Impact of changing climate in the Kairouan Hydrological basin (central Tunisia)

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Abstract: The Merguellil catchment (central Tunisia) has undergone rapid hydrological changes over the last decades. The most visible signs are a marked decrease in surface runoff in the upstream catchment and a complete change in the recharge processes of the Kairouan aquifer downstream. Fluctuations in rainfall have had a real but limited hydrological impact. Much more important are the consequences of human activities such as soil and water conservation works, small and large dams, pumping for irrigation. Several independent approaches were implemented: hydrodynamics, thermal surveys, geochemistry including isotopes. They helped to identify the different terms of the regional water balance and to characterize their changes over time.

Key words: Climate Change; Hydrodynamics; Tunisia.

1. Introduction

All around the Mediterranean Sea, the semi-arid climate and the fragmented environment (geology, topography, etc) has led to high spatial and temporal variability of the different components of the water budget. Major fluctuations in hydrology are consequently observed from one year to the other but serious long-term changes are also the consequence of human modifications of the environment. The different studies that have been performed in the Mediterranean region produced a wide range of results in all compartments of the water cycle.
Tunisia provides many interesting examples of rapid hydrological changes. In Tunisia, the limited water resource is considerably exploited and shared between agriculture (82 %), human consumption, tourism and industry but the multiplication of population by 2.5 in the last 40 years and the extension of irrigation have led to numerous local and regional conflicts. This study profited from the long-term hydrological survey conducted in central Tunisia, near the city of Kairouan, where one of the greatest aquifers in the country has been studied for four decades e.g. Besbes (1978); Ben Ammar (2006, 2007). The present study was based on cross-checking of hydrodynamical and geochemical approaches and identified the drastic changes that have occurred in processes and in flows. The wide range of forms of these modifications may provide a useful framework for extrapolating or comparing with other Mediterranean regions where the causes and processes of changes are identical but observations rarer.

2. Study area

Wadi Merguellil is one of the three main temporary rivers reaching the Kairouan plain (Fig. 1). The Merguellil upstream catchment (1200 km^2) is defined by the big El Haouareb dam built in 1989 over a rocky sill. It presents a hilly topography (altitude between 200 and 1200 m with a median elevation of 500 m) and has diversified conditions of geology, morphology, vegetation and land-use. The Merguellil downstream catchment is part of the very large and flat Kairouan alluvial plain that extends over about 3000 km^2. Our research in the downstream part covered an area of 300 km^2 close to the dam, west of the city of Kairouan.
Three small connected aquifers (Aïn el Beidha, Bou Hafna, Haffouz-Cherichira) are located in the lower part of the Merguellil upstream catchment. Depending on the place and time, they interact with the drainage network in both directions. The Kairouan plain aquifer (Fig. 2) represents much greater water storage capacity because of its horizontal extent and its thickness (up to 800 m of alluvium and colluvium). It was mainly fed by the infiltration of floods. Water table levels are regularly measured in more than one hundred piezometers.

