Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.806221

52 (2014) 1990–1996
February

Taylor & Francis
Taylor & Francis Group

Groundwater evolution of the Continental Intercalaire aquifer of Southern Tunisia and a part of Southern Algeria: use of geochemical and isotopic indicators

Younes Hamed[a,b,*], Riadh Ahmadi[a,c], Rihab Hadji[d], Naziha Mokadem[a], Hamed Ben Dhia[a], Wassim Ali[e]

[a]*Water, Energy and Environmental Laboratory (L3E), National Engineers College of Sfax (Tunisia) (ENIS), Street of Soukra km 3.5, B.P.W: 3038 Sfax, Tunisia*
Tel. +216 98 9106; email: Hamed.Bendhia@uss.rnu.tn
[b]*Faculty of Sciences of Gabes, Department of Earth Sciences, City Campus Erriadh, Zirig, Gabes 6072, Tunisia*
[c]*Institute of Sciences and Technology of Water of Gabes, City Campus Erriadh, Zirig, Gabes 6072, Tunisia*
[d]*Faculty of Technology Sciences of Setif (Algeria), Department of Earth Sciences, Setif, Algeria*
[e]*Department of Earth Sciences, Institute of Applied Geosciences, Section Hydrogeology, Karlsruhe, Germany*

Received 29 November 2012; Accepted 10 May 2013

ABSTRACT

The expansion of irrigated agriculture and the overexploitation of groundwater aquifers are leading to saltwater intrusion, severe deterioration of groundwater quality and soil subsidence at arid areas. The geochemical processes taking place along an 800 km flow line in the non-carbonate Continental Intercalaire aquifer (CI) in North Africa are described using chemical (major and trace element) and isotopic indicators. The aquifer is hydraulically continuous from the Atlas Mountains in Algeria to the Chotts of Tunisia and the geochemical evidence corroborates this. The CI aquifer of North Africa is one of the largest confined aquifers in the world. The aquifer is hydraulically continuous from the Atlas Mountains in Algeria (recharge area) to the Chotts of Tunisia (discharge area) and the geochemical evidence corroborates this. The isotopic study (Delta^{18}O, Delta^{2}H) permits classifying groundwater into three groups. The first group is characterized by low ^{3}H concentrations, low ^{14}C activities and depleted stable isotope contents. It corresponds to an old end-member in relation with palaeoclimatic recharge which occurred during the Late Pleistocene and the Early Holocene humid periods. The second group is distinguished by high to moderate ^{3}H concentrations, high ^{14}C activities and enriched heavy isotope signatures. It corresponds to a modern end-member originating from a mixture of post-nuclear and present-day recharge in relation to return flow of irrigation. The third group is characterized by an average composition of stable and radiogenic isotope signatures. It provides evidence for the mixing between the upward moving palaeoclimatic end-member and the downward moving present-day end-member. Rainfall, originating from a mixture of Atlantic and Mediterranean air masses.

*Corresponding author.

Presented at the 6th International Conference on Water Resources in Mediterranean Basin (WATMED6), 10–12 October 2012, Sousse, Tunisia

Keywords: Continental Intercalaire; Groundwater; Isotopic indicator; North Africa; Tunisia

1. Introduction

The expansion of irrigated agriculture and the intensive agricultural activities induce the risk of groundwater quality degradation through high groundwater pumping rates and overexploitation of the aquifers, leading to seawater intrusion in the coastal aquifers. The use of poor quality water for irrigation reduces crop productivity and can alter soil physicochemical properties causing soil degradation [1,2]. About 25 million hectares, more than 10% of the world's irrigated area, are severely affected by yield suppressing salt built up [3]. The magnitude and intensity of soil salinization increased rapidly in the second half of the twentieth century [4]. In most arid and semi-arid regions in the world, the availability of sufficient freshwater has become a limiting factor for development. In North African regions, where water scarcity was always a dominant problem, the interference with the natural hydrologic cycle as a result of groundwater resources overexploitation and changes in land usage have provoked not only the reduction of the available water but also the deterioration of the water quality. The Continental Intercalaire (CI) aquifer of North Africa is one of the largest confined aquifers in the world, comparable in scale to the Great Artesian Basin of Australia and covers some 600,000 km^2 with a potential reservoir thickness of between 120 and 1,000 m [5]. Together with the Cretaceous Nubian Sandstone of other North African countries (Libya, Egypt and Sudan) it easily forms the largest system of continental aquifers worldwide. The CI aquifer in Tunisia and Algeria may be considered as a type area for large artesian basins, especially since the results may be extrapolated to the west (Grand Erg Septentrionale) and to the east (to the Fezzan of Libya) as well as to the south oF the basins of the southern Sahara (Fig. 1). The overlying aquifer sequence of the Complex Terminal (CT) forms in its own right a very important and large aquifer of a scale equal to many others worldwide. The overlying aquifer sequence of the CT forms in its own right a very important and large aquifer of a scale equal to many others worldwide. In this study, hydrogeologic, hydrochemical and isotopic information from the aquifer system will be integrated and used to determine the main factors and mechanisms controlling the chemistry of groundwater in the study area and to identify the origins of water bodies and their migration pathways. The palaeorecharge history can form an important contribution to the modern debate on climate change, since groundwater forms an archive of conditions during wet phases. In addition, these resources are non-renewable and finite, and despite the scale of the basinal storage, over-exploitation is a serious issue. It is important, therefore, to be able to examine the extent of any current recharge and the extent to which water in this and similar large sedimentary basins is being mined.

