Hydrodynamic and hydrochemical changes affecting groundwater in a semi-arid region: the deep Miocene aquifers of the Tunisian Sahel (central east Tunisia)

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Abstract Like all other Mediterranean countries, Tunisia provides multiple examples of groundwater degradation due to its overexploitation. This is especially the case in the Zéramdine-Mahdia-Jébéniana region (central east Tunisia), where recent measurements revealed an important piezometric drop in the Miocene aquifers. Through hydrodynamic and hydrochemical analysis, we studied the influence of the head decrease on groundwater flow and quality. The spatial and temporal analysis of the piezometry identified two totally independent compartments. This was confirmed by the hydrogeochemical and multivariate statistical analysis. The Miocene aquifer system was divided into two water groups: (1) the Zéramdine-Béni Hassen aquifer which is characterized by freshwater, Na-Ca-Cl-SO_4 facies, and salinity increase from west to east that is coinciding with the principal water flow direction; and (2) the Mahdia-Ksour Essef aquifer, which is defined throughout by high and heterogeneous salinity and Na-Cl facies.

Key words groundwater; piezometry; water quality; overexploitation; Tunisia

INTRODUCTION

The precise characterization of an aquifer is necessary to find a balance between preservation and use, especially in arid and semi-arid regions, where the intense exploitation of groundwater resources has often led to a decrease in the groundwater levels and a degradation of the water quality (e.g. Foster & Loucks, 2006). In fact, the spatial and temporal analyses of hydrodynamics and hydrochemistry are fundamental to identify the water flows (direction and evolution with time), and the groundwater chemical quality (existing facies, their origins, and changes with time) (Harbison & Cox, 2002; Zouhri, 2002; Yermani & Zouari, 2003; Trabelsi *et al.*, 2007; Kouzana *et al.*, 2009). This methodology was applied to the Miocene aquifer of the Zéramdine-Mahdia-Jébéniana regions (central east Tunisia).

The study area (Fig. 1) has a semi-arid to arid climate (mean annual rainfall 340 mm year^{-1} during the 1980–2007 period). Water resources are limited and most of the water demand is supplied by both deep (Miocene) and shallow (Pliocene and Quaternary) aquifers (Bouri & Ben Dhia, 2009). For the past few years, groundwater pumping has largely exceeded resource renewal and created a significant piezometric depression (up to 10 m of decrease between 1995 and 2008). The aim of this study is to characterize the hydrodynamical and chemical properties of the Miocene aquifers and to analyse the factors controlling their spatial variability. The influence of the piezometric decrease on the groundwater flow and water quality was also studied.

GEOGRAPHICAL AND HYDROGEOLOGICAL SETTING

The study area covers the Jemmel, Zéramdine, and Mahdia-Jébéniana plains with a total surface area of 5130 km^2 between 10°32′12″ and 11°10′41″ north parallels and the 34°57′15″ and 35°44′10″ east meridians (Fig. 1). The study area is bordered to the west by the Zéramdine fault corridor and the El Jem half-graben; to the south, by the Sfax plain; to the north, by the Moknine fault and platform; and to the east by the Mediterranean Sea.

