Impacts of hydrological changes in the Mediterranean zone: environmental modifications and rural development in the Merguellil catchment, central Tunisia

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Abstract The Merguellil catchment (central Tunisia), which is typical of the Mediterranean situation, 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 limited hydrological impact. Much more important have been the consequences of human activities, such as soil and water conservation works, small and large dams, and pumping for irrigation. Several independent investigations of the catchment were implemented, based on hydrodynamics, thermal surveys, and geochemistry including isotopes. These helped to identify the different terms of the regional water balance and to characterize their changes over time. However, major uncertainties remain and our results may contradict previous interpretations or calculations. Conservation works, now covering more than a quarter of the upstream catchment, drastically reduce the runoff production from rain events of less than 40 mm. Wadi Merguellil now ends in the big El Haouareb Reservoir, which loses more than half of its water by infiltration through karstic fissures and 30% by evaporation, the rest being pumped or released. El Haouareb Dam was built in 1989 and the reservoir has often dried up in the last decade. The major modifications in groundwater flow resulting from construction of the dam are observed in the geochemical tracers in the first seven kilometres downstream from it. Temperature measurements confirmed the recent invasion of new water. The rest of the Kairouan plain aquifer retains the signature of older recharge, but the whole aquifer is affected by the decrease in the water table (about 1 m per year), the consequence of the ever increasing pumping for irrigation.

Key words anthropogenic change; geochemistry; hydrodynamics; Tunisia; water balance

Un exemple d'évolution hydrologique en Méditerranée: impacts des modifications environnementales et du développement agricole dans le bassin-versant du Merguellil (Tunisie centrale)

Résumé Caractéristique de la situation méditerranéenne, le bassin-versant du Merguellil en Tunisie centrale a connu au cours des dernières décennies des changements rapides de son fonctionnement hydrologique. Les signes les plus visibles sont une forte baisse des écoulements de surface dans le bassin amont et un bouleversement des processus de recharge de la nappe de la plaine de Kairouan à l'aval. Les fluctuations de la pluviométrie ont eu un impact réel mais limité. Bien plus importantes sont les conséquences des activités humaines comme les travaux de conservation des eaux et des sols, les petits et grands barrages ou les pompages pour l'irrigation. Plusieurs approches indépendantes ont été développées: étude hydrodynamique, suivi thermique, géochimie classique et isotopique. Elles ont permis de préciser les différents termes du bilan hydrique régional et de caractériser leurs évolutions temporelles. Il reste cependant de fortes incertitudes et nos résultats peuvent contredire des interpréta-tions ou calculs antérieurs. Les travaux anti-érosifs, qui concernent désormais plus d'un quart du bassin amont, ont très fortement diminué les écoulements pour les pluies de moins de 40 mm. L'oued Merguellil aboutit désormais dans la retenue du grand barrage El Haouareb qui perd plus de la moitié de son eau par infiltration au travers d'un réseau karstique et 30% par évaporation, le reste de l'eau étant pompé ou lâchée vers l'aval. Ce barrage construit en 1989 s'est souvent complètement asséché au cours de la dernière décennie. Les modifications majeures des écoulements souterrains résultant de la construction du barrage sont mises en évidence par les traceurs géochimiques dans les sept premiers

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kilomètres à l'aval du barrage. Les mesures de température de la nappe ont confirmé l'arrivée d'eau récente. Le reste de l'aquifère de la plaine de Kairouan garde la signature d'une recharge plus ancienne mais tout l'aquifère subit une baisse de sa piézométrie (environ 1 m par an), conséquence de la demande en eau pour l'irrigation toujours plus forte.

Mots clefs changement anthropique; géochimie; hydrodynamique; Tunisie; bilan hydrologique

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.

Concerning rainfall, studies based on homogenized data sets at the global scale (e.g. New *et al*., 2001) mentioned drying extending over a very large North Africa region after 1950, while Norrant & Douguédroit (2006) did not identify any really significant trend in the Mediterranean basin for the same period. When focusing on smaller areas, contradictory results have been reported. A long-term decrease in rainfall appeared between 1923 and 2000 in the data set from 50 stations in southern Italy studied by Piccarreta *et al*. (2004), but Serrano *et al*. (1999) found no significant trend in data from 40 stations in Spain and Portugal between 1921 and 1995. From the analysis of five stations in northwestern Algeria for the period 1930–1998, Meddi & Hubert (2003) identified a statistically significant break in the rainfall time series in the 1970s and 1980s. The first conclusion is that the complex pattern of rainfall over the Mediterranean does not reflect an overall trend.

