Aquifer structuring and hydrogeological investigation in North African regions using geophysical methods: case study of the aquifer system in the Kairouan plain (Central Tunisia).

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Abstract

This study presents an integrated methodology to characterize the aquifer structuring, and geometry in the case of geological complexity and lack of hydrogeological data. Gravity methods analysis, seismic reflection, wireline logging, and electrical resistivity tomography techniques are used to identify the lithological and geometrical knowledge of the Mio-Plio-Quaternary aquifer in the Kairouan plain.

In the Kairouan region, the Mio-Plio-Quaternary series form a complex aquifer system formed by siliciclastic fluvio–deltaic deposits. It consists of sandy and sandy clay horizons interbedded with clay levels. The geometry of the Mio-Plio-Quaternary systems is not yet precisely defined. The present study is dealing with the hydrogeological properties of these deeper sand layer reservoirs in the Kairouan basin using an integrated geophysical approach.

Gravity is used in order to define regional structuring, which is characterized by the presence of a deep fault corridor. The interpretation of wireline logging of 15 petroleum wells shows that the Mio-Pliocene deposits (Ségui Formation) contain five reservoirs. The interpretation of fourteen 2D seismic reflection profiles is used to characterize the aquifer structuring and to identify the major aquifer boundaries. The Kairouan plain is marked in the subsurface by the presence of platforms, anticlines, synclines, and grabens: the Sidi El Hani and Chorbane blocks are separated by master deep-seated faults corridor directed N90 to N120.

The groundwater flow and the water resources evolution are deduced from the water level in 26 piezometres in 2013 and monthly water level measurements in 4 monitoring wells during the 1968-2013 period.

Keywords

Hydrogeology structuring; Gravity; Seismic reflection; Well logging; ERT; Groundwater.

1. INTRODUCTION

The aquifer structure characterization and geometric identification are of primary importance in hydrogeology, especially, to implement the geometric 3D model in order to apply a strategy of sustainable groundwater management aquifer and to provide prospective scenarios of groundwater evolution (Lachaal et al. 2011). Previous studies have proved the important contribution of geophysical methods in 3D geometric modeling (Lachaal et al. 2012a). Gravity and seismic reflection methods are widely used for oil and gas exploration. In hydrogeology Gravity and seismic reflection are applied to characterize the aquifer structuring, differentiate the aquifer bounders and identify hydrogeological basin extension. In addition, aquifer bedrock depth can be deduced from seismic reflection, especially in the case of deep and fossil aquifers (Lachaal et al. 2011; 2012b; Gabtni et al. 2012; Houatmia et al. 2015; Poormirzaee et al. 2015). The borehole logging methods are used to identify the aquifer position, study the water salinity and aquifer productivity, and define the wells equipment (Lachaal et al. 2011; Thilagavathi et al. 2014; Chandra et al. 2015; Kumar and Yadayn 2015). Time-domain electromagnetic exploration (TDEM) and electrical resistivity (ER) are widely used in hydrogeology for groundwater exploration (Salah 2013; Karunanidhi et al. 2014; Chekirbane et al. 2014; Aizebeokhai et al. 2015; Mahmoud et al 2015), particularly where the aquifer depth is about several hundred meters. Electrical resistivity tomography (ERT) is used to study groundwater geometry, infiltration, pollution, and salinization in the case of seawater intrusion (Tamma Rao et al. 2014; Metwaly et al. 2014; Adhikary et al. 2015, Lachaal et al. 2022).

In the case of fluvio–deltaic sediment that is characterised by high geological and geometric complexity related to the high lateral and vertical variability, the aquifer characterization needs a multi-technique approach integrating all surface and subsurface methods. To better define aquifer geometry, all available hydrogeologic data and possible investigation methods must be integrated in order to identify the multilayer aquifer, especially, the reservoirs substratum, boundaries, and their lateral and vertical extension (Lachaal et al. 2011; Ghabtni et al. 2012; Ayolabi et al. 2015; Araffa et al. 2015).

In this context, the Mio-Plio-Quaternary aquifer system in the Kairouan region is selected as a study case **(Fig. 1)**, according to the recommendation of the General Direction of Water Resources, Ministry of Agriculture in Tunisia (DGRE). Especially, this area is a water stressed region (Leduc et al. 2007). A national project of groundwater resources characterization in the Sahel and Kairouan Basins was initiated in cooperation between the Water Research and Technology Centre, Ministry of Higher Education and Scientific Research in Tunisia (CERTE), and the DGRE, during the 2010-2014 period.

The studied area covers the Kairouan plain which is situated in east-central Tunisia. It is characterized by a semi-arid to arid climate and stressed water resources. The mean annual rainfall is about 300 mm.year^{-1} (Leduc et al. 2007). Groundwater is the principal origin of water demand. The hydrogeology of the Kairouan region is formed by a complex aquifer system, attributed to the Ségui formation (Mio-Plio-Quaternary) and formed by fluvio–deltaic sediments. The aquifer system is mainly formed of sandy and sandy clay horizons with clay intercalation. Previous studies have shown the Kairouan hydrogeology complexity (Besbes et al. 1978; Ben Ammar et al. 2006; Leduc et al. 2007). The geometry of the Mio-Plio-Quaternary aquifer system is not yet precisely defined. The aquifer is generally considered as two layers (Besbes et al. 1978). The aquifer substratum and the limit between shallow and deep aquifer are not precisely defined. In addition, the discharge zone that is considered as Sebkhat El Kelbia and Sebkhat Sidi Elhani is poorly unproven, because of the lack of hydrological data in the Eastern part of the aquifer. In this situation, the use of hydrogeophysical methods can give new knowledge to aquifer hydrogeology characterization.

The present study aims to deal with the aquifer geometry properties, in particular, to identify the aquifer structure, aquifer substratum and boundaries using the combination of geophysical methods, especially **G**ravity, seismic reflection, borehole logging, and ERT methods. Due to the significant aquifer depth and the scarcity of drilling wells in the Kairouan basin, the Gravity and the seismic reflection profiles were adopted.

2. GEOGRAPHICAL AND GEOLOGICAL SETTING

The study area is formed by the Kairouan plain. That is located in east-central Tunisia, between 3870000 and 3970000 north parallels and the 570000 and 670000 east meridians (UTM), with a total area of 10,000 km^2 **(Figs. 1 and 2)**. The study area is limited to the North by Jebal Cherichira and Merguellil basin, to the South by Sebkhat Cherita Mechertat, to the West by Jebal Chérahil, and to the East by Sebkhat Sidi El Hani and El Kelbia.

The Kairouan plain is separated from NE-SW Atlasic structures by the NS string (Khomsi et al, 2004). The Kairouan platform is marked by collapsed outcrops of Triassic to Mio-Plio-Quaternary and characterized by extended detrital continental Quaternary over several hundred meters thick formed eventually by sand, sand-clay, and clay (Rabhi 1999). The Triassic outcrop (Rhéouis Formation) (Burollet 1956)) is considered the oldest sediment outcropping in the region. It is formed by a complex chaotic aspect of gypsum, clay, and marl, often containing various elements such as limestone, dolomite, and quartz black bipyramid.

The Ségui Formation is the most important outcrop in the region, which covers the essential of the Kairouan plain. The Mio-Pliocene series has a continental origin. It outcrops extensively at the Draa Affene anticline, Jebel Cherichira, Jebel Baten, and northern accident Trozza-Labaiedh **(Fig. 1).**

The Pliocene thickness of several hundred meters consists of gravel and sand intercalated with clay lenses in the western part of the plain, while in the eastern part there is a dominance of clay and silty sand with evaporates.

Quaternary deposits have a continental origin, mainly formed by alternating silts and sands with clays passage levels (Rabhi 1999). These deposits cover large areas and occupy the Kairouan plain.

3. HYDROGEOLOGY CONTEXT

The Mio-Plio-Quaternary aquifer system in the Kairouan plain, represents the most important and largest aquifer system in central Tunisia (Besbes et al. 1978; Nazoumou and Besbes 2001). The region is characterized by strong rainfall variability (Chargui et al. 2013; 2018; 2022) and most of the rainfall comes from violent and highly variable storms during the spring (February–May) and autumn (September, October) seasons (Kingumbi 2006). The region is characterized by the presence of Sebkhats (Salt Lake) as Sebkhat El Kalbia in the North, Sebkhat Sidi El Hani in the center, and Sebkhat Cherita in the South, which represent the outlets of rivers in the region.