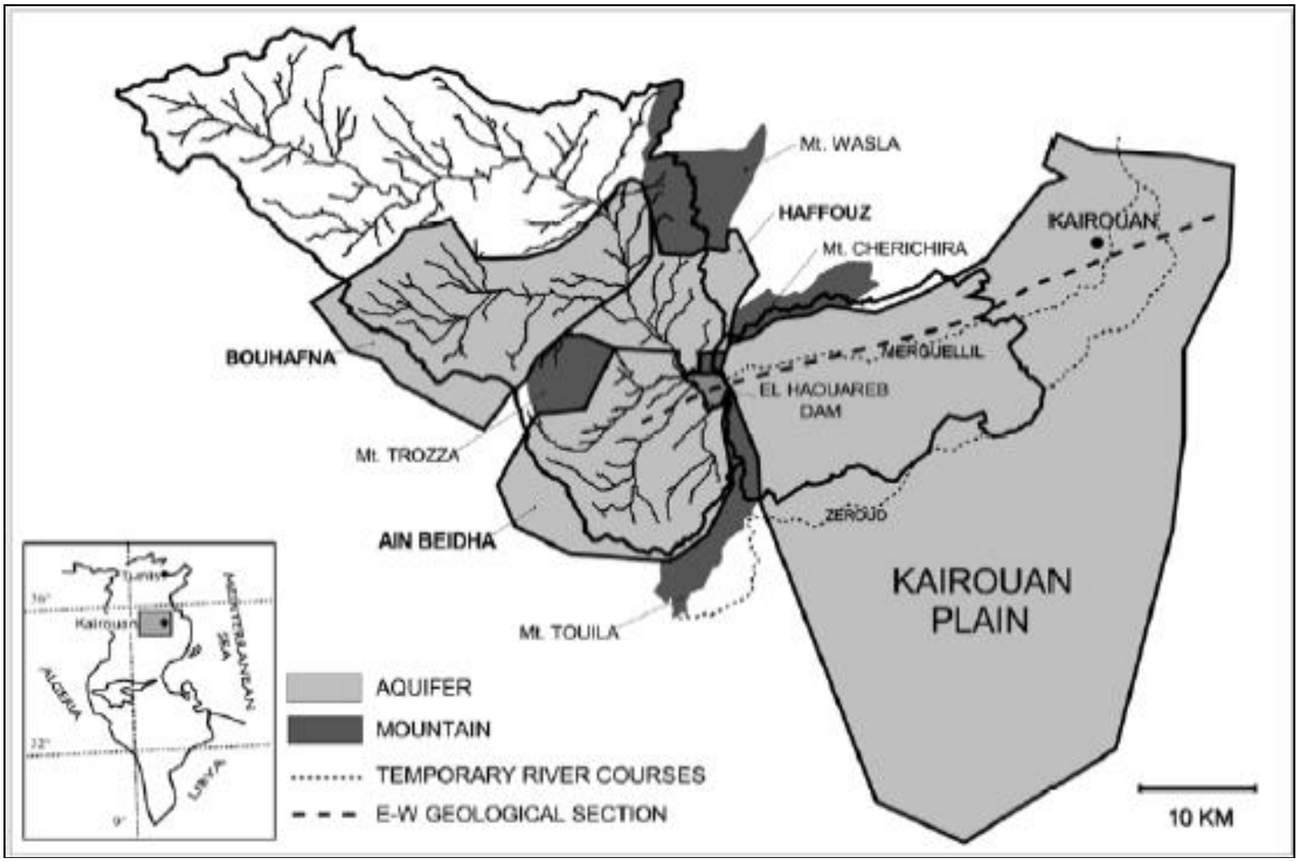

Fig. 1 Location of the study area, limits of the upstream and downstream sub catchments and limits of the different aquifers

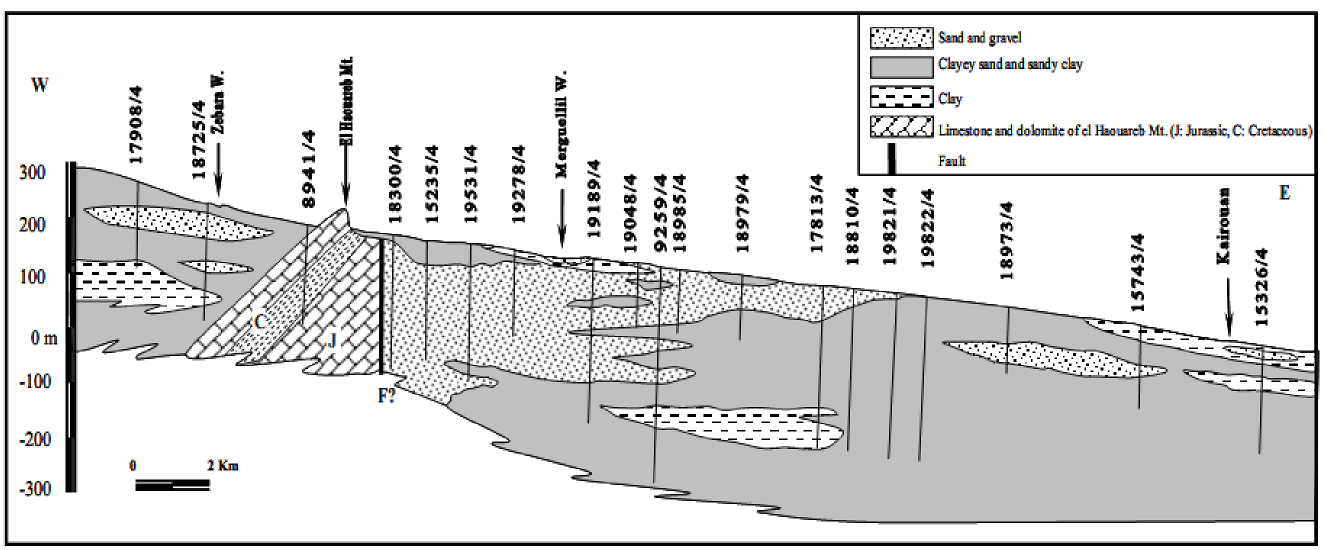

Fig. 2 W–E geological cross-section along Wadi Merguellil: the Tertiary and Quaternary Ain el Beidha aquifer to the west; the Mesozoic karst of Jebel el Haouareb; the thick Quaternary aquifer of the Kairouan plain to the east (whole thickness not represented).

