THE USE OF GEOPHYSICS TO CHARACTERIZE THE STRUCTURE OF THE LUTETIAN AQUIFER AND TO EVALUATE ITS STORAGE CAPACITY (BAHIRA BASIN, MOROCCO)

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Résumé
Caractérisation de la structure de l’aquifère lutétien et évaluation de son emmagasinement par la géophysique (bassin de la Bahira, Maroc)

De nombreux travaux de recherche géophysique ont été réalisés dans le bassin de la Bahira. Cette étude concerne l’interprétation des résultats de ces travaux dans la partie centrale de ce bassin et a pour objectif de caractériser la structure de l’aquifère lutétien et d’évaluer son emmagasinement. La carte des isohypses du toit de cet aquifère élaborée montre que sa structure géométrique est monocline du nord vers le sud et permettra de mieux cibler les sites d’implantation des futurs forages hydrauliques. L’emmagasinement de l’aquifère Lutétien a été évalué par le calcul de sa conductance électrique et l’application d’une formulation empirique de la résistivité d’une roche fissurée et saturée en eau attribuée à Nechai (1964). La valeur de 70 10^6 m² obtenue pour cet emmagasinement, est une donnée utile pour tout programme visant l’exploitation de cet aquifère.

Mots clé : aquifère, structure, forage, géophysique, Bhira, Maroc

Abstract
The Bahira basin has been home of a large number of geophysical surveys and borehole drilling experiments from the oil and water exploration. The present study concentrates on the interpretation of these data in the central part of this basin in order to better characterize the structure of the Lutetian aquifer and to evaluate its storage capacity. The resulting isohypses map of the top of this aquifer images its 3D geometrical structure and shows that the water flow should be directed from north to south. Besides, the storage capacity of the Lutetian aquifer has been evaluated in 70 10^6 m³ using an empirical formulation based on the electrical resistivity of a fissured and water saturated rock. This information will be useful for optimising the exploitation of this aquifer.

Keywords : aquifer, structure, storage, geophysics, Bahira, Morocco

ملخص
استكشاف البنية الداخلية وتقييم مخزون المياه الجوفية للفترة الجيولوجيَّة "ليتسفيان" بواسطة الطرق géophysique (سهل البحيرة، المغرب)

تعد هذه الدراسة بتحليل معطيات أشغال البحث géophysique التي تمثل "ساهل البحيرة" بناءً على دراسات "ليتسفيان" بالدجاجة مراشس. يهدف تشخيص البنية الجيولوجيَّة الداخلية وتقييم مخزون مياه المياه الجوفية المتواجدة بالبقيعي الجيولوجي "ليتسفيان" (البقيعي الشيخالي). بعد تحويل المعطيات الزلزالية الارتدادية والجيوكيميائية إلى بيانات رقمية، يتم رسم خريطة المعادن المتواجدة على سطح البحر المتعلقة بهذا البقيعي الجيولوجي. وتتبين هذه الخريطة أن البقيعي "ليتسفيان" بنياً جيولوجيًّا موحدة تتفاوت من الشمال إلى الجنوب، مما يدل على أن سوء المياه الجوفية المتواجدة فيه يتم في نفس الإتجاه. من جهة أخرى يتم تقييم مخزون مياه هذا البقيعي بـ 70 مليون م³ اعتمادًا على تحليل المعطيات الجيوكيميائية وعلى صيغ تجريبي ربط بين المقاومة الكهربائيَّة للأحجار ومسالاتها.
Introduction

The Bahira basin is a large syncline located between two paleozoic massifs: the Jebilet massif to the south and the Rhamna massif to the north (Fig. 1A). Numerous geophysical surveys have been conducted in this area aiming to improve the knowledge of the aquifer in order to fulfill the increasing need of water for agriculture, which adds to the initial use of water for mineral industry, namely phosphat exploitations of Benguerir and Youssoufia. In addition, several successive droughts, had made near-surface water extremely rare, so that exploitation of deep aquifers is now more necessary.

The study area covers approximately 500 km² in the central part of Bahira basin around thirty kilometres north of Marrakech (Fig. 1A). The objective is two-fold (i) to characterise the structure of the main deep aquifer corresponding to the Lutetian fissured limestones (Fig. 1B) and (ii) to evaluate its storage capacity from geophysical data. The used data (Fig. 1A) result from three reflection seismic sections (PS1, PS2 and PS3), 125 electrical soundings distributed in six profiles (PE1 to PE6), well logging records and a series of water electrical conductivity measurements coming from the Lutetian aquifer. Both the seismic sections and the electrical soundings have been re-interpreted with the help of the recent drill hole data and logging results. The altitude of the top of the Lutetian aquifer has been mapped.