The Kairouan plain constitutes a central collapse basin formed by continental clastic deposits of Mio-Plio-Quaternary (Besbes et al. 1978). These deposits are organized in lens layers with different sizes and extensions. The permeable sediments (sand and gravel) are concentrated in the rivers area in the upstream and central part of the plain, while medium and fine textures are situated downstream near the Sebkhat El Kelbia.

The Mio-Plio-Quaternary aquifer system consists of two hydrogeological unities: shallow and deep aquifers. The shallow system is relatively continuous throughout the plain and composed to Quaternary sediments, with depths less than 50 m. The deep aquifer is confined with more than 50 m of thickness and with depths more than 100 m, the substratum of deep aquifer is not yet defined. Whereas to the western part, the two aquifers are connected, while downstream of a plain deep aquifer is confined (Ben Ammar et al. 2006). Because of the tectonic and sedimentary complexity affecting the region, the geometric characterization of the Mio-Plio-Quaternary aquifer of the Kairouan plain is still incompletely known.

The overexploitation of the Kairouan plain aquifer has led to a general piezometric drawdown of 1 m.year^{-1} (Leduc et al. 2007). Other research studies have addressed the groundwater quality and showed an increase in the salinity (Ben Ammar et al. 2006). The increase of groundwater pumping and the construction of two dams in the region (Sidi Saad dam in 1982, and El Haouareb dam in 1989) mainly for flood mitigation, have significantly changed the natural hydrodynamic comportment (Leduc et al. 2007).

The natural groundwater recharge of Kairouan is provided by infiltration from the Zeroud and Merguellil rivers and direct infiltration from behavior aquifers of Ain Beidha and Haffouz aquifers (Besbes et al. 1978). Since 1988, artificial groundwater recharge begins through the construction of hydraulic structures and small dams and principally from Sidi Saad and El Haouareb dams.

4. MATERIALS AND METHODS

The used Gravity data cover a grid of 2 km spacing, and they were obtained from the Tunisian Company of Petroleum Activities (ETAP). The data were merged and reduced using the 1967 International Gravity formula (Morelli 1976). Free Air and Bouguer Gravity corrections were applied using 2.67 gcm^{-3} as a reduction density and sea level as a datum. Terrain corrections were done using the method of Plouff (1977), a 5-min topography grid, and a density of 2.67 gcm^{-3} (Row et al. 1995).

In addition to the **G**ravity data, we used seismic reflection data. It consists of a grid of 14 2D seismic reflection sections oriented roughly North–South and West–East, and 15 petroleum wells provided by ETAP **(Fig. 2)**. Mio-Plio-Quaternary seismic reflectors has been calibrated and correlated along the seismic reflection grid. In addition, the top Ain Grab Formation reflector (Langhian, Middle Miocene) that is considered as regional repair (Bédir et al. 1996; Khomsi et al. 2004; Lachaal et al. 2011) is also drowned. The outcrops around the region and the time-depth conversion curve of the available petroleum wells were used to calibrate the seismic horizons.

In order to characterize the geometry of the Mio-Plio-Quaternary shallow aquifer in which the depth is less than 50m, geophysical measurements of ERT were carried out in the region in April 2013. The ERT profile was located about 800 m from the Kairouan city and oriented from West to East coinciding with the western part of the L3 seismic reflection profile **(Fig. 2)**.

The used piezometric data were collected by the DGRE during two surveys. The first one is realized in Mars 2013 (humid season) and the second is conducted in August 2013 (dry season). It consists of water level measurements in 26 piezometers. In addition, monthly water level measurements in 4 monitoring wells covering the 1968–2013 period are used in this study. These piezometric data were given by the DGRE.

5. RESULTS AND DISCUSSION

Kairouan region is characterized by structuring in a block because of deep fault corridors. The Kairouan plain consists of two platforms (Bédir 1995): in the North Sidi El Hani platform and in the South the Chorbane platform called also Ktitir platform. These blocks are separated by fault corridors N-45 to N45 (Bédir 1995) which coincides with the transverse fault of El Hdedja (Khomsi et al, 2004).

5.1. Gravity interpretation

The Bouguer Gravity anomaly map was produced from the interpolation of a 2 km grid of Gravity data. The Bouguer Gravity anomaly values range from −50 to 25 mGal. The lower value is located in the western parts **(Fig. 3)**. These data are affected by a regional gradient increasing eastward. This gradient represents the regional Gravity field that is probably related to crustal thickness variations (Buness et al. 1989; Gabtni 2005). Previous work shows the minor influence of the regional Gravity field on the local gravity anomalies (Gabtni et al. 2010).

Three trending anomalies were observed in the Bouguer Gravity anomaly map:

- In the NE, the Bouguer Gravity anomaly map shows, in the Zéramdine region, an N30-N45 trending anomaly which is associated to the Zéramdine fault corridor **(Fig. 3)** (Lachaal et al. 2012b).
- In the SE, the Bouguer Gravity anomaly map shows in the Mahdia and Jebeniana regions an N135 to N45 trending anomaly with is correlated to the El Jem Half graben (Bédir et al. 1992; Lachaal et al. 2012b).
- In the Kairouan region, the Bouguer Gravity anomaly map shows an N45 trending anomaly which is correlated with the thrust fault of Kairouan-Sousse (Khomsi et al. 2004) and Kairouan Graben (Bédir et al. 1996).

In order to study the Gravity anomalies, and generally to delineate the vertical and lateral locations of the subsurface causative sources, a horizontal Gravity gradient map (HGG) was created. The interpretation of HGG anomaly map can contribute to the understanding of the structural and tectonic framework of the Kairouan region **(Fig. 4).** The superposition of the known faults of the HGG map shows HGG maxima **(Fig. 1)**. These HGG anomalies are related to tectonic structures (S1 to S6) forming a deep fracturing corridor **(Fig. 3)**:

- S1: the Zéramdine faults corridor, located in the NE of the study area with N0 to N40 direction;
- S2: the El Jem half graben situated in the SE of the study area with N135 to N45 direction;
- S3: Kairaoun-Sousse fault with N0 to N45 direction;
- S4: El Hdadja Fault with N-45 to N45 direction;
- S5: Chorbane graben located in the SW with N30 to N45;
- S6: A probable graben with N90 to N45 direction;
- S6: Jebel Chérahil.

The HGG map analysis show several blocs: Sidi El Hani, Chorbane (Ktitir), Mahdia-Jébéniana, and Zéramdine platforms.

5.2. Wireligne logging data analysis and aquifer lithology

6.2.1. Sidi El Hani platform

The Sidi El Hani block is limited to the North by Enfidha block through the Kairouan graben which coincides with the transverse fault of Kairouan-Sousse (Khomsi et al. 2004), to the Eastern side by the Zéramdine fault corridor, to the Southern side by Chorbane block and to the West by J. El Haouareb through the north-south axis. Several oil wells (ELH-1, KRN-1, GR-1, MSK-1, SAR-1, ALO-1, and ZAW-1) were drilled in this block. According to the El Hdadja-1 logging well, the Mio-Plio-Quaternary geological series present 703m in depth. The Mio-Plio-Quaternary series is composed of a multilayer aquifer system of sand and sand clay deposits. They are formed by five reservoir levels. Each level is characterized by a low gamma ray registration and a negative spontaneous potential across permeable sandy series. The aquifer levels are distributed upwardly as follows **(Fig. 5)**:

- The first reservoir layer (650-570 m) is formed of translucent sand with quartz.
- The second reservoir layer (560-530 m) is composed of translucent sand with quartz associated with some levels of clays.
- The third reservoir layer (520-440 m) is formed by sand with quartz, characterized by the presence of gravel.
- The fourth reservoir layer (410-390 m) is sand, clear, and translucent with quartz.
- The fifth reservoir layer (80-60 m): is formed by sand with quartz.

5.2.2. Chorbane platform

Chorbane block is limited to the North by Sidi El Hani platform, from the South by the Chorbane graben, from the East by the Mahdia platform, through the El Jem Half graben, and from the West by Jebel Cherahil. Five oil wells are located in the Chorbane block (BBZ-1, NA-1, MH-1, SSS-1, and SLK-1). The Mio-Plio-Quaternary series are crossed by the Nasrallah-1 well. Indeed, the Ségui Formation reaches a depth of 525 m.

