from the recharge area and the water arriving at the discharge area, the following situations can be observed (Fig. 3).

For an aquifer undisturbed by faulting or leakage, recharge areas are represented by younger water (Y) with the lowest salinity (LS). Discharge areas are represented by older (O) water and higher salinity (HS) (Fig. 3-1).

In the case of a two-layer system (confined aquifer fed in part by a superficial aquifer where the water level is higher than the outlet), the flow will be characterized by 2 families of water: the first represents the less saline and most recent water coming from the water table, the second reflects more saline and older water in its discharge areas (Fig. 3-2).

For the case of a more complex aquifer system with leakage from neighboring aquifers, evaporation, mixtures of saline and ancient waters or others, other families of water must be taken into consideration to explain the properties of the flow (Fig. 3-3).

As above additional data were used in the final stages of this methodology to augment the existing data. Complementary hydrogeological data (geologic structure, lithology, piezometric levels, and hydraulic parameters) enable a more exact mapping of aquifer zones and the various groundwater flow patterns. Superimposing exploitation zones on these flow patterns can delineate the most effective operational regions, where further groundwater exploitation of the aquifer may be recommended.

Results

The interpretation of the physico-chemical data of the waters of the Tindouf basin shows (Fig. 4):

- The waters circulating in the Hamadian aquifer are very heterogeneous with 5 samples showing a sodium chloride hydrochemical facies, 4 showing a magnesium sulphate facies, 4 calcium sulphate facies, 1 showing sodium sulphate facies, and 1 calcium chloride facies. The dry residue varies from 896 mg/L to 5,460 mg/L, with the strongest mineralizations that are generally recorded upstream of the flow.
- The Visean aquifer is characterized by three types of water: 2 samples showing sodium chloride hydrochemical facies, 1 sample showing calcium sulphate facies, and 1 sodium sulphate facies. The dry residue varies from 2,348 mg/L (well 43) to 14,006 mg/L (T1) due to the leaching of evaporites.
- The waters of the Devonian aquifer are also of three types of water: 5 samples showing calcium chloride

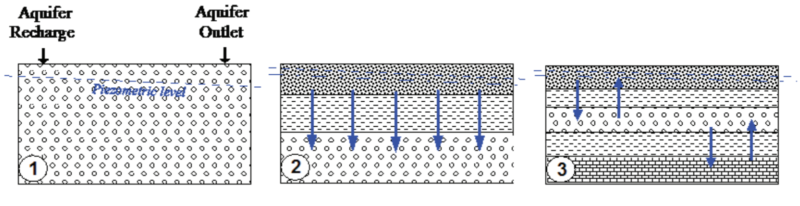

Fig. 3 - Interpretation of groundwater flow patterns in relation to various areas of the aquifer.

Fig. 3 - Interpretazione della distribuzione delle linee di flusso in diverse parti di un acquifero.

