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Lithological and hydrodynamic characterization of the deep aquifer using logging techniques and pumping tests in the Fritissa Area, middle Moulouya, Morocco

Moulay Ahmed Ben Driss[1*], Said Ettazarini[1,2,3], Youssef Hahou[1], Abdelhadi Iflilliss[1]

[1] Geosciences Water and Environment Laboratory, Mohammed V University, Faculty of Sciences, Rabat, 10000, Morocco
[2] Regional Center for Education and Training Professions CRMEF Casablanca-Settat, Av. Stendhal 20340, Casablanca, Morocco
[3] Laboratory of Natural Resources and Environment, Polydisciplinary Faculty of Taza, Sidi Mohamed Ben Abdellah University, BP 1223 Taza Gare, Morocco
* Corresponding author's e-mail: ahmed.bendriss@um5r.ac.ma

ABSTRACT

The current research is an attempt to precise the lithological nature and hydrodynamic characters of deep aquifer in the Fritissa region, Middle Moulouya, Morocco, under arid to semi-arid climate environments. The objective is to determine the aquifer capacity to satisfy the needs of local population and specify the conditions of water exploitation while insuring the resource sustainability. The methodology adopted consists in the application of logging techniques comprising logs of gamma ray (GR), spontaneous potential (SP), normal resistivities (N16) and (N64), lateral resistivity (L48) and caliper. In addition to pumping tests, notably step-drawdown and constant pumping rate tests. The logging operations are completed in two boreholes: Bouyakoubate (F1) and Dkikira (F2), and reveal the carbonate nature of the saturated zones, located at depths of 630 m in Bouyakoubate and exceeding 550 m in Dkikira. Pumping tests are done in the two former boreholes and in a third one in Fritissa locality (F3). Step-drawdown tests precise the critical pumping rates as: Q_{c1}: 288 m^3/h in Bouyakoubate, Q_{c2}: 61.20 m^3/h in Dkikira and Q_{c3}: 292 m^3/h in Fritissa, while constant pumping rate tests show operating pumping rates as: Q_{op1}: 259.2 m^3/h in Bouyakoubate, Q_{op2}: 55.08 m^3/h in Dkikira and Q_{op3}: 262.44 m^3/h in Fritissa. The findings consequently confirm that the exploitation of deep aquifer through the three boreholes is satisfactory to meet the needs of the local populations sustainably. The method of coupling logging with pumping tests therefore proves reliable and applicable in Morocco and elsewhere if the cost problems are overcome.

Keywords: deep aquifer; borehole; logging; pumping test; operating pumping rate; sustainability.

INTRODUCTION

The issue of water scarcity in Morocco, and specifically in the Middle Moulouya area, is indeed a pressing concern, especially given the confluence of factors like climate change, demographic growth, and economic development (Combe and Simonot, 1971; Nadifi, 1998; Bahir and Mennani, 2002; Snoussi et al., 2002; Milano, 2009; Singla, 2009; FAO, 2013). The regional challenges like reduced rainfall, increasingly irregular water availability, and high dependency on groundwater are all worsening the vulnerability of the country's water resources. The Morocco's National Program for Drinking Water and Irrigation Water Supply 2020-2027 is a strategic response to this situation, aiming to boost water security (DRPE, 2023). Sustainable management and efficient use of water are key to lightening some of the pressures on natural resources (FAO, 2013; DRPE, 2023).

With the increase in water stress and the lack of renewal resources, surface water and superficial aquifers are no longer sufficient to meet the needs of the population. This requires thinking about rigid and local solutions. The use of deep aquifers is required in these conditions in order to maintain sustainable availability of groundwater (Waspodo et al., 2020; Agha et al., 2021). The challenge that arises is to ensure sufficient water resources for the various human activities, and at the same time, ensure the sustainability of the continuously diminishing natural resource.

One of the possible solutions commonly adopted is the exploitation of deep waters, encouraged by the geological characterization of deep aquifers that has become possible with the development of available logging technologies (Bourgeois, 1976; Hsieh et al., 2005; Hacini, 2006). Indeed, logging data allow the determination of the lithological nature of the aquifers, their extent as well as other characteristics helpful to estimate water reserves (Serra, 1984. 2008; Liu, 2017). However, the effective determination of the hydrodynamic characteristics and the assessment of the permeability of the aquifer and the quantity of exploitable water, without threatening the sustainability of the natural water resource, remains an important task that requires pumping tests (De Lasme et al., 2012; Gutierrez and Dewandet, 2013; Al-Hayali et al., 2021).

Many researches are devoted to the recognition of aquifers in the Moulouya Basin using various methods, including multi-criteria approaches to delimit potential zones, favorable for groundwater exploitation (Bouazza et al., 2013; Abduljaleel et al., 2024; Ben Driss et al., 2024a; Hilal et al., 2024, Saadi et al. 2024). However, the quantitative evaluation of the capacity of the aquifer to satisfy the needs of the local populations is rarely treated. The aim of this study is to fill the gap relating to the recognition of the deep aquifer in the Fritissa region, located in the Middle Moulouya basin, by determining the geological and hydrodynamic characteristics of the deep aquifer in this area. The information collected, based on log data and pumping tests, provides keys to determining the operating conditions that can ensure the sustainability of the water resource.

DESCRIPTION OF THE STUDY AREA

Geological and hydrogeological contexts

The study area is located between longitudes 3°18’14” W and 3°80’20” W and latitudes 33°30’10” N and 33°78’10” N in eastern Morocco (Fig. 1). It is part of the large Moulouya basin, with an area of approximately 4104 km² and corresponds to the Fritissa region. It is a plain between the Middle Atlas range to the west, the Rechida range to the north, the “High Plateaus” to the east and the Missour basin to the south.

