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Palm grove groundwater assessment and hydrodynamic modelling Case study: Beni Abbes, South-West of Algeria

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Abstract

This paper presents the groundwater modelling of Beni Abbes palm grove in Southwest Algeria. Beni Abbes oasis alluvial aquifer is part of the Saoura Valley aquifer system, including a loose slick contained in a Quaternary alluvial embankment that fills the Beni Abbes basin. To address local needs, industry and agriculture, groundwater has been intensively exploited in recent years. Groundwater of the Beni Abbes oasis in the Saoura Valley oasis chain, is composed of a complex system, whose layer of alluvial terraces ensures a vital role for a 40-hectare palm grove. Due to its architectural position in the local aquifer system, the alluvial aquifer is mainly fed by the Great Western Erg and sometimes by the Saoura River floods. Based on the hydrogeological, hydrochemical characterisation and hydrodynamic modelling of the alluvial aquifer system of the Beni Abbes oasis, the mathematical model of finite difference and finite difference at steady state leads to the estimation of the hydrodynamic parameters of the aquifer and the evaluation of the complete water balance. The main results of this study provide a better understanding of the geometry and functioning of this aquifer currently in a state of concern. Furthermore, it is necessary to undertake integrated water resource management in this oasis in order to ensure sustainable development.

Key words: *alluvial aquifer, Beni Abbes, hydrodynamic, modelling, palm grove, Saoura River*

INTRODUCTION

Beni Abbes oasis is located on the left bank of the Saoura Valley, 6 km long and 5 km wide on average over an area of 40 ha. Water is collected from the large spring, foggaras and wells dug in the alluvial terraces and the lower flow of the Wadi Saoura (the Saoura River). However, the phenomenon of groundwater salinity has become a serious threat. Indeed, groundwater salinisation, caused by several human and natural factors, leads to serious irrigation problems. As a result, 60% of the palm grove's surface area has since been degraded. Bayoudh disease (*Fusarium oxysporum f. sp. albedinis* W.L. Gordon), socio-economic transformations and sometimes bad decisions have contributed to palm grove deterioration. Large terrace waters have been severely polluted by salinity, with 70% of the water volume subject to increasing risks. Due to its geographical position, atmospheric precipitation at Beni Abbes is low and coupled with high evaporation (2153 mm·y^{-1}) [MÉKIDECHE *et al.* 1995]. In addition to the excessive exploitation of wells in the Saoura Valley terraces and the unregulated proliferation of wells in search of fresh water, an option for palm grove irrigation, this phenomenon has been considerably accelerated and has destroyed the entire hydrogeological system in this region. Hydrochemical analyses over a 40-year period show an alarming spatial and temporal evolution of salinity. On the one hand, the drying up of the Saoura Valley due to the impact of the construction of the Djorf Torba dam and, on the other hand, the high evaporation rate, have seriously affected the water quality of the current flux. This situation would only serve to reflect and propose solutions to remedy these constraints on the water resources of this region.

STUDY AREA

LOCATION

Beni Abbes oasis is part of Saoura oasis. It is located between 02°30' and 00°50' West longitude and 30°50' and 29°00' North latitude about 240 km South-West of Bechar and 880 km South-West of Algiers as shown in Figure 1. Saoura's main river, resulting from the junction of Wadi Guirand and Wadi Zouzfana as illustrated in Figure 2, represents Sahara's main river in North-West region of Algeria. It is bordered to the East by the Great Western Erg, to the West by the Hamada of Guir and the Little Hamada. It reaches the Ugarta Mountains in lower Saoura [ALIMEN 1957; MENCHIKOFF 1933]. Due to its geographical position, Saoura Valley belongs to the Saharan area where climatic conditions are severe: low rainfall (<30 mm·y^{-1}) and intense potential evaporation [DUBIEF 1963].

GEOLOGICAL AND HYDROLOGICAL CHARACTERISTICS

Beni Abbes oasis is located on a 500 m high plateau of Hamada de Guir (Fig. 1). This region is associated with the mountains of Ougarta, which are very diverse, ranging from the Precambrian to present [YOUSFI 1991].

Palm grove alluvial aquifer covers an area of about 40 ha and a length of about 1 km. The region's arid climate is characterised by an average annual rainfall of 30 to 40 mm.

Geologically, the area is regionally associated with the Ougarta Mountains, which consist of a wide range of terrain from primary to present [ALIMEN 1957; MENCHIKOFF 1933]. Locally, Upper Devonian soils are known for their discordant resistance to Neocene, and then to Quaternary soils in the form of alluvium and wind accumulation, as illustrated in Figure 2. This study focuses on the Quaternary and alluvial aquifer of the palm grove.

Several research works were conducted for Quaternary of the palm grove [ALIMEN 1957; CHAVAILLON 1964; CONRAD 1969].

Saoura basin belongs to Sahara's major watershed. It is located in the South-West of Algeria and covers an area of approximately 100,000 km^2. The basin is composed of four sub-basins of different size. They are drained by the descending rivers of the Moroccan Atlas and the Saharan Atlas and flow from North to South (Fig. 2).

The Saoura River is vulnerable to flooding in autumn and spring, in the immediate vicinity of Wadi Guir and Wadi Zousfana. Saoura's water inflows are highly variable, with annual inputs estimated at 400 hm^3 at Beni Abbes and 350 hm^3 at Kerzaz [ROGNON 1994; VANNEY 1960]. As a result, Saoura River is experiencing a significant water scarcity [COTE 2002].

Summer is hot and dry and winter is cold and dry. Annual evaporation rate is high (around 2153 mm·y^{-1}). Precipitation in the study area is lower than that of evapotranspiration, so the water balance cannot be determined.

Alluvial terraces and inflow layers are a particular type of groundwater, constituted by wide dispersion of sand and gravel (alluvial terraces) shifted from Saoura, known as Saourien (upper Pleistocene) and Guirien (Holocene) – Figure 3 [YOUSFI, AIT AHMED 1991].

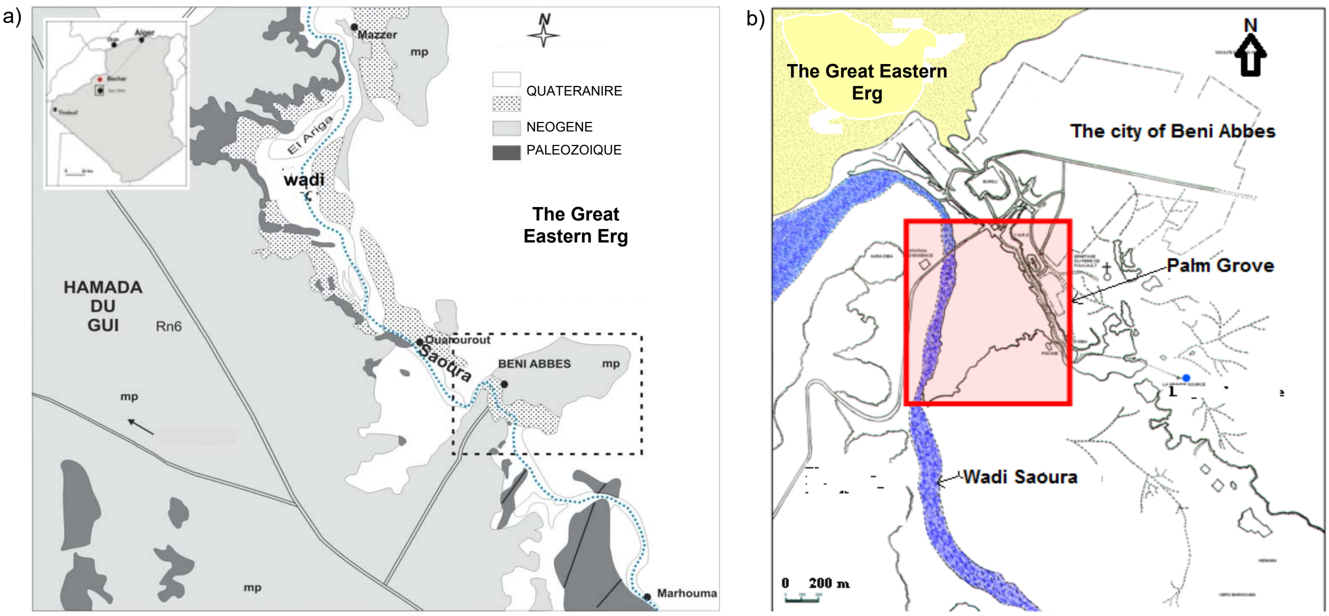


Fig. 1. Study area location: a) Beni Abbes, b) palm grove; source: MERZOUGUI [2011]