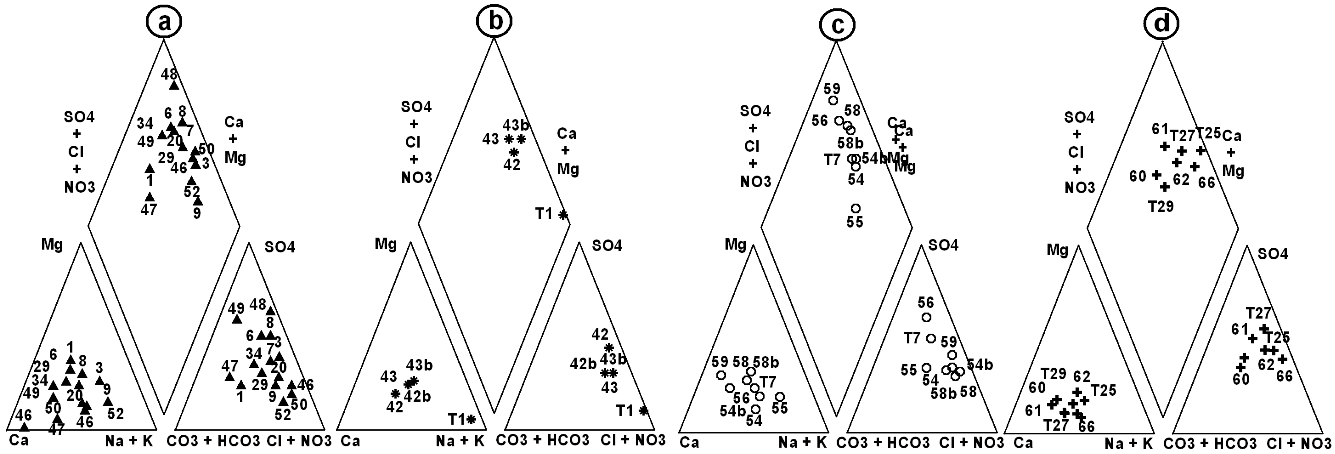

Fig. 4 - Piper diagrams of waters of Tindouf basin. (a) Hamadian aquifer; (b) Devonian aquifer; (c) Visean aquifer; (d) Cambro-Ordovician aquifer.

Fig. 4 - Diagramma di Piper delle acque del bacino di Tindouf per gli acquiferi (a) di Hamada, (b) del Viseano, (c) del Devoniano, (d) del Cambriano e Ordoviciano.

hydrochemical facies, 1 sample showing sodium chloride facies, and 2 calcium sulphate facies. The dry residue varies from 1,264 mg/L (point 55) to 2,592 mg/L (T7).

– In the Cambro-Ordovician aquifer, three types of water can be distinguished: 5 samples showing calcium sulphate hydrochemical facies, 2 sodium chloride facies, and 1 calcium chloride facies. The dry residue varies from 694 mg/L (T 29) to 4,000 mg/L (66).

From Figure 5, four groups of water are distinguished according to their salinity:

1. very low salinity (VLS) water with a dry residue lower than 1,600 mg/L;
2. water with dry residue of 1,600 to 2,130 mg/L: low salinity (LS);
3. water with strong salinity (from 2,300 to 2,370 mg/L): high salinity (HS);
4. water with very strong dry residue from 2,600 to 5,460 mg/L: very high salinity (VHS).

The oxygen 18 contents are reported as a function of deuterium, and the waters are grouped taking into account the tritium contents, i.e. from 0 to 8.3 Tritium Units (TU), between 8.3 and 16.6 TU, and greater than 16.6 TU. The delineation of water origin enables differentiation among three isotopic groups (Fig. 6):

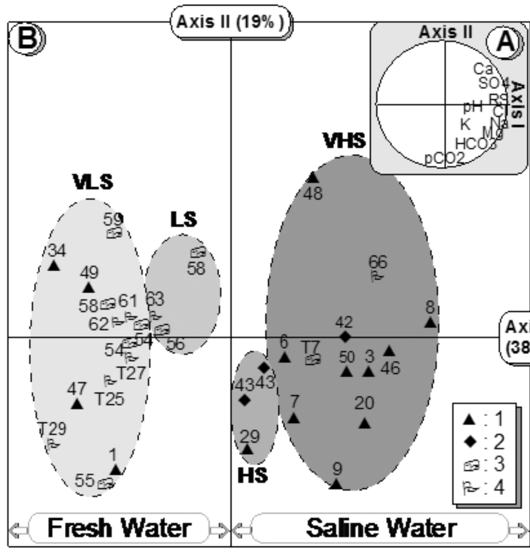

Fig. 5 - . PCA results for the Tindouf aquifer system: (A) Circle of variables (plane I–II). (B) Diagram of individuals (plane I–II). The numbers in the legend represent: (1) Hamadian aquifer; (2) Devonian aquifer; (3) Visean aquifer; (4) Cambro-Ordovician aquifer. The acronyms represent the group of waters based on their salinity (VLS: very low salinity; LS: low salinity; HS: high salinity; VHS: very high salinity).

