Journal of Hydrology 530 (2015) 508–532

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Origin of the groundwater salinity and geochemical processes in detrital and carbonate aquifers: Case of Chougafiya basin (Central Tunisia)

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ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 19 June 2015
Accepted 3 October 2015
Available online 9 October 2015
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Hongtao Wang, Associate Editor

Keywords:
Chougafiya basin
Geochemistry
Isotopes
Groundwater
Mineralization
Recharge

SUMMARY

Comprehensive investigations of groundwaters were performed in the detrital and carbonate aquifers of the Chougafiya basin, central Tunisia. In the present review, hydrochemistry and isotopic tools were combined to get an insight into the processes controlling mineralization, recharge conditions, flow pattern of groundwater and C chemistry in the investigated hydrological system.

Analysis of the dissolved constituents revealed that several processes controlled the observed chemical composition: (i) the dissolution of evaporitic minerals, (ii) cation exchange reactions, (iii) sulfate reduction under anaerobic conditions, (iv) incongruent dissolution of carbonate minerals (calcite, dolomite) coupled with gypsum dissolution and calcite precipitation, and (v) silicates weathering.

Data inferred from ^{18}O and deuterium isotopes in groundwater samples indicated recharge with modern rainfall. Water characterized by lower $\delta^{18}O$ and $\delta^{2}H$ values is interpreted as recharged by non-evaporated rainfall originating from Mediterranean and Atlantic air masses. However, water with relatively enriched $\delta^{18}O$ and $\delta^{2}H$ contents is thought to reflect the occurrence of an evaporation process related to the long term practice of flood irrigation.

The radiogenic (^{3}H) isotope data provided insight into the presence of two recharge periods in the investigated groundwaters. Waters with ^{3}H contents of <1 TU indicated a pre-nuclear recharge. Waters with ^{3}H contents of >1 TU clearly suggested the occurrence of a contemporaneous recharge probably during the last two decades.

Carbon isotopes provided some insights into the timescales of groundwater flow, but mainly revealed that main sources of C are active in the system. These are likely: dissolved biogenic CO_2, carbonate dissolution and incongruent reaction of the carbonate matrix. Mean residence times were determined after correction of the initial activities for dead C from the rock matrix and suggest ages ranging from the present day to the Holocene in both Upper Cretaceous and Mio-pliocene groundwaters.

1. Introduction

Over the past several decades, numerous studies have used a variety of geochemical indicators to assess the origin of saline water within a hydrological system on a local or regional scale (Pascual and Custodio, 1990; Dixon and Chiswell, 1992; Stephen Fisher and Mullican, 1997; Sanchez Martos et al., 1998; Cruz and Silva, 2000; Edmunds et al., 2003; Pulido-Leboeuf et al., 2003; Appelo and Postma, 2005; De Montety et al., 2008; Farid et al., 2013a, 2013b).

Occurring processes depend mainly on context; they are related to: (1) evaporate dissolution (e.g. Sanchez Martos et al., 1998); (2) deep brines or upward leakage from deep saline waters (e.g. Vengosh and Rosenthal, 1994); (3) agriculture return flows (e.g. Stigter et al., 1998); (4) nitrate contamination (e.g. Almasri, 2007); (5) salt water intrusion from Sabkhas (e.g. Farid et al., 2013a, 2013b); (6) fossil sea-water (e.g. Akouvi et al., 2008) or present sea water intrusion (e.g. Gattacceca et al., 2009) and (7) infiltration of polluted saline water (from agricultural or industrial activities) toward the groundwater (e.g. Hem, 1992).

In Chougafiya basin (central Tunisia), like in many other semi arid regions, water resources are limited. Most of the water supply derives from pumped groundwater since no reliable alternative

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http://dx.doi.org/10.1016/j.jhydrol.2015.10.009
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source exists. In this case, available and sustainable groundwater exploitation is becoming increasingly important, specifically where knowledge on groundwater flow conditions, recharge processes, residence time and water quality is limited. Therefore, a better evaluation of groundwater resources in this area is of strategic importance for water resources managers with regard to a continuous decrease in piezometric levels and precipitation amount.

This problem affects mostly surface watercourses regime but also certainly groundwater recharge from the sedimentary zones. Furthermore, these resources are subject to increased exploitation under changing climate conditions and may be stressed in case of improper management. Since the early 1974s, great efforts have been made to thoroughly understand the fresh groundwater resources of the Chougafiya basin and estimate their availability (Amrhein, 1981). A systematic hydrogeochemical investigation has been carried out within a Tunisian–German project in the 1974–1980 periods (Amrhein, 1981) to fully understand the hydrological processes occurring in deep bedrock aquifers. But these investigations failed to focus on saline water and its relation to freshwater. The main concern for a better environment and safer water resources implies changing research priorities by investigating both fresh and saline water in central Tunisia as well as in many parts of the world. In this respect, this study was initiated using stable and radioactive isotopes with an emphasis on chemical characteristics. The aim was to: (1) elucidate the origin and timing of recharge, (2) constrain the relative residence times of the groundwaters and (3) determine the main factors and mechanisms controlling the geochemistry of the groundwaters at a given time.