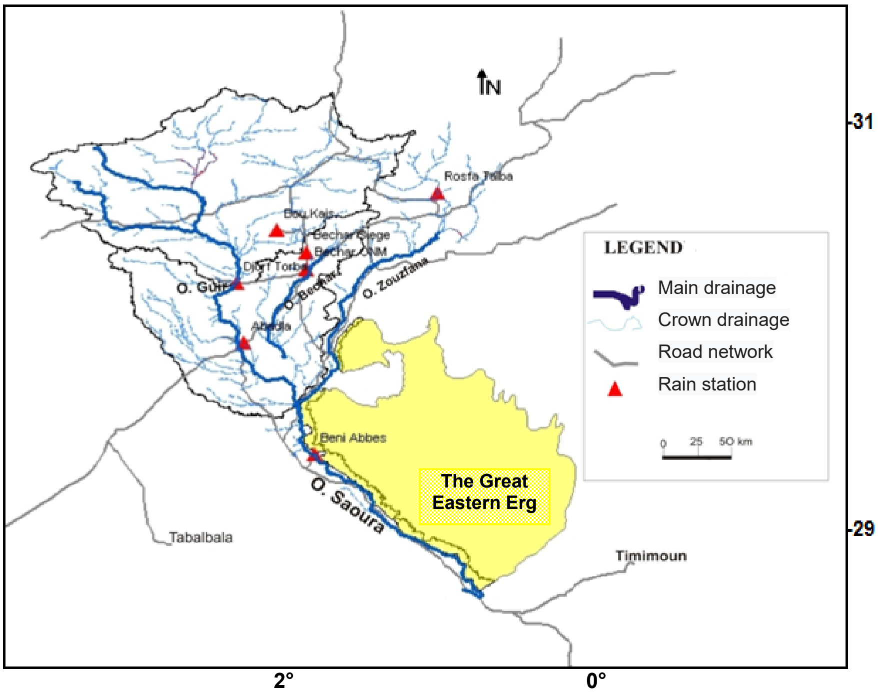
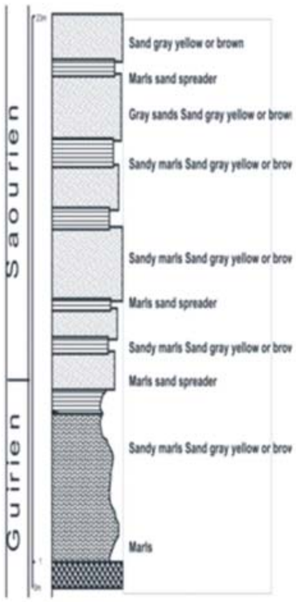


Fig. 2. Hydrographic network of Saoura watershed; source: own elaboration



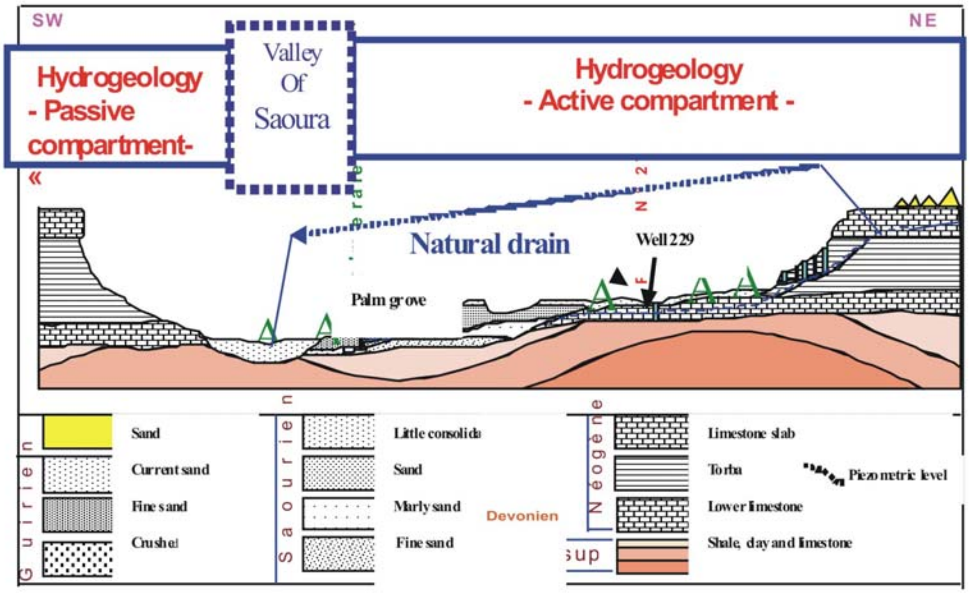


Fig. 3. Quaternary diagrammatic gross; source: ROCHE [1973]

Fig. 4. Beni Abbes region hydrogeological section through Saoura; source: ROCHE [1973], modified by MERZOUGUI *et al.* [2011]

From a hydrogeological point of view, the subsoil of this oasis contains a system of groundwater complexes. Basically, this system is composed of well-defined and extensive groundwater from the Great Western Erg, fed by wadis (rivers) from the North, mainly from the Saharan Atlas.

The main source, generally referred to as the "Sidi Othmane Source", collects groundwater from this aquifer, with a flow rate of 26 to 33 $dm^3 \cdot s^{-1}$ respectively [MERZOUGUI *et al.* 2007; ROCHE 1973]. It has a two-fold function: drinking water supply and palm grove irrigation. This locality is the perfect outlet for this groundwater. Hamada du Guir groundwater is associated with the lake limestone deposits of the Tertiary. It is supplied by the few meteorological waters. This leaf is characterised by a low water capacity. In addition, groundwater in Paleozoic formations can be explored and it can be noticed that it constitutes a multilayer system (Fig. 4).

Saoura Valley also includes aquifer us terraces. Neogene lithology allows water to flow through a natural drain to the aquifer of the palm grove. This explains the existence of a natural drain between the large waters of the Great Western Erg and the large waters of the terraces and infer-flows [BENNADJI *et al.* 1998].

The wells that have been monitored are generally large in diameter, concreted on their side walls, and the water supply is most often from the base. The water is used to irrigate the palm grove.

METHODS

Methodological approach used in this work is based on geological and hydrodynamic characterisation, analysis of aquifer geometry, piezometric maps and geological and hydrogeological sections.

NUMERICAL MODEL DESIGN

Modelling objectives are to quantify the natural flows transiting the aquifer and to understand the distribution of permeabilities allowing the reconstitution of piezometry. Thus, in order to properly manage the underground reservoir in all situations, it is necessary to better understand the hydrodynamic functioning of the aquifer system.