2. Study area

The study area, which occupies an area extent of approximately 10,000 km^2 and lies between the longitudes 5˚00′–10˚00′E and the latitudes 29˚00′–36˚00′N. This basin has an elevation ranging from 700 to ≈1,300 m. It corresponds to a synclinal structure limited in the North by the Algero-Tunisian Atlas, in the West by the Algerian Atlas Mountains, in the South by the Saharan platform and in the East by the Mediterranean Sea (Fig. 1). The drainage network is dendritic to sub-dendiritic reflecting less permeable bed rocks enhancing high concentration of rainwater during flash flood times. The runoff water component during flash flood times is pouring its water to the large continental depression (locally known as «Sebkha» or «Chott») of Chott Melrhir (Algeria) and Chott Djerid in Tunisia (Fig. 1).

3. Geology and hydrology

The North-West Sahara Aquifer System (NWSAS) can be categorized as a multi-layered system of aquifers which embodies a huge stock of non-renewable, fossil water. It displays mostly porous and fissured/fractured structure [6]. This basin comprises a series of aquifer layers which have been grouped into two reservoirs called the CI and the CT It has a thickness of many hundreds of meters and is found in depths ranging from around 400 up to 2,000 m below ground. According to [7] the CI contains a set of layers with very differing lithology, comprising mainly continental sandstone in alternation with marine limestone and clay formations (Fig. 2).

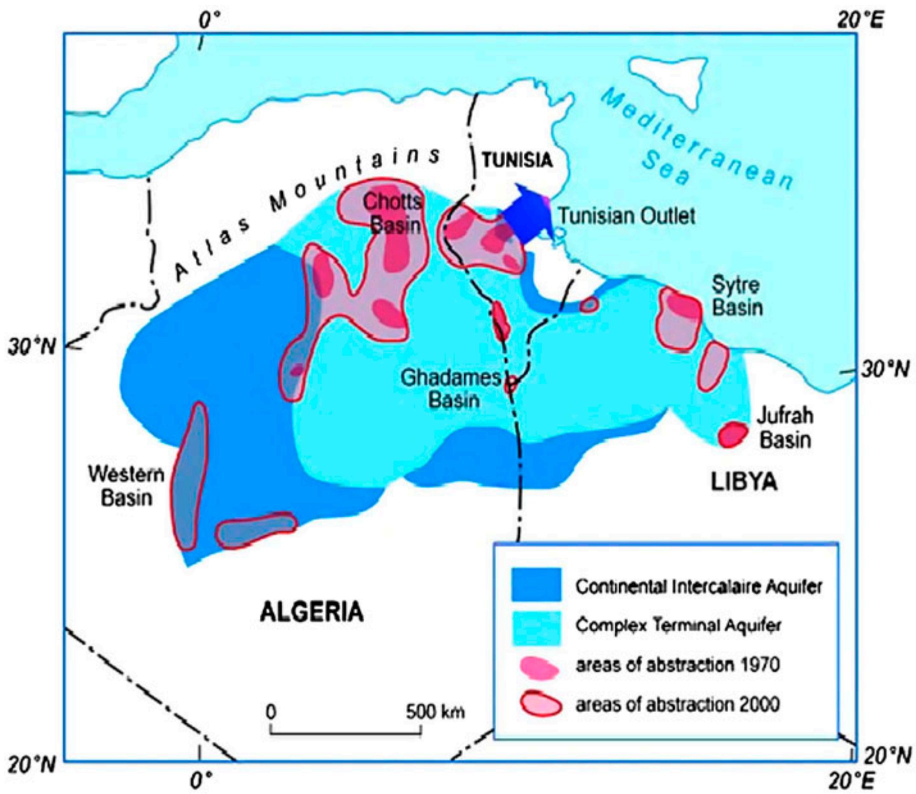

Fig. 1. Groundwater flow dynamics for North-Western Sahara Aquifer System (NWSAS) [24].