Fig. 5 - Risultati della PCA per il sistema acquifero di Tindouf: (A) cerchio delle correlazioni (piano I-II), (B) grafico delle osservazioni (piano I-II). I numeri nella legenda rappresentano gli acquiferi (1) di Hamada, (2) del Viseano, (3) del Devoniano, (4) del Cambriano e Ordoviciano. Gli acronimi rapprresentano i gruppi di acque in base alla loro salinità (VLS: salinità molto bassa; LS: salinità bassa; HS: salinità elevata; VHS: salinità molto elevata).

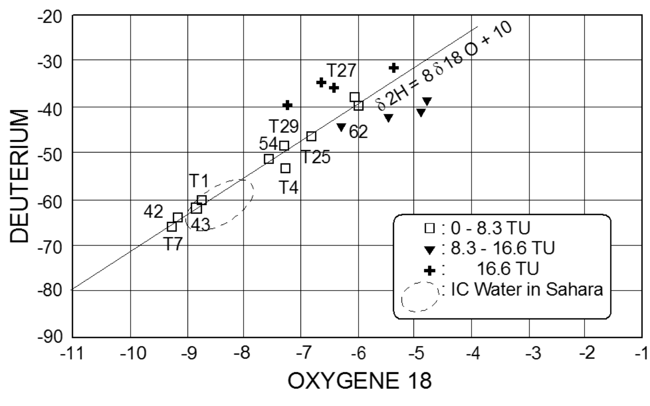

Fig. 6 - Deuterium versus oxygen-18 (values in ‰) in the groundwater of the Tindouf aquifer system.

Fig. 6 - Diagramma deuterio contro ossigeno-18 (valori in ‰) per il sistema acquifero di Tindouf.

- The points of the first group (0 to 8.3 TU) are very close to the line characterizing the ancient water of the Sahara Intercalary Continental aquifer in Algeria, with deuterium levels between -35 and -65‰ and oxygen-18 between -6 and -9‰. This water was recharged 7,000 to 11,000 years ago, when these areas had a temperate climate. Water of this group probably has low carbon-14 content, on the basis of data from well T25. This group corresponds to the old water, and is denoted as "group O".
- The data points of the second group (8.3 to 16.6 TU) are too very close to the line characterizing the ancient water of the Sahara Intercalary Continental aquifer in Algeria (Fig. 6). The slope of the trend of data points in this group is less than the slope of the line for $8\delta^{18}O+10$, which characterizes ancient groundwater that has been affected by evaporation. Water of this group is probably a mix of group O and recent waters and is denoted as "group OY".
- Data points for the third group (tritium values are higher than 16.6 TU) are shown in Figure 6 between the lines $8\delta^{18}O+10$ and $8\delta^{18}O+18$. The first line characterizes ancient water and the second is representative of recent Sahara waters (Guendouz et al., 2003; Moulla & Guendouz, 2004). Data of this group plot along a line with a gentler slope than the line that represents recent water. Oxygen-18 content varies between -5.3 and -7.2‰. Wells of this group are located in the Hamadian and Devonian aquifers and are denoted as "group Y".

Hydrogeological observations, such as piezometric levels and lithology, are used to complete the above data in order to delineate aquifer areas and/or recharge zones.

Based on thermodynamic equilibrium, it is possible to define a chemical evolution in the Tindouf basin aquifer (Figs. 7 and 8).

In Hamadian aquifer, water shows an evolution of the points chemically less evolved (34, 49, and 48) to the more walls and more advanced (50, 52). The first family corresponds to the most recent water with tritium values of 50.7 TU (30.1 to 34.49 TU and 35.7 to 48 TU). As for the second group, the level of tritium is very low.

The waters of the Visean aquifer, samples T1, 42, 43, and 43a, show a more advanced chemical evolution and display an age of about 8,600 years.

The waters of the Devonian aquifer are divided into two groups: one represented mainly by wells 58, and 59, 340 ± 100 years. The water drilling T7 shows a highly developed chemical maturation and show a significantly older age (about 28,000 years).

The distribution of water of Cambro-Ordovician aquifer on the stability diagram Ca/Na shows an evolution of the points less chemically mature (T25, T27, and T29) to more advanced (61, 62, 63, and 66) with a change in direction flow of the west to the east.

The age of the first 3 points varies from 660 years to 2,270 years old (T27 and T29, respectively), while for the second age group is approximately 7,100 years (62).

