JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)
JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 46 (VII–IX): 190–199
https://doi.org/10.24425/jwld.2020.134213
Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://journals.pan.pl/jwld

Received 09.01.2020
Reviewed 13.03.2020
Accepted 25.03.2020

Identification and evolution of the Turonian aquifer case study: Cretaceous basin of Béchar, southwestern Algeria

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For citation: Sadat S., Mansour H., Mekkaoui A., Merzougui T. 2020. Identification and evolution of the Turonian aquifer case study: Cretaceous basin of Béchar, southwestern Algeria. Journal of Water and Land Development. No. 46 (VII–IX) p. 190–199. DOI: 10.24425/jwld.2020.134213.

Abstract

Faced with the challenges of sustainable groundwater resource management in the arid zone, the identification of reserves and their monitoring have become vital. This paper aims to identify the Turonian aquifer in the Cretaceous Béchar basin, and calculate its transmissivity, permeability and storage coefficient, as well as its evolution over time. This Turonian aquifer is characterized by marine limestones (gentle dip shelters 45° to the North and 5° to 10° to the South). Pumping tests revealed a transmissivity T of 10^{-4} to 10^{-2} $m^2 \cdot s^{-1}$, a permeability K of 10^{-6} to 10^{-4} $m \cdot s^{-1}$ and a storage coefficient S of approximately 10^{-3}. Two piezometric campaigns, carried out between (1976–2018), show a converging and constant flow direction from the North–East to the South–West and from the North–West to the South–East towards the outlet of the basin. Decreased values were observed in the North and South–West borders due to isopiezometric lines. However, this water table is not in a stationary state, it shows seasonal and interannual fluctuations in relation to the variable rainfall and the exploitation rate. In terms of facies, the projection of the two hydrochemical campaigns, during 1976 and 2018 on the Piper diagram, did not show any significant evolution, they are concentrated in the chlorinated and sulphated calcium and magnesium facies.

Key words: *Cretaceous basin, quantitative evolution, hydrodynamics, piezometers, Turonian aquifer*

INTRODUCTION

Water is a vital resource, at the heart of many challenges for populations and many human activities. Demographics, urbanization and economic development have a strong impact on water demand and use. However, in the future, the availability of this resource will be affected by climate change. Therefore, its evolution is one of the major areas of reflection in terms of sustainable management.

Groundwater, particularly in arid areas, is a vital but limited socio-economic resource [NYENJE, BATELAAN 2009]. Today, the use of water for domestic and industrial purposes is increasing, threatening its sustainability and having negative consequences on agriculture, forestry, industry and drinking water supply [ALIBOU 2002; JASORTIA *et al.* 2012; KADI 1997].

Indeed, the current situation of aquifer systems has become a key area of concern. The quantitative and qualitative state of aquifers results from a combination of natural and anthropogenic factors [BENRABAH, ATTOUI 2016; JAHANGIR, SOLTANI 2019]. In addition, the duality between the demands of operators in this category of water and the need to ensure their sustainability is a challenging issue.

Like the inland cities, the Béchar urban area has been on the threshold of water stress in recent decades, due to a soaring population of 243 374 inhabitants [Department of Planning and Land Use 2015 (Fr. Direction de planification et aménagement du territoire – DPAT)], climate change and excessive use. The study region, which is located in South-West Algeria where the climate is arid [DUBIEF 1963], groundwater tables are the main source of supply for people, the largest and most demanding of which is the Turonian groundwater, which provides more than 30% of drinking water and irrigation needs [KABOUR *et al*. 2011].

This article therefore aims to better understand and study pre-Saharian aquifers for a more effective management. To this end, it is necessary to identify the Turonian nappe in the Cretaceous sedimentary basin of Béchar, to study its spatio-temporal evolution and to consider its future evolution.

MATERIAL AND MEHODS

STUDY AREA

The region studied belongs to the Cretaceous Béchar basin, also known as the "Béchar Salt Basin" [DELEAU 1952]. It is located in the South-West of Algeria (Fig. 1), between longitudes 1°15′ and 3°15' W and latitudes 31°20′ and 32°15′ N. This basin is bounded to the North and West by the Algerian-Moroccan border and the northern carboniferous massifs (Antar and Horriet), to the East by the structure of Ben Zireg and to the South by the Mennouna--Djihani chebka.

It covers an area of 4000 km^2 [BENYOUCEF 2012; IDROTECNECO 1976] and is connected to the ErRachidia – Boudenibe basin of about 8000 km^2 [IDROTECNECO 1976]. Its width varies from 40 to 70 km and its longitudinal extension is from 500 to 600 km. It is represented by a more or less irregular landscape, inclined from North to South, favouring the flow of wadis (Saf Saf-Guir, Messaoueur and Béchar).

Given its geographical position, this area is not considered to be part of the Sahara. It is characterized by a warm summer with a medium temperature (T = 45°C) and a harsh winter (T = 2°C). The average precipitation is 100 mm per year.

From a geological point of view, it is a sedimentary basin formed by subsidence, in response to the elevation of the High Atlas [CHOUBERT 1939; DELEAU 1952], which has attracted the interest of several geologists, on the spatial and temporal modalities and organization of deposits, as well as on the filling mechanisms in relation to the global geodynamic framework [BENYOUCEF 2012; CLARIOND 1933; CLARIOND 1939; DELEAU 1951; DELEAU 1952; LEVY 1949; MENCHIKOFF 1936; PAREYN 1961].

