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title: **Hydrological changes in the Mediterranean zone: impacts of environmental modifications (changing climate) in the Merguellil catchment (central Tunisia)**

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INTRODUCTION

All around the Mediterranean Sea, the semi-arid climate and the fragmented environment (geology, topography, etc.) have led to high spatial and temporal variability in the different components of the water budget. Major fluctuations in hydrology are consequently observed from one year to another, but serious long-term changes are also the consequence of human modifications of the environment. The different studies performed in the Mediterranean region have produced a wide range of results in all aspects of the water cycle.

Tunisia provides many interesting examples of rapid hydrological changes. Its limited water resources are considerably exploited and shared between agriculture (82%), human consumption, tourism and industry, but the population rise—by a factor of 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 et al., 1978; Ben Ammar et al., 2006). The present study was based on cross-checking of hydrodynamic 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.

STUDY AREA

Wadi Merguellil is one of the three main temporary rivers reaching the Kairouan plain (Fig. 1).

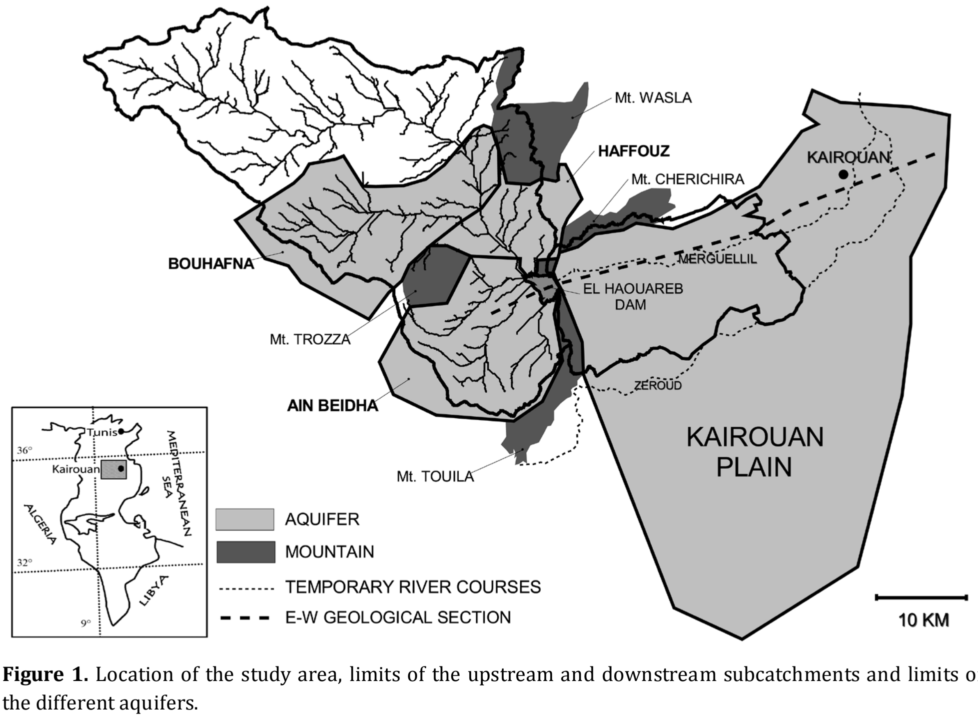

Figure 1. Location of the study area, limits of the upstream and downstream subcatchments and limits of the different aquifers.

The Merguellil upstream catchment (1200 km^2) is defined by the 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 (springs flowing into the river beds, floods recharging alluvium and linked aquifers). The Kairouan plain aquifer represents a 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. Completing the regular hydrodynamic survey started 40 years ago by the Tunisian Ministry of Agriculture, different cooperating institutes (e.g. IAEA, IRD, Universities of Sfax, Tunisia, and Paris XI, France) recently performed many physical and chemical field measurements (electrical conductivity, temperature, pH, alkalinity) and geochemical and isotopic analyses (major ions, ^{2}H, ^{3}H, ^{13}C, ^{14}C, ^{15}N, ^{18}O) in rivers and aquifers throughout the catchment.