According to the NA-1 well logging, the Mio-Plio-Quaternary series contain a multilayer aquifer system composed of five levels of reservoirs. The sandy nature is deduced by low gamma ray readings, slight separation between the macro-resistivity and micro-resistivity recording, and through the records of scoring Neutron porosity levels. The Mio-Plio-Quaternary reservoir system is composed also of five layers, from bottom to top **(Fig. 5)**:

- The first reservoir layer (450-300 m) is formed by sand white, ocher, yellow, medium to very coarse with small siliceous pebbles, sometimes weakly consolidated.
- The second reservoir layer (270-240 m) is formed by sand white and medium size.
- The third reservoir layer (180-150 m) is made with sand white and medium to very coarse, sometimes weakly consolidated.
- The fourth reservoir layer (120-90 m) is composed of sand white, medium to very coarse.
- The fifth reservoir layer (50-20 m) is formed by sand yellow, medium to very coarse, and sometimes weakly consolidated.

The NNE-SSW correlation was drowning using the interpretation of well logging **(Fig. 5)**. It shows two structural blocks (Sidi El Hani and Chorbane blocks) which are separated by fault corridor N-45 to N45 (Bédir 1995). Thinning of Mio-Plio-Quaternary deposits was observed from NE to SW. From the SW, the Mio-Plio-Quaternary series are limited by Jebal Chérahil which shows the ancient outcrops formed by Aquitanian to Upper Senonian deposits (Rabhi 1999).

5.3. Seismic reflection profiles interpretation and seismic stratigraphy study

The wireline logging of petroleum wells was used to identify the different aquifer layers in each geological block. The interpretation of 2D seismic reflection profiles shows the boundaries of each aquifer system and their lateral changes of facies. In order to identify the aquifer structure, limits, and reservoir evolution we use the interpretation of seismic profiles.

5.2.1. L1 seismic reflection profile

The L1 seismic reflection profile extends 62.55 km from NNE to SSW **(Fig. 6)**. It is calibrated with the time-depth conversion curve registered in the ELH-1 petroleum well where the Mio-Plio-Quaternary deposits reach 703m in depth. The profile shows a tectonic structuring marked by the individualization of two tectonic blocks: Sidi El Hani and Chorbane blocks, bounded by deep faults corridors (Bédir 1995).

L1 profile shows the presence of several tectonic structures. To the NNE, the Kairouan-Sousse fault resulted from compression structures materialized by folds and syncline gutters. To the SSW, the El Hdadja fault, generates a positive flower structure (Khomsi et al. 2004). In addition, we note the presence of the Sidi El Kilani fault corridor with an N120 direction that separated the Sidi El Hani and Chorbane blocks.

The seismic-stratigraphic analysis highlights the presence of downlap configurations at the base of the Mio-Plio-Quaternary Ségui Formation. This seismic pattern is characteristic of channelized sedimentation marking the Mio-Plio-Quaternary horizons. Toplap features end the reservoirs horizons at the top.

From SSW to NNE, the profile shows the presence of channel sedimentation, especially, in the upper part of the profile at the depth of 100 ms in TWT (two-way travel time). These deposits are characterized by reflections of low continuity and medium to high amplitude. Channel deposits are from fluvial plain deltaic environment consisting of pebbles and gravel mixed with locally clayey sands. They are characterized by high porosity and high permeability.

5.2.2. L2 seismic reflection profile

The L2 profile is localized in Sidi El Hani plate form with NNE-SSW direction and is 21.75 km long **(Fig. 7)**. In the southwestern part, the reflectors are continuous, parallel, and have the same amplitude.

The Mio-Plio-Quaternary series maintain the same thickness. That reflects uniform sedimentation with low hydrodynamic energy.

In the NNE direction, the profile shows the presence of faults zone related to deep faults corridor, formed by sub-vertical faults with low magnitudes. At the depth of 500 ms in TWT, the L2 profile shows the same channel sedimentation observed in the L1 profile. In the NNE part, the profile highlights the effect of the Kairouan-Sousse fault which forms a geological limit to the Mio-Plio-Quaternary aquifer systems. It controls the spatial distribution and thicknesses of different series (Khomsi et al, 2004). In addition, the chaotic configuration associated with channel sedimentation was observed in the profile.

5.2.4. L3 seismic reflection profile

This L3 profile covers Sidi El Hani and Zeramdine blocks with E-W direction **(Fig. 8a)**. At the intersection with L1 geo-seismic line and in 100 ms in TWT, the profile shows a chaotic seismic facies configuration. This configuration has been associated with channel sedimentation that is formed by sands.

In the Eastern part of the seismic reflection line L2, fold structures called Bir El Taib has an NNE-SSW direction (Ghribi 2010). It separates the Sidi El Hani block from Zeramdine one. Several works suppose that El Kelbia and Sidi El Hani Sebkhats represent the Kairouane aquifer Eastern boundary. According to the L1 profile, the Mio-Plio-quaternary reservoir is continued under the El Kelbia Sebkhat. That concludes that the Kairouan basin is continued to the East side and the Eastern aquifer boundary is formed by the Bir El Taib fold and not by the El Kelbia and Sidi El Haria Sebkhats. This hypothesis needs a supplementary hydrogeological and geophysical investigation in the region.

The seismic-stratigraphic interpretation shows the presence of downlap horizon strata termed marking lens sedimentation. In addition, a toplap strata termed was observed characterizing the top of the first and second reservoir levels.

5.2.4. L4 seismic reflection profile

The L4 profile is localized in the Sidi El Heni platform with 51 km from WNW to ESE **(Fig. 9)**. In the West side, the L4 profile shows the continuity of the Mio-Plio-Quaternary reservoir under the Sidi El Heni Sebkhat. In fact, the Kairouan basin continued in the East direction. The hypothesis of Sidi El Heni Sebkhat forms the aquifer outlet, and the West boundary is rejected.

5.3. Electric resistivity tomography study

5.3. 1. ERT data acquisition

The ERT profile localization has been chosen in the Eastern side of the L2 profile. This area is characterized by the presence of detrital deposits of Mio-Plio-Quaternary, and the presence of channel deposits. The use of ERT method aims to confirm the sedimentation type **(Fig. 2)**.

The used system is Terrameter SAS 4000 produced by ABEM Instruments, it is a multi-electrode system that can provide automatic management of the electrodes. This system is composed of 64 electrodes and products geoelectric profile along 315 m with a spacing of 5 m. The apparent resistivities are measured along the DDP method (device Dipole-Dipole). This device is very sensitive to horizontal changes in resistivity and therefore ideal for detecting vertical structures.

5.3.13. ERT data inversion and interpretation

Thus, ERT data recorded in the field are apparent resistivities. To delineate the resistivity-depth image along the profile line using the ERT data, modeling of geo-electrical is performed. The ERT model consists of produce pseudo-meter depth profile (2D resistivity section) using an inversion modeling software: Res2Dinv. The iterative method gave us a geological model corresponding to the field data. 2D resistivity-depth images along the profile lines obtained by the inversion of the observed data are shown in **figure 8b$_1$.**

The resistivity of the Mio-Plio-Quaternary deposits varies within a wide range from 0.1 to 270 Ohm.m. The variation of the resistivity shows a strong spatial variability of the Mio-Plio-Quaternary lithology. The lens structure of the Kairouan plain is very complex with successions of clays, marls, and sands. **Figure 8b$_2$** shows the presence of lenticular structure that is characterized by resistivity varying from 70 to 200 ohm.m. This lens forms the shallow aquifer.

Referring to the location of this electrical profile (the eastern part of L3 seismic reflection profile which show the channels and taking into account the sand and gravel deposit), we conclude that the area highlights part of a channel deposit. This result confirms those obtained by seismic reflection and allows us to fully appreciate the presence of channel sedimentation located in the upper groundwater of Mio-Plio-Quaternary in the Kairouan region. This reservoir is covered by silt to clay layers marked by resistivity varying between 7 and 70 ohm.m (ABEM 2010). The soil is characterized by a saltwater zone with lower resistivity varying between 0.3 to 1 ohm.m (ABEM 2010), characterizing the lower permeability.