Sedimentary deposition includes from bottom to top (Fig. 2):

– the Cretaceous discordant on the carboniferous subsoil includes: the Albian (20 m), starting with a discontinuous conglomeratic to microconglomeratic horizon, evolving upwards to gypsum clays, then to reddish to versicolor clays; the Cenomanian (40 m) represented by beige to greenish, fossiliferous marls; the Turonian (25–50 m) forms massive whitish limestone cliffs and platelets [FABRE 1976; 2005], perfectly circumscribing the edges of the basin; the Senonian, well known both in outcrops and in boreholes, is a gypsum clay containing locally halite beds; its depth is significant (>800 m);
– the Tertiary, lying in a gully unconformity on Senegalese clays; the Eocene (25 m) includes a level of powdery and coarse sandstone, followed by gypsum sandy marl and lacustrine limestone; the Oligocene (16 m) gullies lacustrine limestones, composed of pink sandy marls and limestone sandstones with some coarse elements; the Miocene (50 m), composed of coarse sandstones, sandy marls with conglomeratic lenses;
– Quaternary (15 m to 60 m), gravelly sandstone, fine sand and limestone interspersed in marl and clay.

The Cretaceous stack is structured as an asymmetric elongated East-West asymmetric syncline with a complex anticline wrinkle; its North flank is steep, with the passage

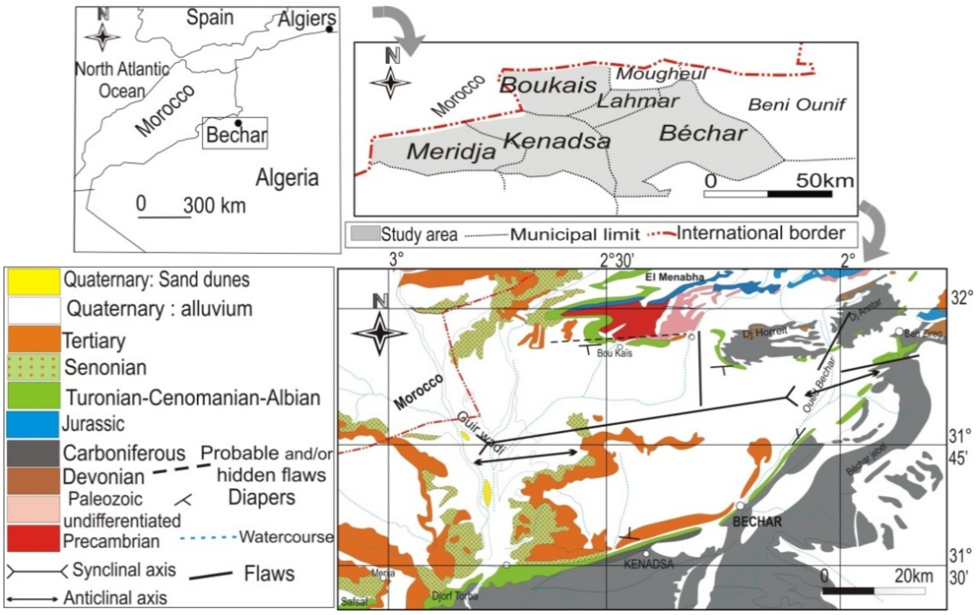

Fig. 1. Geographical location of the Cretaceous basin of Béchar; source: own elaboration

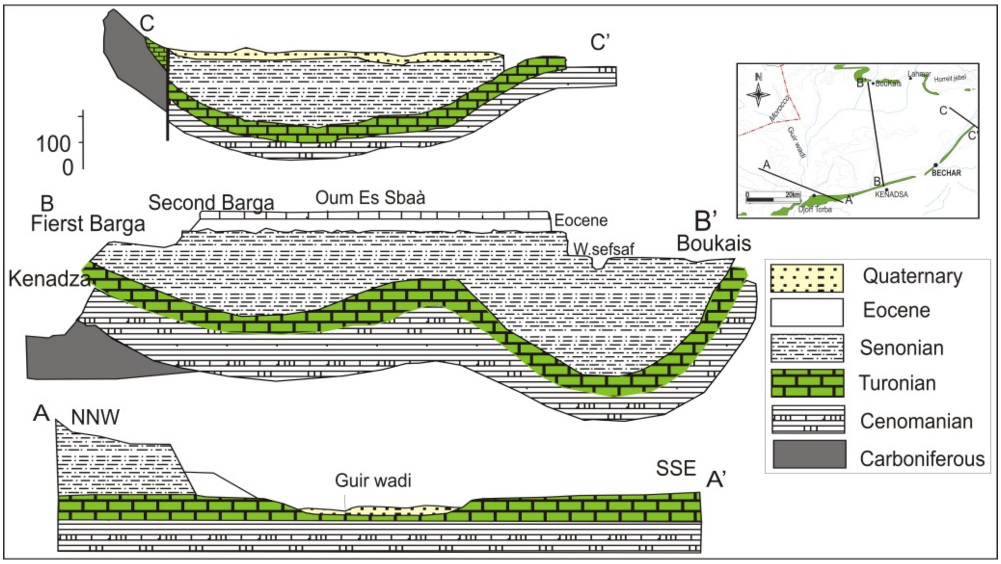

Fig. 2. Interactive hydrogeological cross section of the Turonian aquifer; source: IDROTECNECO [1976], modified

of the South Atlas fault and its southern flank is slightly sloping; it is fragmented by NE-SW oriented Atlas faults. The tertiary is tabular.

From a hydrogeological point of view, this basin includes three aquifers, Turonian, Eocene and Quaternary [BOURGEOIS 1960; GUERRE1974; IDROTECNECO 1976]. The Turonian aquifer is located in the Turonian limestones; its depth varies from 25 to 50 m. It is edge-free and more constrained towards the mid-point. It is widely used and illegally exploited, making it difficult to establish a complete overview. However, according to an attempt to identify the works that actually exploit the Turonian aquifer, we found that there at least 34 operating boreholes, 250 wells and 4 springs [ANRH 2008; DHW 2011].