CHANGE PROCESSES AT WORK

Climate variability

Previous studies in Tunisia showed that there is no statistical break in the long-term rainfall series of the 20th century (Sakiss et al., 1994). This was confirmed by Kingumbi et al. (2005), who analysed rainfall data in Tunis since 1901: the only break that appeared for six out of the 15 variables was in different years between 1948 and 1952. In Gafsa, located southeast of the Kairouan region, Kingumbi et al. (2005) did not find any break after 1961. However, within this long term steadiness, the high variability typical of the Mediterranean precipitation can be observed.

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, pumping 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 was 304×10^6 m^3 in 16 years).

The reservoir dried up completely in 1994, 2000, 2001, 2002 and 2004. Infiltration to underlying aquifers was estimated from the daily measurements of the reservoir water level through an iterative calculation calibrated in depletion periods. Evaporation and rainfall were measured at the site of the dam. But the main cause of uncertainty in estimating water volumes is the silting up of the dam, which represented 20.5 × 10^6 m^3 over 17 years. A few very violent floods contribute most of the sediments and can abruptly change the relationship between the level, area and volume of the lake. In February 2006, we updated the reservoir budget since construction of the dam. Water stored in the reservoir comes from the Merguellil inflow (90%) and from the rain falling on the lake (10%). It is shared between infiltration (52%), evaporation (30%), pumping (12%) and dam releases (6%). The uncertainty of the total budget of the reservoir water is estimated at about 5%.

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 Reservoir is pumped to a nearby large irrigation scheme (between 1 and 6 × 10^6 m^3 per year). In some small 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 demand for water exceed local resources. During the last 10 years, the irrigated area increased by about 10% in the upstream catchment, and now covers 3500 ha (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. Official figures for agricultural water demand are significantly underestimated compared with the results of our detailed local field investigations. Overexploitation of the aquifer is reflected in the drop in the water table: between 0.25 and 1.0 m per year for the last two decades, depending on local values of pumping intensity and hydrodynamic characteristics. The Bou Hafna Oligocene aquifer in the upstream catchment is also overexploited (with a resulting drop in the water table of up to 30 m in 30 years).

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 of 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.

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 water volumes. Even now, we were unable to find any traces of a possible return of irrigation water to the plain groundwater (a more detailed study based on 15N content is in progress). If it exists at all, this phenomenon is probably slight.

Natural recharge of the Kairouan aquifer was indirect and resulted from infiltration of Merguellil floods. Very exceptional events, such as the one in 1969, extended over the whole plain and induced remarkable rises in the water table (Besbes et al., 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 4 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 13×10^6 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.

Decreases in the plain water table may result from the natural return to equilibrium (after exceptional events such as that of 1969), drawdown induced by pumping, or even a long-term change caused by the new recharge process (in place and flow). The last two causes cannot easily be differentiated because they interfere in the same direction: a wet year brings more water to the reservoir and requires less irrigation water for the same crop. Piezometers located farthest from the El Haouareb Dam are obviously less sensitive to hydrological events happening in, or close to, the reservoir, and their temporal change is more easily linked solely with the exploitation of the aquifer. The comparison of present levels with much older observations made by Stépanoff (1935) showed an identical depth of the water table in the 1930s and in the 1970s. The depletion of the plain aquifer caused by the development of irrigation first became visible in the 1980s.

Considering the first ten years after completion of the dam, Kingumbi et al. (2004) proposed a mean annual budget comprising 14×10^6 m^3 of surface water infiltrating under the dam with 5×10^6 m^3 of groundwater from the Aïn el Beidha aquifer.

According to these authors, this mixture flows directly into the plain aquifer (9×10^6 m^3) or goes out through karstic springs (10×10^6 m^3), of which most again infiltrates and joins the groundwater flow recharging the plain aquifer. Our own calculation of infiltration under the dam resulted in an average of 11×10^6 m^3 for the first ten years, and 9.5×10^6 m^3 for the whole period 1989–2005. The discrepancy between the previous and our estimate is linked with the uncertainty in calculations, especially evaporation uptake, as well as the link between the level of the lake and recharge intensity.

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