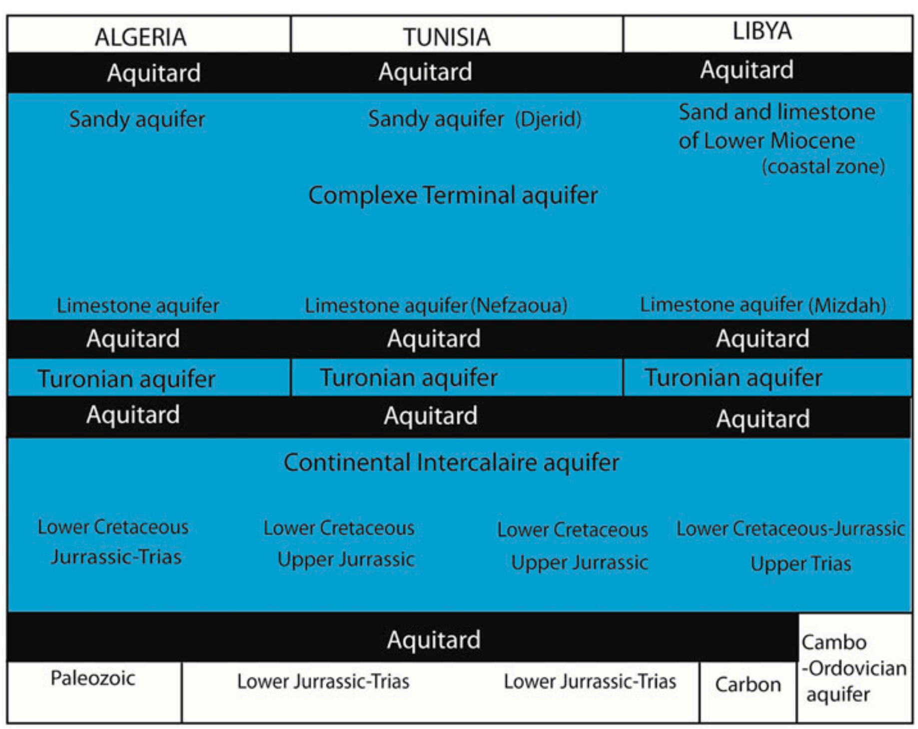

Fig. 2. Geological characteristics of the aquifers in North Africa [18].

The lithologic units in the study area extend from Cretaceous to Quaternary. Available lithologic logs of wells drilled in the study area indicate that the multi-layer groundwater flow system is subdivided, based on lithology and position, into three distinct hydrostratigraphic units [8]. These units consist of three main aquifer systems, namely, from the bottom to the top, the CI, the CT and the Mio-Plio-Quaternary (MPQ) shallow aquifers:

3.1. The CI aquifer

The CI aquifer is composed by fluvio-deltaic continental deposits [5,9,10] produced intercalations of detrial levels with horizons of clay silts and frequent gypsum layers. The CI aquifer is located within a succession of clastic sediment of Mesozoic age, the thickness and lithology of which vary laterally [11]. The aquifer is continuous from north to south from the Saharan Atlas to the Tassilis of the Hoggar (Algeria) and west to east from western Algeria to the Libyan Desert through southern Tunisia [12]. It can be found at depths of 800–2,500 m with a thickness of around 300–1,200 m. The groundwater of the CI is mainly paleogroundwater which dates back to the Pleistocene and early Holocene under a cooler and humid climatic regime [11]. The CI has its recharge source in the Algerian and Tunisian Atlas Mountains (270 $mm^3\,year^{-1}$) [13]. It is mainly confined and discharges in the Chotts (Fejej, Djerid, El Gharssa, Garat Douza and El Guettar) of Tunisia and in the Gabes gulf (Mediterranean Sea, Fig. 1) [14–16]. Recent recharge is observed at the periphery of the Sahara basin [12]. The water is geothermal with temperatures between 45 and 70˚C. Currently, the basin suffers by an overexploitation of groundwater. Causing the extinction of the artisianisme and a drop of the geothermalisme (Fig. 3) and also a soil subsidence in Douz area in November 2012 [17] (Fig. 4). Increased pumping led to a rapid sinking of water tables on the plain. During the 1980s, the average annual drop in water tables in the basin was one meter [18]. In the most heavily pumped areas annual drops of up to 2.5 m were recorded. Increased pumping also led to drastic changes in the time and direction of travel of underground water.