5.4. Hydrodynamics of the shallow aquifer in the Kairouan plain

The superposition of the piezometric map of the humid season (Mars 2013) and the geological outcrops in the region are illustrated in **figure 10**. The piezometric map is drawn using the interpolation of 26 observation wells. The groundwater level varies from 120 in upstream to 25m in downstream around Sebkhat El Kelbia. The piezometric map shows major sub-vertical water flow from SE to NW; from the El Houareb dam to Sebkhat El Kelbia and Sidi El Hani. The hydraulic gradient is ranging between 3.83‰ and 1.8‰, respectively, in the upstream and downstream.

Two sectors may be considered as recharge zones for the studied groundwater. The first one is the El Haouareb dam situated in the upstream region. The second one is assured by the infiltration from the Ain El Beidha aquifer. The two-water recharge origins are mixed in subsurface in the Karst reservoir with different proportion (Ben Ammar et al. 2006). The discharge fields are located in the Western direction.

The recorded piezometric level over the 1968–2014 period revealed three piezometric behavior types **(Fig. 11):**

– A continuous piezometric drawdown: that was unregistered in all the monitoring wells **(Fig. 11).** The piezometric decrease varied from 0.44 m year^{-1} (12737/4 piezometer) to 1.45 m year^{-1} (20315/4 piezometer). The middle and the downstream areas are characterized by high piezometric drawdown. However, in upstream, the groundwater level was lower, due to the recharge influence from the El Hawareb dam and Ain El Bitha aquifer (Leduc et al. 2007). In the downstream region (12737/4 piezometer), the groundwater level has decreased by 19.4 m in 12737/4 piezometer and 24.61 m in 13264/4 piezometer during the last 44 years (from 1969 to 2013) because of strong pumping and a limited recharge. The piezometric drawdown is increasing during the last few years. In fact, and according to the 12727/4 piezometer the piezometric drawdown is about 0.17 m year^{-1} during the 1969-1996 period, 0.63 m year^{-1} during the 1996-2012 period and it growing to 4 m year^{-1} during the 2012-2013 period. The significant increase of the piezometric drawdown in the last period resulted from the important increase of illegal and unauthorized wells after the Tunisian revolution of September 2011-January 2012.

– The seasonal piezometric fluctuation was very important on the downstream, which represents the pumping area of the aquifer. It exceeds 1.91 m in the 20302/4 piezometer **(Fig. 11a).** During the humid season (September–March) the piezometric is higher, however, the dry season (April–August) is characterized by lower piezometric. This piezometric fluctuation is related to the pumping effect for irrigation and rainwater infiltration.

– An occasional piezometric fluctuation: Leduc et al. 2007 show the presence of two occasional piezometric fluctuations in 1969 and 1989 studying the recorded groundwater level recorded in 13147/4 monitoring well. The same ascertainment is observed in the 13264/4 piezometer **(Fig. 11d)**, which is located in upstream. The first one is caused by the 1969 flood, which represent typical of exceptional infiltration, reflecting a strong inter-annual variability of precipitation (Chargui et al. 2013). The second occasional piezometric fluctuation is caused by the El Haouareb dam construction which increase the aquifer recharge (Leduc et al. 2007).

7. Conclusions and perspectives

In this paper, different geophysical methods have been integrated (Gravity, seismic reflection, well logs, and ERT) in order to characterize reservoirs and water resources of the Mio-Plio-Quaternary aquifer system in the Kairouan plain. A geophysical study was undertaken to determine lateral and vertical reservoir extension, as well as to characterize the Mio-Plio-Quaternary aquifer.

Wireline logging analysis highlights the identification of the Mio-Plio-Quaternary multilayer aquifer system that consists of five reservoir aquifers levels separated by impermeable clay layers.

The interpretation of Gravity and seismic profiles permitted to establish of a consistent subsurface representation of reservoir architecture. In fact, sedimentary clastic deposits in the Kairouan plain are controlled and influenced by major deep faults such as the Kairouan-Sousse and El Hdadja faults. These structures have contributed to the reservoir levels distribution of Mio-Plio-Quaternary and their modes of arrangement. Mio-Plio-Quaternary series are compartmentalized into Sidi El Hani, Chorben, and Zeramdine blocks under the influence of the tectonic structuring. In addition to the upper Mio-Plio-Quaternary sandy level reservoir, other reservoir horizons were identified and correlated for the first time. And the base of the aquifer reservoirs was identified. In addition, the Eastern aquifer boundary was highlighted for the first time, which is the Bir El Taib fold.

Seismic-stratigraphic analysis of the Mio-Plio-Quaternary series shows the presence of channel sedimentation characterizing the Kairouan multilayer aquifers. This result was confirmed by ERT profile that shows sand and clay lenses corresponding to channel deposits. Downalp prograding horizons marked the base of the Ségui Formation which coincides to the base of the Mio-Plio-Quaternary aquifer system. The geometric characterization of the Mio-Plio-Quaternary aquifer system can be refined by an advanced study based on a dense seismic reflection grid and more wireline data.

The piezometric study in 26 piezometres shows that the principal groundwater flow is from west to east. In addition, a general drop in water table was defined using the groundwater water level measurements during the 1967-2013 period.

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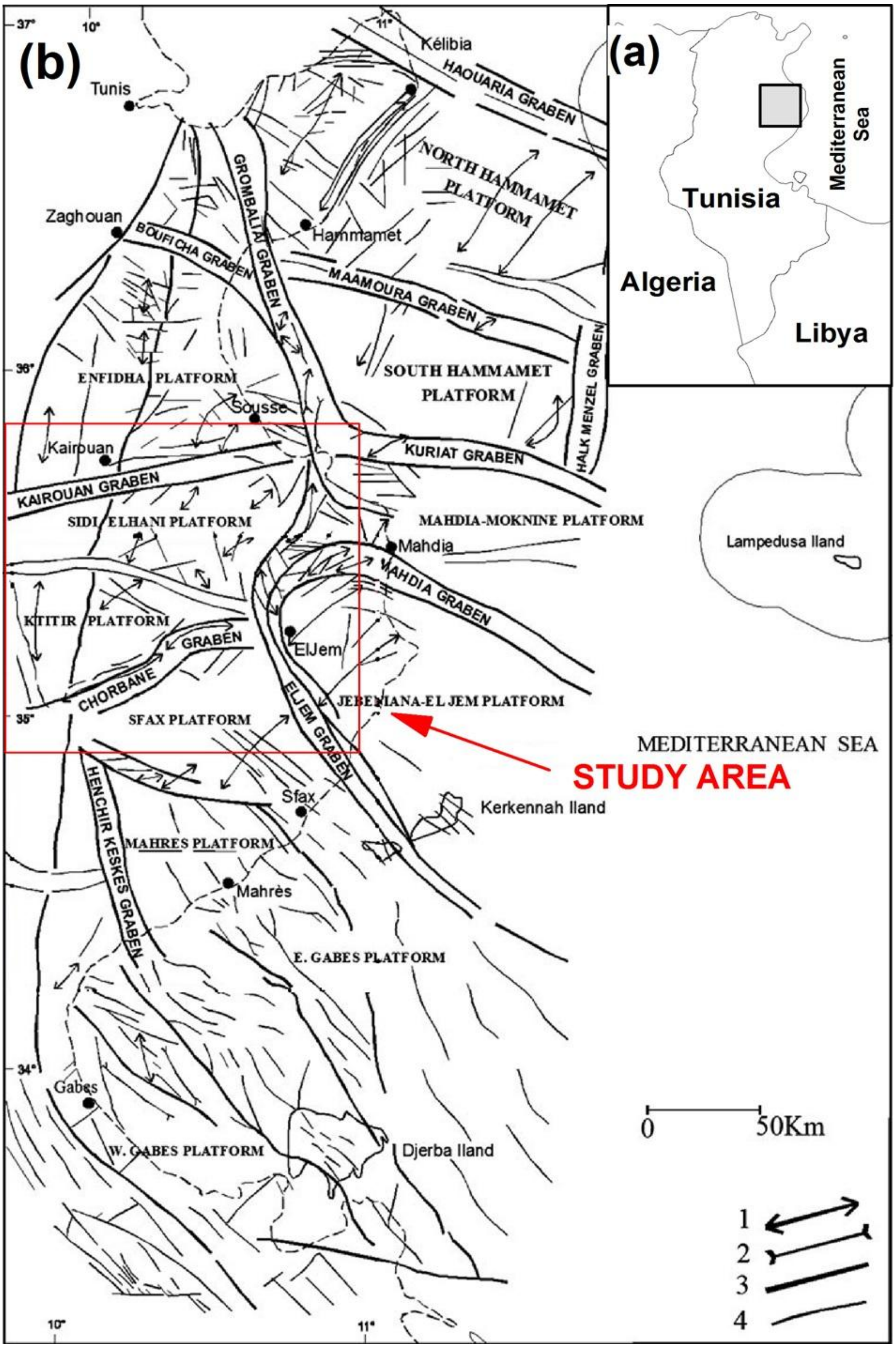