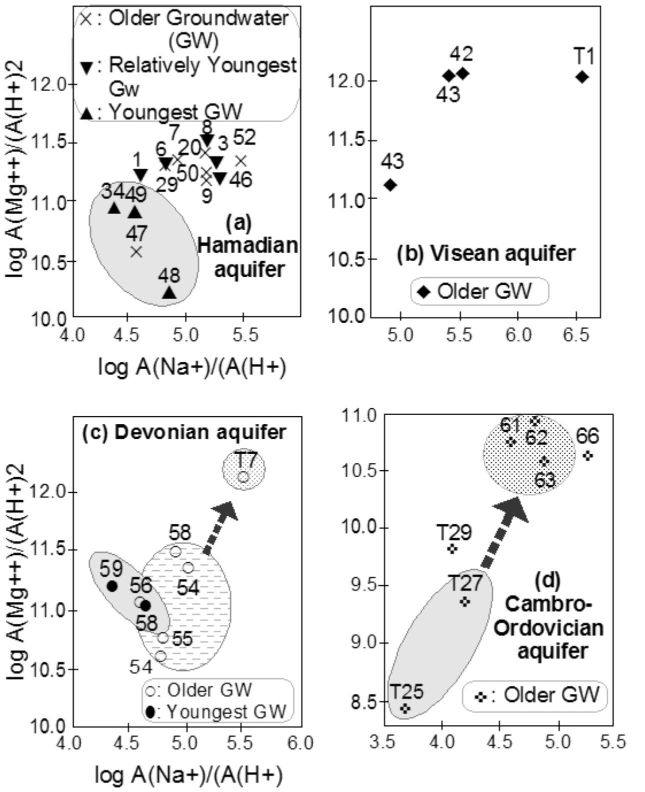

Fig. 7 - Equilibrium diagram Mg/Na for the (a) Hamadian aquifer; (b) Visean aquifer; (c) Devonian aquifer; (d) Cambrian and Ordovician aquifer.

Fig. 7 -. Diagramma di equilibrio Mg/Na per gli acquiferi (a) di Hamada, (b) del Viseano, (c) del Devoniano, (d) del Cambriano e Ordoviciano.

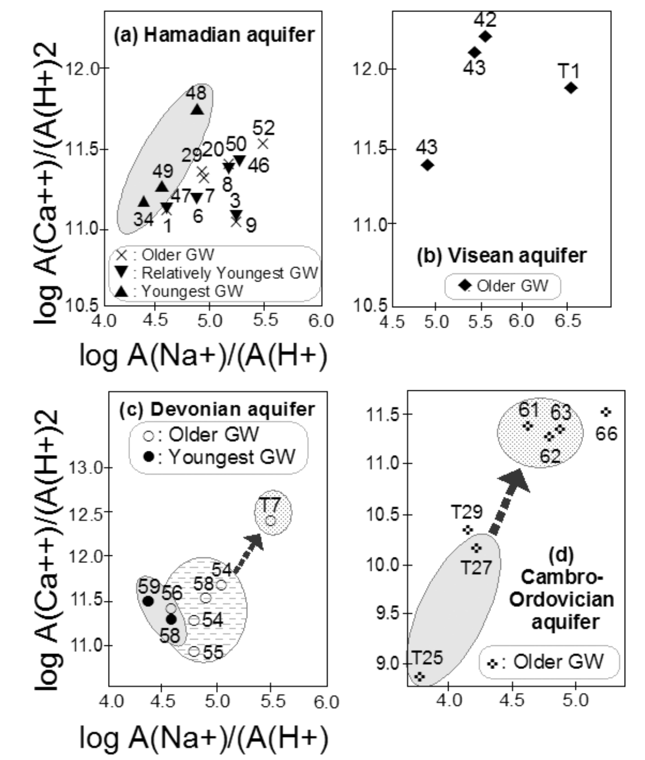

Fig. 8 - Equilibrium diagram Ca/Na for a) Hamadian aquifer; (b) Visean aquifer; (c) Devonian aquifer; (d) Cambrian and Ordovician aquifer.