2.1 El Haouareb dam

The El Haouareb dam was built to protect the city of Kairouan against floods. Before then, the infiltration of the Merguellil floods in the river bed was the most important recharge of the Kairouan plain aquifer. For instance, in

1969, the rise in the water-table induced by the catastrophic floods was higher than 10 m on the Merguellil side. Since 1989, the surface runoff of the Merguellil upstream catchment has been stopped by the dam. This water is now shared between infiltration through karstic fissures (the most important term), evaporation, pumpings and releases. Water infiltrating beneath the El Haouareb reservoir joins the groundwater flow from the Ain el Beidha Tertiary-Quaternary aquifer, goes through the karstic Mesozoic limestone of the El Haouareb sill and recharges the alluvial Plio-Quaternary aquifer of the Kairouan plain. There is no surface runoff downstream from the dam, except the very exceptional dam releases (less than 6 % of the water stored by the dam, which is 304x106 m^3 in 16 years). The reservoir dried up completely in 1994, 2000, 2001, 2002 and 2004.

2.2 Water consumption

Because of its limited and unreliable spatial and temporal availability, surface water is of limited interest for regional development. When it exists, a small proportion of water in the El Haouareb dam reservoir is pumped to a nearby large irrigation scheme (between 1 and 6 Mm^3 per year). In some small dam reservoirs of the upstream catchment, water is also pumped by 270 farmers but this represents a very limited consumption (an average of 10,000 m^3 per year per reservoir). In fact, most water is taken from the upstream and downstream aquifers. Groundwater is pumped for irrigation and to supply drinking water to the Kairouan region but also to the Mediterranean coast where water needs exceed local resources. During the last 10 years, the irrigated area increased about 10 % in the upstream catchment, and now covers 3500 ha (out of which 670 ha are fed by small reservoirs). In the same period, the irrigated area in the plain increased from 3000 to 8800 ha. As a consequence, the number of boreholes in the thick alluvial Kairouan aquifer has increased continually in spite of the legal prohibition. Most of the boreholes are for private farms while a few others with a high pumping rate are for public irrigation schemes or drinking water supplies.

3. Impact of changes in the Kairouan plain aquifer

In the downstream part of the Merguellil catchment, the overexploitation of the Kairouan plain aquifer has led to a general drop of the water-table. This could induce long-term changes in water quality by pumping older waters from deeper layers or reversing the gradient with the salt lake area downstream Kairouan that is the natural outlet for the regional flow. But in fact the construction of the big El Haouareb dam is by far the most important factor to be discussed, because of its many consequences upstream and downstream from the dam.

3.1 Hydrodynamics

Because of the semi-arid climate and the depth of the unsaturated zone, under natural conditions, the direct infiltration of rainfall over the plain was not able to reach the Plio-Quaternary aquifer in significant amounts. Even now, we were unable to find any traces of a possible return of irrigation water to the plain groundwater.

Natural recharge of the Kairouan aquifer was indirect and resulted from infiltration of Merguellil floods. Very exceptional events, like the one in 1969, extended over the whole plain and induced remarkable rises in the water table Besbes and all (1978). Other floods concerned only a limited width and a variable length of the river bed depending on the strength of the flood, and groundwater recharge occurred discontinuously in the most pervious parts of the bed. Figure 3 shows the 8 m rise in the piezometer M7 in 1969 and much smaller rises in 1973 and 1974. This natural process still occurs when reservoir water is released, which is very rare and amounted to only 13 × 106 m^3 in the last 17 years.

The construction of the El Haouareb dam stopped the natural recharge process and the Plio-Quaternary aquifer is now essentially fed by groundwater flow from the upstream catchment through the El Haouareb karst sill. The creation of an artificial hydraulic boundary limit (the reservoir) at a much higher elevation than the previous river elevation led to a new geographical pattern of recharge where infiltration is limited to the area close to the dam, over its whole aquifer width but with no extent downstream. Head changes in the reservoir are transferred through the karst and progressively disappear into the plain aquifer. In the two years following completion of the dam, the water table showed a continuous rise, up to 7 m close to the dam which could still be identified at a distance of 6 km downstream. In piezometer M7, this impact was of 4 m, i.e. half of the 1969 flood; in piezometer M14, 27 km downstream from the dam, the impact of the construction of the dam was no longer visible (Fig. 3).