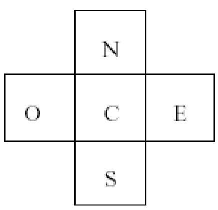
For this purpose, a modelling program called ASMWIN (Aquifer Simulation Model) developed in Switzerland (ETH Zurich) was used [KINZELBACH, RAUSCH 1995; MAILLOUX *et al*. 2002] for this study case. This model has been described in detail in several publications [BABA HAMED 2005; GOSSEL 2008; HANI 2018; OUELD BABA 2005; RENIMA 2018; SENOUSSI 2011].

For any deterministic type of water modelling, three elementary physical laws are strictly necessary: mass conservation law, Darcy's law and state equations.

The integration of the three elementary equations of water circulation in a porous medium combines gives the diffusivity equation [BONNET 1978].

Discretion is generally achieved by the finite difference method. If the meshes are square, the steady-state hydrodynamic equation is as follows:

Dupuit's hypotheses (horizontal velocities) describe the fact that the exchange balance is balanced [ROCHE 2005]:



$$Q + Inf + \sum Tci\ (Hi - H) = 0$$

Where: TCi is the transmissivity between meshes C and i.

Equilibrium equation applied to any mesh size is as follows:

$$A \cdot S\ (Ht + dt - Ht)/dt = Q + Inf + \sum i = 1\ Tt\ (Ht,i - Ht)$$

Where: A – area of the mesh (= dx2 for a square mesh of side dx); S = storage coefficient (free or captive, as appropriate); Ht: charge at the date t; t = time; dt = a time step; i = number of meshes in North, South, East and West; Inf = infiltration.

GRID DESIGN

The map presented in Figure 5 is used as a reference and the model is obtained by scanning the topographic map at 1:1000. For spatial discretization, a uniform square mesh of 25 m side length was placed over 1 km^2 of the area, of which 800 meshes were active, as shown in Figure 6.

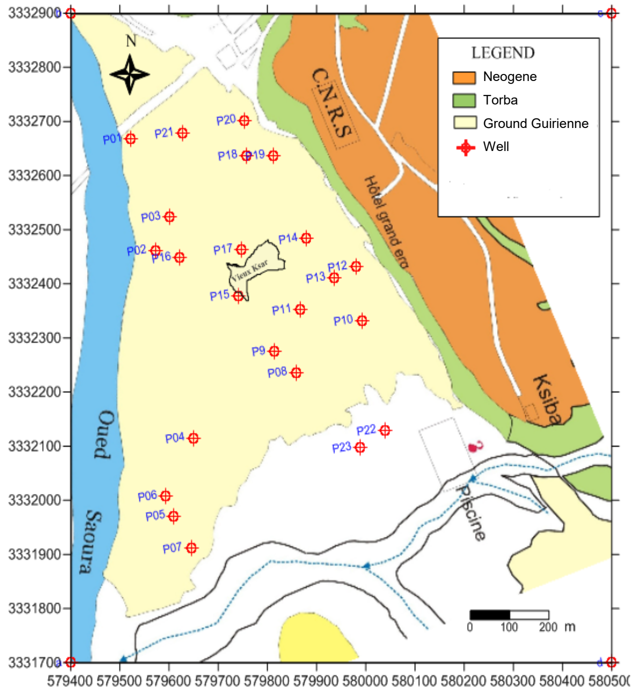


Fig. 5. Wells (P01–P23) location in palm grove; source: own elaboration

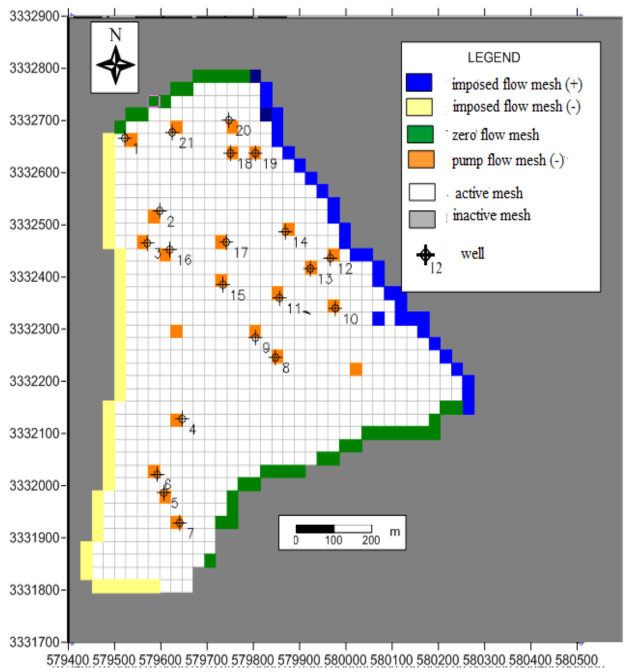


Fig. 6. Model grid design and discretization; source: own elaboration

BOUNDARY CONDITIONS

Alluvial filling of Beni Abbes palm grove has been studied in its entirety, and it can be considered as a single layer for the model. Domain boundaries were defined in accordance with the section established by ROCHE [1973].

Neogenetic formations represented by the Hamas cliff of the Great Western Erg are located in the eastern part. To the West, the filling is limited by the neogenetic formations of Guir Hamada. The following boundary conditions have been imposed (Fig. 6):
- East: limit of inlet flow imposed (erg supply),
- West: limit of output flow imposed (wadi),
- South and North: a zero flow limit imposed.

RESULTS AND DISCUSSION

DEPOSIT CONDITIONS AND FEEDING

Beni Abbes palm grove is located at the base of the Great Western Erg, along the Saourien and Guirien wadis, opposite Mio-Pliocene cliff.

Early on, the Beni Abbes oasis was most likely important because of the existence of a single source in the Saura River that irrigates only the main palm grove and provides drinking water to part of the population. The Middle and Upper Devonian formed the rock base of the Hamada in the region. A statistical study of the cracks in the slab of the cliff provides an understanding of the circulation pattern in Hamadien formations.

Water from these neogenetic lands flows through the Quaternary alluvial terraces. The palm grove of Beni Abbes is fed by the infiltration of water from the large spring used for irrigation. The lateral contribution of the Mio-Pliocene is then secondary [ROCHE 1973]. The thickness of the aquifer varies between 10 and 20 m.

The influx of wadis, i.e. the level of the base of the aquifer, would be located around the raft at 453 m a.s.l.

Aquifer systems consist of two lithological units: limestone and sandy marl from the Mio-Pliocene and Quaternary formations.

As a result, the reservoir consists of three layers of Quaternary deposits (sand, sandy clay, conglomerate) with an average thickness of 15 m, all resting on a folded schistose substrate from the Upper Devonian (Fig. 7).

HYDRODYNAMICS AND PIEZOMETRY

Water from the great spring irrigates the palm grove and wells are dug in the alluvial aquifer. Continuous discharge flow is close to 8 $dm^3 \cdot s^{-1}$ [2008 and 2016], with 1/3 of the amount discharged in the 1960, 0.22 $dm^3 \cdot s^{-1} \cdot ha^{-1}$ or an irrigated flow of 683 $mm \cdot y^{-1}$.

Sources and foggara draining water in the Neogenic slope provide a total flow rate of less than 3 $m^3 \cdot h^{-1}$, the other flow rate crossing the lower beds of the Mio-Pliocene then into the Quaternary terraces (80 $dm^3 \cdot s^{-1}$). A total flow rate of 83 $dm^3 \cdot s^{-1}$. Quaternary formations transmissivity, calculated on two piezometers (one located 200 m North of the ksar and the other near the deposit), is equal to 2.10^{-4} and $4.4.10^{-4}$ $m \cdot s^{-1}$ [MERZOUGUI *et al*. 2007].