DATA AND METHODS

This study is based on several identification campaigns and several types of data:

- data from long-term pumping tests of boreholes [BETA-Consult 2011; DHW 2011];
- lithological sections of boreholes and piezometers;
- identification campaign and piezometry (2018);
- piezometric chronicles of the four control piezometers PZ1, PZ2, PZ3 and PZ4 (2008 to 2017, ANRH);
- support card [IDROTECNECO 1976].

The interpretation of the pump test curves was made by Jacob's semi-logarithmic approximation [JACOB 1947], which includes three main equations for transmissivity T ($m^2 \cdot s^{-1}$) (Eq. 1), permeability K ($m \cdot s^{-1}$) (Eq. 2) and stocking coefficient S (Eq. 3):

$$T = 0.183Q : C \quad (1)$$

$$K = T : e \quad (2)$$

$$S = 2.25Tt_0 : x_2 \quad (3)$$

Where: Q = the pumping flow rate ($m^3 \cdot s^{-1}$), e = the aquifer depth (m), t_0 = the fictitious time at origin (s_0), x_2 = the distance between the borehole and observation piezometer (m).

RESULTS AND DISCUSSION

LITHOLOGY AND GEOMETRY OF THE TURONIAN AQUIFER

The Turonian aquifer represents the marine deposit. Turonian limestones are characterized by a monotony of facies and slight variation in depth. Indeed, the correlations of the borehole cross-sections clearly demonstrate the aquifer's sustainability (Fig. 3). It is a synclinal structure elongated from East to West as shown by the map of the Turonian aquifer (Fig. 4).

HYDRODYNAMIC CHARACTERISTICS

According to Jacob's semi-logarithmic approximation, the drilling descent curves (BEK, Hycobar 4, Ouakda 2, Ouakda 4 and Kenadsa 1) and the Lahmar s drilling descent and ascent curve (Fig. 5) were represented. Table 1 summarizes the results obtained.

Any hydrogeological interpretation depends on understanding the geology of the site [MANGIN 1974]. Indeed, the geological sections of the boreholes and the descent curves lead to the existence of the drain.

The descent curve of the BEK borehole (Fig. 5), located on the southern edge of the basin, was chosen as an indication. It has two slopes; the first is relatively steep, the second is smooth. On the basis of its geological section, it is possible to deduce the presence of two aquifers: Quaternary and Turonian. They are separated by a semi-permeable formation, which explains the drainage phenomenon.

For the first slope of 10 seconds up to 1000 seconds corresponds to the Quaternary groundwater in the transient regime begins in the BEK borehole under the action of an 8 $dm^3 \cdot s^{-1}$ pump, the transmissivity obtained is estimated at $1.24 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$.

The second slope is related to the Turonian groundwater, from 1000 seconds until the end of the test, underlines the installation of a transitional regime, moving to a pseudo-stabilization, the calculation of which allowed to have

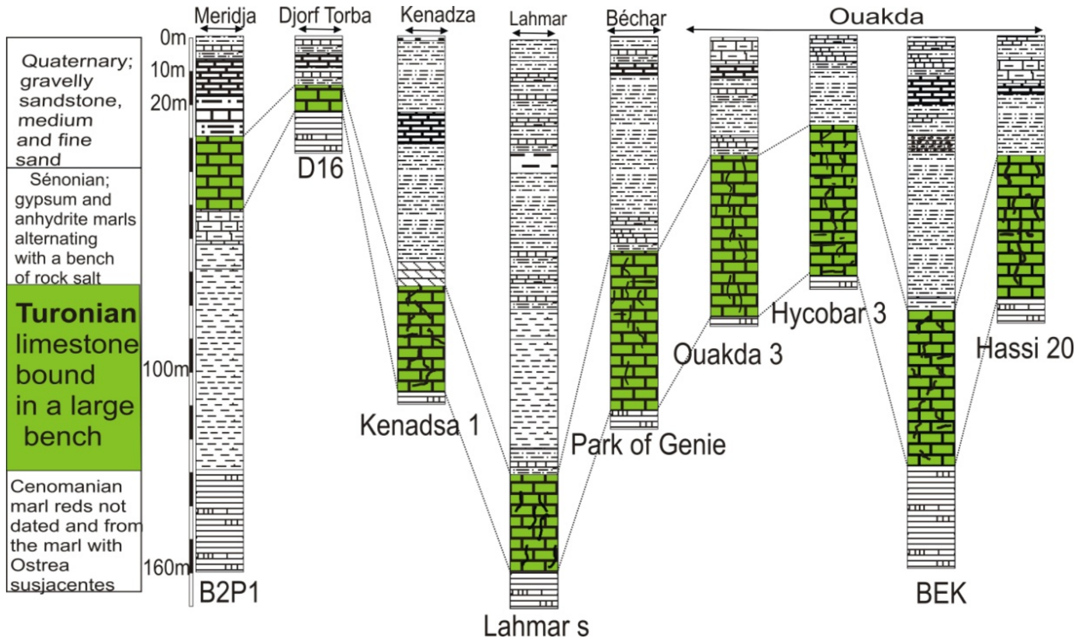

Fig. 3. East-West correlation of sections of the Turonian aquifer; B2P1 = name of drilling; BEK = Bzazel El Kalba; source: own elaboration