Finally, the electrical conductance of the Lutetian aquifer has been computed for each electrical sounding; This value has been used to determinate the storage capacity of the Lutetian aquifer using the Nechai’s formalism (Nechai, 1964), once the confined conditions have been discussed.

1. Geology and hydrogeology

The study area shows geological formations from Palaeozoic to Plio-Quaternary, all in a geologically conform position (Fig. 1B). The Palaeozoic substratum, made up of schists, is outcropping to the north, in Rhamna. It then rapidly deepens towards the centre of the plain, where it reaches depths of 2000 m (Benzekken and al., 1964). To the south, it outcrops again in Jebilet. The sedimentary series consist mainly in thick phosphate layers exploited in Benguerir and Youssoufia. They are made up of alternating layers of soft phosphates, marls and phosphateous limestones (Michard, 1976). Above this series, exists a thick silicified and fissured limestones of Lutetian age.
(Azmany and al., 1978). The top layer is made up of sandy marls and lacustrine limestones, of Plio-Quaternary age (Boujo, 1976).

Two major aquifers have been encountered by drilling: the fissured Lutetian limestones and the karstified Turonian limestones (Fig.1B) (Archambault and al., 1975; Boudarga, 1991). Only the Lutetian limestones are studied in this contribution. They lay on top of the phosphateous series and outcrop to the north of Bahira basin, deepening towards its centre below the Plio-Quaternary cover. As described by Bougadra (1991), they are fractured and fissured, thus constituting a potentially productive aquifer. Errouane (1996) shows that in all drill holes within the study area, the water table is found above the top of the Lutetian limestones, which means that they are fully saturated with water.

2. Structure and storage capacity of the Lutetian aquifer

Electrical soundings have been re-interpreted using new logging records coming from recently wells carried out in the study area. Figure 2A shows the geoelectric section obtained along the PE3 electrical profile. The sedimentary series appear as a south dipping monocline. The thickness of the Lutetian limestones varies from a few meters to the north to one hundred meters to the South.

![Figure 2A](image)

**Figure 2.** A. Geoelectrical section established from the interpretation of the electrical soundings data along the PE3 profile. B. The top of the Lutetian aquifer elevation according to the interpretation of the PS1 and the PE1 profiles. 1, phosphatic marl; 2, limestone; 3, marly sandstone; 4, calcareous sandstone; 5, resistivity value in Ohm.m; 6, datum plane (medium elevation of the land surface); 7, interpreted fault; 8, electrical sounding location; 9, seismic CDP (Common Deep Point); 10, well.

The top of Lutetian limestones is clearly identified in the logs recorded in each hole. In the seismic sections, this boundary shows high reflectivity as result of the high impedance contrast between the limestones and the Plio-Quaternary marls above. Velocity analysis carried out for each seismic section has led to the appropriate velocity laws, which have permitted to transform the time-
sections \((x, t)\) to depth-sections \((x, z)\) using a software based on Unger's methodology (Kchikach and al., 2003; Jaffal and al., 2002; Unger, 1988). We present the result of this processing obtained for the PSI profile on the Fig. 2B. This result has been obtained for the PE1 profile which goes with PSI. Faults have been introduced each time a sudden depth change occur at the top of the Lutetian limestones.

The complete isohypseses map of the top of the Lutetian aquifer (Fig. 3) is the result of the interpretation of the seismic and geoelectrical sections as well as that of boreholes. It shows a general dip from north to south, and then a reverse dip when one reaches the Palaeozoic Jebilet massif.

The second objective of this study was the evaluation of the storage capacity of the Lutetian aquifer using geophysical data. The concepts of hydraulic conductivity, porosity and storage have been described in terms of water movement through a porous medium. In many aquifers, however, water moves predominantly through fractures. This is the case of the Lutetian aquifer in the study area.

The specific storage is the volume of water released from storage in an unconfined aquifer per unit surface area of aquifer per unit decline in water table elevation (De Marsily, 1972). In a confined aquifer specific storage is defined as the volume of water released from storage in a unit volume of aquifer for a unit decline in water table elevation (Brandon, 1986; Jacob, 1950; Jacob and Lohman, 1952).