Fig. 8 -. Diagramma di equilibrio Ca/Na per gli acquiferi (a) di Hamada, (b) del Viseano, (c) del Devoniano, (d) del Cambriano e Ordoviciano.

Discussion

The combination of the different water groups allows the identification of six water categories according to their salinity and isotopic content (Tab. 1). The Hamada aquifer is marked by the presence of all water categories. This indicates the influence of the evaporation and local inflow on water chemistry.

Tab. 1 - Water categories in Tindouf aquifers.

Tab. 1 - Gruppi di acque negli acquiferi di Tindouf.

Water category	Chemical and isotopical groups	Observation well	Aquifer[a]
OLS	(VLS + LS) O	47	H
		58, 54, 54b, 56, 55	D
		61, 62, T25, T27, T29, 63	CO
OYLS	(VLS + LS) OY	1	H
YLS	(HS + VHS) O	34, 49	H
		58b, 59	D
OHS	(HS + VHS) O	7, 9, 20, 29, 50	H
		43, 43b, 42	V
		T7	D
		66	CO
OYHS	(HS + VHS) OY	3, 6, 8, 46	H
YHS	(HS + VHS) Y	48	H

[a] *H=Hamadian aquifer; D: Devonian aquifer; V: Visean aquifer; CO: Cambrian and Ordovician aquifer.*

Samples collected from the Visean limestone aquifer are characterized by old water of high to very high salinity (OHS). Water of the Devonian aquifer that comprises three water categories (i.e, LS, YLS, and OHS) indicates a flow from south towards north. The Cambro-Ordovician sandstone aquifer is represented by OLS and OHS. The passage from one category to another is controlled by an inflow of recent water through the numerous faults that affect these formations, and/or by the residence time of water in the aquifer.

The hydrogeological conceptual model describes flow paths in the aquifer and the evolution of groundwater from recharge zones to discharge zones.

Considering water categories and geological context, six groundwater flow paths are defined (Tab. 2 and Fig. 9). Flow path F1 characterizes the transition zone between the Hamada of Tindouf and the Sebkha of Tindouf, which constitutes its principal discharge system. The F2 axis shows that the waters of the Hamada emerge in the sebkha or in the central part of the basin. Flow path F3 indicates the hydraulic continuity between the Hamada formation and the subjacent layers of the Visean limestone. Water supply of these aquifers is governed by the amount of rainfall on the Hamada formations that are considered in hydraulic continuity with lim estone in a large west–east-directed band and by infiltration through the outcropping zones of the aquifer located in the Atlas (Idrotecno, 1979; Progress Sarl-Annaba, 1999). Flow path F4 represents water from the Devonian aquifer which is characterized by a very low salt content. Axis F5 is marked by south-to-north-directed flow and also by infiltration of recent water through he many fault lines affecting the lower Devonian formation. Flow path F6 shows the west-to-east-directed water flow of the Cambro-Ordovician aquifer and water supply through fractures near wells T27 and T29.

Tab. 2 - Groundwater flow paths of Tindouf aquifers.

Tab. 2 - Percorsi di flusso negli acquiferi di Tindouf.

Flow path	Water categories	Observation well
F1	OYLS, OHS, OYHS	1, 3, 6, 8, 9, 7
F2	YLS, OHS	34, 29, 20
F3	OLS, YLS, OHS, OYHS, YHS	47, 48, 49, 42, 43, 43b, 46, 50
F4	OLS	54, 54B, 55
F5	OLS, YLS, OHS	56, 58, 58b, 59, T7
F6	OLS, OHS	T25, T27, T29, 61, 62, 63