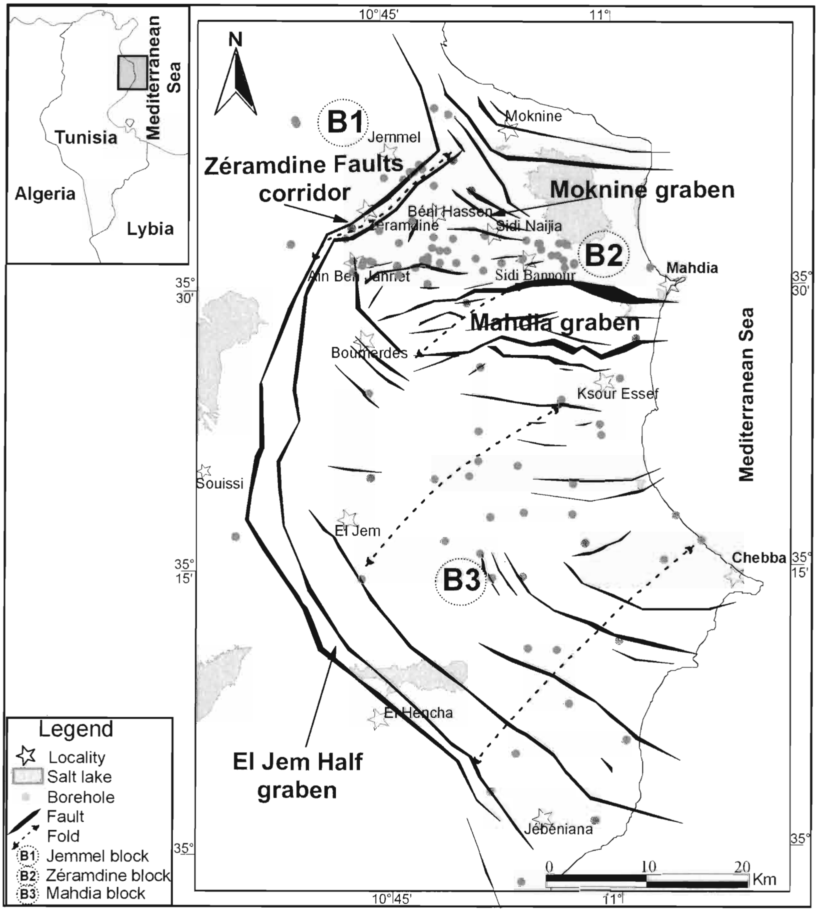


Fig. 1 Structural map of the Zéramdine-Mahdia-Jébéniana Neogene blocks.

In the Zéramdine-Mahdia-Jébéniana region, the Miocene series contains a very complex aquifer system of fluvio-deltaic sediments. This hydrogeological system consists mainly of sand and sandy clay interbedded with clay layers, attributed to the Saouaf (Serravalian-Tortonian) and Segui (Mio-Pliocene) formations (Gaaloul, 1995; Mannaï-Tayech, 2009). The Miocene sand layers contain two multi-layered aquifers, the Zéramdine-Béni Hassen (ZBH) and Mahdia-Ksour Essef (MKE) aquifers, separated by the Mahdia graben (My Maliki, 2000).

The geometry of the ZBH aquifer is complex and heterogeneous. It is characterized by the presence of an upper zone in the Zéramdine, Béni Hassen, and Ain Ben Jennet regions, where the aquifer is unconfined. Towards the east, the reservoir becomes deeper; the water table becomes a confined aquifer (Hubert, 1968; Ben-Akhy, 1998). Southwards, in the Mahdia-Jébéniana region, the MKE aquifer is composed of four layers, bordered to the north by the Ksour Essef fault, and to the west and the south by El Jem half-graben.

MATERIALS AND METHODS

The piezometric data used in this study originates from the 1995–2008 survey by the DGRE (General Direction of Water Resources, Tunisian Ministry of Agriculture). It consists of monthly water level measurements in 31 wells (14 in the northern block, ZBH, and 17 in the southern block, MKE) (Fig. 2).

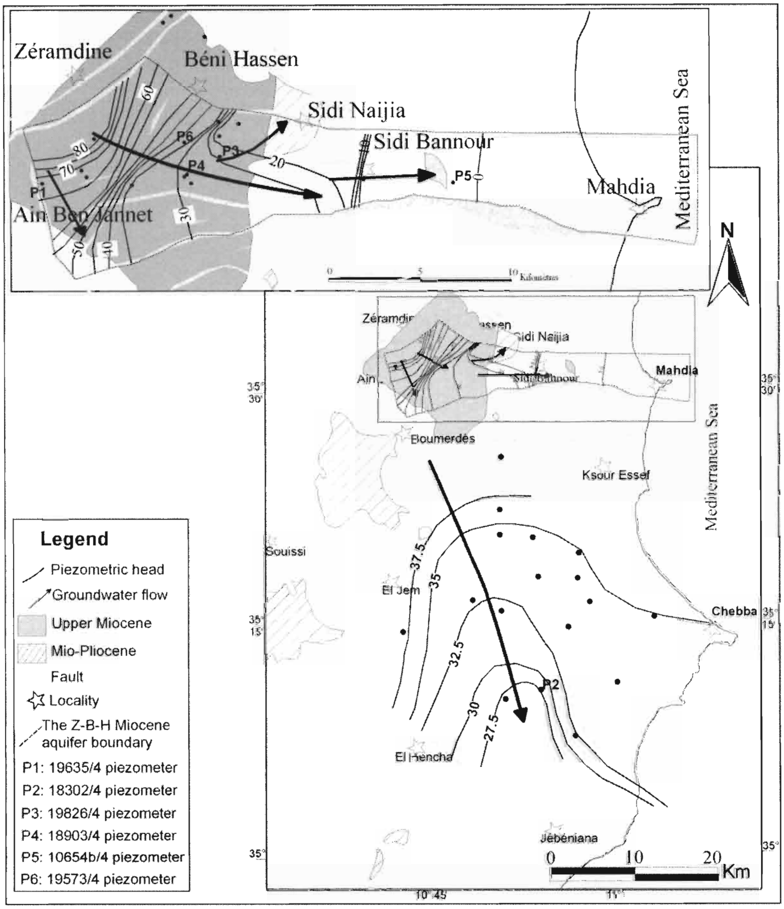


Fig. 2 Structural and piezometric map of the Miocene aquifer in the Zéramdine-Mahdia-Jébéniana blocks (September 2007).