Because of the karstic nature of the El Haouareb sill, one would expect groundwater transfers from upstream to downstream to be rapid. In fact, the delay between a flood in the reservoir and the increase in flow of the karstic springs at the foot of the dam is very variable and can be longer than two weeks. Piezometers at the foot of the dam also show a gradual advance of the pressure transfer from the south to the north. The El Haouareb karst reacts quickly when the level in the dam is high and much more slowly when the reservoir is low or dried up.

Considering the infiltrated volume between November 2004, when the dam and the karst were empty, and the end of March 2005, when the karst was again fully saturated, we estimated the variation in water storage in the karst at about 4.6 Mm^3. This figure does not represent total storage in the karstic mass but only the maximum variation affecting the upper part of the karst under the influence of climatic fluctuations.

Several numerical models of the Kairouan plain aquifer have been built for recent decades, all based on the same main assumptions Besbes and all. (1978), Nazoumou and all. (2001). These models could be significantly improved in two ways: by taking into account more realistic values of pumping rates (official figures that were used are significantly lower than the results of field surveys among farmers); by mixing hydrodynamic and geochemical information for a better estimate of groundwater inflows to the plain aquifer. The El Haouareb karst system has not yet been modelled.

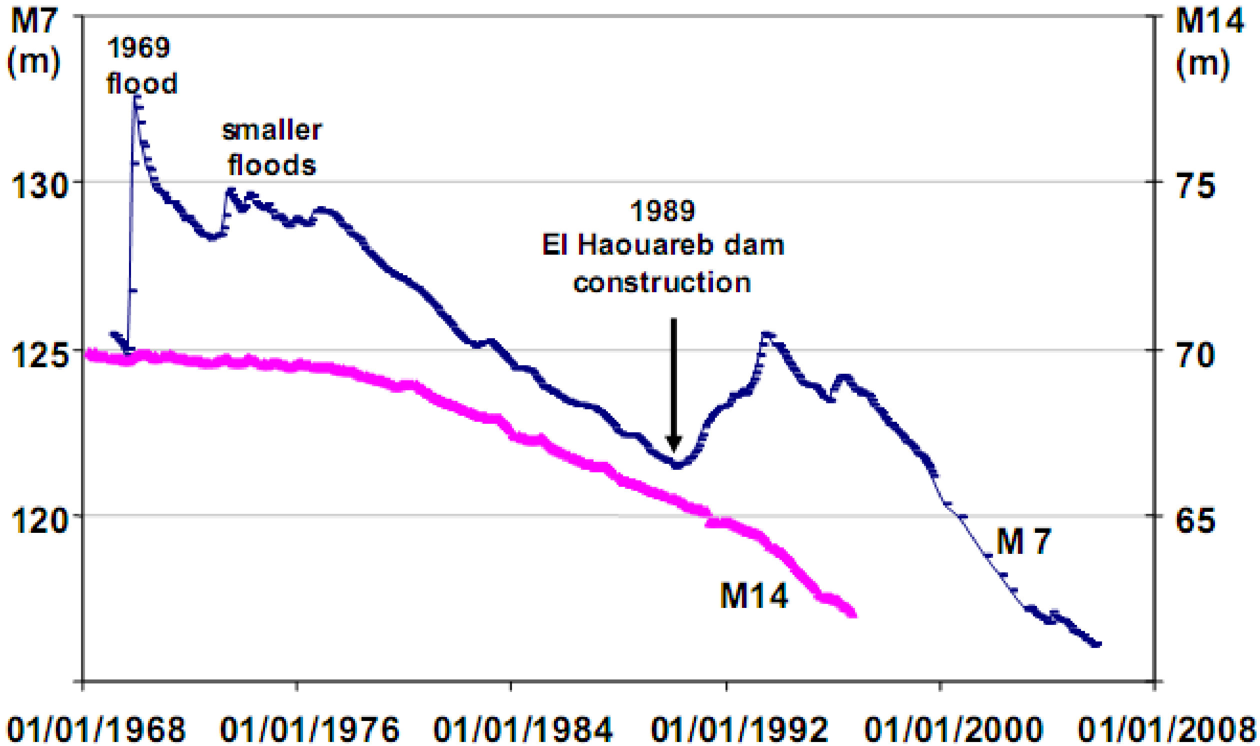

Fig. 3 Changes in the level of the water table of the Kairouan plain in recent decades: upstream (M7) recorded the main regional events while downstream (M14) seems to be only affected by pumping for irrigation (location of M7 and M14 is given in Fig.4).