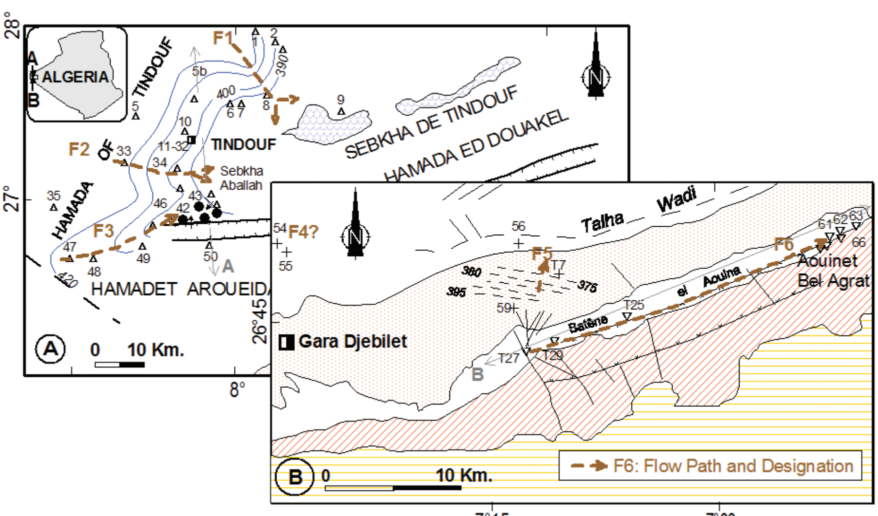

Fig. 9 - Conceptual Model and major groundwater flow paths in (A) the Hamadian and Visean aquifers and (B) the Devonian and Cambro-Ordovician aquifers.

Fig. 9 -. Modello concettuale e linee di flusso principali negli acquiferi (A) di Hamada e del Viseano, e (B) del Devoniano e Cambro-Ordoviciano.

Four aquifer systems were identified (Fig. 9):

- The Hamadian aquifer is 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 waters of exceptional floods that have accumulated on the enormous and thick spreading plains essentially made the supply. Mainly the great Sebkha of Tindouf and the Abdullah's Sebkha (Fig. 9A) make the outlet of the aquifer. 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.
- The Visean aquifer, which is the main aquifer of exploitation in this recent period, has presented favorable hydrological conditions particularly in the area of Sebkha Abdullah (Fig. 9A). Indeed, studies have allowed the identification of a system that has shown, locally, 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 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 eastern sector. Another possibility could be to recover operating losses through evaporation at the Abdullah Sebkha. The design of watershed development, unsuited to this type of aquifers containing evaporite 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 crops out in the extreme south of the study area (Fig. 9B). Due to its structural arrangement, it might contain probably modest reserves with good quality. This aquifer could be fed in some places by surficial water and the contribution of the underlying aquifers (Cambro-Ordovician) due to 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 sandstone is very affected by fracturing, particularly in its central part. It has the advantage of benefiting from water inflows from the surface through the fractures. The poor performance observed on almost all the borehole wells (except T29) is probably due to poor borehole design. In general, water quality remained good to fair. Groundwater flow in this aquifer is directed from west to east.

Conclusions

The processing and analysis of a very small number of data acquired on the aquifers of the Tindouf basin made it possible to identify groups of waters with different chemical and isotopic characteristics and to define the axes of underground flow.

The conclusions of this study are in agreement with the generally accepted conceptual hydrogeological scheme for this aquifer. However, in this study, new results were obtained, thanks to the use of statistical methods and the analysis of piezometric data, with regard to:

- the description of a complex flow system by grouping different qualitative and quantitative variables;
- the characterization of the main axes of underground flows through water families identified by mineralization, origin, and age of groundwater.

These results are consistent with the chemical evolution obtained through thermodynamic calculations for this aquifer system. Finally, this approach makes it possible to identify the main axes of groundwater flow and consequently to identify the areas favorable to the design and construction of new wells.

Funding

Funds for this research were provided by the Water Resources and Sustainable Development Laboratory. University of Badji Mokhtar Annaba, BP 12, Annaba 23000, Algeria

Competing interest

The authors declare no competing interest.

Author contributions

Fayçal TOUMI: collection data, writting originaly draft. Samir HANI: Data processing and formal analysis. Nabil BOUGHERIRA: Draft preparation and formal analysis.Azzedine HANI: supervision. Hicham CHAFFAI: supervision.Larbi DJABRI: supervision. All authors read and approved the final manuscript.

Additional information

Supplementary information is available for this paper at https://doi.org/10.7343/as-2023-626

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DOI 10.7343/as-2023-626

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