Groundwater samples were collected in July 2008 from 31 wells (21 in the Zéramdine area and 10 in the Mahdia Jébéniana area). Electrical conductivity (EC), temperature (T), and pH were measured in the field. SO_4^{2-} concentration was determined using the gravimetric method. Cl^- was analysed using titration (Mohr method). HCO_3^- and CO_3^{2-} were measured by titration with sulphuric acid. Cations Ca^{2+}, Na+, Mg^{2+} and K^+ were analysed by atomic absorption spectrometer. In addition to our analysis, we used data from previous sampling campaigns: 22 wells in 1995 (My Maliki, 2000) and 12 others in 1995–2007 analysed by the DGRE.

RESULTS AND DISCUSSION

The spatial and temporal analysis of groundwater levels is used to investigate the groundwater compartments and the piezometric evolution in the study area.

Hydrodynamics of the Miocene aquifer system in the Zéramdine/Mahdia/Jébéniana regions

The hydrodynamic compartments of the Miocene series The piezometric map of September 2007 shows two hydrodynamic regions, separated by the Mahdia graben, which forms an impermeable screen between them (Fig. 2).

The first is in the northern part, in the Zéramdine block, where groundwater head ranges between 85 m and 0 m. This ZBH aquifer is characterized by three water flow directions. The major one is from west to east, with a hydraulic gradient varying between 15.5‰ and 1.5‰ in the upstream and downstream parts of the aquifers, respectively. Two other secondary water flow directions also exist. In the southern upstream, the groundwater flows from northwest to southeast, from the Ain Ben Jennet region to the Boumerdès region. The hydraulic gradient is about 0.8‰. Finally, in the central area the third water flow direction is from the south to the north, from the central area to Sidi Naijia region, with a hydraulic gradient of 1.7‰. The latter water flow has appeared in the last few years and resulted from the intense pumping. The recharge area of the ZBH aquifer is located in the Zéramdine, Béni Hassen, and Ain Ben Jennet regions (Hubert, 1968; Ben-Akhy, 1998).

The second hydrodynamic region, in the southern part has lower piezometric levels, varying between 40 m near the Boumerdes fold and 25 m closer to the coastline (Fig. 2). This is the MKE Miocene aquifer. The flow direction, from northwest to southeast, coincides with the main flow direction of the Sahel of Sfax aquifer (My Maliki, 2000; My Maliki *et al.*, 2000). This supports the possibility that the Sahel of Sfax aquifer recharge area is located on the northern side. Two sectors may be considered as recharge zones for the studied groundwater. The first, located in the southwest areas, is represented by the Upper Miocene series outcropping near the Ain Ben Jennet and Chorbane regions. The second is located near the El Jem half-graben faults.

The piezometric depression of the Miocene aquifer The study of piezometry over the 1968–2008 period revealed three piezometric behaviour types (Fig. 3):

- The seasonal piezometric fluctuation was very significant in the upstream part of the ZBH zone, which represents the recharge area of the aquifer. It exceeds 1 m in the 19635/4 piezometer (Fig. 3(a)). In the MKE aquifer, the piezometric fluctuation was about 0.25 m (18302/4 piezometer) (Fig. 3(b)). The higher piezometric head was observed during the humid season (September–March), when 84% of the annual rain falls. The lower piezometric head

