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Modeling the recharge and the renewal rate based on ^{3}H and ^{14}C isotopes in the coastal aquifer of El Haouaria, Northern Tunisia

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Abstract

Estimation of groundwater recharge in a semi-arid area is difficult due to the low amount and variability of recharge. In the El Haouaria region (N.E. Tunisia), this hydrodynamic survey revealed a decrease in unconfined groundwater reserves of approximately 11% over the last 30 years due to the abstraction of water. Over that same time period, the groundwater table displayed a natural decrease of about 10 m in depth over an area of 230 km^2. Hydrogeological investigations have shown that two aquifers which vertically integrate all of the permeable zones in the region can be distinguished: a shallow aquifer formed by filling the Quaternary and another deeper one in the Pliocene. These two aquifers are separated by a semi-permeable layer through which vertical exchange by seepage is possible. Two analytical models, taking into account the long term decrease of the water table, were used to interpret ^{3}H and ^{14}C content in groundwater. Forty groundwater wells were sampled to obtain additional information on isotopic characteristics of the groundwater defined in previous studies. The median annual renewal rate (recharge as a fraction of saturated aquifer volume) varies between 0.2 and 0.3 %. For representative characteristics of the aquifer (30 m of saturated thickness, porosity 14%) this implies a recharge of 10 to 12 mm/yr. Which is lower than estimates of 18 to 36 mm/y obtained using hydrodynamic methods.

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Keywords: Recharge, radioactive isotopes, modeling, renewal rate, coastal aquifer, Tunisia

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1. Introduction

The El Haouaria aquifer is a relatively small aquifer, located on the Cap Bon peninsula in Tunisia, characterized by a semi-arid climate. Because of the low amount of recharge and variability in recharge conditions, the estimation of groundwater recharge and associated hydrodynamic functioning have been difficult to estimate. This study aims to integrate hydrogeological data with established geochemical tools to estimate the groundwater recharge and renewal rates of the aquifer. This was accomplished using radioactive isotopes tritium and carbon 14.

The El Haouaria plain forms a depression facing east-west bordered by the sea on both sides, with outcrops of the Oum Douil formation in the north and south (Fig.1). El Haouaria groundwater is composed of an overburden of quaternary sediment 50 meters deep and a dunal cap under which rests a large Pliocene deposit 200 meters deep making up the central filling of this depression. According to geological cross sections done on boreholes in the region, the quaternary deposits are made up of intercalations of sandy layers and clay with travertin and tuff locally at the summit. These two aquifer levels are separated by a semi-permeable layer of clay 10 to 15 meters thick which divides the deep aquifer located in the Pliocene deposits from the groundwater table made up of quaternary sediments (Fig.1). Our hydrogeological study showed that communication exists between the groundwater towards the deep aquifer at Dar Chichou and another one in the opposite direction at Gareât El Haouaria (salty lake located in the center of the plain), where the deep aquifer supplies the groundwater.

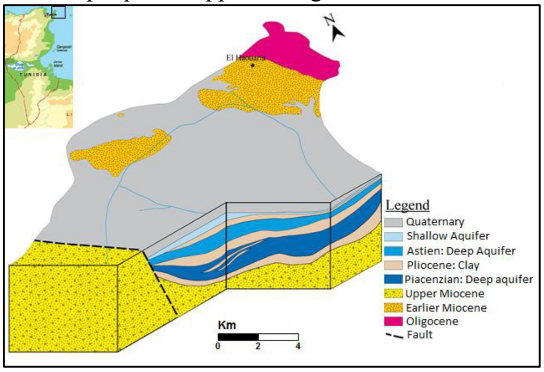

Fig. 1. Location of the study area and Bloc Diagram of El Haouaria region

2. Conceptual model of recharge

The measured activity of ^{14}C, like that of Tritium, could be considered representative of the water's residence time in the aquifer [1]. The conceptual model estimates renewal rates using the definition of recharge processes and aquifer boundaries along with incorporating constraints from hydrodynamic and geochemical approaches [1]. In the El Haouaria plain, groundwater is recharged quickly across the land and provides the aquifer with water which has almost the same isotopic values as the atmosphere. The relatively low depth of the groundwater (30 m on average) suggests that groundwater infiltrates during recharge, which is consistent with the geochemical characteristics, showing a lack of vertical stratification of the aquifer water. Despite obvious simplistic characteristics, a simple model of vertical mixing seems to be the best adapted to estimate the natural rate of groundwater renewal:

$$An_i = (1 - Rr) * An_{i-1} * e^{-ln2/Pe} + Rr * Ap_i$$

Where: An_i = Activity in the aquifer for the year i, Rr = Annual renewal rate, Pe = period of radioisotope (^{14}C or ^{3}H) and Ap_i = activity in the rain for the year i.