The simplified stratigraphic column of the study area (Fig. 2) is constructed on the basis of the available geological maps. It expresses the description of the dominant lithologies for each stratigraphic level. The cover, of secondary and tertiary ages, rests unconformably on the Paleozoic basement. At the base, the Lower Jurassic formations are represented by Liassic limestones and red and green marls (GSM, 1985). The

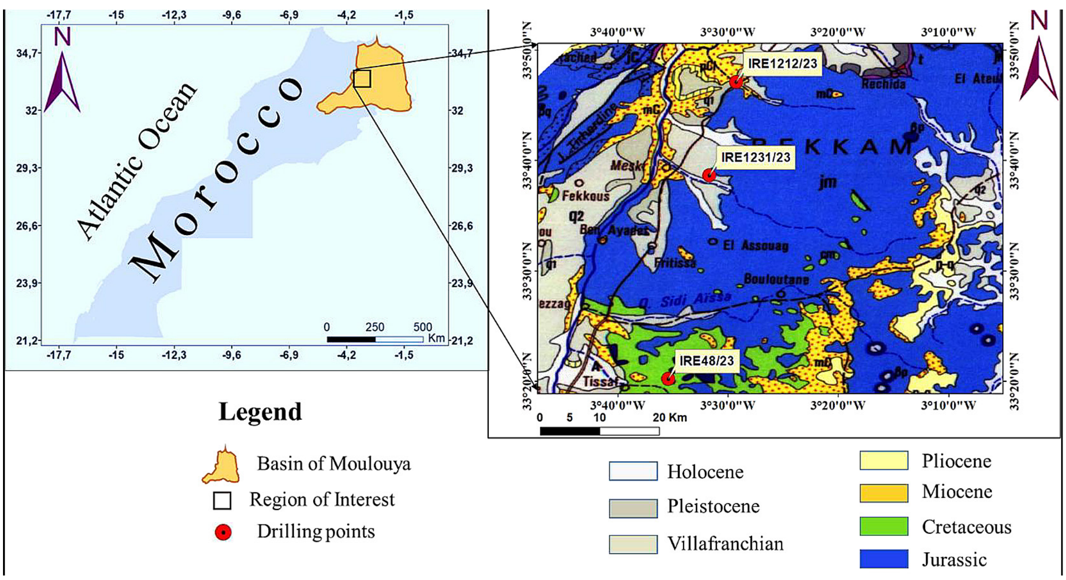

Figure 1. Location map and simplified geological map of the study area

Middle Jurassic deposits consist of dolomites, sandy limestones and limestones of Aalenian-Bajocian age, followed by compact limestones of the Upper Bajocian, marly limestones and red sandstones of the Bathonian, then sandstone formations of Callovian to probable Oxfordian ages, according to the available maps of the Geological Service of Morocco (GSM, 1972). After a large gap, the stratigraphic column continues with marls and clayey limestones of the Cretaceous, directly covered by Tertiary formations represented by conglomerates, limestones and marls of the Miocene, then by limestones, sands and conglomerates of the Pliocene. The Quaternary corresponds to complex formations including deposits of sand, silt, conglomerate, limestone, marl and clay ranging from Villafranchian to the Holocene for the most recent deposits (Fig. 2) (Combe and Simonot, 1971; Labassi, 1991; GSM, 1972,1985).

In the current research, the geological and hydrodynamic characterization work focuses on the deep aquifer system levels: second and third ones (Fig. 2) corresponding to the Jurassic formations.

Climatic and hydrological framework

The study area is mainly drained by Moulouya River (Fig. 3A) from south to north. This is the main river that has a discontinuous and uneven flow system in relation to the rainfall regime. Indeed, the rainfall data for Moulouya River provided by the Agency of Moulouya Hydraulic Basin (AMHB, 2023) show maximum flows exceeding 10000 m^3/s in August 2015, May 2016 and June 2016 (Fig. 3B). But from 2019, the recorded flows remain below the threshold of 500 m^3/s at the Tendit station, indicating an irregularity in the surface water flow in both time and space. The climate data for the year 2023 show monthly average temperatures varying between 5.8 °C in September and 30.1 °C in March. Annual precipitation is limited to 75.7 mm/year with a change in monthly rainfall between 0 mm and 30.6 mm. Thus, the climograph diagram constructed for the Fritissa region (Fig. 3C) illustrates the arid character with eleven dry months. Variability is also observed for the quality of surface water in the Moulouya basin. It varies naturally over time depending on rainfall and spatially from upstream to downstream (Combe and Simonot, 1971, Ben Driss et al., 2024a,b). In addition, random and sudden changes occur when wastewater is discharged into natural water bodies (Talhaoui et al., 2020; El Kati et al., 2022).

MATERIALS AND METHODOLOGY

Materials

The approach adopted in this study includes two main steps (Fig. 4): The first consists of the application of geophysical logging techniques

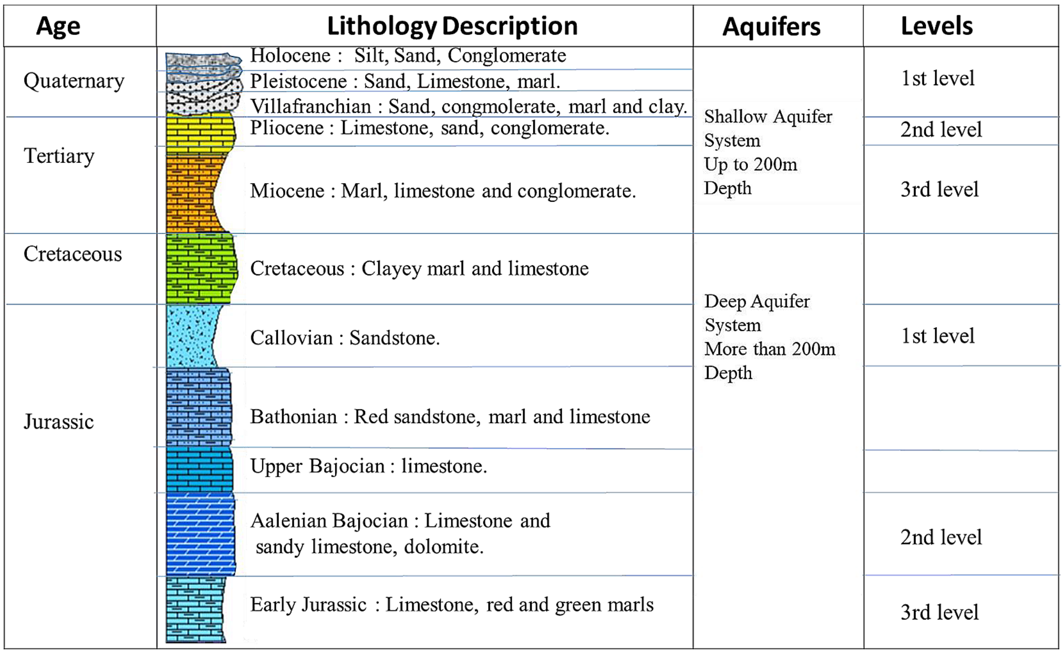

Figure 2. Simplified stratigraphic column showing dominant lithologies and corresponding aquifer systems and their levels