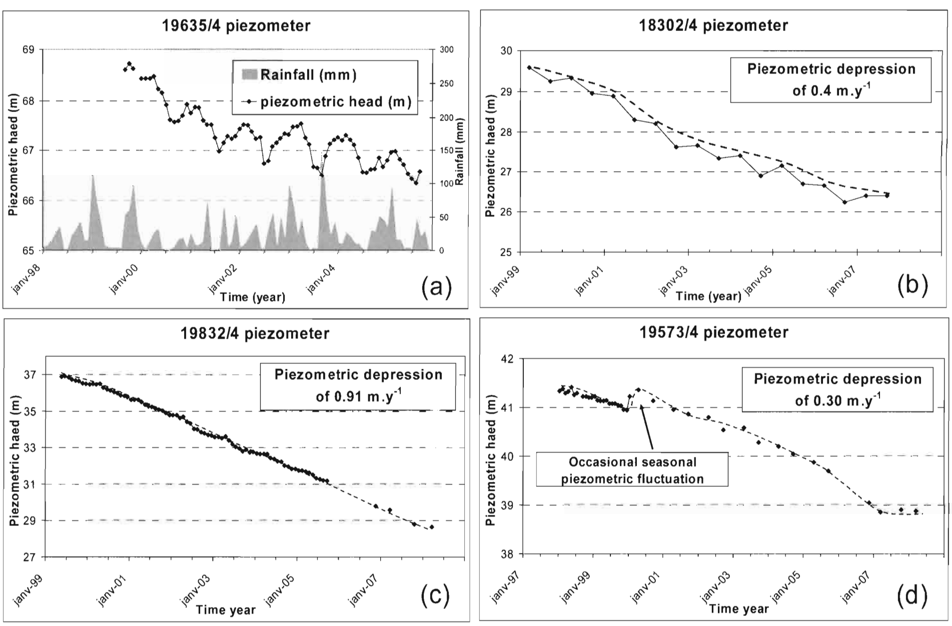


Fig. 3 Piezometric fluctuations of Miocene aquifers in the Zéramdine-Mahdia-Jébéniana blocks: (a) and (b) typical seasonal fluctuation and rainfall at Monastir, (c) typical piezometric depression, and (d) typical occasional seasonal fluctuation.

was registered during the dry season (April–August). The seasonal piezometric fluctuation is explained by the direct effect of rainwater infiltration in the recharge area.

- A continuous piezometric depression was identified in all the piezometers (Fig. 3(c)). The piezometric decrease varied from 0.3 m year^{-1} (18903/4 piezometer) to 2.0 m year^{-1} (19826/4 piezometer). Piezometric depression was higher in the ZBH region than in the MKE aquifer. The high piezometric depression was observed in the middle and downstream of the ZBH aquifer. However, it was lower in the Miocene outcrops, due to the recharge influence. In the Chiba region (10654bis/4 piezometer), the piezometric head has decreased by 18.2 m during the last 43 years because of strong pumping and a limited recharge.
- An occasional seasonal piezometric fluctuation of 0.5 m was observed in the 19573/4 piezometer (Fig. 3(d)), which is located near the recharge zone, in 1997 and 1998. This third piezometric behaviour category is typical of an exceptional infiltration, reflecting a strong inter-annual variability of recharge.

Hydrochemistry

The aims of this section are to chemically characterize the different Miocene aquifers and to study the spatial and temporal evolution of groundwater quality in the study area.

Groundwater mineralization The Total Dissolved Salt (TDS) of the Miocene water varies between 0.92 g L^{-1} and 10 g L^{-1}. The pH values range from 7.3 to 8.2. The spatial distribution of the salinity presents some contrasts between the different tectonic blocks and the hydrogeological systems. The salinity map revealed the presence of two zones (Fig. 4). The first zone, in the middle part of ZBH Miocene system, has fresh water with a salinity ranging from 0.92 g L^{-1} at the

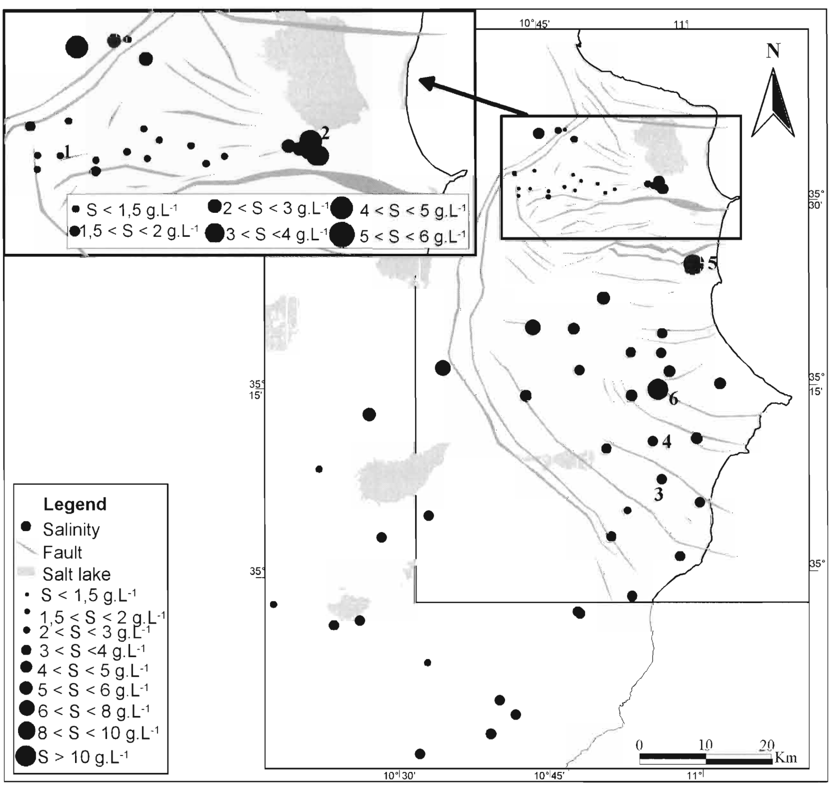


Fig. 4 Spatial distribution of the salinity in the Zéramdine-Mahdia-Jébéniana Miocene aquifers.