Storage coefficient values at the palm grove range from 2.10^{-2} and 6.10^{-2} in the North, to 10^{-2} and 10^{-3} in the South. The piezometric map provided in 1991 (Fig. 8) was similar to the one drawn up in April 2016. It presents a general flow from the North-East to the South-West.

Groundwater inputs from the Great Western Erg (15 $dm^3 \cdot s^{-1}$), water flows through a natural drain and seguias, throughout the slope and by infiltration of irrigation water from the large spring (the part reserved palm groves 11 $dm^3 \cdot s^{-1}$), for a total flow of 26 $dm^3 \cdot s^{-1}$.

Average water level depth of the palm grove relative to the ground is about 2 to 10 m.

In Beni Abbes oasis, the exploitable water resources are limited. Therefore, the Great Source presents a flow rate of 28 $dm^3 \cdot s^{-1}$, foggaras' flow rate is of 5 $dm^3 \cdot s^{-1}$, drilling's flow rate is of 10 $dm^3 \cdot s^{-1}$, while the wells loaded with salt water have an estimated flow rate of 2 $dm^3 \cdot s^{-1}$ each. A total of 50 wells are dug in the alluvial terraces.

Salinity diffusion, where a spectacular spread of salinity is observed, affects 70% of the water mass of alluvial terraces.

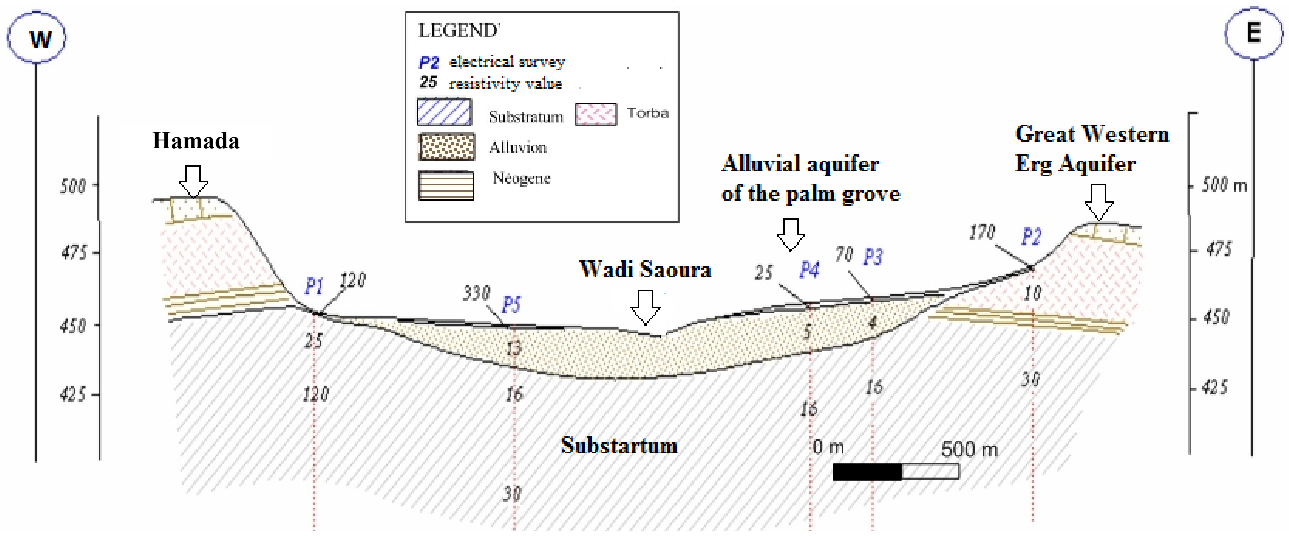


Fig. 7. Palm grove alluvial aquifer condition and deposition; P1–P5 = wells as in Fig. 5; own study

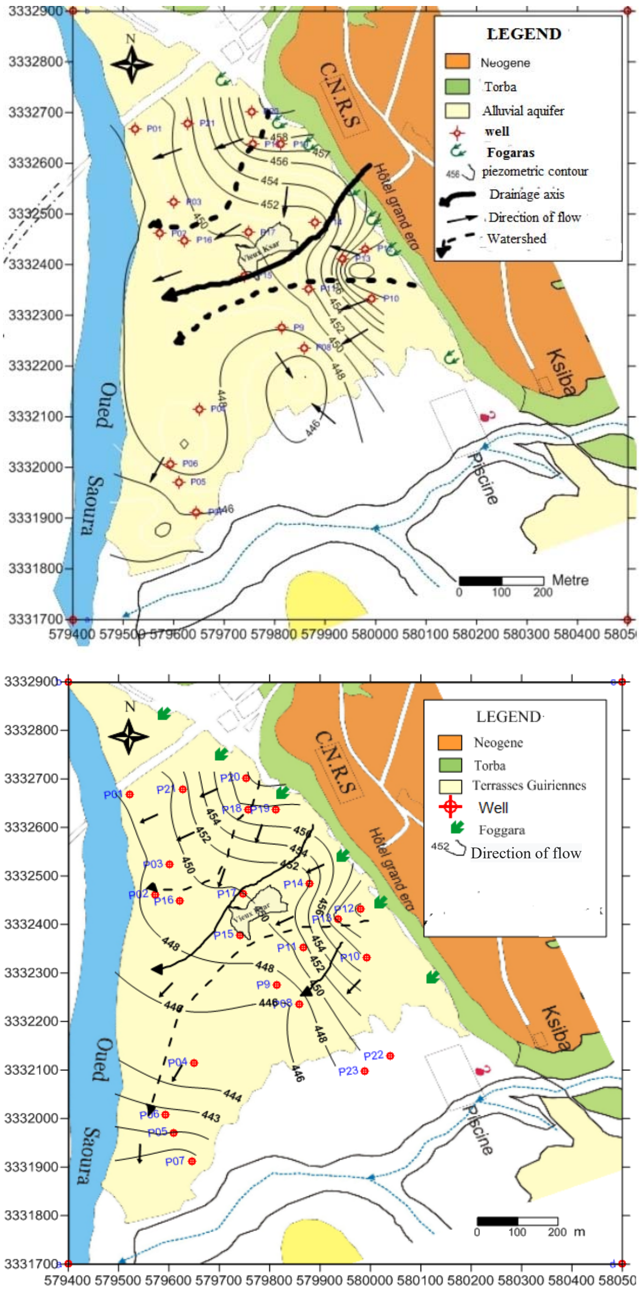


Fig. 8. Palm grove alluvial piezometric contours: a) April 1991, b) April 2016; P01–P23 = wells; source: own study

Unreasonable use of water resources due to changes in user segregation such as inadequate irrigation systems, waste and social changes, have effectively contributed to the deterioration of groundwater. Wastewater discharged without prior treatment in Wadi Saoura can pollute groundwater and pose a threat to public health, the environment and ecological balance.

WATER QUALITY AND SALINITY

The hydrochemical data series collected is discontinuous, but it is very useful in studying the spatial and temporal evolution of physico-chemical constituents. Nevertheless it allows histograms and quantities of dissolved salts to be drawn, as well as exogenous salinity migration. Currently, a clear trend from west to east is highlighted, with retrograde hydrochemical zoning from more than 15 g·dm^{-3} to less than 6 g·dm^{-3} (Fig. 9). The dissolution processes of gypsum, halite or anhydrite promote the salinization of groundwater. It also corresponds perfectly with the under-saturated of water state covered by these minerals.