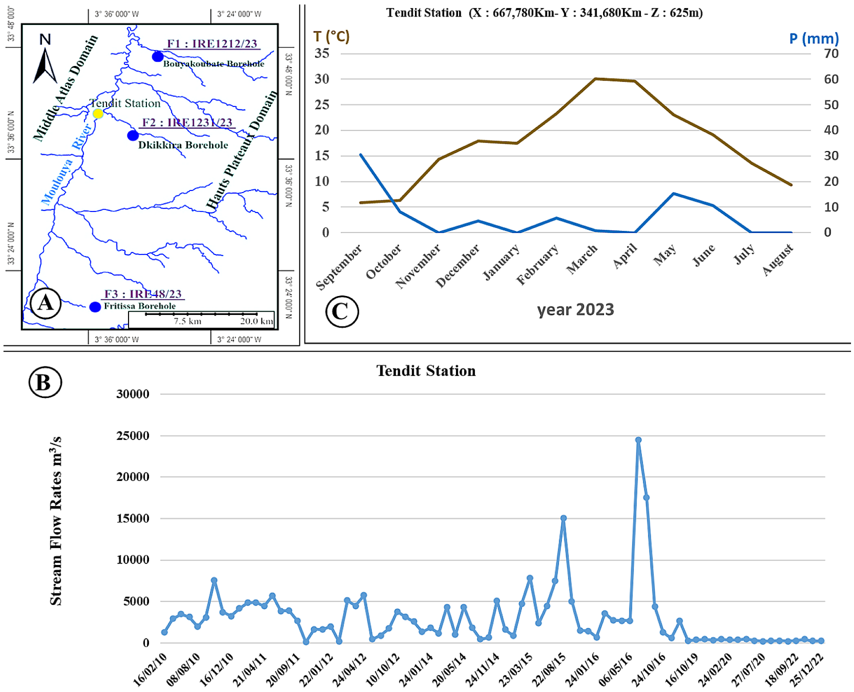

Figure 3. (a) Discontinuous stream network linked to the Moulouya River and location of drilling and observation points; (b) flow rates evolution of Moulouya River in Tendit station during 2023; (c) climograph diagram for the Tendit station

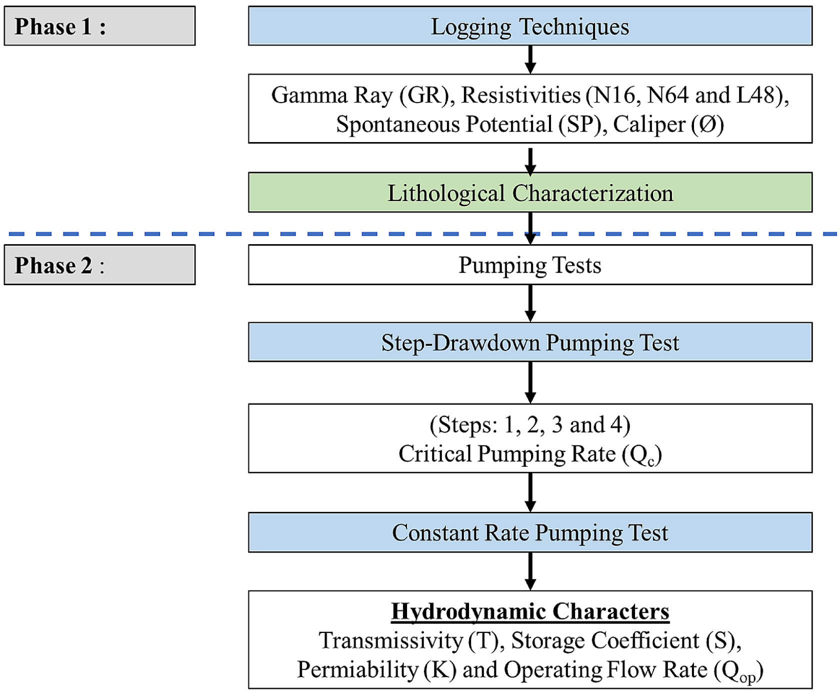

Figure 4. Methodology flowchart used in the current research

during the drilling processes and the second is reserved for pumping tests. The logging operations are carried out using the device (SPR single point resistance) equipped with probes allowing the measurement of gamma ray (GR), spontaneous potential (SP), resistivity (R) in terms of short normal resistivity (N16), medium normal resistivity (N64) and lateral resistivity (L48), and the caliper (Ø).

The pumping tests are carried out with a pump capable of reaching a flow rate of 300 m^3/h with a total manometric height (TMH) of 100 m installed in the borehole and connected to the discharge pipe (Fig. 5).

The current study is based on field data supplemented by data provided by the Moulouya Hydraulic Basin Agency of Oujda (ABHMO) and the Directorate of Water Research and Planning (DRPE) in Rabat. In addition to the use of geological maps of Morocco 1/1000000 and that of Debdou 1/100000. Geographical Information System, particularly ArcGIS 10.8, is used for mapping and creating of thematic maps. Specific software, including OUAIP version.2 and GES For, helped in data processing. OUAIP is used for automatically determining the hydrodynamic characters and critical pumping flow rate that guide the deep-water exploitation, based on data provided as input by the user (Bourdet et al., 1983; Duffield, 2007; Gutierrez and Dewandel, 2013). While GES For allowed the construction of the lithological column of the drilling as well as the associated technical information.