Béni Othman borehole (no. 1) to 4.45 g L^{-1} at Chiba-3bis (no. 2) (Fig. 4). In the shallow part, water salinity is low, and does not exceed 1.5 g L^{-1}. The salinity increase from west to east, corresponding to the main groundwater flow direction, and exceed 4 g L^{-1} in some locations. The salinity increase could be explained by a longer contact time with rocks during water circulation. The second zone, in the southern part of the MKE Miocene aquifer, has a very high salinity, varying between 3.43 g L^{-1} in the Sidi Abdel-Aziz borehole (no. 3) and 13.4 g L^{-1} in Zelba 2 (no. 4). However, the salinity variation does not always correspond to water flow direction. Some wells have high salinity (around 10 g L^{-1} in the Ksour Essaf borehole (no. 5) and 13.4 g L^{-1} in Zelba-3 (no. 6)). This can be explained by the fluvio-deltaic nature of the Miocene sediments and their rapid facies variations. The high salinity (10 g L^{-1}) recorded in the Ksour Essef borehole in the south of the Mahdia graben could be explained by the reservoir lithology, dominated by clay and gypsum. In addition, this region is characterized by a low hydraulic gradient and a very slow water movement. Thus, an increase in the dissolved salts is expected as the contact with the rock is longer. MKE salinity values are very close to those found in the Sahel of Sfax Miocene aquifer (My Maliki, 2000), confirming a hydraulic continuity between them.

Hydrochemical facies The different geochemical facies appear in the Piper diagram (Fig. 5). The ZBH samples are widely variable, but with an overall domination of the Na-Ca-Cl-SO_4 type. The MKE samples in the aquifer are more coherent, with a dominating Na-Cl facies.

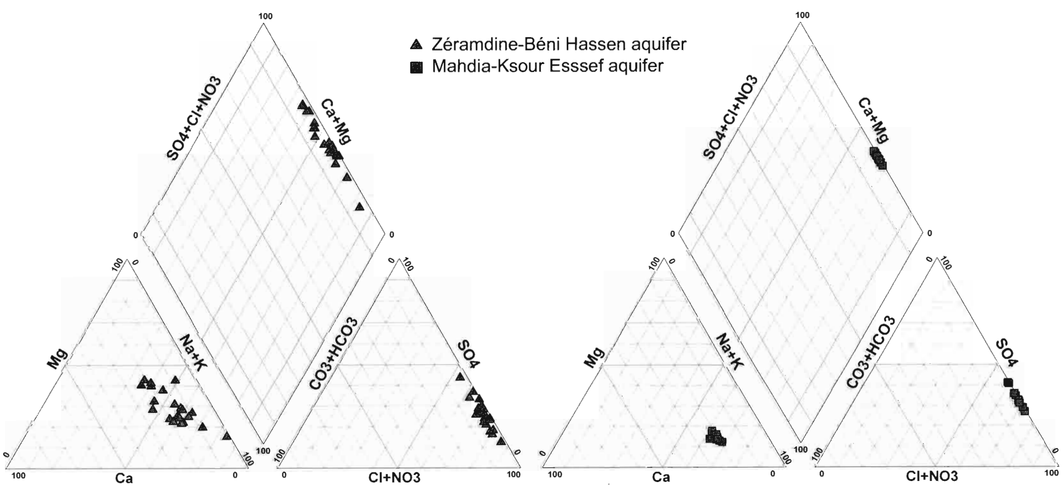


Fig. 5 Piper diagrams of the Zéramdine-Mahdia-Jébéniana Miocene aquifers.