3.2. The CT aquifer

The term CT describes a multi-layer aquifer which consists of the Upper Cretaceous formations in the northern Saharan basin, i.e. the Upper and

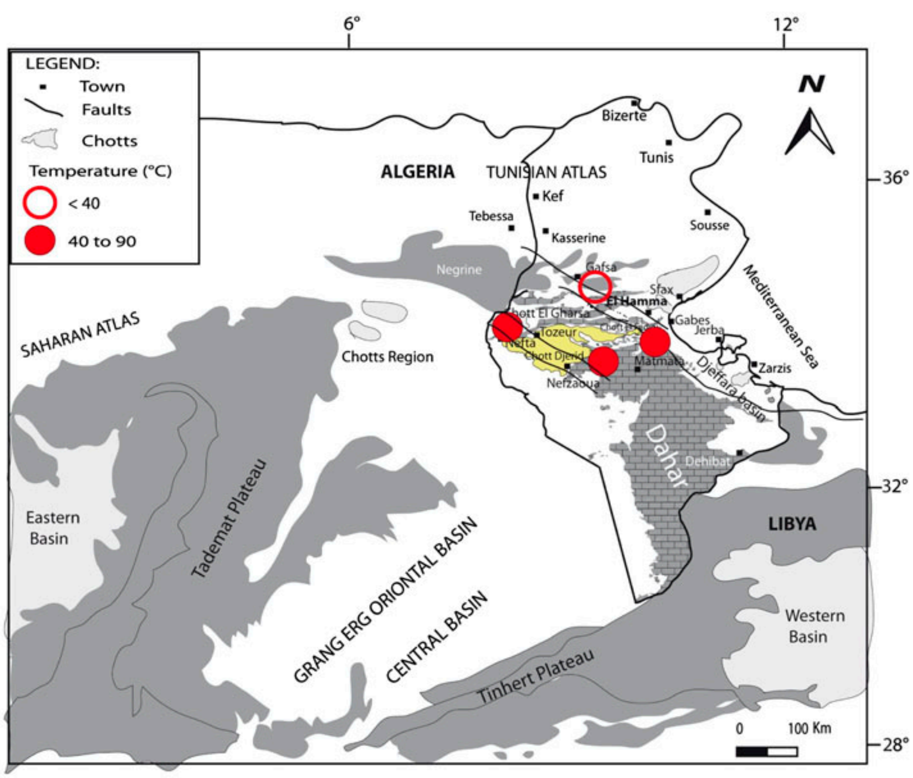

Fig. 3. Distribution of temperature in southern Tunisia [16].

Fig. 4. Photography of subsidence soil in Kebili area (southern Tunisia) (November 2012).

Lower Senonian and sandy formations of the Eocene and the Mio-Pliocene. The CT formations are relatively heterogeneous and are composed of three main aquifer horizons separated by semi-permeable to impermeable strata. The main productive levels are located either in the carbonates levels of the Upper Cenomanian Zebbag Formation and Upper Senonian Abiod Formation, Beglia and Segui Formations in the mining region.

3.3. The shallowest aquifer

The shallowest aquifer, which is an unconfined superficial unit and occurs within the MPQ aquifers. It is constituted by coarse sand with thin levels of red clays and quartz, which indicate clearly a humid paleoclimate and a paleogeography dominated by perennial fluvial system. This aquifer is essentially recharged by the excess of irrigation water coming from CI and CT deep aquifers, in oasis area.