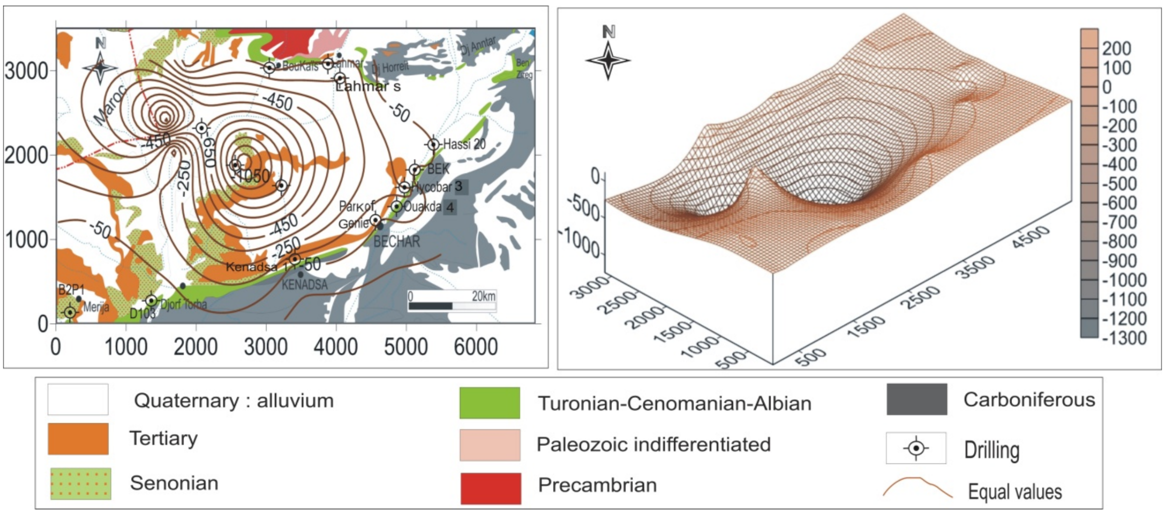

Fig. 4. Roof map of the Turonian aquifer; source: own elaboration

a transmissivity of the order of $1.42 \cdot 10^{-3}$ $m^2 \cdot s^{-1}$, which corresponds to the cracked limestones. Same analysis for the remaining Ouakda 4 and Kenadsa 1 boreholes located to the southen of the basin.

In the northern edge, the drainage phenomenon is no longer visible (Fig. 5), as advocated by the geological drilling section Lahmar s and its curves of descent and ascent, which have shown the following:

When descending and under the action of a flow rate of 7 $dm^3 \cdot s^{-1}$, two distinct time intervals are observed: the first interval starts from 0 to 100 seconds, corresponding to the emptying time, the second interval of 100 seconds until the end of the pumping, indicates a transient state and the beginning of a stable state. The rise is very fast up to 900 seconds, going up to stabilization. Transmissivity values range from $2.56 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$ to $2.13 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$, with an average of $2.34 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$ and an average permeability of $7.81 \cdot 10^{-6}$ $m \cdot s^{-1}$. In terms of storage coefficient, it is estimated at $1.2 \cdot 10^{-3}$ [IDROTECNECO 1976].

Table 1 summarizes the hydrodynamic characteristics of the Turonian aquifer. It can be noticed that the values of K and T are determined for permeable limestones with a slight variation from one point to another (increase towards the Djorf-Torba dam outlet). This could be related to the degree of fracturing which increases towards the site of Djorf-Torba (fault zones). Where the fractures are even more significant for groundwater flow in fault zones. Fractures control whether the fault core will act as a conduit, barrier, or a combined conduit-barrier system [CHELIH *et al*. 2018].

Table 1. Hydrodynamic characteristics of the Turonian aquifer

Designation	Q_{es} ($dm^3 \cdot s^{-1}$)	e (m)	T_1 ($m^2 \cdot s^{-1}$)	T_2 ($m^2 \cdot s^{-1}$)	K_2 ($m \cdot s^{-1}$)	S
Hassi 20[1)]	14.7	42.6		$2 \cdot 10^{-3}$	$4.69 \cdot 10^{-5}$	
BEK	8.0	47.5	$1.24 \cdot 10^{-4}$	$1.42 \cdot 10^{-3}$	$2.98 \cdot 10^{-5}$	
Hycobar 4	15.0	43.0		$1.48 \cdot 10^{-3}$	$3.44 \cdot 10^{-5}$	
Ouakda 2	15.0	39.0		$1.3 \cdot 10^{-2}$	$3.33 \cdot 10^{-4}$	
Ouakda 3[1)]	35.0	45.0		$11.5 \cdot 10^{-3}$	$2.55 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$
Ouakda 4	6.5	40.0	$3.72 \cdot 10^{-4}$	$9.9 \cdot 10^{-4}$	$2.47 \cdot 10^{-5}$	
Kenadsa 1	13.0	32.0	$4.96 \cdot 10^{-4}$	$5.95 \cdot 10^{-3}$	$1.86 \cdot 10^{-4}$	
B2P1[1)]	3.3	31.0		10^{-2}	$3.22 \cdot 10^{-4}$	
Boukaisaquaculture[1)]	5.0	17.0		$3.96 \cdot 10^{-4}$	$2.33 \cdot 10^{-5}$	
Lahmars	7.0	30.0		descent $2.13 \cdot 10^{-4}$	$7.10 \cdot 10^{-6}$	
				ascent $2.56 \cdot 10^{-4}$	$8.53 \cdot 10^{-6}$	

[1)] Bibliographic value [IDROTECNECO 1976].
Explanations: Q_{es} = pumping rate; e = aquifer depth; T = downhill transmissivity (T_1 = Quaternary tablecloth, T_2 = Turonian tablecloth); K_2 = permeability of the Turonian aquifer; S = storage coefficient.
Source: own study.