Methodology

Logging techniques are well known for their effectiveness if used in a multivariate approach where information on multiple variables combined allows for robust interpretation of the data (Bourgeois, 1976; Serra, 1984. 2008; Hsieh et al., 2005; Hacini, 2006; Liu, 2017).

Logging operations are carried out at the end of the mud rotary drilling and before the descent of protective casing in two boreholes: at Bouyakoubate (F1) and Dkikkira (F2). This step is important for the lithological characterization of the formations crossed by the drilling, and the location of the position where the strainer tubes and solid tubes should be installed.

Gamma ray radiation (GR) is a measure of the natural radioactivity existing in certain rocks. It allows the distinction between radioactive lithological categories such as clays and marls considered impermeable, from a hydrogeological point of view, and non-radioactive formations, such as dolomite sands and limestones with significant permeability. Resistivity is used to analyze the extension of the aquifer along the borehole. The resistivity of the conductive mud is used as reference in the borehole.

Short normal resistivity is measured with a two-electrode device which passes current from an electrode on the tool through the mud and into the formation. The Schlumberger short normal device employs 16 inches spacing (Serra, 1984.

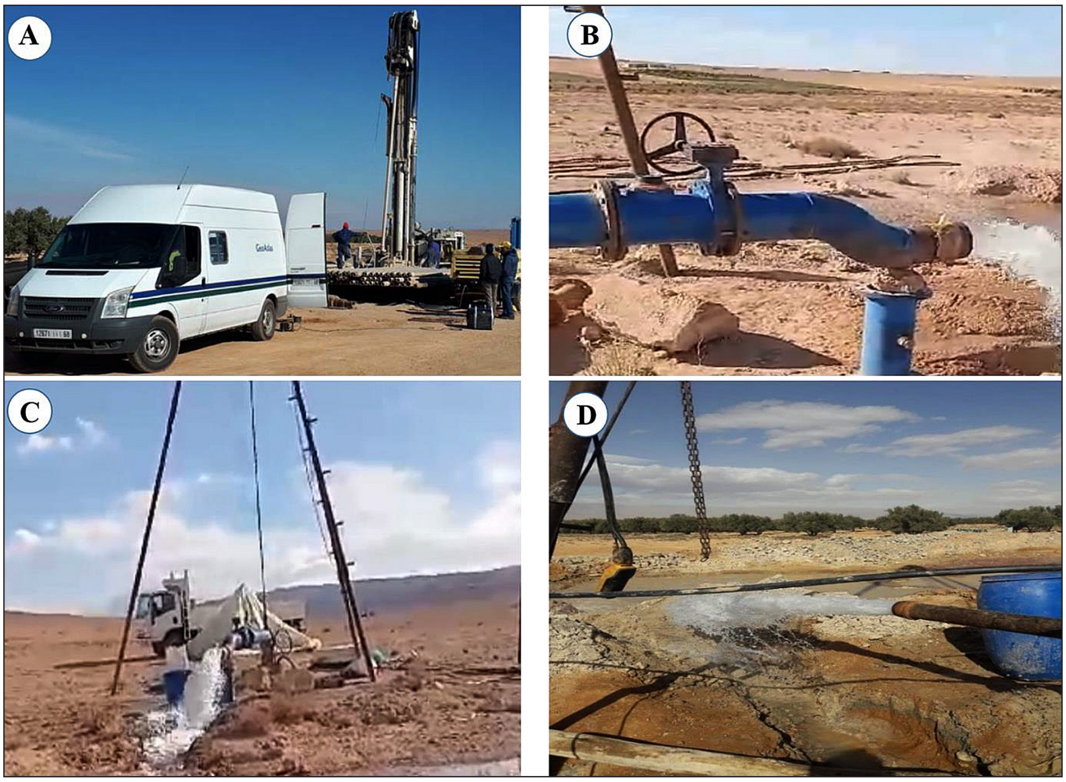

Figure 5. Pictorial illustrations showing logging process in Dkikira location (a) and pumping process in Bouyakoubate (b), Dkikira (c) and Fritissa (d)

2008; Liu, 2017). Medium normal resistivity is obtained with a deeper investigating design that uses 64 inches spacing. The radius of investigation is very nearly equal to twice the electrode spacing (Serra, 1984. 2008; Liu, 2017). While lateral resistivity is measured by using a different electrode arrangement, where a constant current is passed between two electrodes A and M and the potential difference is measured between electrode M and a third electrode N, and where electrodes M and N are located on two consequent spherical equipotential surfaces centered on A. Generally, the spacing (48 inches) is approximately equal to the radius of investigation (Serra, 1984. 2008; Liu, 2017).

The short normal resistivity (N16) and the medium normal resistivity (N64) to the current propagated in the rocks are compared to the lateral resistivity (L48). At the level of the aquifers L48 is influenced by N64 so the two variables have approximate values. Otherwise, L48 approaches N16 indicating the influence of the conductive mud. Spontaneous potential (SP) caused by electromotive forces of electrochemical origin is a variable whose change depends on several factors including: lithology, moisture content and groundwater circulation. Monitoring the SP profile allows locating abrupt changes indicating the change in lithology or aquifer conditions. The caliper is the measurement of the borehole diameter taken during drilling and depends on the conditions of the rock crossed, the abrupt change in diameter indicates fractured levels. (Serra, 1984; Sharma, 1997; Rider, 2002; Serra, 2008; Liu, 2017) or karstified carbonate rocks.

In addition, pumping tests constitute a reliable approach to provide quantitative information on the effective productivity of an aquifer (Neuman, 1975; Bourdet et al., 1983, Onetie et al., 2010; Dewandel et al., 2011; Lasm et al., 2012; Ehoussou et al., 2018).

Pumping tests are carried out in three boreholes: the two boreholes F1 and F2 in addition to a third borehole in Fritissa (F3), reaching the same aquifer to the south of the study area (Fig. 3). For this last borehole, a casing is installed in its upper part without logging tests.