Figure. 1 Location map of the study area: a) Tunisia location and b) Major structural elements in Eastern Tunisia (Bédir 1995). 1 anticlines, 2 synclines, 3 first order faults, 4 second order faults

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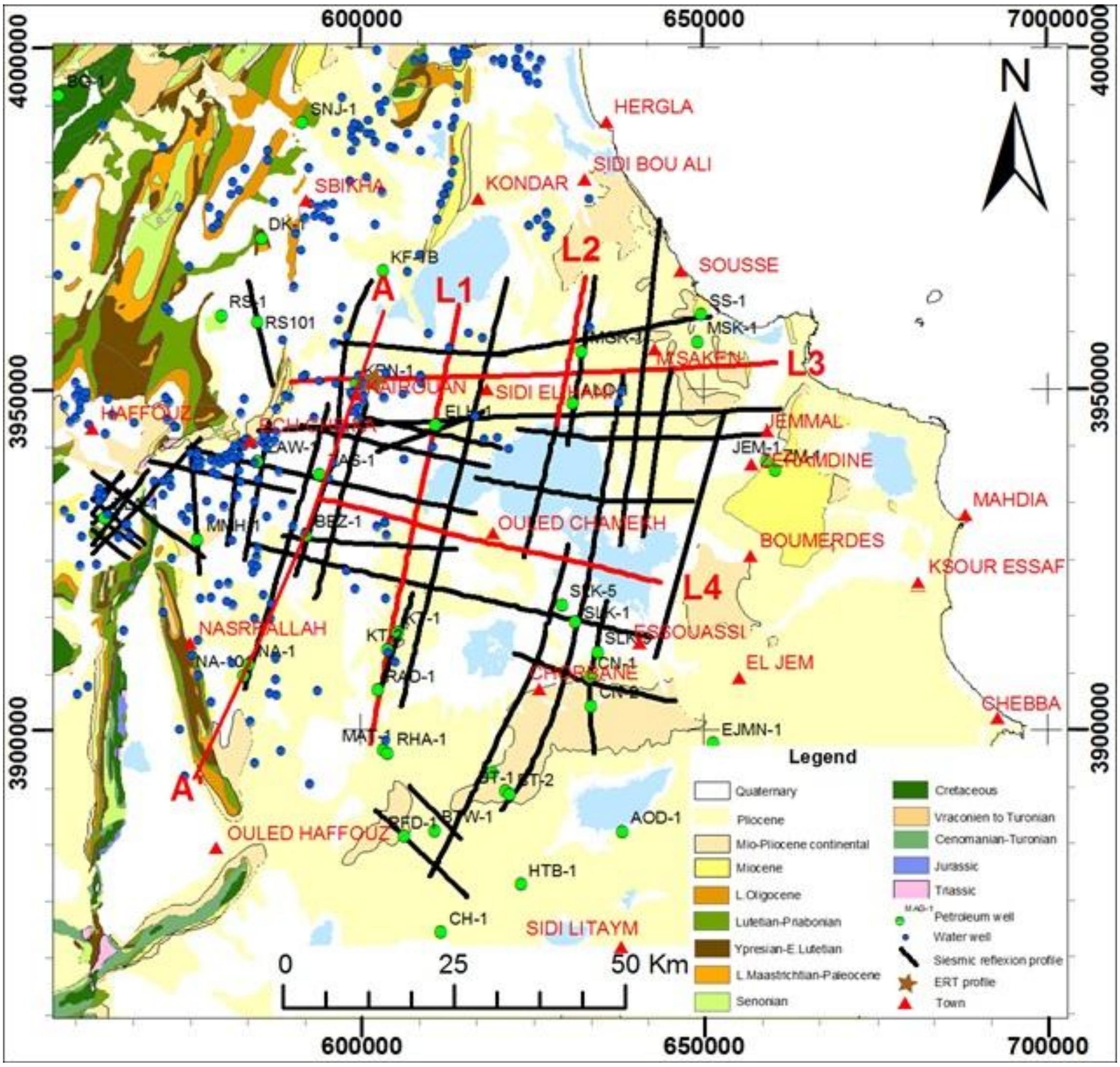

Figure. 2 Simplified geological map (Ben Haj Ali *et al.* (1985) modified), and location of water and petroleum wells, seismic reflection profiles, and hydrogeological cross sections.

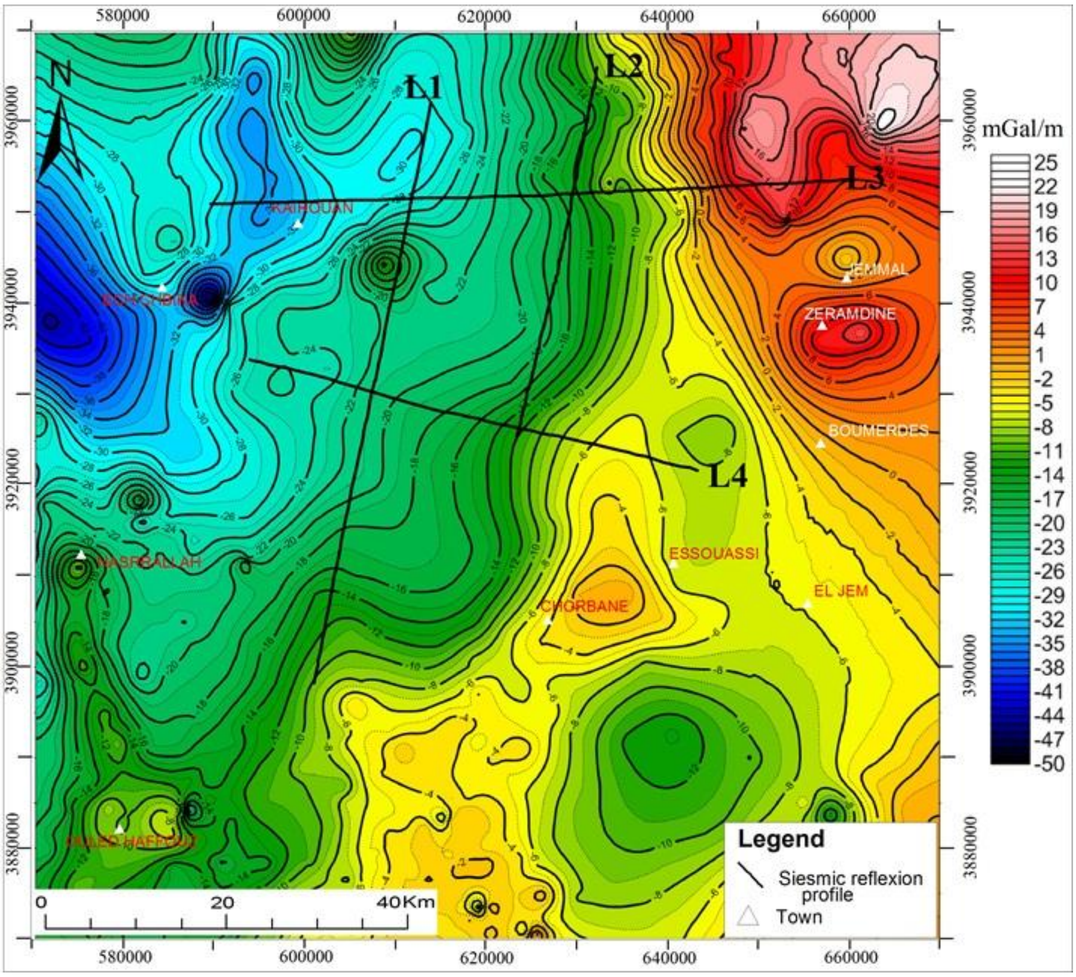

Figure. 3 Gravity Bouguer map of the Kairouan sector.