4. Materials and methods

Water samples for laboratory analyses were collected at the humid season of 2011 from the southern Tunisia and a part of southern of Algeria. A total of 45 groundwater samples were collected from the CI wells with depths ranging between 200 and 1,800 m. Cation and anion analyses were performed at the laboratory of "Water, Energy and Environmental: L3E" of the National Engineers College of Sfax (Tunisia), using a Dionex DX 100 ion chromatograph equipped with a CS12 and an AS14A-SC Ion Pac columns and an AS-40 auto-sampler. Radiocarbon analyses were carried out at the laboratory of the National Engineering College of Sfax, Tunisia, by scintillation counting on C6H6 synthesised from $BaCO_3$ stripped in the field from 150 L of water samples. Hydrogen and oxygen isotope analyses were performed in the laboratory of the International Agency of Atomic Energy (IAEA) in Vienna, by employing, respectively the standard CO_2 equilibration [19] and the zinc reduction techniques [20], followed by analysis on a mass spectrometer. Oxygen and hydrogen isotopes analyses were reported to Delta notation relative to Vienna-Standard Mean Oceanic Water, where $\text{Delta} = [(RS/RSMOW) - 1] \times 1{,}000$; RS represents either the $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the sample, and RSMOW is $^{18}O/^{16}O$ or the $^{2}H/^{1}H$ ratio of the SMOW. Typical precisions are ± 0.1 and $\pm 1.0\%$ for oxygen-18 and deuterium, respectively. Tritium (^{3}H) analyses were performed in the laboratory of the IAEA by electrolytic enrichment and liquid scintillation counting method [21]. Tritium contents were reported in Tritium Unit (TU), in which one TU equals one tritium atom per 10^{18} hydrogen atoms.

5. Results and discussion

5.1. Chemical composition of groundwater

The EC and the TDS range from 0.37 to 11.2 mS cm^{-1} and from 0.47 to 6.85 $g\,L^{-1}$, respectively. Gener-

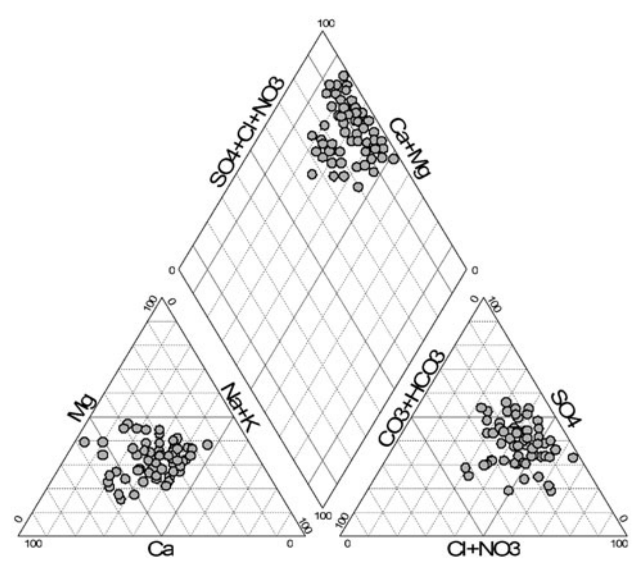

Fig. 5. Piper diagram of the aquifers groundwaters in the study area.

ally, EC and TDS increases from the mountainous regions (the piedmont zone of the Gafsa chain in the North of the study area) towards the discharge area (southern part). Two hydrochemical facies could be identified including facies 1: Ca–Mg–HCO_3 (predominant water type in the carbonate-rock aquifers because calcite and dolomite are abundant in these aquifers) and facies 2: Ca–Mg–SO_4. Water types were defined by use of the trilinear plotting technique [22]; the trilinear diagrams are shown in Fig. 5. These water facies, are mainly influenced by the dissolution of evaporates, the dedolomitization and the cation-exchange process; and supplementary by anthropogenic process in relation with return flow of irrigation waters.

5.2. Isotopic composition of groundwater

Based on the stable isotopes of water molecule (Delta^{18}O, Delta^{2}H and Delta^{3}H) and radiogenic carbon activities in the DIC and Delta^{13}C, it was possible to identify various types of groundwater and mixing process in the system: (1) an old palaeoclimatic groundwater. This groundwater was likely recharged during the Late Pleistocene and Early Holocene periods under a cooler climatic regime; (2) a relatively recent groundwater, that indicates the presence or the influence of modern water (less than 50 years) or possible contamination of a groundwater sample with modern atmospheric water vapour during sampling. This groundwater is interpreted as contemporaneous recharge at the high-altitude surrounding mountains; (3) a mixing groundwater resulting from the dominant upward leakage from the deep CI artesian water table. Tritium contents in these groundwaters provide evidence to the presence of pre-1950 and post-1960 recharge periods. The monsoon recharge belongs to two air masses: (1) Atlantic air masses that circulate from the west over Northern Africa and (2) Mediterranean air masses that come from the north (Fig. 6) [23].