Origin of groundwater mineralization Binary diagrams are effective tools for studying the origin of dissolved salts in water. The dominant ions are Na^+, Ca^{2+}, Cl^-, and SO_4^{2-}. The Na^+/Cl^-, diagram (Fig. 6(a)) presents a significant correlation between studies samples and the halite dissolution line, confirming that halite dissolution is an important source of the water salinity. The Ca^{2+}/SO_4^{2-} diagram (Fig. 6(b)) shows a positive correlation between the points and the gypsum ($CaSO_4$, $2H_2O$) dissolution line, indicating that the gypsum dissolution is a second important source of minerals in the water. The ratio points are not correlated with the line of calcite ($CaCO_3$) dissolution (Fig. 6(c)). In addition, $(Ca^{2+}+Mg^{2+})/HCO_3^-$ ratio points are not correlated with the line of dolomite ($CaMgCO_3$) dissolution (Fig. 6(d)). The halite and gypsum dissolution are then the dominant processes controlling the water salinity. These minerals are abundant in the fluvio-deltaic Miocene series (Gaaloul, 1995; Mannaï-Tayech, 2009). All of the ionic ratio diagrams underline the differentiation of the two water groups, ZBH and MKE aquifers.

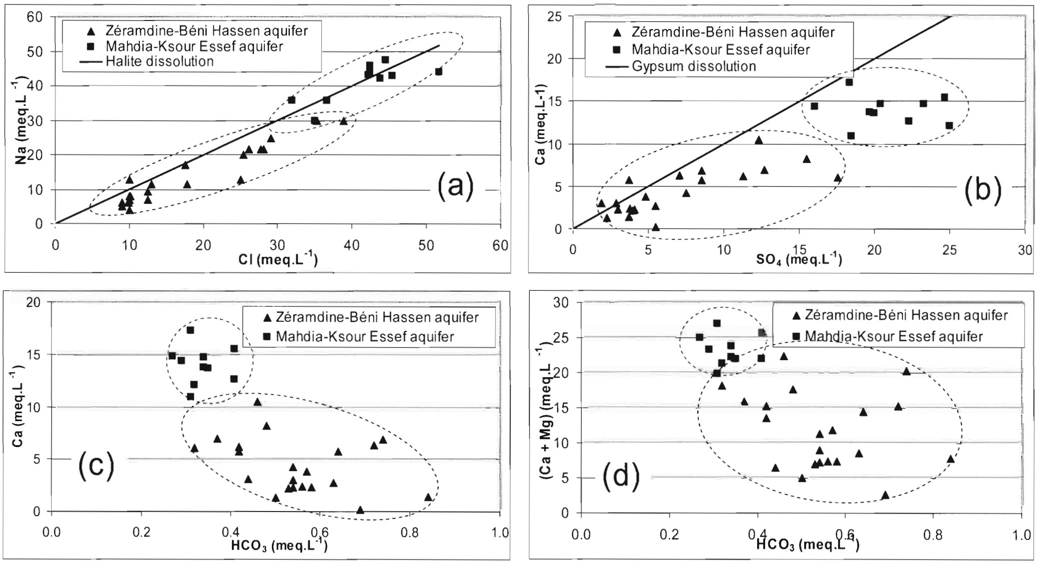


Fig. 6 Ionic ratios of Miocene groundwater in the Zéramdine and Mahdia-Jébéniana blocks.

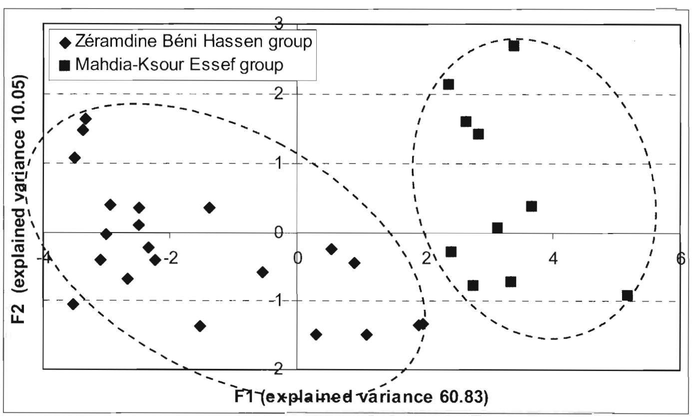


Fig. 7 Plot of loadings for the first two axes (F1 and F2) with varimax normalized rotation.

Principal component analysis (PCA) Multivariate statistical methods are widely used to determine the correlation between the water chemical parameters (e.g. Cloutier *et al.*, 2008). We considered 31 samples and 12 physico-chemical parameters (T, pH, EC, TDS, Mg^{2+}, Na^{+}, Ca^{2+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, and CO_3^{2-}) in a PCA interpretation with the XLSTAT Software (2009.6.02). The F1–F2 plane projection (Fig. 7) differentiates two water groups corresponding to the two hydrogeological units determined by hydrodynamic and hydrochemical studies, the ZBH and the MKE aquifers.