The monitoring of the drawdown of the water level, using an electric probe, is done by simultaneously measuring the flow rate and the time of the descent (t) and the time of the rise (t') of water.

In step-drawdown pumping test, the monitoring of the evolution of the drawdowns in the boreholes, according to the controlled flow rates, allows the graphic determination of the critical pumping rates from the evolution curves (Cooper and Jacob, 1946; Sheahan, 1971). A critical pumping rate refers to the maximum flow rate at which water can be extracted from an aquifer without causing detrimental effects, such as excessive drawdown, long-term depletion and negative effects on surrounding wells and ecosystems. The values of critical pumping rates thus defined are adopted for the next step.

The constant rate pumping test is a long-term test conducted by pumping a well at a constant rate while monitoring the drawdown occurring in the well and in nearby observation wells (Bennett and Patten, 1962; Lin et al., 2017; Gunawardhana et al., 2021). The data concerning flow rate, drawdown and the times of water rise and descent are used to calculate the specific capacity, transmissivity, storage coefficient and operating flow rate.

The specific capacity Q_{sp} (m²/h) reflects the intrinsic productivity of the aquifer. It is the quotient of the pumped flow rate and the measured drawdown Equation 1:

$$Specific\ Capacity\ Q_{sp} = \frac{Q}{s} \quad (1)$$

where: Q is the pumped flow rate in (m^3/h) and s is drawdown induced by pumping (m).

The aquifer transmissivity can be determined graphically, from the drawdown versus flow graph, through the logarithmic approximation proposed by (Cooper and Jacob, 1946), based on the Theis's Equation 2.

$$T = 0.183 \times Q \times \Delta s \quad (2)$$

where: T is transmissivity expressed in m^2/s; Q is the pumping rate of the first step in m^3/s; Δs is the variation of the drawdown (m) over a logarithmic cycle of time.

The choice of the Cooper and Jacob (1946) approximation is made by consideration that it is more adapted to the captive nature of the aquifer studied (Biémi, 1992; Soro et al., 2010).

The storage coefficient (Todd, 1980) is expressed as shown in Equation (3):

$$S = \gamma_w \sum_{i=1}^{n} (m_{vi} \times h_i) \quad (3)$$

where: n is the number of intercalary clay layers; γ is the volumetric weight of water (N/m^3); h is the thickness of the intercalary layer i (m); m refers to the volumetric compressibility coefficient (m^2/N).

The aquifer permeability K (m/s) is the capacity of an aquifer to allow water to pass through a given section. It is calculated as follows, Equation 4:

$$K = \frac{\rho g}{\mu} \quad (4)$$

where: μ is the kinematic viscosity of the fluid (fresh water, salt water or oil); ρ is the density of the fluid; g refers to the acceleration of gravity.

The operating flow rate is the sustainable yield determined from the long-term pumping flow rate with 10% less for the safety of the aquifer, Equation 5:

$$Q_{op} = Q_c - (Q_c \times 0.1) \quad (5)$$

where: Q_{op} represents the drilling operating flow rate (m^3/h) and Q_c is the critical pumping rate (m^3/h).

RESULTS AND DISCUSSION

Lithologic characterization of the aquifer

In the Bouyakoubate location (F1)

The logging is applied in the deep aquifer between 500m and 860m in a carbonate context. The gamma ray values are relatively low and have two levels. A slice ranging from 10 to 18 CPS is observed between 500 m and 525 m depth. This part of the log showing slight radioactivity suggests the presence of marly limestones. While a second GR slice between 5 and 10 CPS dominates the column between depths 525 m and 860 m. It corresponds to the very weakly radioactive dolomitic limestones, confirmed by the debris resulting from the drilling work. The lithology of the aquifer is therefore of a dolomitic limestone nature with weak marly intercalations.

The diameter detector revealed some levels of the column where the rocks are weakened by fracturing or karstified. These anomalies are found at levels 645 m and 670 m where the secondary porosity of the formations is expected to be significant.

The spontaneous potential (SP) is exploited in a carbonate context in the study area, and therefore it is considered related to the abrupt change of the lithology and the saturation conditions of the rocks. It is therefore used to confirm the gamma-ray results. The resistivities N16 and N64 are followed along the column of the borehole. Between depths 500m and 630m the medium normal resistivity N64 is higher than the short normal resistivity N16 meaning that the aquifer water conductivity is lower than that of the fluid in the borehole. From depth 630 m to 860 m the N16 curve joins that of N64 suggesting the dilution of the drilling fluid at the level of the saturated zone of the aquifer.

The lateral resistivity (L48) provides a qualitative image of the variations in the rock resistivity along the borehole. From the depth of 630 m the values of lateral resistivity are practically identical to those of N64 and N16, which

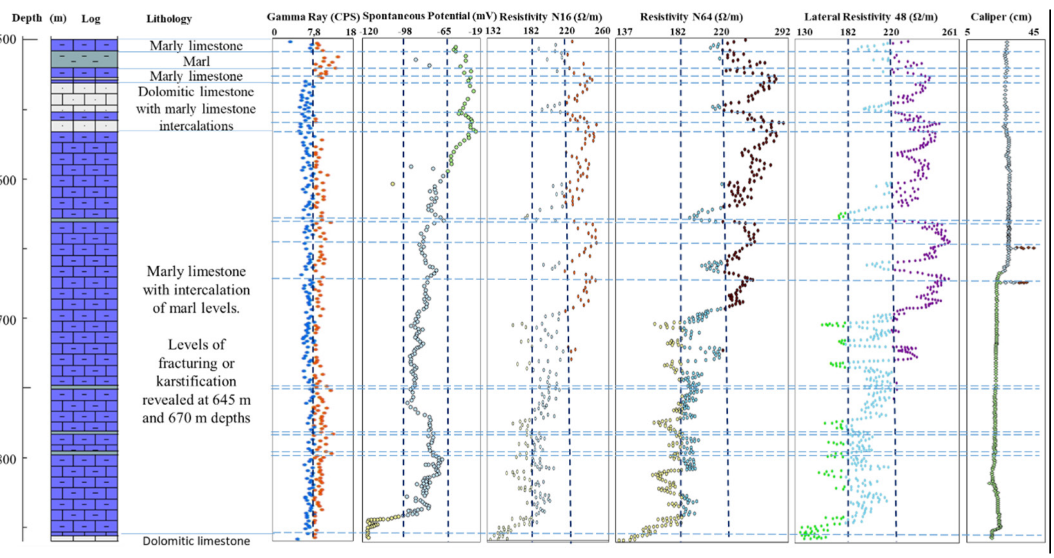

Figure 6. Lithological column obtained from logging analysis in Bouyakoubate well (F1)

confirms the situation in the saturated zone of the deep aquifer. The synthesis of the data and their graphical interpretation is illustrated in Figure 6.