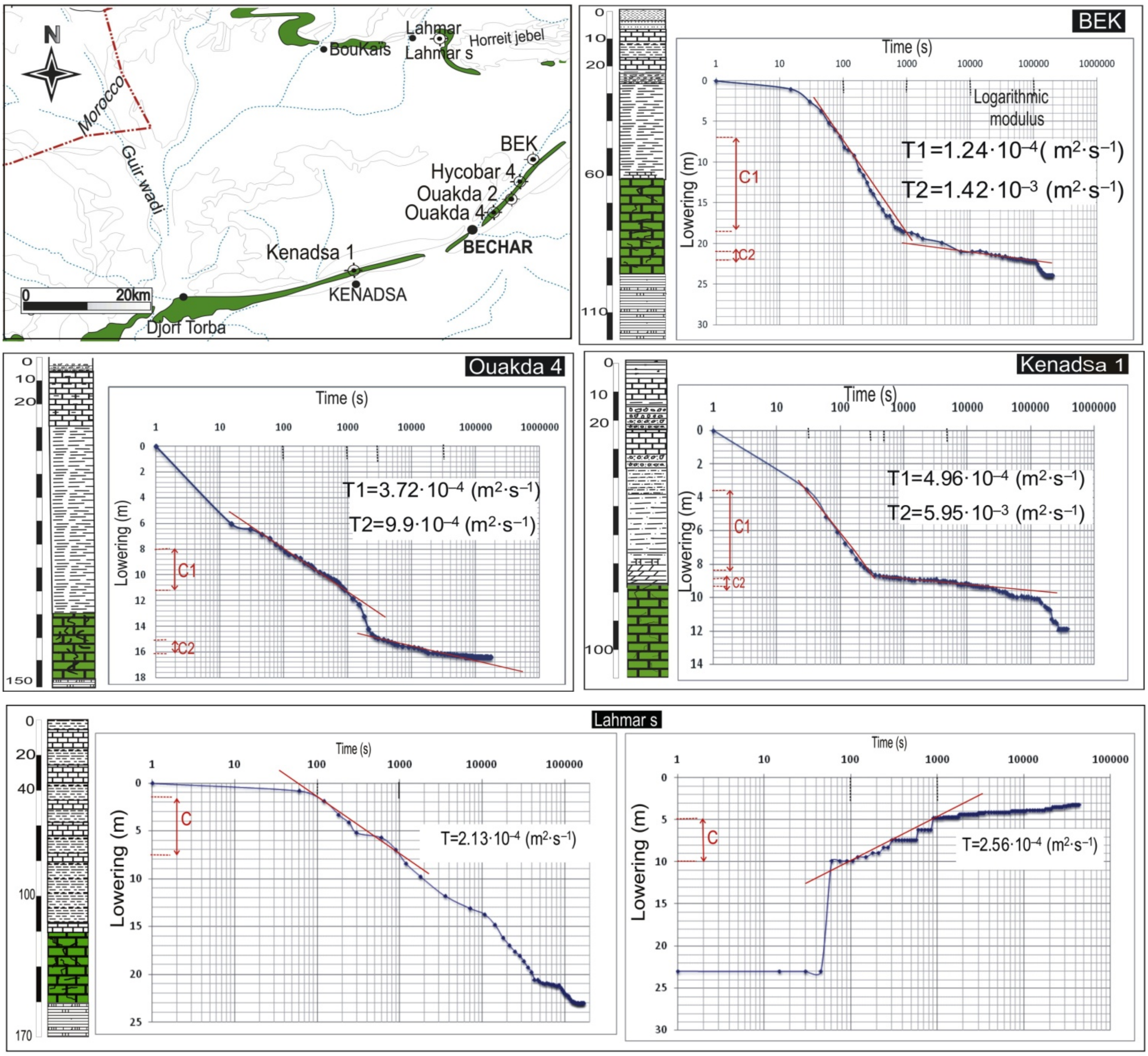

Fig. 5. The graphs of the pumping tests of the BEK, Ouakda 4, Kenadsa 1 and Lahmar s; source: own study

PRECIPITATION EVOLUTION

The average annual rainfall recorded at the Béchar station (1973–2016) shows very contrasting fluctuations (Fig. 6), compared to the annual average of 100 mm per year, the recurring years in deficit 60.47% are deducted, interrupted by a few rare years of surplus 39.53% whose rainfall will be more than twice the average (1992–1993 or 225 mm).

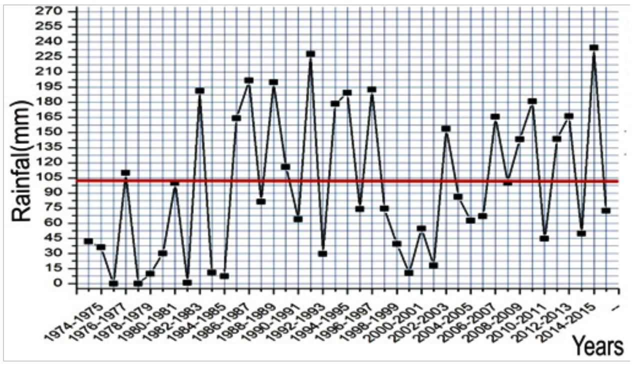

Fig. 6. Variation in average annual rainfall (Béchar station, 1973–2016) source: own study

In monthly terms, rainfall is low, averaging 7.79 mm per month (Fig. 7). However, the seasonal contrast is clearly visible; fall is wetter than the other seasons. In October and November, the rains are about 15 mm. In winter, they become moderate, ranging from 5 mm to 10 mm, then become insignificant in summer, with the exception of May, rainfall reaches 11.5 mm. These annual and seasonal fluctuations affect surface runoff and infiltration.