2. Study area

The Chougafiya endorheic basin is bounded by North–South structural features and the Atlas Mountain reliefs in the western part. The eastern part of the study area is occupied by the endorheic depression of Sabkhas el Batten (Figs. 1 and 2). The combination of relief presence and active tectonic environment makes this zone the host for some productive aquifers.

In the studied basin, the mean annual precipitation is below 350 mm and the mean annual temperature is 19.8 °C. The lowermost temperatures are noted in January (13.6 °C), while the highest are observed in August (33.4 °C). The mean potential evapotranspiration is 1712 mm $year^{-1}$. The semi arid climate of the region is marked by hot dry summer and mild wet winter seasons.

2.1. Geological setting and tectonics

Recently, Anderson (1996), Abbes (2004) and Rigane and Gourmelen (2011) described the regional geology of central Tunisia. In the present part of this work, an account is given essentially on aspects related to hydrogeological interpretation. Geophysical investigations (Borgi and Andrieu, 1979) and boreholes recompleted recently in the region have allowed more details to understand the hydrogeology of the Chougafiya basin.

The studied area is characterized by up-lifts and subsiding blocks. These geological structures have controlled the sedimentary formations which exhibit substantial variability, both in lithology and thickness. The geological succession extends from the Triassic to the Quaternary. Jurassic sediments are not exposed, but are known to exist from exploration drilling. A simplified geology with major structural characteristics is displayed in Fig. 2.

The present architecture of the study area is dominated by the North–South corridor as defined recently by Rigane and Gourmelen (2011). This structure is guided by major inherited structures giving rise to trending faults and folds resulting from early tectonic regimes (Anderson, 1996; Abbes, 2004; Rigane and Gourmelen, 2011). Consequently, the occurrence of several deep faults is a feature of the region. Major fault systems cut across the basin and represent active fault systems (Fig. 2). The principle directions of displacement zones are SW–NE, N–S and NW–SW. Flexure folding and faulting associated with uplift along the margins of the highlands bounding the Chougafiya plain have produced additional discontinuities in the stratigraphy, which significantly affects the hydrogeological environment (Figs. 2–4) (Borgi and Andrieu, 1979; Amrhein, 1981; Anderson, 1996).

2.2. Hydrogeology

According to geological configuration (Fig. 2), the following hydrogeological units have been defined: the Upper Cretaceous, the Paleocene, the Lower Eocene, the Oligocene, the Mio-pliocene and the Quaternary. Due to the complex and heterogeneous geological structure, including fault zones and the irregular morphology of the secondary basement, the mentioned units do not represent continuous aquifers, and local hydraulic connections between water-bearing horizons are not likely to occur (Amrhein, 1981). Fig. 3 summarizes the principal hydrostratigraphic series of the study area.

- The Upper Cretaceous aquifer is represented by "Abiod Formation" dated to the Campanian–Lower Maastrichtian age (Abbes, 2004). Two simplified geological cross sections are shown in Fig. 4. Sedimentary formations are displayed in horst and graben structures affected by N–S striking faults along the edges of the Ruissate Mountain. This structure seems to have controlled the formation of the Upper Cretaceous deposits and plays a major role in the groundwater flow. These carbonate deposits extend along Fej Ruissate (Fig. 4a) and Regoub Dhaouia areas (Fig. 4b) and show a significant lateral variation in facies and thickness. They are composed basically of a fissured chalky micritic limestone sequence intercalated with marly-chalks, marly limestone and gray marls. This formation outcrops in Regoub Dhaouia region and sometimes under a thin cover of Quaternary sediments (Fig. 4b). Accordingly it forms an unconfined aquifer in this area, but it becomes confined in other places by the low permeability of the confining levels related to the Upper Cretaceous (in the eastern and south eastern edges of the Ruissate Mt.) or to the Paleocene Formations (in Fej Ruissate, Bir Fandra and in north western edge of the Ruissate Mt.) (Fig. 4a and b). Despite the higher hydrostatic pressure and the higher yield, the confined sections do not represent a viable aquifer due to high salinity, depth constraints and the presence of hydrogen sulfide (H_2S) in the groundwater.

Seismic profiles and lithostratigraphic correlations (Borgi and Andrieu, 1979; Amrhein, 1981; Farid, 2007) show that the Upper Cretaceous aquifer is affected by major deep faults which are likely to generate some lateral compartmentalization leading to the complexity of groundwater flow and hydraulic continuity. This phenomenon is particularly marked from west to east where units variable thickness and lithological change affect piezometry and, especially, the chemical and isotopic composition of the water (Figs. 1 and 4a and b). This hypothesis will be discussed later using geochemical tools.

Data from RS101 deep borehole (Figs. 1 and 4a) indicate a porosity of about 15–25% (Amrhein, 1981). The transmissivities of these carbonate sequences vary according to the degrees of tectonic fracturing and/or karstification. The depth of this unit is extremely variable ranging from 30 to more than 800 m below surface level and the thickness is about 54–770 m. All boreholes