3.2 Geochemistry

In the natural state, floods recharging the Kairouan aquifer were generated by rain falling in the upstream catchment and quickly transferred to the plain. Infiltration through the river bed was also a rather rapid process and did not significantly affect the geochemical signature of the river water before it joined the groundwater. In most cases, the electrical conductivity of the plain groundwater is between 2000 and 3000 $\mu S.cm^{-1}$ (Fig. 4). Dominant ions are Ca^{2+}, Mg^{2+} and $SO4^{2-}$ as in the Wadi Merguellil water. The small dams in the upstream catchment and the El Haouareb dam increase the salinity of the surface water: the stored water evaporates and exchanges with the reservoir bed material occur over periods of weeks or months. In the El Haouareb dam, extreme values measured in 2005 and 2006 were 1500 and 2500 µS.cm-1 (this was the first regular survey) and the range of variation is much higher in small dams where loss due to evaporation may be higher Grünberger and all. (2004).

Electrical conductivity measurments were used to evaluate the mixing ratio of water coming from the dam or from the Aïn el Beidha aquifer when they gather and recharge the Kairouan plain aquifer. Calculations for autumn and winter 2004, just after complete drying up of the dam reservoir, estimated their respective contributions at 60 % and 40 %. This rough calculation will be repeated with similar more recent episodes.