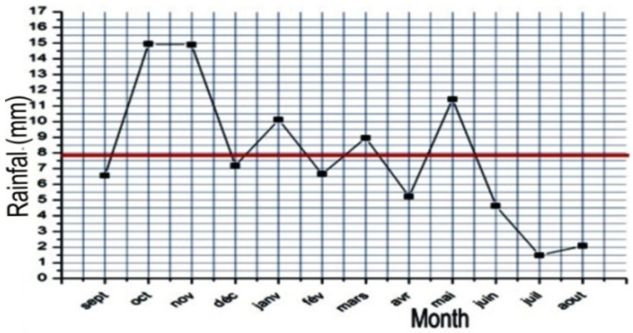

Fig. 7. Inter-annual average rainfall variations (Béchar station, 1973–2016); source: own study

PIEZOMETRIC EVOLUTION

- **Overall piezometry**

The map in Figure 8 gives an overview of the piezometric evolution of Turonian groundwater. It is based on two campaigns separated by a 42-year time interval. The 1976 season [IDROTECNECO 1976] reflects the initial state of Turonian groundwater, indicating two converging flows; from North-East to South-West and North-West to South-East, towards the right source near the Djorf-Torba dam.

During the 2018 season, the flow directions remained the same. However, it can be seen that towards the eastern edge of the slick, the isopiezometric lines of the two campaigns, which range from 683 to 920 m, overlap, reflecting a decrease in the piezometric level. On the other hand, the isopiezometric lines of the two campaigns become parallel in the center of the basin and towards the outlet, reflecting a moderate decrease.

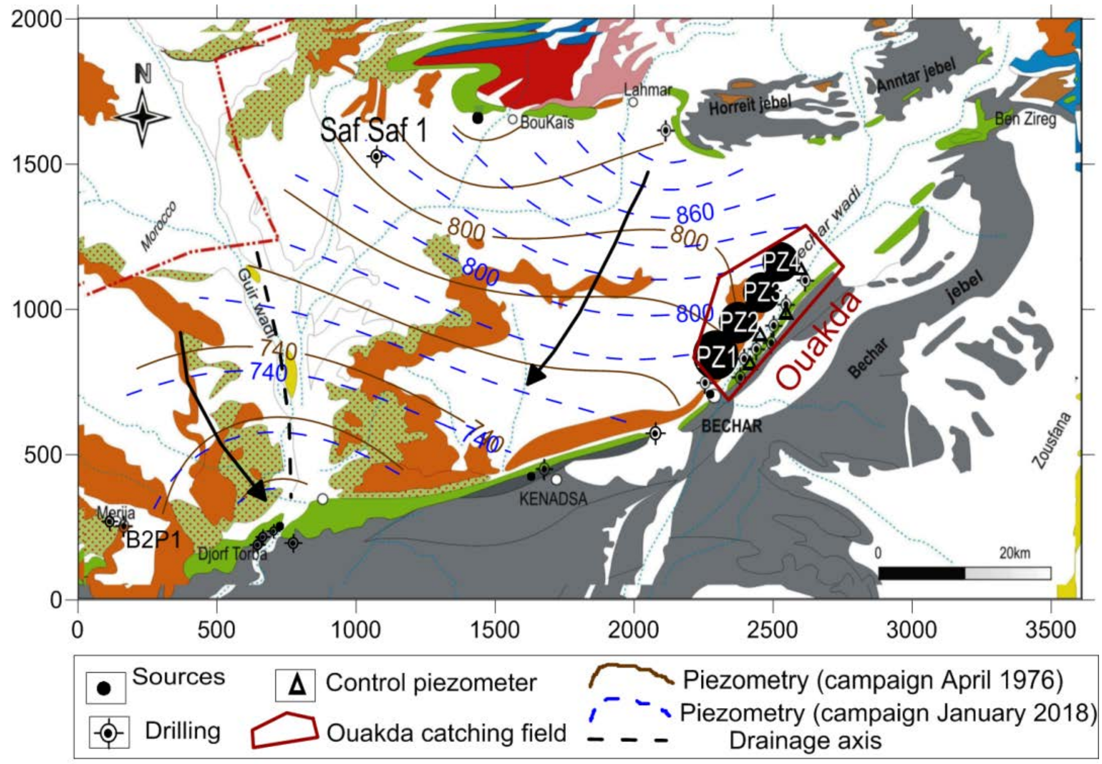

Fig. 8. Piezometric map for April 1976 and January 2018; PZ1–PZ4 = piezometers; source: own elaboration

- **Variation of the piezometric level in the Ouakda pilot zone**

Given its position at the eastern end of the Turonian aquifer, and the fact that this area is more exposed to water supply and irrigation drilling (Ouakda plain, a site of intense agricultural activity), the piezometric study of the Ouakda region is of great interest. As a result, this area was equipped with four control piezometers (Tab. 2).

Table 2. Characteristics of control piezometers PZ1–PZ4

Elements	PZ1	PZ2	PZ3	PZ4
$X^{1)}$	02°11'07"W	02°09'40"W	02°07'68"W	02°06'11"W
$Y^{1)}$	31°38'28"N	31°39'69"N	31°41'19"N	31°45'31"N
$Z^{1)}$ (m)	810	821	833	843
$NS_{max}{}^{2)}$ (m)	30.4	31.2	26.6	32.8
$NS_{min}{}^{2)}$ (m)	23.5	18.7	12.75	15.0
Standard deviation$^{2)}$	1.4	2.1	2.44	2.84
Average$^{2)}$ (m)	26.34	25.26	17.29	23.04

Source: $^{1)}$ ANRH [2008]; $^{2)}$ own study.

CONSEQUENTIAL ASPECTS

The correlation matrix between the five variables shows a high correlation (R = 0.7) between PZ1 and PZ3 and PZ3 and PZ3 and PZ4, a correlation (R = 0.3) between PZ4 and PZ1 and PZ2 and PZ1, while the other variables show a low correlation to insignificant extent (Tab. 3).