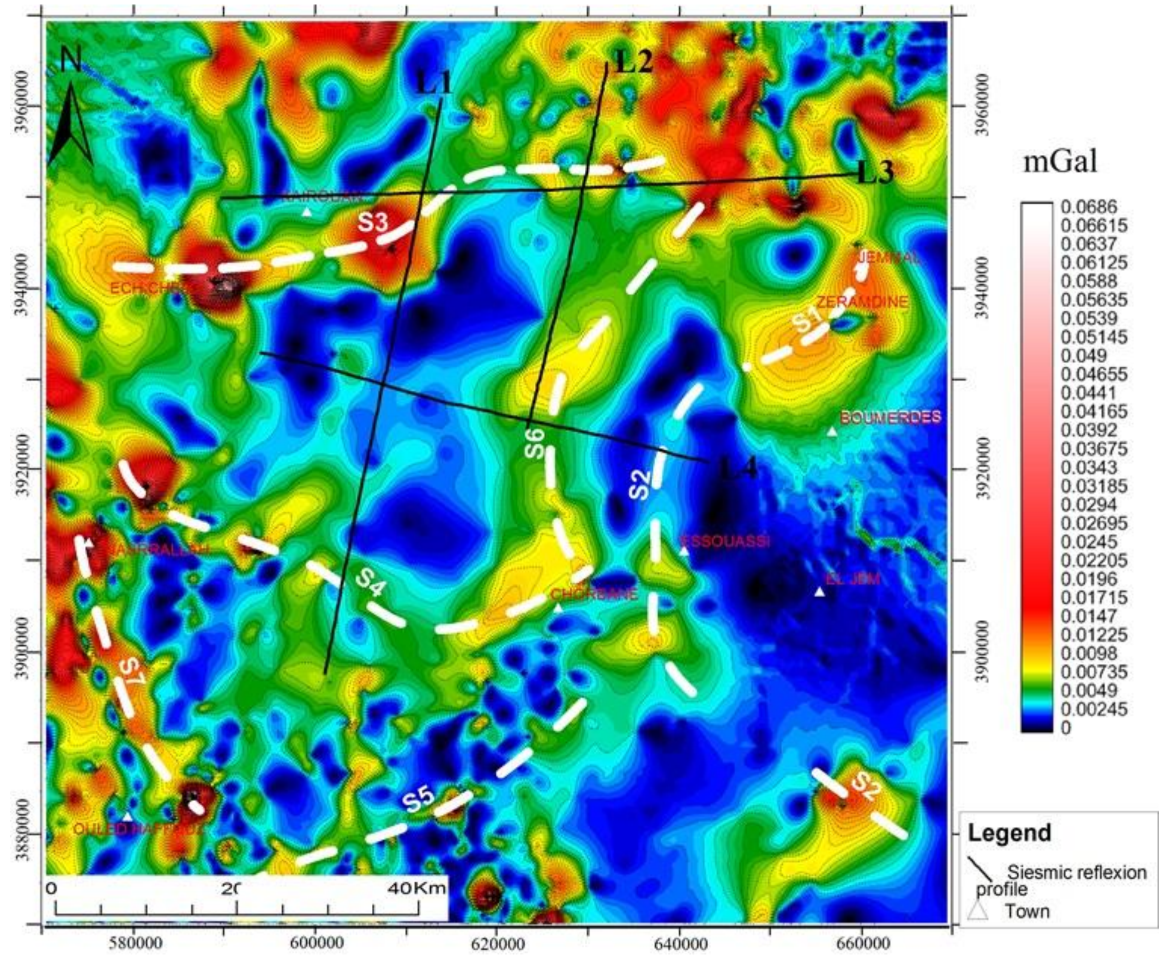

Figure. 4 Horizontal gravity gradient map of the Kairouan sector. S1: the Zéramdine fault corridor, S2: the El Jem half graben situated in the SE of the study area, S3: Kairaoun-Sousse fault, S4: El Hdadja Fault, S5: Chorbane graben, and S6: Jebel Cherahil.

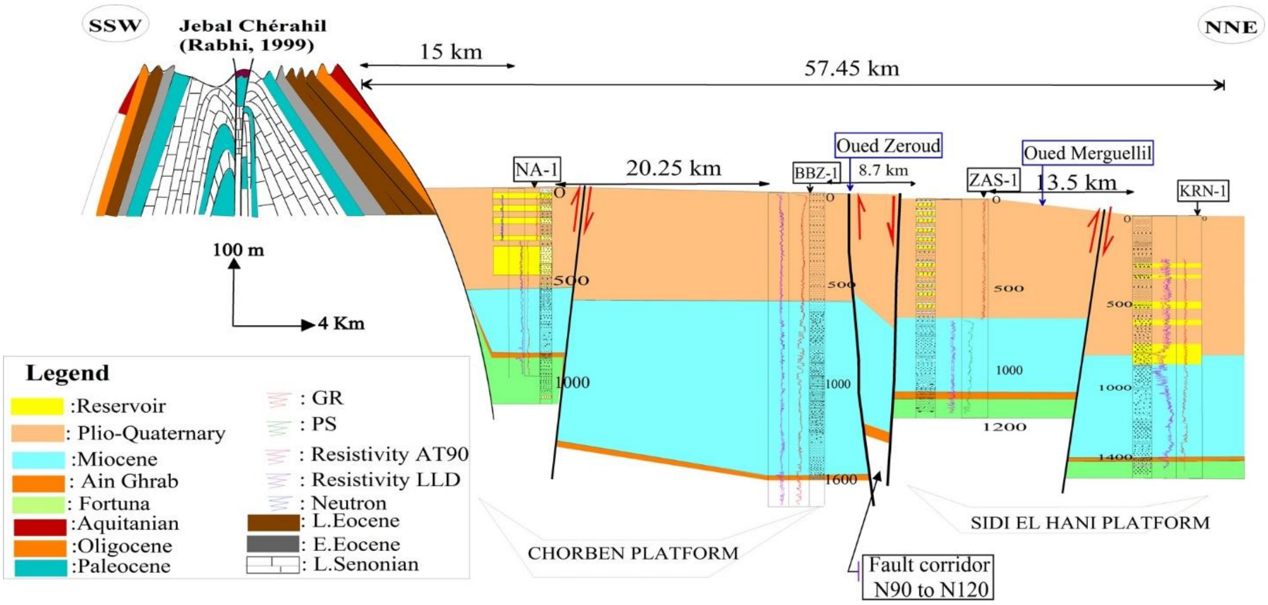

Figure. 5 A-A' hydrogeological correlation showing the different compartments, the distribution, the lateral and vertical evolution of Mio-Plio-Quaternary aquifers in the Kairouan basin, and the contribution of the wire line logging wells in the determination of the hydrogeological aquifer structure.

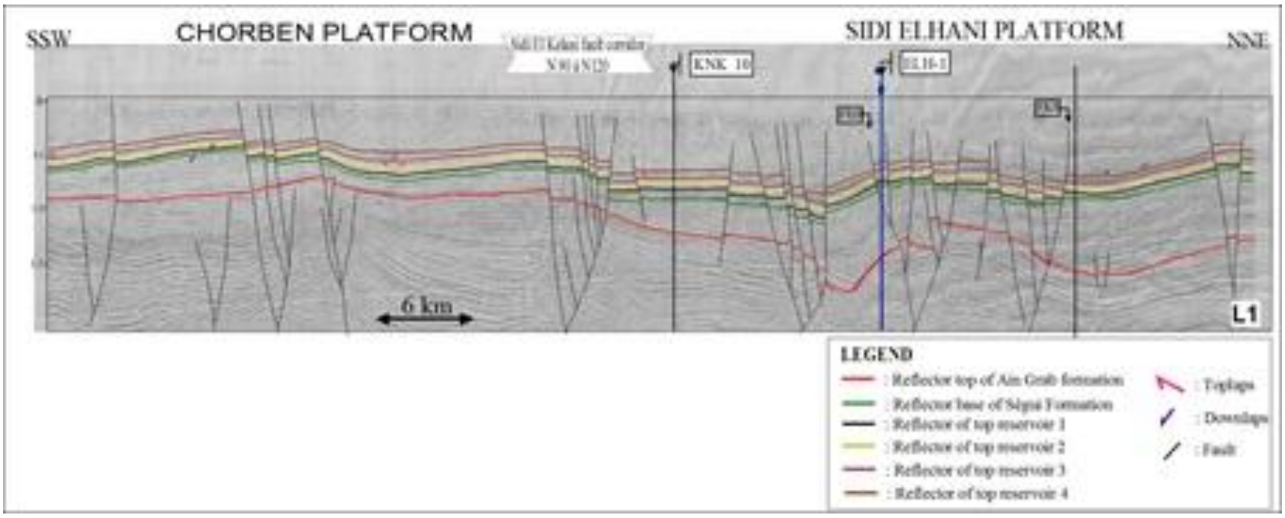

Figure. 6 L1 seismic reflection profile showing the NNE-SSW structuring of the Plio-Mio-Quaternary reservoir Horizons.