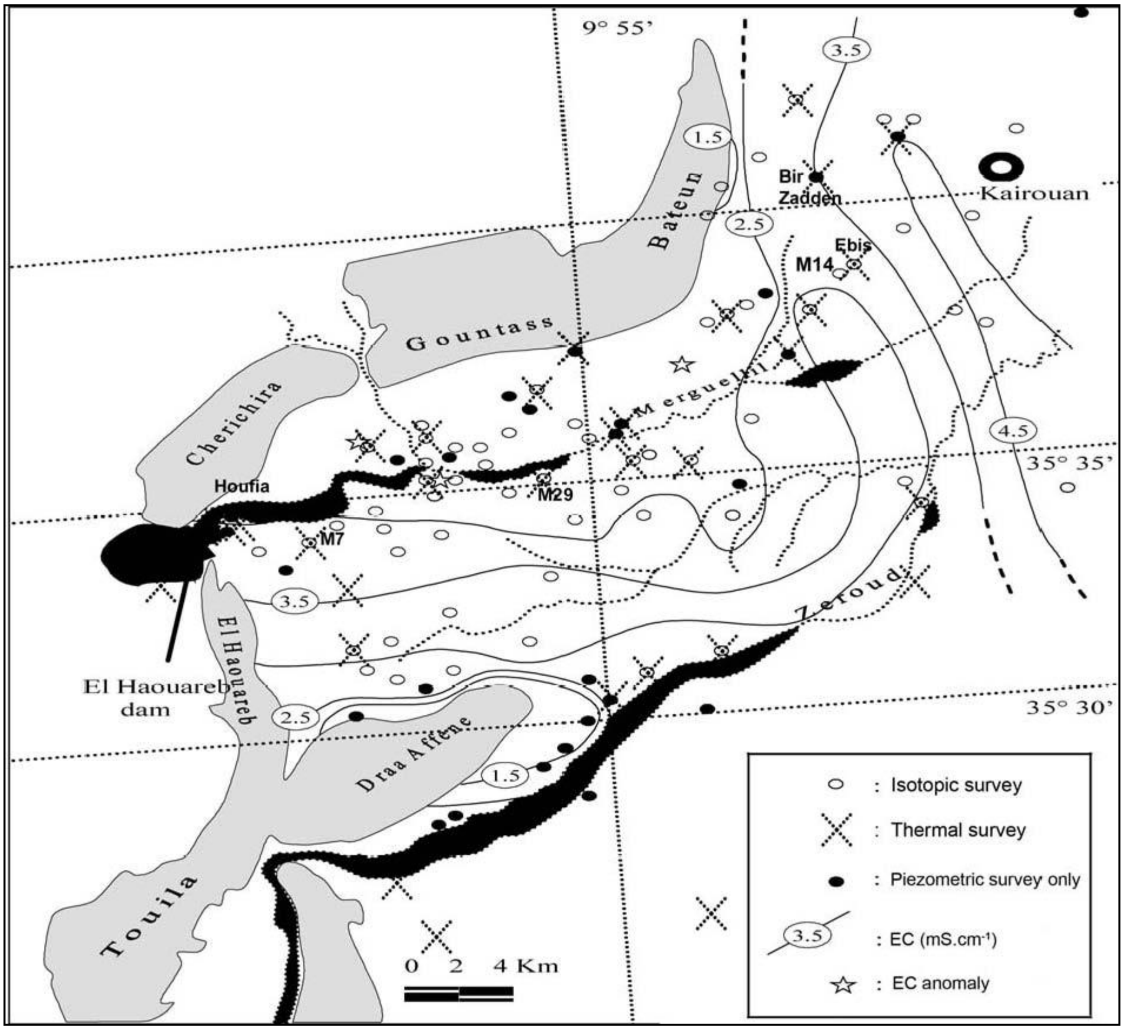

Fig. 4: Wells of the Kairouan plain aquifer surveyed for piezometry, geochemistry and thermics. Isolines of electrical conductivity (EC). river courses indicated by dotted lines, with areas usually covered by floods (before 1989) in black.

Isotopic studies, firstly undertaken by Ben Ammar and all (2006) and still ongoing, provide an efficient tool for estimating the origins and proportions of groundwaters. The mean value of $\delta^{18}O$ in rainfall is between -5.0 and -5.5 ‰ vs VSMOW. Values are of the same order in the Aïn el Beidha aquifer that extends close and beneath the El Haouareb reservoir Fig. 5. Identical values are also observed in the Kairouan plain aquifer far from the dam. Observed ^{18}O values in the El Haouareb dam varied between -6.54 and +7.41 ‰ vs VSMOW. The mixing of the evaporated dam water with the Aïn el Beidha unchanged water and the groundwater infiltrated in the Kairouan aquifer before 1989 is visible in the first seven kilometres downstream from the dam, with a proportion of recent evaporated water inversely proportional to the distance from the dam Ben Ammar (2007).

Ben Ammar and all (2006) obtained a variable contribution (of between 21 and 66%, 50% on average) of the reservoir water to the plain recharge, depending on both sampling dates and tracers (^{2}H, ^{3}H, ^{18}O), Ben Ammar et al. (2006) obtained a variable contribution (of between 21 and 66 %, 50 % on average) of the dam water to the plain recharge, the rest being supplied by the Aïn el Beidha aquifer. This calculation was adjusted with more recent data provided by our ongoing survey. Particular attention was paid to extreme events in the El Haouareb lake such as its complete drying up in 2002 and 2004 and the highest level ever observed in 2006. A calculation based on ^{18}O and ^{2}H contents for autumn 2005 gave a mixture of 35 % of the Ain el Beidha groundwater and 65 % of the dam water, which is in good agreement with results from other methods or periods.