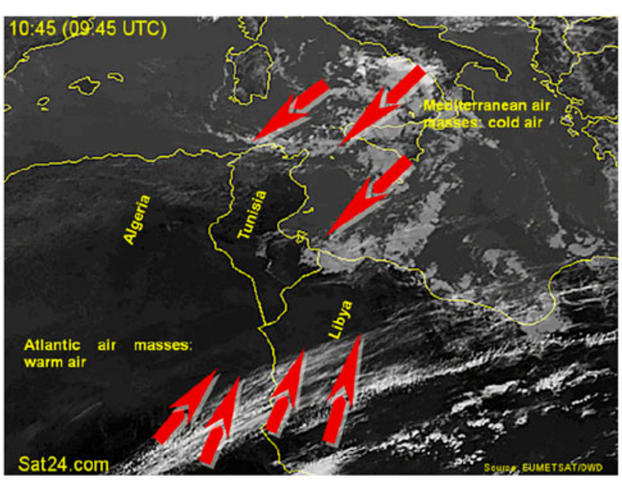

Fig. 6. Main air masses trajectories toward Southern Tunisia and Algeria.

6. Conclusion

This article has discussed the southern Tunisia problem of groundwater overexploitation in urban-industrial-agricultural areas. The hydro-chemical study demonstrates that groundwater acquire their salinization through natural mineralization and anthropogenic processes. These are the dissolution of evaporates (halite, gypsum and/or anhydrite). The isotopic investigation provides valuable information on the conceptual model of mixing between deep and shallow groundwater end-members. It indicates that the old groundwater end-member is moving by upward leakage towards the intermediate aquifer to mix with the recent end-member that moves downward. Developing communication channels between government and business is an important component of any groundwater management strategy. For example, part of the groundwater levies might be earmarked for extension, technical advice, or subsidization of groundwater conservation efforts. To some degree, such persuasive measures may soften the impact of the blunt regulatory measures that are needed to stop the urban pumping race.

Acknowledgements

The authors would like to express his sincere thanks to colleagues of the National and International Committee of the 6th International Conference Water Resources in Mediterranean Basin (WATMED6) and the participants in this international collogue. Finally, we gratefully acknowledge to the Water, Energy and Environmental Laboratory (Tunisia), Faculty of Sciences of Sétif (Algeria) and University Institute of Applied Geosciences, Section Hydrogeology (Germany) without which this contribution would not have been possible.

References

[1] K.K. Tanji, Agricultural Salinity Assessment and Management, ASCE Manuals and Reports on Engineering Practice No. 71, American Society of Civil Engineers, New York, 1990.
[2] J.D. Oster, Irrigation with poor quality water, Agric. Water Manage. 25 (1994) 271–297.
[3] S. Postel, Water in Crisis. A Guide to the World's Fresh Water Resources, in: P.H. Gleick (Ed.), Water in Crisis, Oxford University Press, New York, pp. 56–66, 1993.

[4] I.P. Abrol, J.S.P. Yadav, F.I. Massoud, Salt Affected Soils and Their Management, FAO Soils Bulletin 39, Land and Water Development Division, Rome, 1988.

[5] G. Castany, Bassin sédimentaire du Sahara septentrional (Algérie-Tunisie)-Aquifères du Continental Intercalaire et du Complexe Terminal [Sedimentary basin of northern Sahara (Algeria and Tunisia), aquifers of Continental Intercalaire and the Complex Terminal], Bulletin Bureau Recherches Géologiques Minières (BRGM) [Geological Research Bureau Bulletin (BRGM)] 3 (1982) 127–147.

[6] W. Struckmeier, A. Richts, WHYMAP and the World Map of Trans-boundary Aquifer Systems at the Scale of 1:50000000 (Special Edition for the 4th World Water Forum, Mexico City), WHYMA, Hannover, 2006.

[7] M. Besbes, Conceptual framework of the North-Western Sahara Aquifer System, in: B. Appelgren (Ed.), Managing Shared Aquifer Resources in Africa. United Nations Educational, Scientific and Cultural Organization (IHP-VI Series on Groundwater 8), Paris, 2004, pp. 163–170.