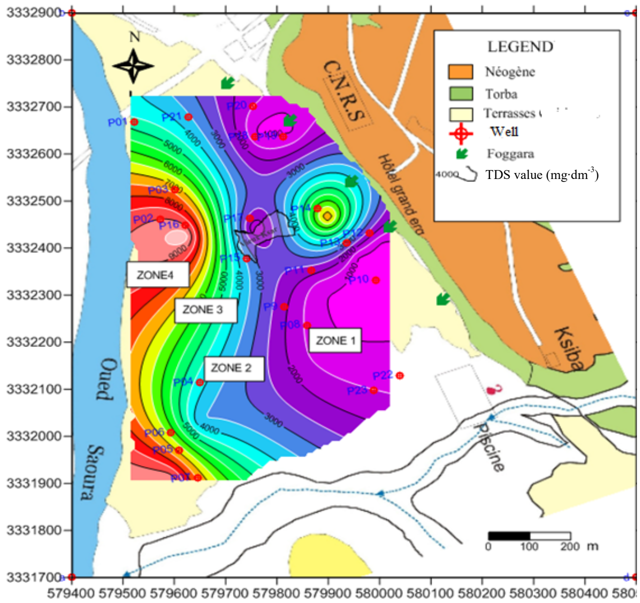


Fig. 9. Map of the spatial evolution of the total dissolved solids (TDS); source: own study

Cationic exchange phenomena and dissolution/precipitation processes of carbonate minerals (calcite, dolomite and aragonite) are generally responsible for the variation in cation concentrations (Ca^{2+}, Mg^{2+} and Na^{+}) in Saoura groundwater [LACHACHE *et al*. 2018].

With regard to groundwater in the palm grove alluvial aquifer, the evolution is clearly evident from West to East.

The values of cations and anions are multiplied by 3 to 7 on zone 3, twice on zone 2 and 1.5 times on zone 1. The waters of the erg web contain calcium sulphate, as shown by the analyses of the large source.

The spatial evolution map of the total dissolved solids (TDS) allowed to identify three zones of salinity, from the least concentrated zone 01 (0.3 to 3.0 g·dm^{-3}) in the palm grove centre (zone 2: from 3 to 7 g·dm^{-3}) to a zone 3 and zone 4 more concentrated (20 g·dm^{-3}) the edge of Wadi Saoura (Fig. 9).

Dry groundwater tailings values range from 850 to 9245 mg·dm^{-3}, while TDS values range from 861 to 9467 mg·dm^{-3}.

HYDRODYNAMIC MODELLING AND DEVELOPMENT

The steady-state and transient numerical model has made it possible to refine the spatial distribution of permeability and transmissivity over the entire domain and to establish the balance of the transient steady-state aquifer in a single-layer aquifer. A good calibration in state and transient conditions has been demonstrated by the maximum points very close to the law (Fig. 10).

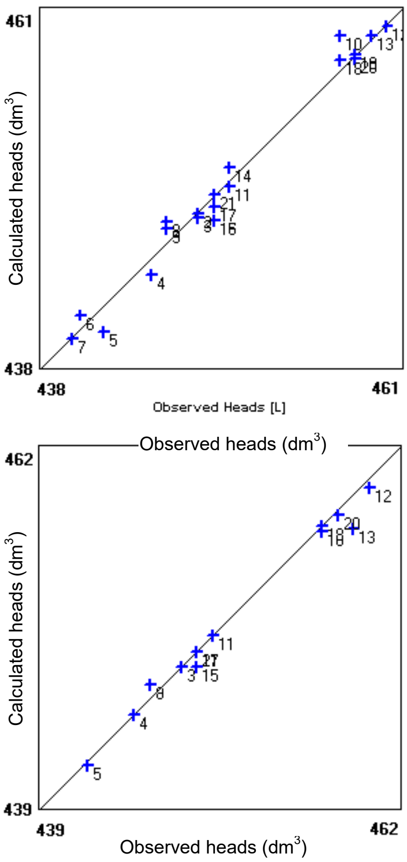


Fig. 10. Calculated heads vs. observed heads for the steady state and transient modes: a) steady state, b) transient (2016 data); source: own study

After the permanent calibration of the steady-state simulation, the model restored the hydrological balance of the alluvial layer of Beni Abbes palm grove, namely the recharge, lateral inflows and the quantity of water withdrawn from the wells.

Table 1 presents the distribution of outflows at the limits or the overall assessment, from which the model results are presented.

Table 1. Water budget in steady-state in Beni Abbes palm grove

Flow's direction	Flow term flows ($Mm^3 \cdot year^{-1}$)					
	natural drain	well	emptying groundwater	evaporation	recharge	total
In	25	–	–	–	3	**28**
Out	–	16	3	13	–	**32**
In – out						**–4**

Source: own study.

For a practitioner, permeability is the most important result because its maps help to guide the location of agricultural wells [BABA HAMED 2005; KOUANE 2008].

Therefore it can be noticed:

– an zone with very low permeability of the order $1.2 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$,
– a zone of low permeability of about $4 \cdot 10^{-2}$ $m^2 \cdot s^{-1}$ in the western part of the ksar,
– a zone of strong permeabilities of the order of 0.11 $m^2 \cdot s^{-1}$.

As shown in Figure 12 for calibration of the model, we adopted a zonation highly cut-off permeabilities to account for the heterogeneity of the aquifer. Five beaches permeability includes between 10^{-5} and 10^{-2} $m^2 \cdot s^{-1}$ have been defined (Fig. 12).

Calibration of the transient model has refined the spatial distribution of the aquifer storage coefficient (Fig. 13). This parameter's zoning coincides with the geological nature and thickness of the aquifer.

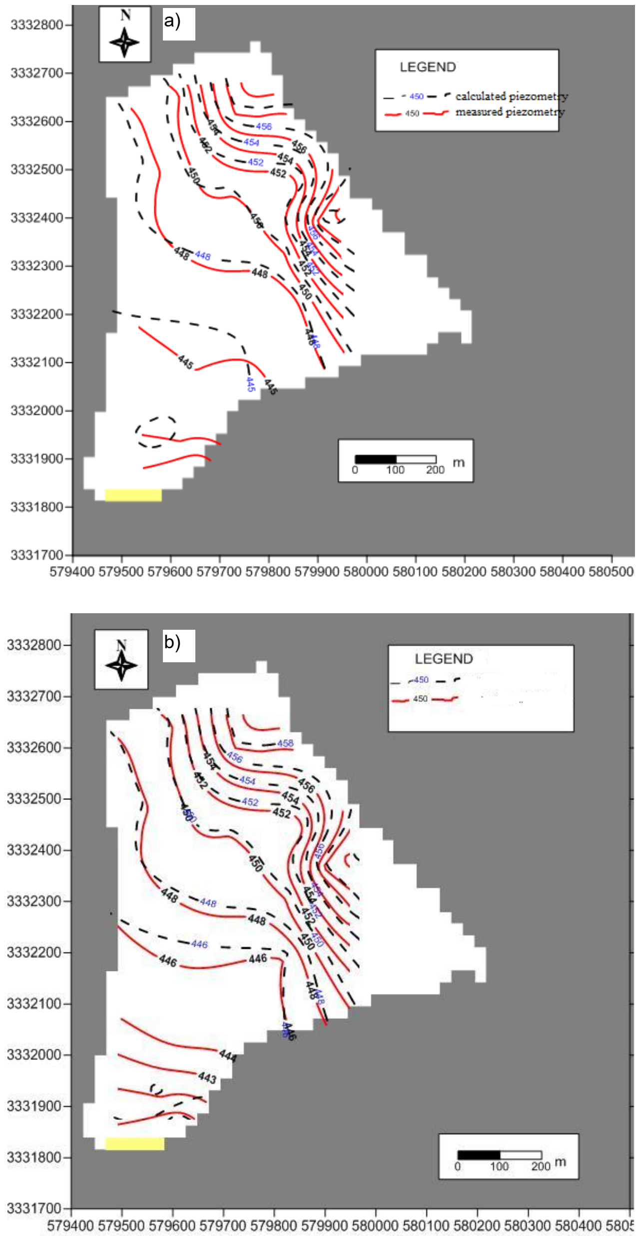


Fig. 11. Simulated groundwater contours in palm grove: a) steady state, b) transient (2016 data); source: own study