Chemical evolution of ZBH and MKE Miocene aquifers The study of water quality variation in some boreholes during the 1995–2008 period, shows an increase in TDS concentration that ranges between 0.2 (S. 17707/4) and 0.7 g L^{-1} (S. 18902/4) (Fig. 8(a) and (b)). This increase was observed in the middle and downstream of the ZBH aquifer. In the MKE aquifer, water analyses data are less available. However, the comparison of the available observations shows a little increase in TDS, about 0.1 g L^{-1} in the 19156 borehole (Fig. 8(b)). Overall, we can conclude that a little increase of the TDS concentration was observed in the Miocene aquifers.

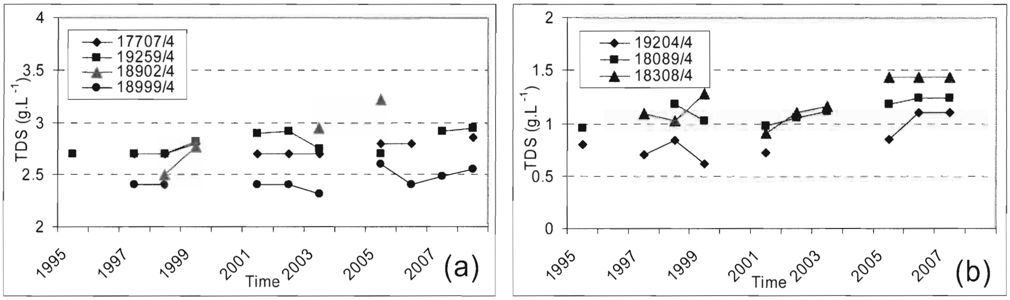


Fig. 8 TDS temporal variation of the Zéramdine-Mahdia-Jébéniana Miocene aquifers.

CONCLUSION

The study of groundwater flow and quality in the Miocene aquifers in the Zéramdine-Mahdia-Jébéniana region identified two hydraulic systems: the ZBH and MKE multi-layered aquifers. These aquifers are separated by the Mahdia graben and they are characterized by two main types of hydrochemical facies: Na-Ca-Cl-SO_4 in the ZBH and NaCl in the MKE aquifer. The mineralization results from the dissolution of abundant halite and gypsum in the studied region. A piezometric depression (varying between 0.2 and 2.0 m year^{-1}) and an increase in water salinity (varying between 0.1 and 0.7 g L^{-1}) were observed in the two aquifers during the 1995–2008 period. However, a groundwater flow perturbation was not recorded in the central area of the ZBH aquifer, represented by a flow direction from south to north. As a consequence, it seems necessary to implement a sustainable water management programme in the region.

REFERENCES

Beni-Akhy, R. (1998) Etude des impacts anthropiques sur les eaux souterraines du Sahel oriental tunisien: caractérisation hydrogéologique, modélisation mathématique et cartographie de la vulnérabilité environnementale. PhD thesis, University of Tunis II.

Bouri, S. & Ben Dhia, H. (2009) A thirty-year artificial recharge experiment in a coastal aquifer in an arid zone: The Teboulba aquifer system (Tunisian Sahel). *CR Geoscience*. doi:10.1016/j.crte.2009.10.008.

Cloutier, V., Lefebvre, R., Therrien, R. & Savard, M. M. (2008) Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. *J. Hydrol.* **353**, 294–313.

Foster, S. & Loucks, D. P. (2006) Non-renewable groundwater resources. Series on groundwater no. 10. International Hydrological Programme (IHP), UNESCO Division of Water Sciences, France.

Gaaloul, N. (1995) Les environnements siliciclastiques du Néogène du Sahel de la Tunisie: palynologie et biosédimentologie. PhD thesis, University of Tunis II.

Harbison, J. & Cox, M. (2002) Hydrological characteristics of groundwater in a subtropical coastal plain with large variations in salinity: Pimpama, Queensland, Australia. *Hydrol. Sci. J.* **47**(4), 651–665.

Hubert, C. (1968) Etude hydrogéologique du Vindobonien dans la région de Zéramdine-Béni Hassen. Technical report, DGRE, Tunis.

Kouzana, L., Mammoua, A. B. & Felfoulb, M. S. (2009) Seawater intrusion and associated processes: case of the Korba aquifer (Cap-Bon, Tunisia). *CR Geoscience* **341**(1), 21–35.

Mannaï-Tayech, B. (2009) The lithostratigraphy of Miocene series from Tunisia, revisited. *J. Afr. Earth Sci.* **54**, 53–61.