The model presumes homogenous isotopic features throughout the depth of the groundwater and constant storage, meaning, the output of water is exactly compensated by the infiltration of rainwater.

Since the climate has not changed significantly in the last 4000 years [1], the equation describing groundwater is considered stable over this period until 1980. After this date, by taking into consideration the piezometric drop in groundwater shown by hydrodynamic analysis [3], the same model can be written for a variation of the water supply:

$$An_i = \left[(1 - Rr) \times An_{i-1} \times e^{-\ln 2/Pe} \times \left(1 - \sum_{n=1}^{i-1} H_n \right) + (Rr \times Ap_i) \right] / \left[1 - \sum_{n=1}^{i-1} H_n \right]$$

Where: H_n represents the relative decrease (a dimensional value) of the groundwater supply in year n, compared to the initial supply of the aquifer in 1972, before the beginning of the long-term piezometric decrease.

2.1. Renewal rate and estimating recharge deduced from tritium levels

The model takes into consideration the radioactive decrease in tritium and represents the annual change in the isotopic composition according to past volume and activity of the aquifer and infiltrated rainwater up to the sampling date of 1960. The annual renewal rate can be calculated for each representative elementary volume presumed homogenous from a few square kilometers above ground to a depth equal to the wet depth of the aquifer. Due to their smallness, whether or not horizontal transfers are taken into account does not significantly change the results (Fig.2a). To reduce the difficulties associated with a selective approach, the aquifer is considered based on its average characteristics in order to calculate the representative recharge rate in the study area. According to the average saturated thickness of the aquifer in 2001 (30 m) and the average (4.7 TU) and median (4.4 TU) values of Tritium, the median groundwater renewal rate is calculated at around 0.2% per year (Fig.2a).
Previous measurements of tritium were taken from the El Haouaria quaternary aquifer. Values varied from 13 to 32 TU [3], their median was 20.5 TU for an average of 21.4 TU and a standard error of 5.6 TU. These results gave a median renewal rate of around 0.3% per year in 1980 (Fig.2a). Determining the renewal rate of the aquifer thus made it possible to calculate the recharge rate from the following equation: R = T x P x Rr [2], Where: T represents Thickness of aquifer in m and P the porosity in %.
Presuming a saturated depth of 30 m for the El Haouaria plain and a possible porosity of 14%, median recharge would be around 12 mm/year.

2.2. Renewal rate and estimating recharge deduced from carbon 14 levels

Previous measurements, from 1982, of ^{14}C in the groundwater (10 in all) showed activity from 72 to 109 pMc [3]. Their median was 95 pMc with an average of 94 pMc and a standard error of 10 pMc. The new recent analyses supplement these measurements. The median ^{14}C activity measured on the El Haouaria plain was 74 pMc with an average of 70 pMc and standard error of 9 pMc.

The renewal rate calculated for 1980 is nearly 0.2%. Focusing the calculations for the new data, the renewal rate is 0.04%, with a median value of activity of 74 p Mc and an average of 73 pMc (Fig.2b). This median value thus leads to an annual recharge of around 3 mm/year, using the same hypotheses for calculating as in the previous paragraph for tritium.