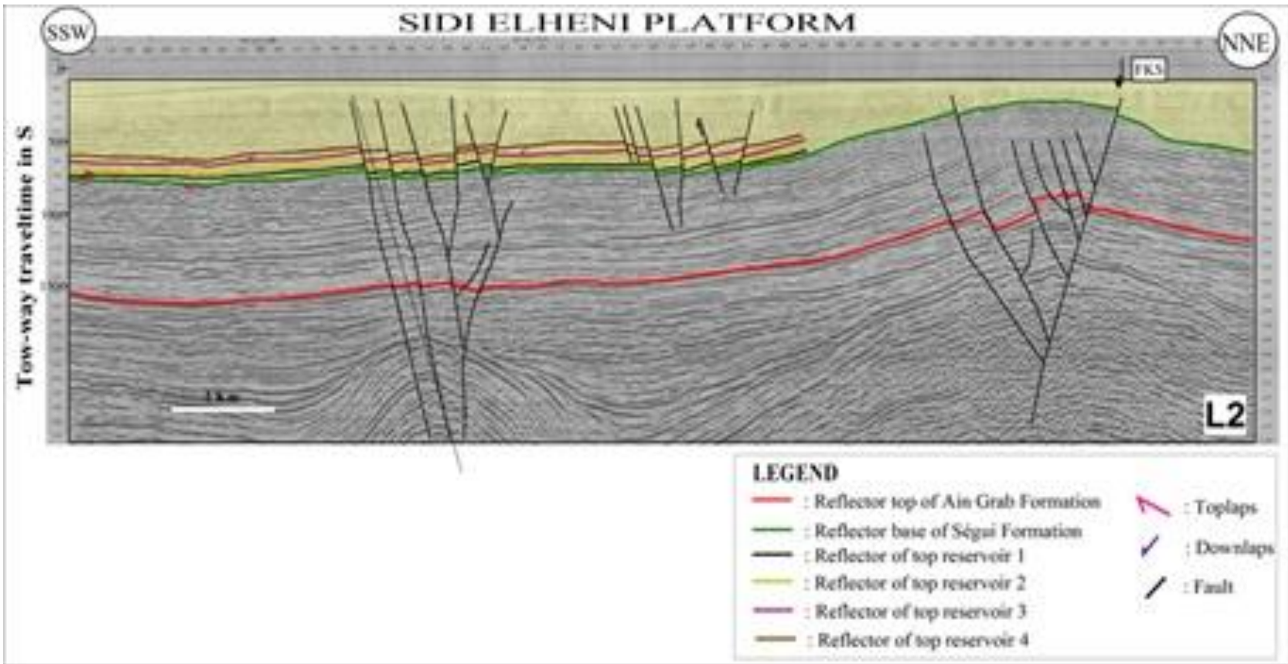

Figure. 7 L2 seismic profile reflection showing the NNE/SSW variation of the Plio-Mio-Quaternary reservoir layers and the NNE aquifer boundary.

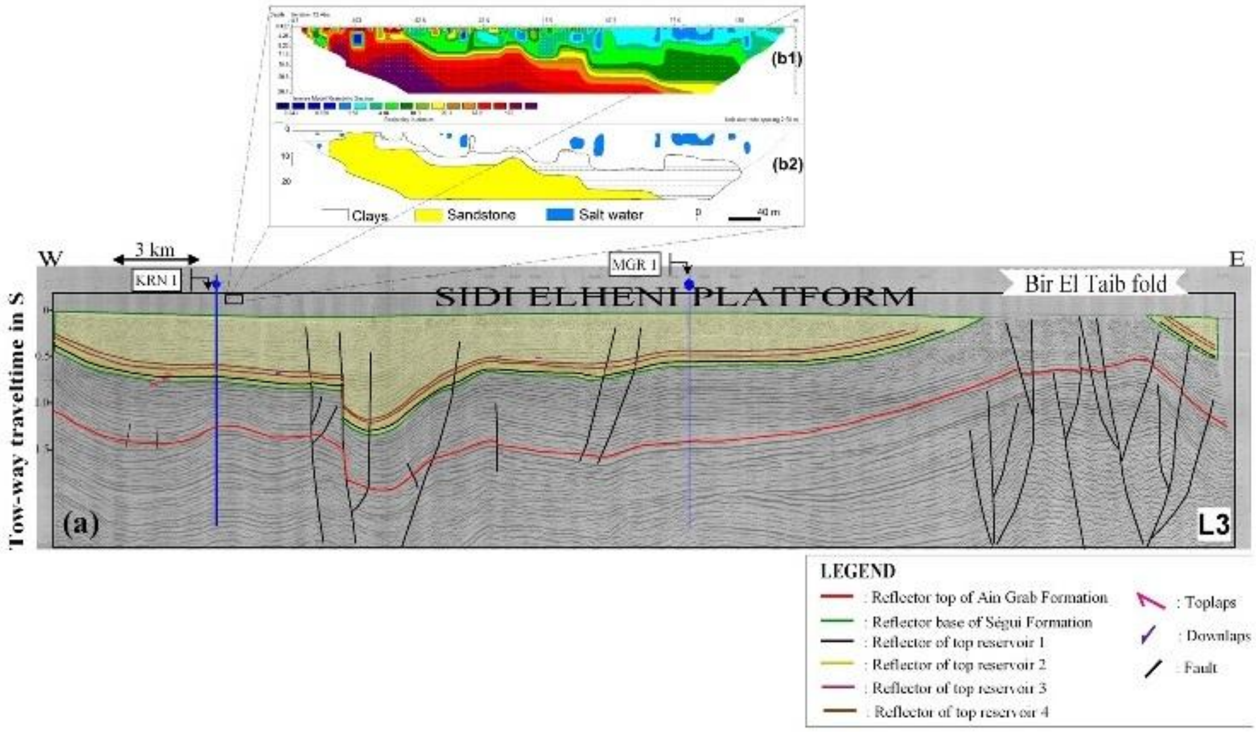

Figure. 8 a) L3 seismic reflection profile showing the W-E variation of the Plio-Mio-Quaternary reservoir layers, and the aquifer East boundary. b) 2D interpreted resistivity depth sections along the ERT profile lines: b_1) The inversion model resistivity section. b_2) 2D interpreted lithological section.

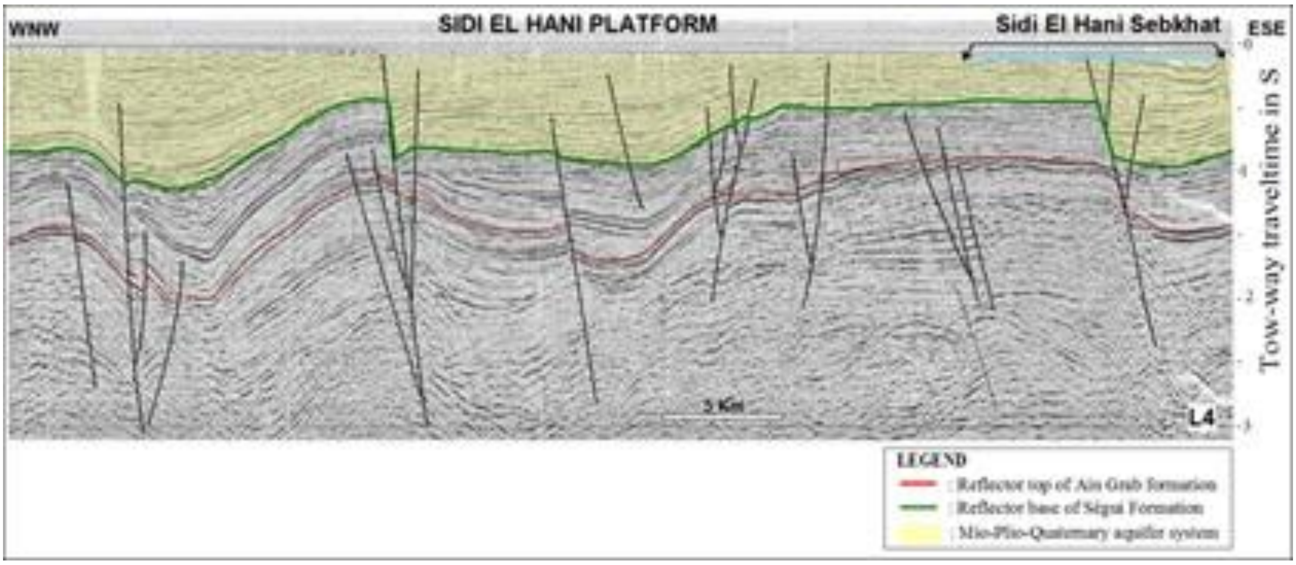

Figure. 9 L4 seismic reflection profile showing the WNW-ESE variation of the Plio-Mio-Quaternary reservoir layers.