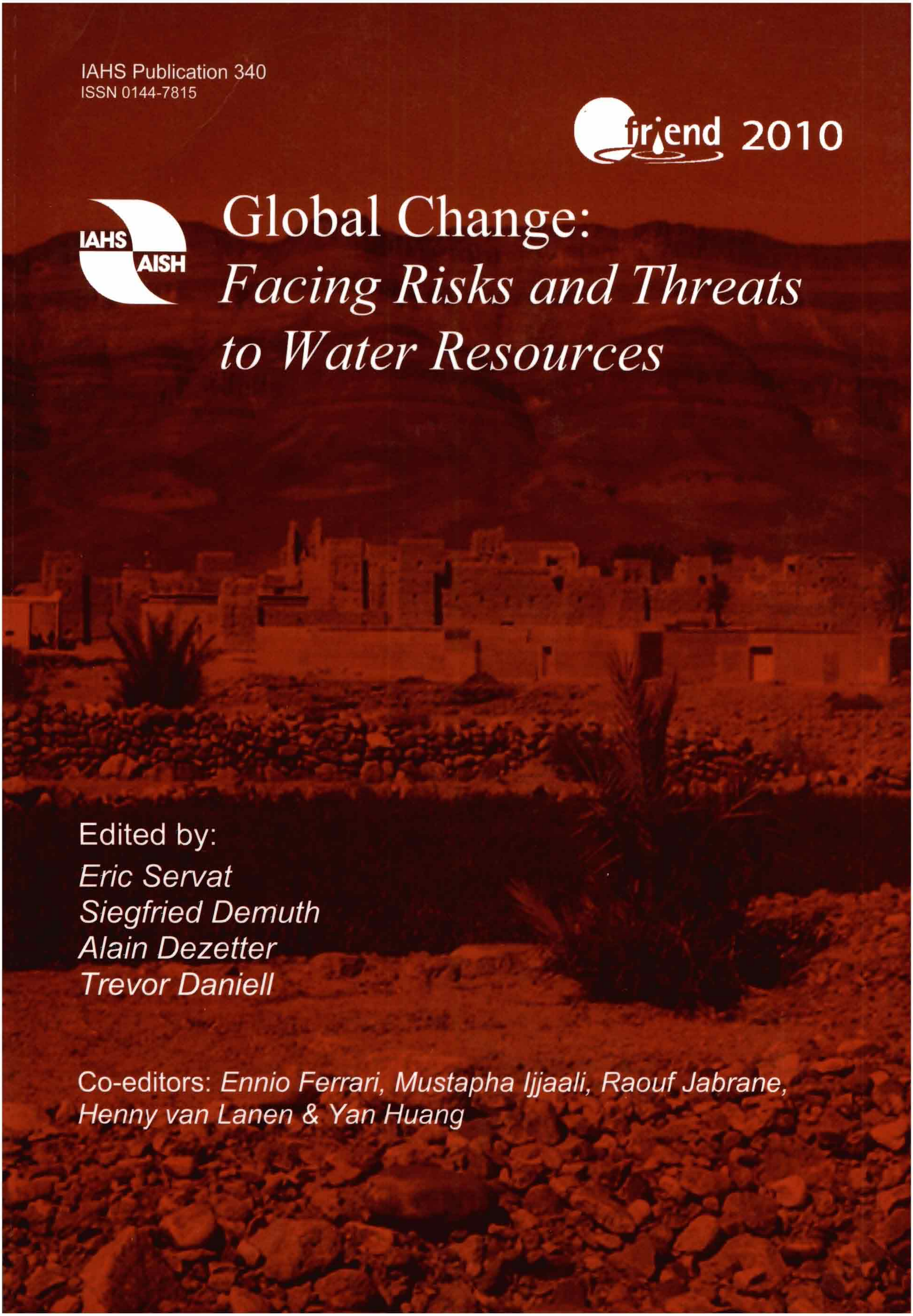
My Maliki, A. (2000) Etude hydrogéologique, hydrochimique et isotopique de la nappe profonde de Sfax (Tunisie). PhD thesis, University of Tunis II.

My Maliki, A., Krimissa, M., Michelot, J. L. & Zouari, K. (2000) Relation entre nappes superficielles et aquifère profond dans le bassin de Sfax (Tunisie). *CR Geoscience* **331**, 1–6.

Trabelsi, R., Zairi, M. & Ben Dhia, H. (2007) Groundwater salinization of the Sfax superficial aquifer, Tunisia. *Hydrogeol. J.* **15**, 1341–1355.

Yermani, M. & Zouari, K. (2003) Approche géochimique du fonctionnement de la nappe profonde de Gafsa Nord (Tunisie centrale). *Hydrol. Sci. J.* **48**, 95–108.

Zouhri, L. (2002) Hétérogénéité des cotes piézométriques et structuration en blocs dans les aquifères côtiers marocains. *Hydrol. Sci. J.* **47**(6), 969–982.



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