[8] Y. Hamed, Caractérisation hydrogéologique, hydrochimique et isotopique du système aquifère de Moularés-Tamerza [Hydrogeological, hydrochemical and isotopic characterization of the aquifer system of Moulares-Tamerza], PhD thesis, University of Sfax, 2009.

[9] A. Cornet, Introduction à l'hydrogéologie saharienne, Revue de Géographique [Introduction to the Saharan hydrogeology, Review of Geographical], Physique et de Géologie Dynamique VI [Physics and Dynamic Geology VI] (part 2) (1) (1964) 5–72.

[10] A. M'Rabet, Stratigraphie, sédimentation et diagenèse carbonatée des Séries du Crétacé inférieur de Tunisie centrale [Stratigraphy, sedimentation and diagenesis of carbonate series of lower cretaceous of central Tunisia], Thèse Doctorat, Etat Univ Paris XI, Orsay, 1987, p. 540.

[11] UNESCO, Etude des ressources en eau du Sahara Septentrional, Projet ERESS, Nappe du Complexe Termina [Study of water resources in the Northern Sahara, ERESS project, water table of the Complex Terminal], Tech. Rep. 6 (1972) 23–47.

[12] W.M. Edmunds, P. Shand, A.H. Guendouz, A.S. Moulla, A. Mamou, K. Zouari, Recharge characteristics and groundwater quality of the Grand Erg Oriental basin, BGS, London, 1997.

[13] B. Appelgren, International consultant, UNESCO-FAO, Scope of the international workshop on transboundary aquifers in the African region, Proceedings of the International Workshop Tripoli, Libya, 2–4 June, 2002.

[14] A. Guendouz, A.S. Moulla, B. Remini, J.L. Michelot, Hydrochemical and isotopic behaviour of a Saharan phreatic aquifer suffering severe natural and anthropic constraints (case of Oued-Souf region, Algeria), J. Hydrol. 14 (2005) 955–968.

[15] Y. Hamed, L. Dassi, R. Ahmadi, M. Gouasmia, La guerre de l'« or bleu » dans les régions Méditerranéennes (Afrique du Nord), la Tunisie exemple typique [The war of "blue gold" in the mediterranean regions (North Africa), Tunisia typical example], 5th International Conference on Water Resources in Mediterranean Basin, Lille, France, 26–28 May, 2010.

[16] Y. Hamed, R. Hadji, H. Ben Dhia, W. Ali, Groundwater evolution in the CI aquifer of Southern Tunisia and a part of Southern Algeria: Hydrochemical and isotopic indicators, Colloque WATMED 6, Sousse, 10–12 October, 2012.

[17] Y. Hamed, S.A. Al-Gamal, W. Ali, A. Nahid, H. Ben Dhia, Palaeoenvironments of the continental intercalaire fossil from the late cretaceous (Barremian-Albian) in North Africa: a case study of southern Tunisia. Arab J Geosci. (2012). doi: 10.1007/s12517-012-0804-2.

[18] OSS, Système aquifère du Sahara Septentrional. Gestion commune d'un basin transfrontière [Northern Sahara aquifer system. Common management of a transboundary basin], Synthesis Report, Tunis, Tunisia, 2003, pp. 12–19 (in French).

[19] S. Epstein, T.K. Mayeda, Variations of ^{18}O content of waters from natural sources, Geochim. Cosmochim. Acta 4 (1953) 213–224.

[20] M.L. Coleman, T.J. Shepherd, J.J. Durham, J.E. Rouse, G.R. Moore, Reduction of water with zinc for hydrogen isotope analysis, Anal. Chem. 54 (1982) 993–995.

[21] L.L. Thatcher, V.J. Janzer, R.W. Edwards, Methods for determination radioactive substances in water and fluvial sediments, in: Techniques of Water Resources Investigations, U.S. Geological Survey, Washington, 1977, pp. 79–81.

[22] A.M. Piper, A graphic procedure in the geochemical interpretation of water-analyses, Trans. Am. Geophys. Union 25 (1944) 914–923.

[23] S.A. Al-Gamal, An assessment of recharge possibility to North-Western Sahara Aquifer System (NWSAS) using environmental isotopes, J. Hydrol. 398 (2011) 184–190.

[24] A. Mamou, Caracteristiques, evaluation, gestion des ressources en eau du Sud Tunisien (Characterisation, evaluation and management of the water resources of southern Tunisia), PhD thesis, University of Paris South, France, 1990.