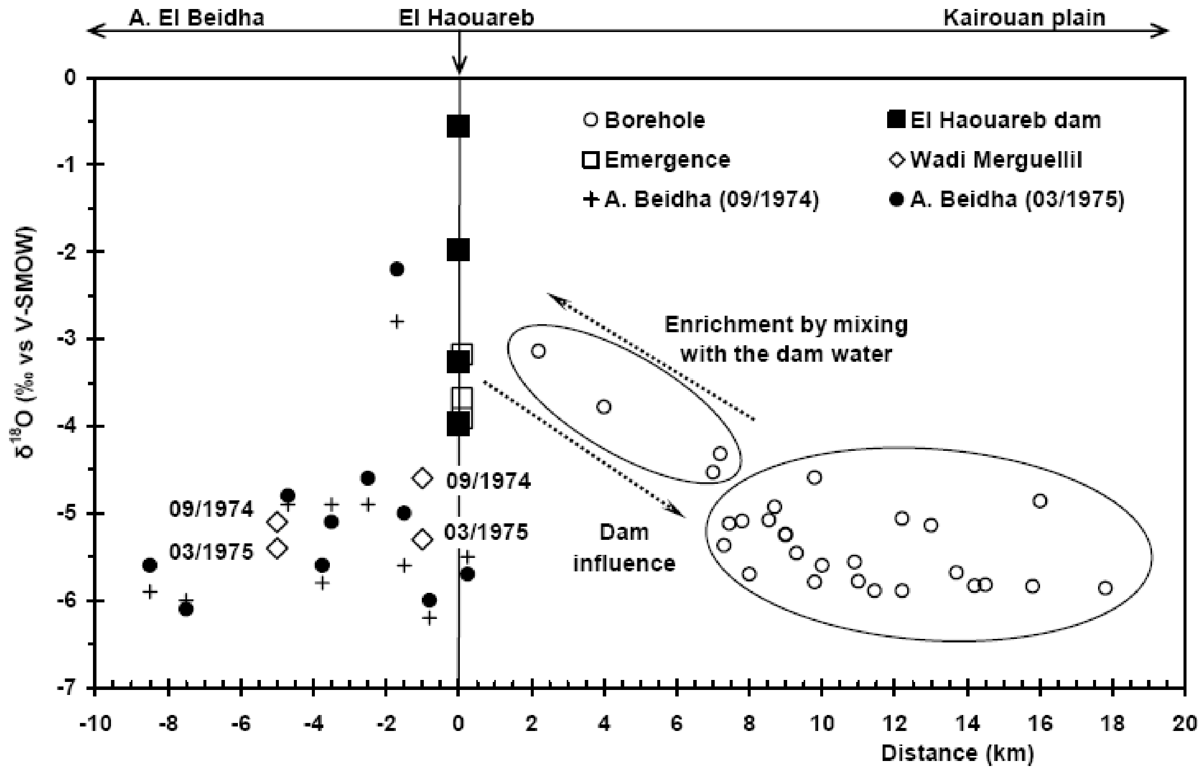

Fig. 5: Isotopic content ($\delta^{18}O$) of groundwater before (left, Aïn el Beidha aquifer), in (Km 0) and after (right, Kairouan plain aquifer) the El Haouareb karstic sill

3.3 Thermal dynamics

Thermal profiles in 30 piezometers screened at different depths for the first 150 m of aquifer were performed in 2006, using a SEBA temperature recorder with an accuracy of 0.05 °C. Thermal gradients were mostly positive with increasing depths (Fig. 6"type 3"), with an average value of +0.018°C.m^{-1}. This is lower than the local geothermal gradient (+0.029 °C.m^{-1}) calculated from measurements in three oil boreholes located in the plain [6] and values of the regional heat flux Bouri and all. (1998) and thermal conductivity of the Kairouan plain sediments. This low gradient could attest to the infiltration in the plain of the most recent Merguellil floods, obviously before 1989. The interpretation of thermal gradients in terms of groundwater flows (Reiter, 2001) revealed a marked heterogeneity in flow velocities, which can be linked to the horizontal and vertical variability of sedimentary facies and the uneven infiltration capacity of the river beds. Some profiles were more unexpected, with decreasing temperature with depth (Fig.6 "type 1") attesting to an upwards flux of fresh water. Because fresher waters are generally observed in the upstream part of the plain aquifer and near the bordering relief where recharge occurs, the inverse gradient close to the dam is a sign of the rapid transit of recently infiltrated water from the dam lake through the karst to the plain aquifer. The thermal information is in accordance with independent chemical and isotopic data.

This new type of investigation revealed the heterogeneity of groundwater flow in the plain aquifer that could not be seen with the usual hydrodynamical analysis. It confirmed that the groundwater flow through the karst occurs at different speeds depending on location and is linked with differences in limestone fracturing.