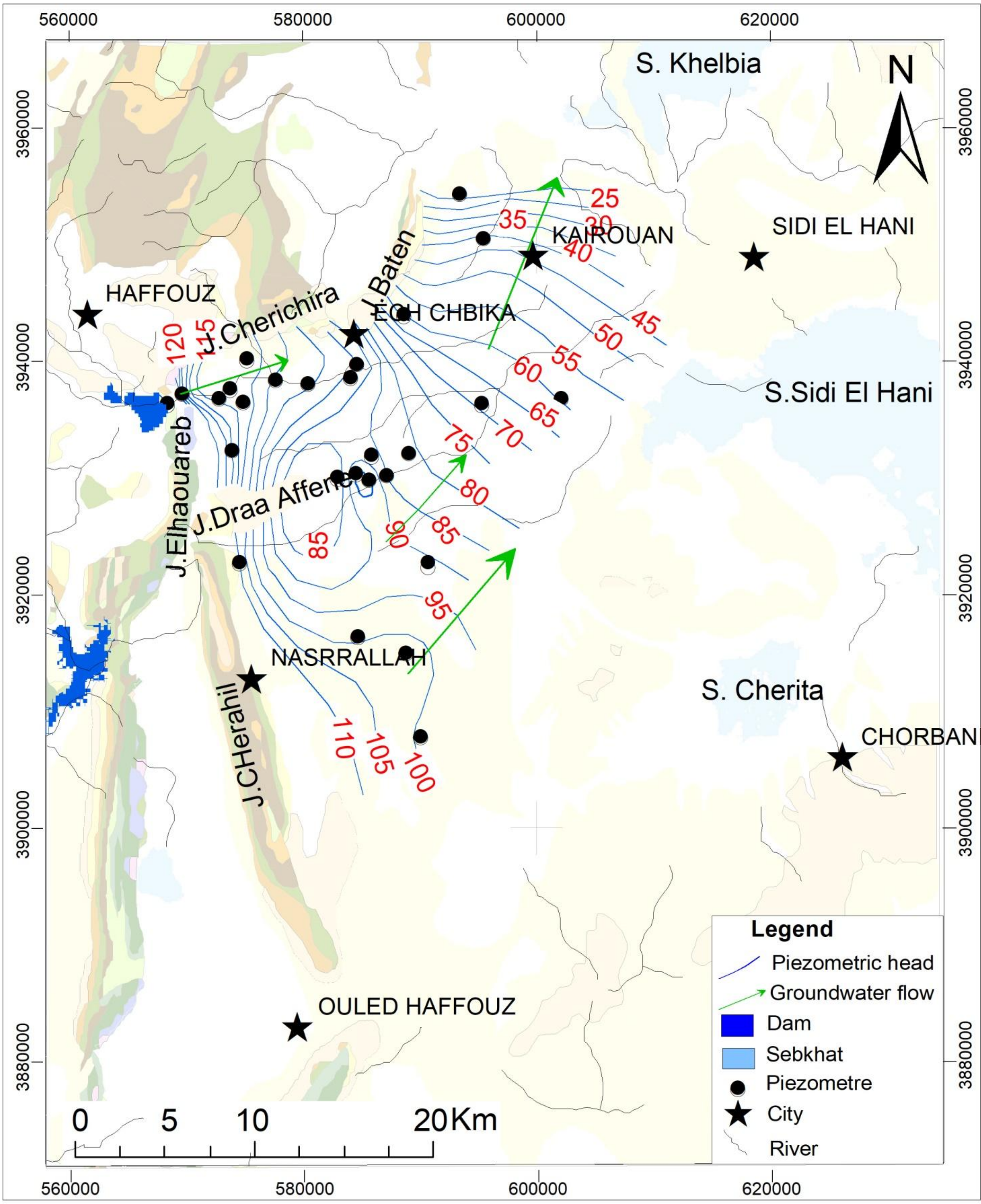

Figure. 10 Piezometric head map of Mio-Plio-Quaternary aquifer in the Kairouan plain (Mars 2013).

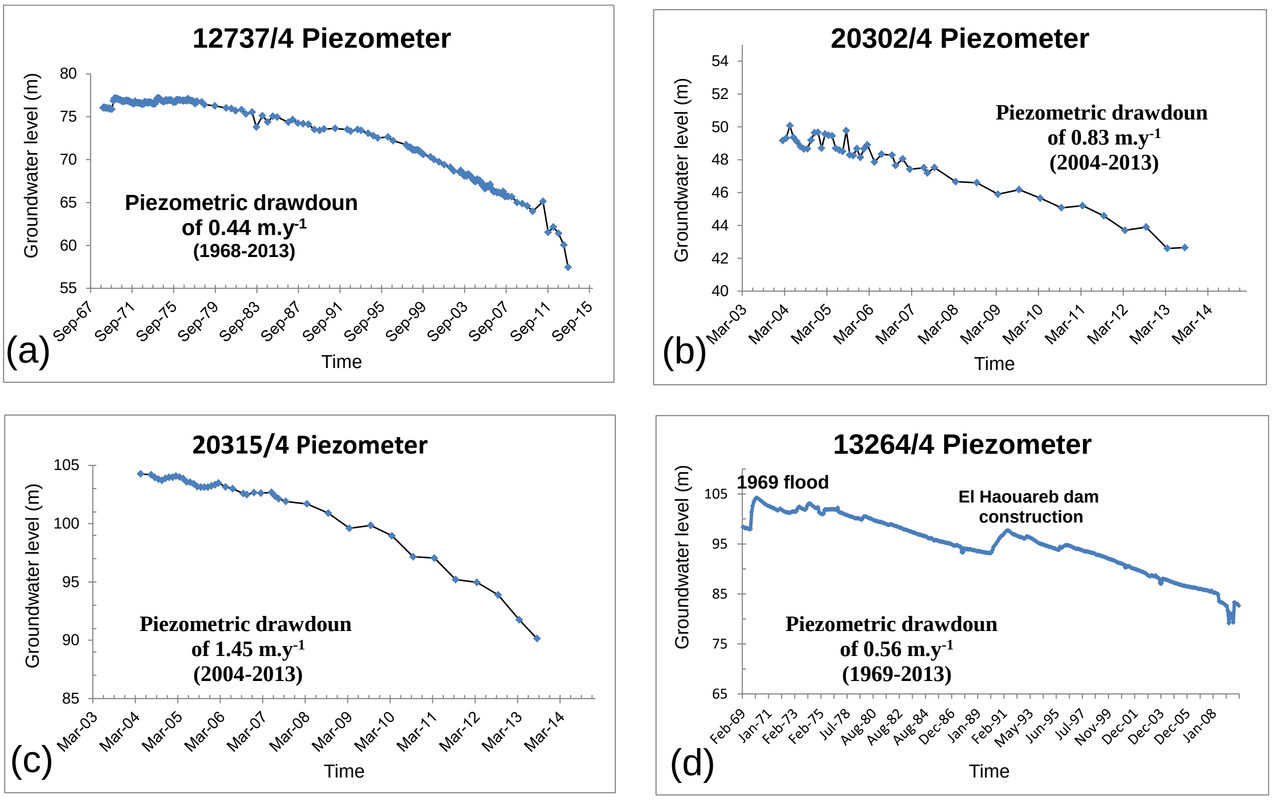

Figure. 11 Piezometric fluctuations of Kairouan aquifer: (a) 12737/4 piezometer, (b) 20302/4 piezometer, (c) 20315/4 piezometer, and (d) 13264/4 piezometer.