NUMERICAL MODEL AND SIMULATION RUNS

Among the issues raised, the evaporation losses in the development of the model were not considered, a disadvantage of the ASMWIN model on the one hand, and the required answers to be provided on the other:

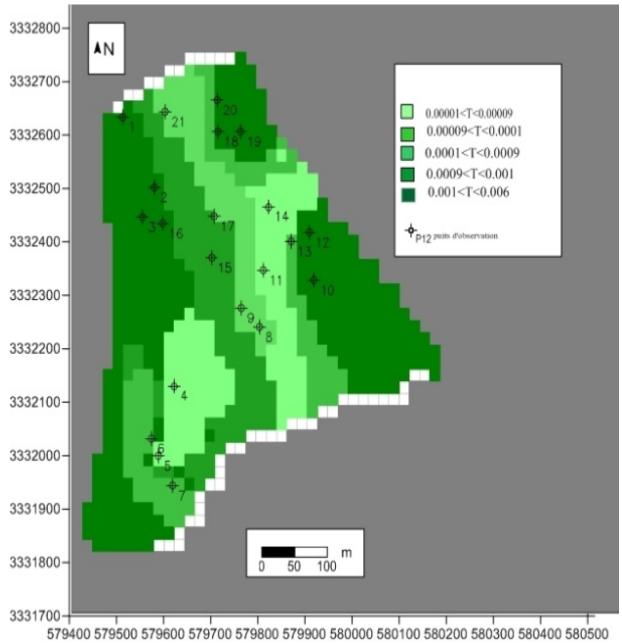


Fig. 12. Permeability calibration map of Beni Abbes palm grove; source: own study

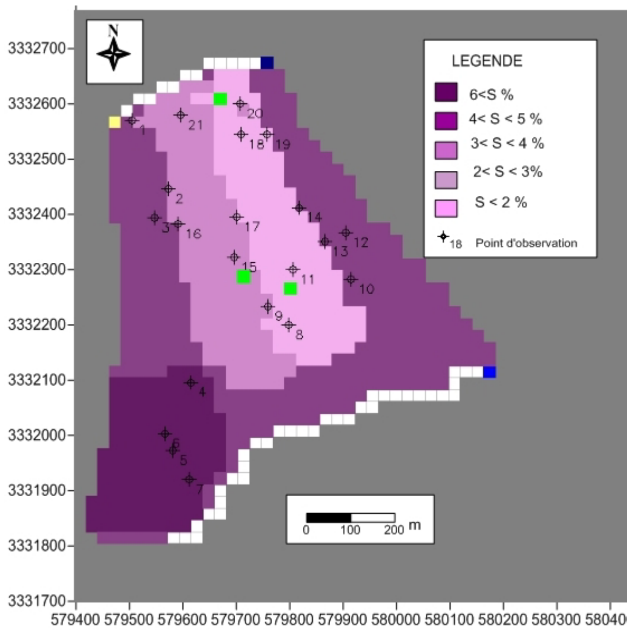


Fig. 13. Storage coefficient adopted for calibration of the transient model; source: own study

– construction of a groundwater dam and its impact on changing groundwater behaviour;
– influence of artificial recharge by treated water in annual modulus;
– in the alluvial aquifer, the accuracy of the calibration is affected by the inaccuracy of the sampling in the aquifer as well as by the permeability and transmissivity data of the alluvial aquifer; the calibration consisted of visualizing a level drop between 0 and 2 m.

In addition, a simulation of aquifer exploitation over a 20-year period was carried out. This simulation shows an exploitation of the aquifer with the same current regime. The results of this simulation are presented by the evolution of the piezometric level in three areas, at the edge of the erg in the centre and west of the palm grove.

The curves presented in Figure 14 show a decrease in the piezometric level of about 2 m in the entire groundwater.

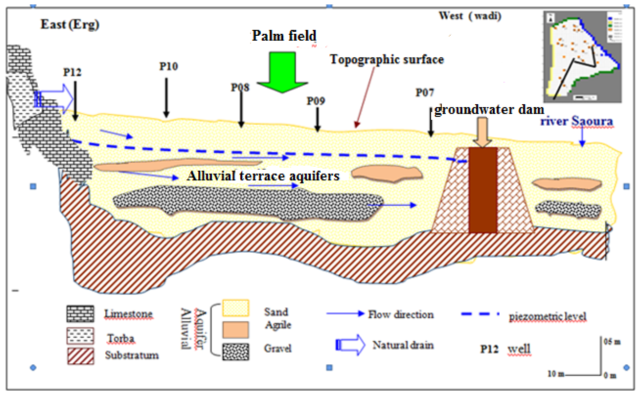


Fig. 14. Schematic representation of an alluvial groundwater aquifer with a groundwater dam; source: own study

The maps of the calculated potentials and drawdowns resulting from this first simulation show a decrease in the water level of several meshes located south of the palm grove with significant pumping in this area.

Moreover, a simulation with the construction of a groundwater dam (Fig. 14) was also conducted. The creation of a groundwater dam west of the palm grove, along the entire length of the aquifer, at the edge of the wadi, 400 m wide and 10 m high. The dam will be located one metre below ground level. This hydraulic structure will increase the water level of the groundwater table by storing water from the natural drain of the alluvial aquifer, the groundwater table of the erg.

The 10-year simulation, while maintaining the same operating regime, shows an average water level rise of 2 to 3 m in the centre of the palm grove and to the south with a slight decrease to the west.

Finally, a simulation with artificial recharge of purified wastewater (Fig. 15) was performed. An artificial recharge of about 28 $dm^3 \cdot s^{-1}$ was assumed using treated wastewater,

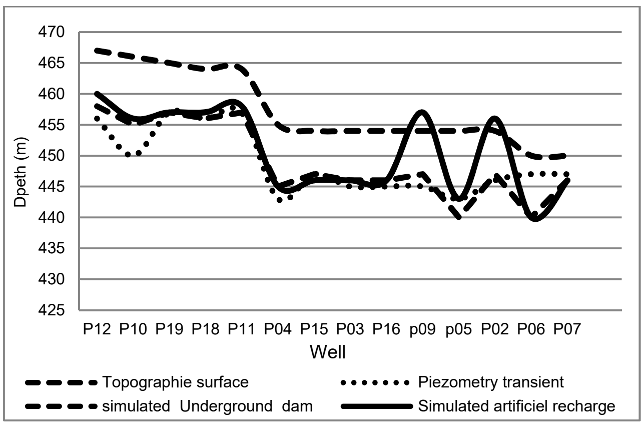


Fig. 15. Piezometric curves of different simulated scenarios; P01–P19 = wells; source: own study

which was then injected into nine wells and a recharge of the entire area to be modelled, in the presence of the groundwater dam.

Two scenarios were identified that show that artificial recharge by direct infiltration into the wells, causing a significant rise in the piezometric level that can be harmful to the palm grove.

The curves that represent the variation in water level drawdowns show a significant increase in groundwater level.

However, the second scenario, with artificial recharge throughout the field, maintains the same height of the water level as the transitional regime.