In the Dkikira location (F2)

The logging is performed in the deep aquifer at Dkikira location between 200 m and 550 m in a carbonate context, characterizing the entire region studied. The gamma ray values fall into three different classes: the first tranche where the GR values vary between 45 and 74 CPS, and found between depths of 200 m to 260 m; the lithology of the aquifer is therefore of a marly nature, relatively radioactive. The second tranche with GR values from 14 to 45 CPS, encountered between depths of 260 m and 380 m. This part of the log presenting an average radioactivity suggests the presence of marly and marly limestone levels, confirmed by the other parameters, in particular spontaneous potential and resistivity. The third slice of GR values between 8 and 14 CPS is dominating the column between 380 m and 550 m depths. It corresponds to weakly radioactive dolomitic limestones with some moderately radioactive marly intercalations.

The abrupt change in diameter is revealed at the depth of 250 m. At this level, the secondary porosity of the formations is significant, the cause of which may be fracturing, karstification or both.

Spontaneous potential (SP) makes it possible to locate the lithological changes of the formations crossed by the drilling and which are confirmed by the gamma ray changes. The normal resistivity N64 is higher than the normal N16 between depths 320 m and 340 m and between 360 m and 550 m, meaning the aquifer has lower conductivities than the fluid in the borehole, which means that the formation water is softer than the borehole filtrate.

The lateral resistivity (Lateral 48) remains significantly lower than N64 but close to N16 in the log from the depth of 320 m, which suggests the influence of the drilling mud on the lateral resistivity. In this case, the saturated zone of the deep aquifer is not yet reached by the drilling. The synthesis of the drilling logging data made it possible to establish the lithological section (Fig. 7).

The integration of the logging method in this study, successfully used in previous aquifer studies (Sharma, 1997; Rider, 2002; Ahoussi, 2008; De Lasme et al., 2021), allows the refinement of the results obtained in the present study and provides more details on the lithology of the deep aquifer of the Fritissa region in the Middle Moulouya. Indeed, the aquifer intercepted by these boreholes is a deep reservoir of carbonate nature. Its exploitable extent is difficult to delimit given the limited number of logs carried out for the deep aquifer. However, the data from the logs at the Bouyaakoubate borehole (F1) highlighted the exploitable saturated zone of the aquifer reached from a depth of 630 m. While in the drilling of Dkikira (F2), the exploitable saturated zone is not yet reached at the depth of 550 m. This means that the continuation of drilling is required to reach the saturated zone. Indeed, the drilling work continued up to 750 m depth, after the application of the logs, allowed to reach the exploitable saturated zone of the aquifer.

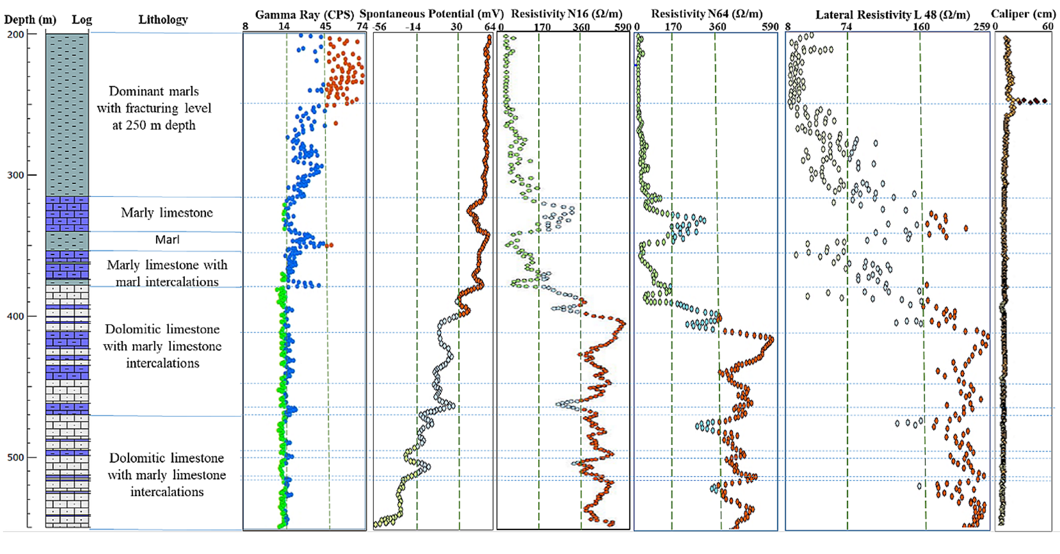

Figure 7. Lithological column obtained from logging analysis in Dkikira well (F2)

HYDRODYNAMIC CHARACTERS OF THE AQUIFER

The pumping test operations begin with step tests, using variable flow rates, then long-term tests with constant flow rates. The determination of the hydrodynamic characteristics of the deep aquifer at each of the three boreholes is done with the help of the Ouaip Version.2 software (BRGM) in accordance with the Theis's Model (1935).