Storage capacity can be calculated using electrical resistivity data and the Archie’s methodology (Archie, 1942) for a saturated consolidated or unconsolidated sedimentary formation with primary porosity (Intergranular porosity). For a fissured confined aquifer, we can use the Nechaj’s formalism (Nechai, 1964). In the two cases, we have developed the empirical formulas to establish a relation between the electrical conductance and the storage capacity (formulas 1 and 2).

**First case:** Archie’s law:

\[
\rho_g = a \times \rho_w \times \phi_i^{-m} \quad (1)
\]

- \(\rho_g\): global resistivity of the saturated formation in Ohm x m
- \(\rho_w\): water electrical resistivity in Ohm x m
- \(\phi_i\): intergranular porosity

Where \(m\) (cementation factor) and \(a\) are assumed constant within a formation. The Finch’s works in 1979 shown that for a weakly cemented detritical rock, \(m = 1\) and \(a = 1.5\) (Finch, 1979).

**Second case:** Nechaj’s empirical formula

\[
\frac{1}{\rho_g} = \frac{2\Phi_f}{3\rho_w} + \frac{(3-2\Phi_f)}{(3-\Phi_f)p_p} \quad (2)
\]

- \(\Phi_f\): fissure porosity
- \(\rho_p\): electrical resistivity of rocky matrix in Ohm x m
Or, for a unit volume of a geological formation as illustrated in figure 4, the storage capacity is not other than the saturated thickness multiply by the porosity:

\[ dw = e \times \phi \]

\( dw \): unit storage capacity
\( e, \phi \): respectively thickness of the saturated aquifer and its porosity.

On the other hand, the electrical conductance of an aquifer (C in Seimens per meter) is given by:

\[ C = e \times \sigma_g = \frac{e}{\rho_g} \]

\( \sigma_g \): global conductivity of the saturated formation in Seimens x m\(^{-1}\)

\( l \Rightarrow \phi^m = \frac{a \times \rho_w}{\rho_g} \Rightarrow e \times \phi^m = \frac{e}{\rho_g} \times a \times \rho_w \)

\[ \Rightarrow dw (m) = C \times a \times \rho_w \Rightarrow W (m) = a \times \rho_w \int_0^s \! C ds \]

Figure 4. Schema showing the concept of the unitary storage.

The Lutetian aquifer as described by Errouane (1996) and Bougadra (1991) justify the conditions of the Nechâl’s formalism. \( \rho_p \) is of the order of 2000 to 10000 Ohm x m in our case (values extracted from the literature); the second term of equation (2) can be neglected and at the electrical conductance of the aquifer can be expressed as:

\[ C = \frac{e}{\rho_g} = \frac{2e \Phi_f}{3 \rho_w} \Rightarrow dw = 1.5 \times C \times \rho_w \Rightarrow W = 1.5 \times \rho_w \int_0^s \! C ds \]

\( S \): surface of the study area in m\(^2\)
\( W \): storage capacity of the aquifer in all the study area

Thus, the total storage capacity can be obtained by integrating (3) over the whole area of the aquifer and in multiplying the result by 1.5 \( \times \rho_w \). For this, we have first established the electrical conductance map of the Lutetian aquifer over the whole study area and then plotted the curve of the accrued distribution of its conductance (Fig. 5). The integral of this curve can be calculated using a planimeter instrument or the AUTOCAD software.

Knowing the average value of the water electrical conductivity from borehole data (2000 \( \mu \)S/cm), the storage capacity finally obtained is equal to 70 - 10\(^9\) m\(^3\). It must be noticed however that this value
may be overestimated due to the presence of secondary clay within the fractures, which may lower the value of $p_s$.

![Electrical conductance (in siemens x m^-1)](image)

**Figure 5.** Curve of the accrued distribution of the electrical conductance according to the study area.

**Conclusions**

The interest of combining the data resulting from the Lutetian aquifer a reasonable mean porosity of 5% and an average thickness of 10 meters, the total water volume would be $75 \times 10^6$ m$^3$.

The value of the storage gotten by the geophysical method is therefore reliable and should be useful for the decision makers in charge of intensive irrigation in Bahira basin and in other similar situations. The following suggestions should be taken into account in the future:

- An exhaustive reinterpretation of all available seismic and electrical resistivity data in the whole of the Bahira basin would obviously be of great interest to the hydrogeologists.
- In a similar sedimentary basins where aquifers verify the confined conditions, geophysical methods should be used to evaluate their potential hydraulic.

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**Références**