RECOMMENDATIONS

Based on this case study, several recommendations can be considered:

– an improvement of Tighira's traditional irrigation water sharing system, through the construction of four large storage basins;
– an improvement of traditional hydrotechnics, in order to modernize this system, by maintaining the sharing of the quantity of water inherited from each owner of the palm grove.

It should be noted that the foggara network (Saoura, Gourara, Touat and Tidikelt),an ingenious technique for collecting and using water, which was significant in the past, is now neglected, because this ancestral technique no longer has a place in today's modern world.

Half the foggaras no longer work. For example, the wilaya of Adrar has a total of 1400 foggaras, of which 907 foggaras are permanent (in service) and 493 foggaras have been dried (35% of foggaras – not in use) [SENOUSSI, BENSANIA *et al*. 2011]. Modern techniques make it possible to reach deep groundwater, mobilise a larger amount of water and the pivots ensure that large areas are watered.

Saoura Valley foggaras and especially the Beni Abbés Oasis foggaras are also abandoned. The balance wells remain inanimate, testifying to a glorious past of physical effort.

However, this technique is in decline due to the lack of maintenance and rehabilitation, and so the traditional oasis, long celebrated, is gradually declining and community water management is erasing the oasis culture. National agricultural development programmes, aimed at giving a second wind to these oases, by creating new areas, are facing serious irrigation problems. Thus today, the "land of the foggaras" adheres to the short distance and competes with the most modern forms, but all face the problem of water.

Recovery and reuse of treated wastewater for irrigation has a plausible alternative, for which this case study propose an optional lagooning system for wastewater treatment that takes into account the quantitative elements of discharges and qualitative water.

CONCLUSION

Lithological, climatic and soil conditions in the alluvial layer of the palm grove have led to intensive use of groundwater for irrigation. Consequently, the problem of protecting the aquifer against saline invasion of inflow and contamination of freshwater bodies, its main outlet, the aquifer of the terminal complex (groundwater of the Great Western Erg). Despite the unreliability of some of the data collected, hydrogeological, hydrochemical and hydrodynamic modelling of the aquifer system of the Beni Abbes palm grove has made it possible to identify and analyse approximately the behaviour of the piezometric level and how the system works. The hydrochemical analysis of a profile confirms that the numerical modelling of slow groundwater flows in the aquifer system was carried out under stable and transient conditions. The steady state and transient calibration allowed a distribution of the transmissivities to be made.

Groundwater is in deficit, where the influence of climate change on groundwater recharge is insignificant, while the natural drain that permanently supplies the alluvial aquifer has a limiting factor in recharge, there is an increase in water, on the contrary in dry periods. The multiplication of hydraulic structures leads to an overexploitation of the palm grove's water and a significant drop in the piezometric level.

The proposed sampling for the hydrochemical study covered 17 wells located in the palm grove. Samples were collected in March and April 2016 and analyses were carried out in ANRH laboratories, Adrar region. Analysis of global mineralisation, physico-chemical parameters and pollution parameters [NO^{2-}, NO^{3-}] was performed. A piezometric and hydrodynamic campaign was carried out on the alluvial layer of the palm grove. Twenty-one wells in the palm grove were monitored worldwide. Two piezometric surveys were carried out in April for the years 2008 and 2016. This data was compared with the 1963 data provided by Roche in 1973. A series of pumping tests determined the hydrodynamic parameters of the aquifer. The hydrodynamic modelling of the Beni Abbes palm grove by the ASMWIN programme has made it possible to understand the hydrodynamic functioning of the aquifer, by estimating the lateral recharge of the aquifer and the effective recharge of infiltration and the influence of the pumped samples on groundwater flow. The steady-state numerical model has made it possible to refine the spatial distribution of permeability and transmissivity over the entire domain and to take stock of the steady-state aquifer. The transient model refined the spatial distribution of the aquifer storage coefficient.

The exploitation of the model by carrying out the scenarios made it possible to define the future behaviour of groundwater in the event of overexploitation and artificial recharge of purified water.

REFERENCES

ALIMEN H. 1957. Tertiary and Villafranchian in the north-western Sahara. Compte Rendu de la Société géologique de France p. 238–240.

BABA-HAMED K., BOUANANI A., TERFOUS A., BEKKOUCHE A. 2005. Modèle transitoire de la plaine des alluvions de la plaine d'Hennaya (Tlemcen, NW-Algérie) [Transitory model of the alluvium aquifer of Hennaya plain (Tlemcen, NW-

Algeria)]. Le Journal de l'Eau et de l'Environnement. Vol. 4. No. 6 p. 7–17.

BABA-HAMED K., BOUANANI A., TERFOUS A. 2005. Modèle transitoire de la plaine des alluvions de la plaine d'Hennaya (Tlemcen, NW-Algérie) [Transitional model of the alluvial plain of the plain of Hennaya (Tlemcen, NW-Algeria)]. The newspaper of the water and the environment. ENSH Blida p. 7–17.

BENNADJI A., BENNADJI H., CHEVERRY C., BOUNAGA N. 1998. Beni-Abbes: Decline of a palm grove. Sécheresse. Vol. 9. No. 2 p. 131–137.

BOMBA A., TKACHUK M., HAVRYLIUK V., KYRYSHA R., GERASIMOV I., PINCHUK O. 2018. Mathematical modelling of filtration processes in drainage systems using conformal mapping. Journal of Water and Land Development. No. 39 (X–XII) p. 11–15. DOI 10.2478/jwld-2018-0054.

BONNET P. 1978. Méthodologie des modèles de simulation en hydrogéologique [Methodology of hydrogeological simulation models]. PhD Thesis. Orléans. BRGM pp. 478.

CHAVAILLON J. 1964. Les formations quaternaires du Sahara nord-occidental [The Quaternary Formations of the North-Western Sahara]. Geology and prehistory. Paris. CNRS pp. 393.

COMBES M. 1966. Hydrogeological study of the Hamada du Guir. Commune of Bechar Villaya of the Saoura. Study S.E.S. 68DH.1M.1'I./ of the Circonscription of T.P.H. Oasis and Saoura. 8 survey cards, 4 pl, 14 p.

CONRAD G., ROCHE M.A. 1965. Étude stratigraphique et hydrogéologique de l'extrémité méridionale de la Hamada du Guir [Stratigraphic and hydrogeological study of the southern end of Hamada du Guir]. Bulletin de la Société Géologique de France. T. 7 p. 695–712.

COTE M. 2002. Des oasis aux zones de mise en valeur – l'étonnant renouveau de l'agriculture saharienne [From oases to development zones – the astonishing reneval of Saharian agriculture]. Méditerranée. T. 99. No. 3.4 p. 5–14.

DE MARSILY G. 1981. Hydrogéologie quantitative [Quantitative hydrogeology]. Paris. Masson ISBN 2-225-75504-3. pp. 216.

DERDOUR A. 2010. Modélisation hydrodynamique de la nappe des grès Crétacé de Remtha. Monts des Ksour [Hydrodynamic modelling of the cretaceous sandstone watertable of Remtha's Synclinal. Ksour Mountains]. MSc Thesis. Tlemcen. Unversity of Tlemcen pp. 101.

DUBIEF J. 1959. Le climat du Sahara [The climate of the Sahara]. Université d'Alger. Institut de recherches sahariennes. Mémoire hors série. T. 1 pp. 312.

DUBIEF J. 1963. Le climat du Sahara [The climate of the Sahara]. Université d'Alger. Institut de recherches sahariennes. Mémoire hors série. T. 2 pp. 275.

GAALOUL N., REKAYA M., JLASSI F. 2008. Salinisation des eaux souterraines de la nappe phréatique de la Côte Orientale au nord-est de la Tunisie [Salinization of underground water from the water table of Côte Orientale in northeastern Tunisia]. Revue Géologues. No. 159 p. 59–64.