Step-Drawdown pumping tests

Critical flow rates are determined for the Bouyakoubate borehole, for the Dkikira borehole after drilling is continued to a depth of 750 m, in addition to a third borehole situated in Fritissa (F3). The process involves pumping at variable flow rates and determining the flow rates at which the drawdown drops sharply in the borehole. The step pumping test results obtained by the OUAIP software are shown in Figure 8. The step-drawdown pumping results show critical pumping rates of 288 m^3/h in borehole F1, 61.20 m^3/h in borehole F2 and 292 m^3/h in borehole F3. These values are the limits not to be exceeded for the following phases of the pumping tests. Preliminary information on the critical pumping rates highlights varying potentialities between the three drilling points, where the aquifer is expected to be more productive at Fritissa (F3) and Bouyakoubate (F1) localities while it may be relatively less productive at Dkikira (F2) point. The specific capacity values considered in this study are those of the first step which naturally induces a drawdown of the water table level during 2 hours, the pumping period of the steps (Ehoussou et al., 2018). The specific capacity values of the three boreholes are: 92.12 m^2/h for F1, 0.125 m^2/h for F2 and 133.33 m^2/h for F3. These values provide information on the state of the aquifer in terms of transmissivity, linked to the porosity of the aquifer rocks, and they are correlated with the critical pumping rates (Neuman, 1975; Bourdet et al., 1983, Onetie et al., 2010; Dewandel et al., 2011; Lasm et al., 2012).

Constant rate pumping tests

The processing of the long-term pumping data (72 hours) is carried out using the OUAIP

	Bouyakoubate Borehole (F1)			Dkikira Borehole (F2)			Fritissa Borehole (F3)		
	Flow (m^3/h)	Drawdown (m)	*Qsp* (m^2/h)	Flow (m^3/h)	Drawdown (m)	*Qsp* (m^2/h)	Flow (m^3/h)	Drawdown (m)	*Qsp* (m^2/h)
Step 1	234	2.54	92.12	50.4	39.11	0.125	180	1.35	133.33
Step 2	252	6.17		64.8	53.87		216	2.62	
Step 3	270	8.34		79.2	57.88		252	3.90	
Step 4	288	10.48		93.6	63.77		288	6.40	
Critical Pumping Rate	**288**			**61.2**			**292**		

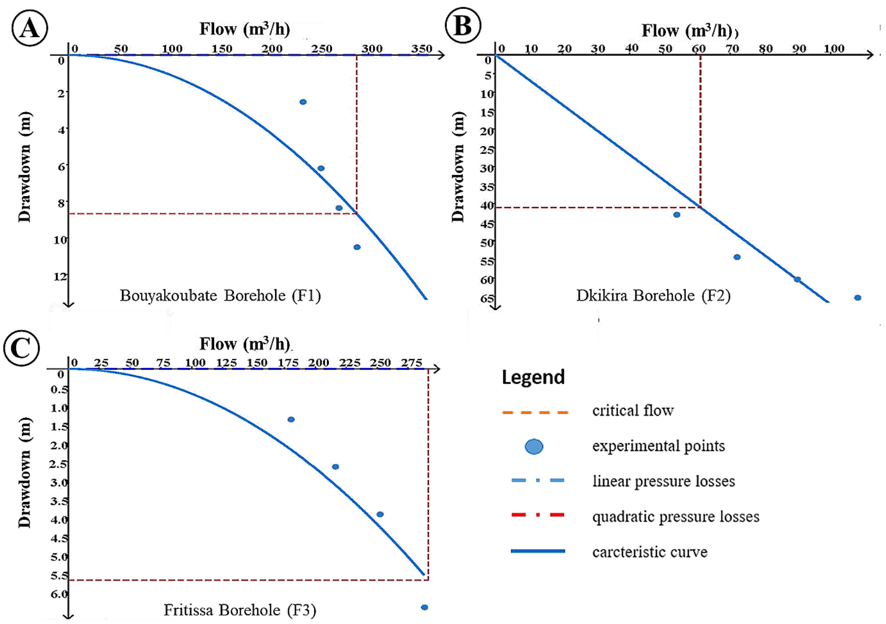

Figure 8. Step-Drawdown test results for the three boreholes

software and the logarithmic approximation of Cooper and Jacob (1946). The results obtained include the transmissivity, the storage coefficient, the permeability and the operating flow rate for the three boreholes. Figure 9 illustrates the evolution of drawdown during constant rate pumping tests, while the table summarizes the hydrodynamic parameters calculated for the three boreholes.

The constant rate pumping test is completed for the Bouyakoubate F1 borehole with a flow rate of 288 m^3/h until the end of the test and with a drawdown of 11.80 m. It reveals a transmissivity $T = 1.46 \times 10^{-2}$ m^2/s, a storage coefficient $S = 6.89 \times 10^{-7}$ and a permeability $K = 2.43 \times 10^{-5}$ m/s. The drawdown level is stabilized indicating that the deep aquifer can be exploitable under these conditions. The Dkikira F2 drilling shows that it is an artesian aquifer with a flow rate of 61.20 m^3/h, a transmissivity $T = 7.72 \times 10^{-4}$ m^2/s, a storage coefficient $S = 1.22 \times 10^{-10}$ and a permeability $K = 1.39 \times 10^{-6}$ m/s. While the Fritissa F3 drilling, with a flow rate of 291 m^3/h, shows a transmissivity $T = 1.65 \times 10^{-2}$ m^2/s, a storage coefficient $S = 8.52 \times 10^{-4}$ and a permeability $K = 2.42 \times 10^{-5}$ m/s. The pumping rate is stabilized and the drawdown is around 7.81 m.