Table 3. Inter-piezometer correlation matrix

Elements	PZ1	PZ2	PZ3	PZ4	Effective precipitation	Precipitation
PZ1	1					
PZ2	0.35	1				
PZ3	0.73	0.02	1			
PZ4	0.39	–0.16	0.78	1		
Effective precipitation	0.20	0.29	0.05	–0.02	1	
Precipitation	–0.11	0.21	–0.21	–0.21	0.52	1

Source: own elaboration

PIEZOMETRIC FLUCTUATIONS

The piezometric chronicles (from 2008 to 2017), a time interval of 9 years, allow to deduce average static levels (PZ1: 26.34 m; PZ2: 25.26 m; PZ3: 17.29 m and PZ4: 23.04 m), while indicating significant variations. Indeed, the PZ1 indicated a maximum amplitude between 30.4 m on 23.09.2008 and 23.5 m on 26.06.2011.

PZ2 suggests a difference of 12.5 m between NS_{max} 31.2 m on 20.07.2008 and NS_{min} 18.7 on 20.12.2009 with a standard deviation of 2.1 m. The PZ3 certifies an amplitude of 13.85 m between NS_{max} 26.6 m on 23.09.2008 and NS_{min} 12.75 m on 18.01.2017, including the standard deviation 2.44 m. The PZ4 amplitude observed is very important: 17.8 m between the NS_{max} 32.8m on 23.09.2008 and NS_{min} 15 m on 20.02.2014 with a standard deviation of 2.84 m.

Thus, variations in groundwater level (increase, decrease and stabilization) reflect the image of the evolution of Turonian groundwater on the edge of the hydrogeological basin. Since October 2008, reports have shown a decrease in static levels due to possible over-pumping of AEP wells, followed by dramatic increases and disturbances until they stabilize near their average values (Fig. 9).

COMPARATIVE EVOLUTION OF TEMPORAL PATTERNS OF PRECIPITATION AND PIEZOMETRY

The static level of PZ1 highlights the sawtooth variations strongly influenced by rain infiltration with visible monthly fluctuations showing a significant decrease (Fig. 9). The fluctuations observed are related to rain. The same observations were made for the other piezometers PZ2, PZ3 and PZ4. However, PZ4 has a too high value 02/2014 probably due to a measurement error. It can be observed that excessive precipitation is still frequent. In addition, the temporal evolution of the piezometric curve shows a succession of increases and decreases in the static level of Turonian groundwater, controlled by precipitation, which is the result of exploitation of the groundwater.

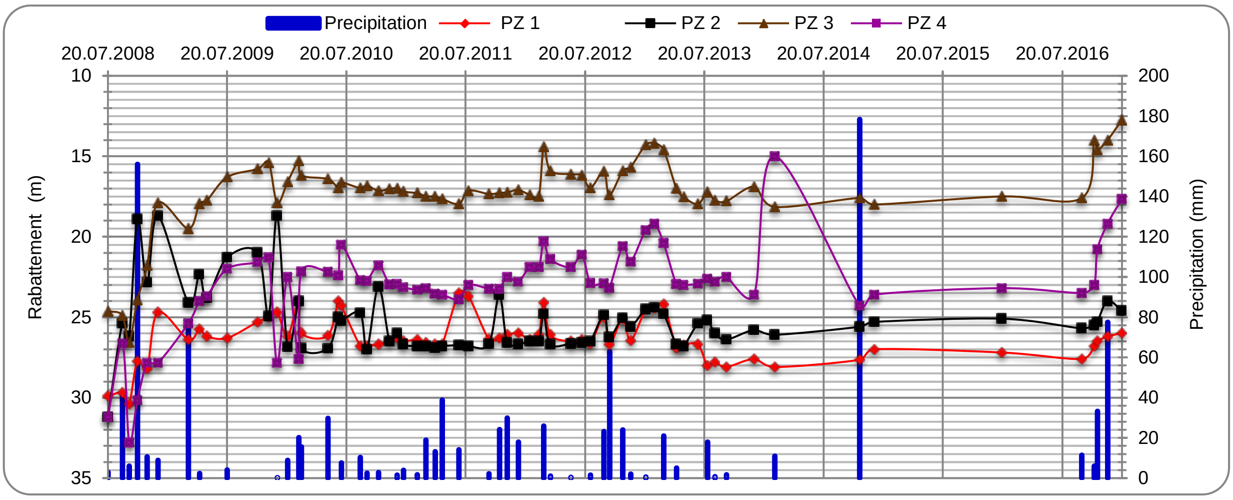

Fig. 9. Piezometric evolution of the Turonian aquifer and variation of precipitation (2008–2017); PZ1–PZ4 = piezometers; source: own study

Table 4. Hydrochemical characteristics of the waters of the Turonian aquifer (1976 and 2018)

Year	pH	*EC* (mS·cm^{-1})	RS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3^{-}	HCO_3^{-}
			mg·dm^{-3}								
1976	7.33	1.62	1280.2	101.89	51.93	219.45	1.47	428.84	184.15	10.80	265.98
2018	7.81	1.49	940.93	81.72	65.39	139.19	1.64	206.83	271.39	21.82	215.07

Explanations: *EC* = electrical conductivity of water, RS = dry residue.
Source: own study.