GOSSEL W., SEFELNASR A.M., WYCISK P., EBRAHEEM A.M. 2008. A GIS-based flow model for groundwater resources management in the development areas in the eastern Sahara, Africa. In: Applied Groundwater Studies in Africa. Eds. S. Adelana, A. MacDonald. IAH Selected Papers on Hydrogeology. Vol. 13. Chapt. 20 p. 43–64.

GTZ Algerian-German Technical Cooperation. 2006. Integrated Management of Beni Abès Waters Restitution and Evaluation Workshop, Internal Report p. 56.

KINZELBACH W., RAUSCH R., CHIANG W.H. 1995. Aquifer simulation model help. L'aide du logiciel ASMWIN.

KOUAME K.J., JOURDA J.P., BIEMI J., LEBLANC Y. 2008. Groundwater modelling and implication for groundwater protection: Case study of the Abidjan aquifer, Côte d'Ivoire. In: Applied Groundwater Studies in Africa. Eds. S. Adelana, A. MacDonald. IAH Selected Papers on Hydrogeology. Vol. 13. Chapt. 27 p. 458–472.

LACHACHE S., NABOU M., MERZOUGUUI T., AMROUNE A. 2018. Hydrochemistry and origin of principal major elements in the groundwater of the Béchar–Kénadsa basin in arid zone, South-West of Algeria. Journal of Water and Land Development. No. 36 (I–III) p. 77–87. DOI 10.2478/jwld-2018-0008.

MAJOUR H., HANI A., DJABRI L. 2018. Salinity and modelling of the Annaba aquifer system, North-East of Algeria. Journal of Water and Land Development. No. 37 (IV–VI) p. 113–120. DOI 10.2478/jwld-2018-0030.

MEKIDECHE D., SAI N., TOUAT S., YOUNSI N. 1995. Carte hydrogéologique de la région de Béchar [Hydrogeological map of the Béchar region]. Rapport interne. Notice explicative. Béchar, Algérie. DHWB pp. 74.

MENCHEKOFF N. 1933. La série primaire de la Saoura et des chaînes d'Ougarta [The primary series of Saoura and chains of Ougarta]. Bulletin du Service de la Carte géologique d'Algérie. No. 11 p. 109–123.

MERZOUGUI T. 1998. Valorisation des ressources en eau de la haute Vallée de la Saoura (entre Taghit et Kerzaz) [Valorization of the water resources of the upper Saoura Valley (between Taghit and Kerzaz)]. Eng. Thesis. University of Oran, Algeria pp. 175.

MERZOUGUI T. 2011. Caractérisation hydrogéologique et modélisation d'un aquifere alluvial en zone hyper aride: cas de la nappe de la palmeraie de Beni Abbes (vallee de la Saoura, sud ouest Algerien) [Hydrogeological characterization and modeling of an alluvial aquifer in hyper-arid zone: Case of the Beni Abbes palm grove (Saoura valley, southwestern Algeria)]. MSc. Thesis. Tlemcen. Universite Abou Bekr Belkaid pp. 193.

MERZOUGUI T., MEKKAOUI A., MANSOUR H., GRAINE-TAZROUT K. 2007. Hydrogeology of Béni Abbès: Potential, hydrodynamics and influence on the palm field (Valley of Saoura, Algerian South-West). In: Aquifer systems management: Darcy's legacy in a world of impending water shortage. Eds. L. Chery, G. de Marsily. IAH Selected Papers on Hydrogeology. Vol. 10. Chapt. 20. Taylor and Francis Group p. 269–279.

OUELD BABA SY M. 2005. Recharge et paleorecharge du systeme aquifere du Sahara septentrional [Recharge and paleo recharge of the aquifer system in northern Sahara]. PhD Thesis. Tunis. Universite de Tunis El Manar pp. 271.

RENIMA M., REMAOUN M., BOUCEFIANE A., SADEUK BEN ABBES A. 2018. Regional modelling with flood-duration-frequency approach in the middle Cheliff watershed. Journal of Water and Land Development. No. 36 p. 129–141. DOI 10.2478/jwld-2018-0013

ROCHE M.A. 1973. Hydrogéologie de la haute Saoura (Sahara nord occidental) [Hydrogeology of Haute Saoura (North-Western Sahara)]. Bulletin du Service Géologique de l'Algérie. No. 43. Paris. CNRS pp. 91.

ROCHE P.A. 2005. Hydrologie. Chap. 6 cours DEA Sciences et techniques de l'environnement [Hydrology. Chap. 6 courses DEA Environmental Sciences and Technologies]. Ecole nationale des Ponts et Chaussées.

ROGNON P. 1994. Biographie d'un désert, le Sahara [Biography of a desert, the Sahara]. Paris. L'Harmattan. ISBN 2-7384-2954-8 pp. 345.

SENOUSSI A., BENSANIA M., MOULAYE S., TELLI N. 2011. The foggara: A declining multisecular hydraulic system. Review of Bioresources. Vol. 1. No. 1 p. 47–54.

VANNEY J.R. 1960. Pluie et crue dans le Sahara Nord Occidental (Mars 1959) [Rain and flood in the North-Western Sahara

(March 1959). L'Institut de Recherches sahariennes de l'Universite d 'Alger. Monographies régionales 4 pp. 118.

YOUSFI N., AIT-AHMED C. 1992. Contribution à l'étude hydrogéologique de la Grande Source et de la palmeraie de Béni-Abbès (Sahara occidental) [Contribution to the hydrogeological study of the Grande Source and the Beni-Abbes palm grove (Western Sahara)]. Eng. Thesis. University of Sciences and Technology of Oran, Algeria pp. 440.

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Ocena i hydrodynamiczne modelowanie wód podziemnych w gaju palmowym na przykładzie oazy Beni Abbes południowozachodnia Algieria

STRESZCZENIE

W pracy przedstawiono modelowanie wód podziemnych w gaju palmowym Beni Abbes w południowozachodniej Algierii. Aluwialny poziom wodonośny oazy Beni Abbes jest częścią systemu wód podziemnych doliny rzeki Saoura, łącznie z wodami zawartymi w czwartorzędowym aluwialnym obwałowaniu, które wypełnia basen Beni Abbes. Wody te w ostatnich latach były intensywnie eksploatowane, aby zaspokoić potrzeby ludności, przemysłu i rolnictwa. Wody gruntowe oazy Beni Abbes, jednego z elementów łańcucha oaz doliny Saoury, stanowią złożony system, którego warstwa aluwialnych tarasów spełnia kluczową rolę dla utrzymania 40-hektarowego gaju palmowego. Z powodu swojego usytuowania w lokalnym systemie poziomów wodonośnych poziom aluwialny jest zasilany z Wielkiej Pustyni Zachodniej, a czasami także przez wylewy rzeki Saoura. Wykorzystując dane hydrogeologiczne i hydrochemiczne, zbudowano model aluwialnego poziomu wodonośnego oazy Beni Abbes, który umożliwił ustalenie parametrów hydrodynamicznych poziomu i ocenę całkowitego bilansu wodnego. Wyniki tych badań pozwalają lepiej zrozumieć geometrię i funkcjonowanie poziomu wodonośnego, będącego obecnie w stanie zagrożenia. Niezbędne jest zorganizowanie zintegrowanego zarządzania zasobami wodnymi oazy, aby zapewnić jej zrównoważony rozwój.

Słowa kluczowe: *aluwialny poziom wodonośny, Beni Abbes, gaj palmowy, hydrodynamika, modelowanie, rzeka Saoura*