Therefore, the results obtained for the operating flow rates confirm that boreholes of Bouyakoubate F1 and Fritissa F3 can be operated with respective permanent flow rates of 259.2 m^3/h and 262.44 m^3/h. The operating of the two boreholes would provide a cumulative volume of around 12 519.36 m^3/day. While the operating of borehole F2 at a permanent flow rate of 55.08 m^3/h, the equivalent of 1321.92 m^3/day, is also possible. The needs estimated by ABHMO (2016) for the Outat El

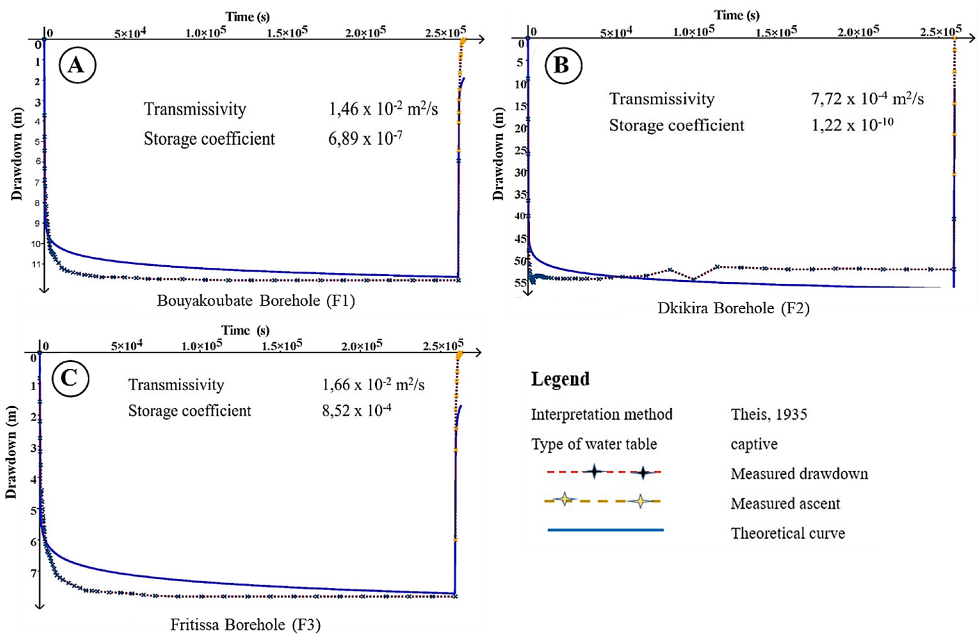

Figure 9. Extended constant pumping test results for the three boreholes

Table 1. Summary of the aquifer hydrodynamic parameters calculated for the three boreholes

ParameterS	Bouyakoubate drilling (F1)	Dkikira drilling (F2)	Fritissa drilling (F3)
Critical pumping rate Q_c (m^3/h)	288.0	61.20	292.0
Pumping rate Q (m^3/h)	288.0	61.20	291.60
Pumping duration t (s)	2.5×10^5	2.5×10^5	2.5×10^5
Drawdown Δs (m)	11.80	54.30	7.81
Transmissivity T (m^2/s)	1.46×10^{-2}	7.72×10^{-4}	1.65×10^{-2}
Storage coefficient S (dimensionless)	6.89×10^{-7}	1.22×10^{-10}	8.52×10^{-4}
Permeability K (m/s)	2.43×10-5	1.39×10-6	2.42×10-5
Specific capacity Q_s (m^2/h)	24.40	1.12	37.33
Operating flow rates Q_{op} (m^3/h)	259.20	55.08	262.44

Haj region, belonging to the Fritissa commune, show an evolution from 52 034 m^3/year in 2016 to 58 867 m^3/year in 2020. It is expected that these needs will reach 70 956 m^3/year in 2035, equivalent to 194.40 m^3/day (ABHMO, 2016).

A total exploitable volume of 13 841.28 m^3/day for these three structures, taking into account the safety of the aquifer, therefore represents a reasonable estimate of the long-term resource, provided that the absence of hydraulic interaction observed during the tests is confirmed in the simultaneous operating regime. In the current state of knowledge, this quantity makes it possible to cover almost the total needs of the area in periods of low consumption. In peak periods, these structures could provide a maximum of 70 % of the total flow required (ABHMO, 2016). The coverage of needs is therefore not sufficient in the event of the withdrawing of one of the three water points. Thus, the recommendation to add water points as support structures, if necessary, is justified.

CONCLUSIONS

The article discusses the usefulness of logging combined with pumping test operations for characterizing deep aquifer lithology and estimating sustainable water flow rates. It demonstrates that the combining of logging techniques: gamma ray, spontaneous potential, resistivity (N16, N64, L48), and caliper, effectively identifies and define the geological layers of the aquifer. While pumping tests reveal reliable to quantify groundwater volume that can be sustainably exploited.

The logging at the Bouyakoubate locality, between depths of 500 m and 860 m, revealed that the lithology at this point is marked by marly levels, overlying a dolomitic formation that passes downwards to marly limestones constituting the aquifer from 525 m depth. The resistivity data suggest the existence of a saturated zone of the aquifer from 630 m depth. For the Dkikira borehole, the logging data accomplished between depths 200 m and 550 m, revealed that the lithology is dominated by marls, down to a depth of 380 m. The deep section between 380 m and 550 m is dominated by limestones and dolomites. However, the results obtained from the resistivities showed that the conditions of the saturated zone of the aquifer have not yet been achieved, which required that the drilling in the borehole be continued to a depth of 750 m.

The hydrodynamic characteristics of the deep aquifer are estimated using step-drawdown pumping and constant rate pumping tests in three boreholes in the study area: Bouyakoubate (F1), Dkikira (F2) and Fritissa (F3). The critical pumping rates obtained of 288 m^3/h (F1), 61.20 m^3/h (F2) and 292 m^3/h (F3), illustrate the lateral variation of the hydrodynamic characteristics of the deep aquifer influencing the values of the operating flow rates: 259.20 m^3/h, 55.08 m^3/h and 262.44 m^3/h in the three boreholes respectively. These estimates are made taking into consideration a 10% margin of the critical pumping rates to ensure the sustainability of the aquifer and avoid its depletion. The total volume from the operating of the three boreholes exceeds the local needs estimated by the Moulouya Hydraulic Basin Agency.

Although the lithological and hydrodynamic characterization is determined for the deep aquifer of the Fritissa region, the lateral evolution of the aquifer characteristics requires the application of logging and pumping techniques in several points, with a good spatial distribution a larger area. Thus, the method used in this research can be applicable in other areas, in Morocco and elsewhere, to achieve a double objective: the recognition of deep aquifers and the determination of the conditions for their sustainable exploitation.

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