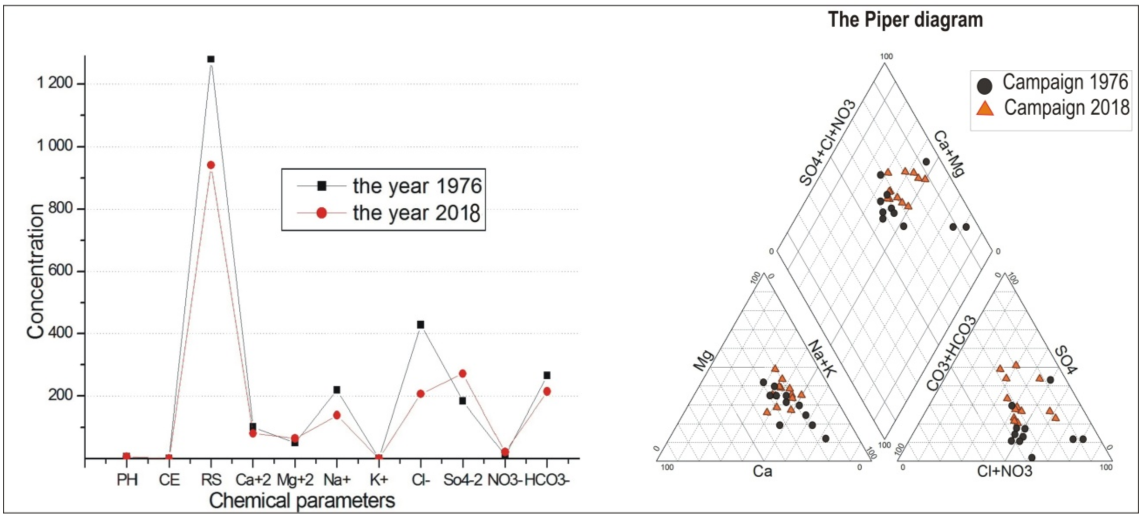

Fig. 10. Comparison of the hydrochemical characteristics of the waters of the Turonian aquifer (1976 and 2018) and Piper diagram with indication of the groundwater samples; source: own study

QUALITATIVE EVOLUTION

The qualitative evolution is based on a comparison of the 1976 and 2018 campaigns, and the results are reported in Table 4.

It can be seen that the 1976 season has relatively high concentrations of major elements compared to 2018 (Fig. 10). The pH shows no variation whose waters of the Turonian groundwater are characterized by a neutral to slightly basic PH, but clearly shows the existence of a decrease in the concentration of certain parameters such as electrical conductivity *EC*, dry residue *RS*, Ca^{2+}, Na^{+}, Cl^{-} and HCO_3^{-}. This is due to the renewal of the waters of the Turonian aquifer and its own expansion.

The Piper diagram in (Fig. 10) shows no significant changes; during the 1976 season, the water in this aquifer overlaps between two facies: chlorinated and sulphated calcium and magnesium and chlorinated sodium and potassium. In 2018, all structures are projected into chlorinated and sulphated calcium and magnesium facies.

In addition, the nitrate value is within the WHO tolerance level (50 mg·dm^{-3}) in the drilling of the El Hoda Mosque (Fig. 11), probably due to human activities, septic tanks and fertilizer use.

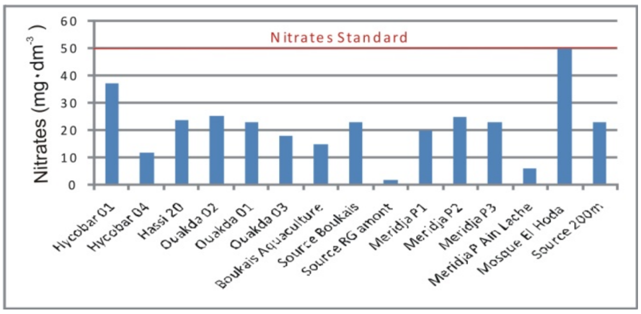

Fig.11. Nitrates content of Turonian aquifer waters

CONCLUSIONS

The Turonian aquifer is located in the Cretaceous Béchar basin or Béchar saline basin. It extends to Morocco under the name of ErRachidia-Boudnib basin, with a pre-Saharian position. This geological entity was created by isostatic compensation of the over-reaction of the High Atlas. It is a Cretaceous and Tertiary sedimentary filling, where the Turonian underlines a eustatic incursion highlighted by marine fossiliferous limestones that perfectly circumscribe this basin. This aquifer is deformed into an elongated East-West syncline, with a steep and gentle North flank to the South. The correlations of the boreholes underline a monotony of nodule-facies, with no significant lateral changes. Its depth ranges from 25 to 45 m. The Béchar region is characterized by a diverse precipitation regime, with an average of 100 mm per year, and a few years of excess rainfall alternating with long years of drought. The groundwater sheltered in this aquifer, known as the Turonian aquifer, is free on the edge and captive towards the center. It plays a major role for the city of Béchar. Pumping tests showed a permeability of 10^{-6} m·s^{-1} to 10^{-4} m·s^{-1}, a transmissivity of 10^{-4} m^2·s^{-1} to 10^{-2} m^2·s^{-1} and a storage coefficient of about 10^{-3}. The piezometric maps of 1976 and 2018 show a significant decrease in the North-East and South-East edges. On the latter, the Ouakda pilot zone is located, which was subjected to a piezometric control using four piezometers. The piezometric chronicles from 2008 to 2017 show fluctuations with amplitudes ranging from 27.8 m to 6.9 m. The precipitation deficit reflects the decreases in the static level. As a consequence, the Turonian groundwater level is considered to be decreasing, compensated by rainfall (natural recharge), through the drainage of superimposed groundwater, via faults (Toumiat and Boukais fault), re-infiltration of irrigation water (Ouakda catchment area) and water resulting from the interaction between the Djorf-Torba dam and the Turonian groundwater.

Considering the recharge space for this groundwater, it is recommended to enhance recharge devices. The water in this aquifer consists of chlorinated and sulphated calcium and magnesium facies. Nitrates is a preventive sign of pollution and needs special attention and appropriate regulation. Finally, based on these findings, it can be concluded that the Turonian aquifer is an open, reactive and well-drained reservoir.

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