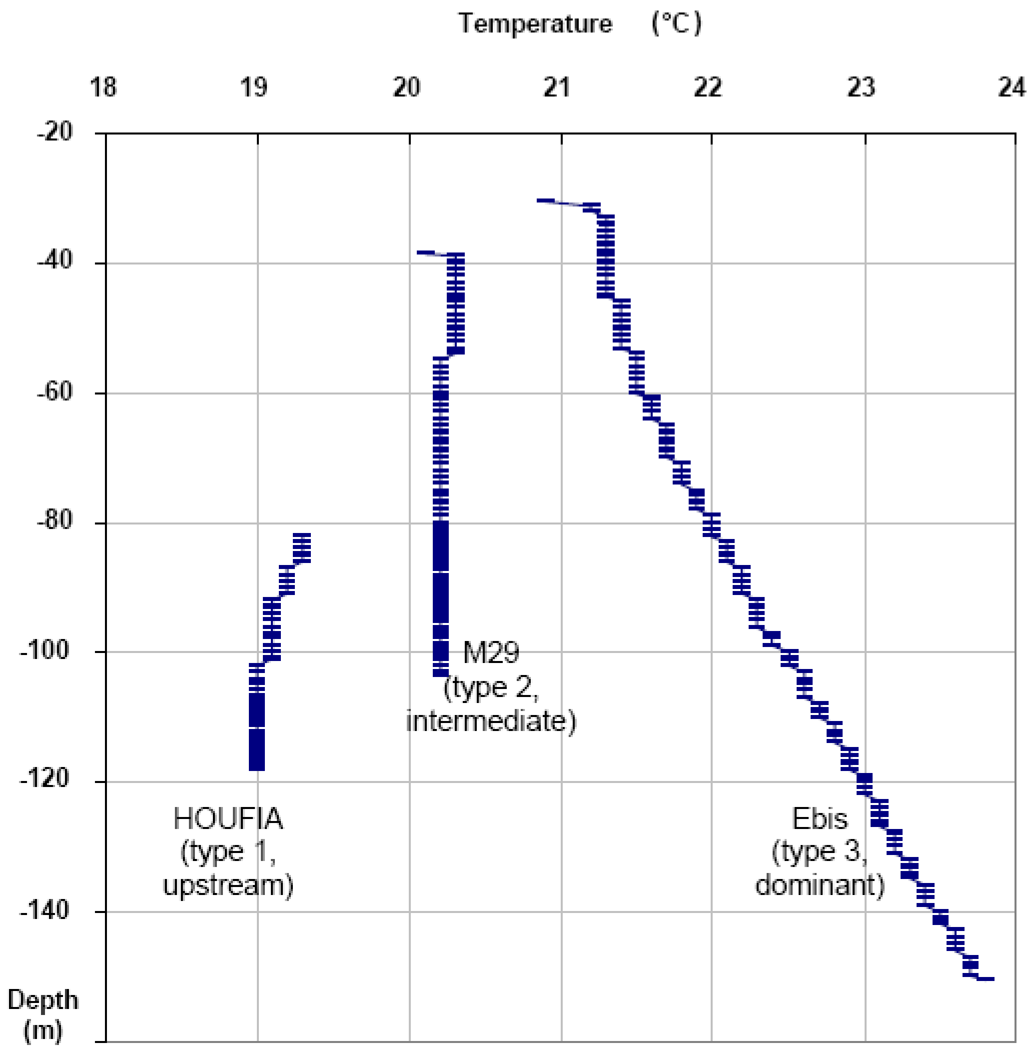

Fig. 6: Thermal gradients measured in piezometers in the Kairouan plain. Most of the profiles show increasing temperature with depth (type 3).

4 Conclusions

The Kairouan aquifer, by far the largest regional resource, is not managed at present. The official ban on wells deeper than 50 m is rarely respected and groundwater is in fact a free-access resource. For social and political reasons, authorities do not want to increase measures limiting overexploitation. The present development of irrigated agriculture is unsustainable. As technical solutions will not be sufficient to really solve the problem, other approaches need to be developed that include social and economic factors. This could be achieved through negotiations between stakeholders at local and regional levels in order to combine better general welfare (including equity between upstream and downstream inhabitants), increased efficiency of water use, and preservation of natural resources. A sense of common interest will need to be developed between the different parts of the catchment, and between farmers and other protagonists; in other words, it is a long-term task.

All the problems described in this study (uneven distribution of water resources in a semi-arid region, methodological problems in the acquisition and interpretation of data, diverging interests between communities at various scales leading to general overexploitation, etc.) are typical of the Mediterranean context. The Merguellil catchment is thus representative of a regional situation. Among many other similar cases in Algeria, we could cite the Mitidja plain or the Ghriss plain, close to Oran, reported by Bekkoussa and all. (2007). In Morocco, the aquifer of the Haouz plain near Marrakech studied by Abourida and all. (2003) has experienced both a decrease in the water-table (up to 12 m in 6 years) because of pumpings and an increase in other areas (up to 15 m in 10 years) because of the return of irrigation water, brought in excess by large channels from

remote mountain rivers. As in the Merguellil catchment, the conjunction of different approaches significantly improved the estimation of the regional water budget that has been drastically changed by human activities.
In all cases, many drastic modifications have occurred. The changes in the last decades, which involve a combination of human activities and environmental responses, affect both internal and boundary conditions over a large range of time scales. The construction of management models is therefore risky when information is not available at sufficient density.

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