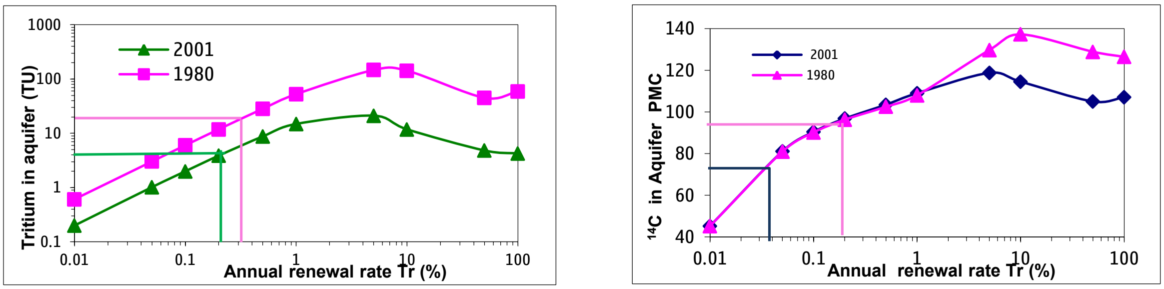

Fig. 2. Estimating renewal rates using tritium (a) and ^{14}C (b)

3. Discussion and conclusion

Despite the relatively high uncertainty for Tritium, the similarity of the results can be considered a reciprocal

validation of these two radioisotopes, which are very different in both nature and half-life.
The differences between the results obtained for the calculation of the renewal rate from the model using tritium (Rr varies between 0.2 and 0.3 mm/year) and ^{14}C (Rr varies between 0.04 and 0.2%) can be explained by the following:

1. Groundwater use in 1980 was not significant; therefore, was nearly equal to recharge in terms of volume. Currently, the abstraction has greatly expanded with irrigation becoming more frequent. Both of these factors encourage the mixing of old and new water through upward seepage following demand for deep water. The mixed water could come from returned irrigation water. These two factors explain the difference between the results in calculations of renewal rates from ^{14}C between 1980 (Tr=0.2%) and 2001 (Tr=0.04%).
2. A low ratio of old water, which is rich in dissolved inorganic carbon, compared to new water predominantly influences the final concentration of ^{14}C in the mixture. This hypothesis is confirmed since a comparison of the calcium concentrations in the aquifer water in 1980 and 2001 showed a significant increase of Ca^{2+} levels over time. This increase in calcium could indicate a growing fraction of water oversaturated in calcium carbonate minerals due to higher residence time in the aquifer.
3. For tritium, which is an intrinsic tracer for water molecules, its concentration depends solely on the ratio of volumes of water making up the mixture. Use of this radioisotope to determine renewal time is thus more reliable with respect to ^{14}C. The 11% piezometric decrease of the El Haouaria aquifer since 1972 has not led to a change in the calculated renewal rate. In fact, the results obtained by the second model which uses water supply variation (piezometric decrease) in equation (2) did not provide any notable difference compared to the results obtained without a decrease by using equation (1). For the El Haouaria above ground aquifer, calculating the renewal rate from the ^{3}H model before the groundwater level started to decrease shows a probable range of 0.2 to 0.3%. In terms of water residence time in the aquifer, these values are equal to average flow-through times between 300 and 500 years. This is consistent with stable isotopes which indicate a mixture of recent water and water that is older than 4000 years BP. An attempt was also made to quantify the recharge of this region using other approaches. Piezometric observations made for the last 30 years or so in the Cap Bon show that the quaternary groundwater in El Haouaria aquifer has decreased (11%) but that this decrease is not generalized to all of the water wells. The quantification of the Cap Bon recharge was estimated at 36 mm/year by the water balance method [4], 32 mm/year by Jemai, [5], 18 mm/year by Paniconi [6] and 10 to 12 mm/year by the isotopic method. The recharge figures are less than those of 32 to 36 mm/year estimated by the water balance. The difference between the first method of estimating the annual recharge and the other methods could be primarily explained by the difference in the temporal observation scale: the water balance is strictly annual. Piezometric movement is the result of annual fluctuation and medium-term change. The isotopes are the result of a mixture occurring over several decades during which increased use, periods of drought and damage to vegetation cover greatly perturbed the balance of resources in underground water. However, the results are quite consistent. The conceptual model using radioactive isotopes (^{3}H and ^{14}C) are interpreted in terms of renewal rate; the median was 0.2 to 0.3 %, respectively, which means a recharge of about 12 mm/yr, which is consistent with other methods of estimating recharge.

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