Complexity is also identified in surface runoff. Even commonly accepted ideas, for example that forested areas have less surface runoff, and consequently less soil loss than open areas (e.g. Chirino *et al*., 2006), have to be considered with caution. For instance, when comparing three French catchments, Cosandey *et al*. (2005) found apparent inconsistencies that led to more subtle interpretations. Obviously, part of the discrepancy between these results can be explained by the different methods of measurement and interpretation, or by the difference in analytical scales. In fact, the extreme variability of the Mediterranean hydrology requires a combination of cautious approaches and a large set of well-documented regional studies as references.

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.

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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 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.

The Kairouan station is the source of the longest rainfall data set in the catchment, typical of a semi-arid climate. Since 1925, the annual mean rainfall has been 310 mm, with extreme values of 108 and 634 mm (the two months of September and October 1969 alone received a total of 573 mm). A network of 30 more recent stations scattered throughout the study area gave an annual mean varying between 265 mm in the plain and 515 mm in the highest part of the catchment. Measured in a Colorado tank, mean evaporation over the last 15 years at the El Haouareb site was 5.6 mm per day.

The Merguellil catchment is endorheic and its rivers have sporadic flow, measured at five stations in the upstream catchment. The rivers are fed by the rain falling on the hilly upstream parts and floods can be very violent. About 80% of the annual flow is produced in only 12 days. Between 1989 and 2005, the mean annual flow of Wadi Merguellil calculated at the entry of the El Haouareb Reservoir was 17×10^6 m^3, with a minimum of 2.5×10^6 m^3 in 2000/01 and a maximum of 37.6×10^6 m^3 in 2004/05. These figures can be compared with the exceptional flood in the autumn of 1969, estimated at about 175×10^6 m^3 (Bouzaïane & Lafforgue, 1986). Before the construc-

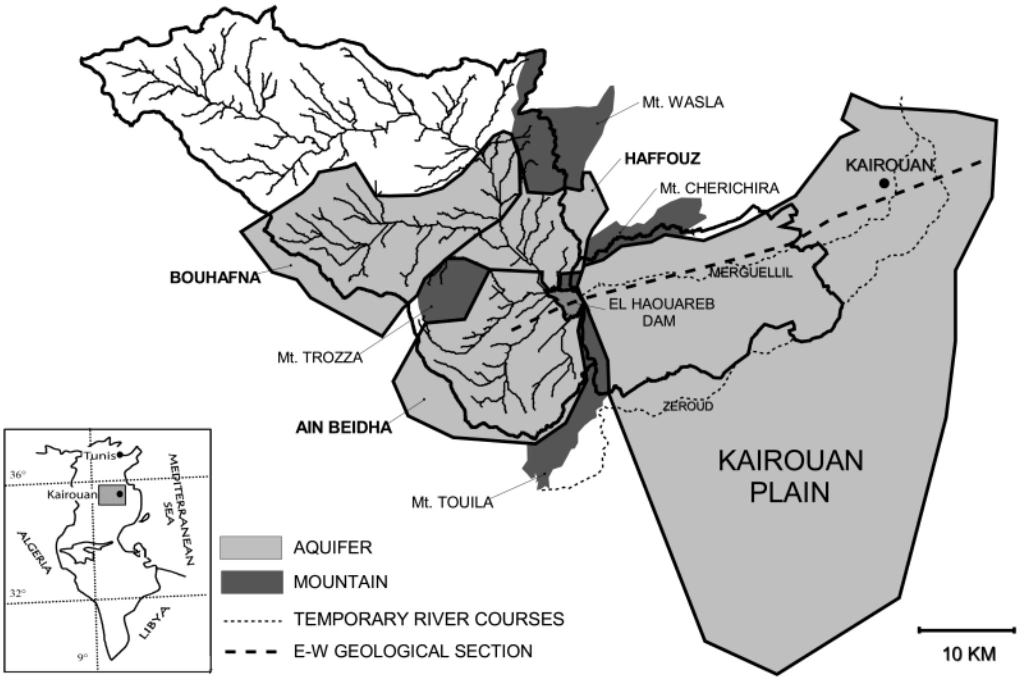

Fig. 1 Location of the study area, limits of the upstream and downstream sub-catchments and limits of the different aquifers.

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tion of the El Haouareb Dam, the smaller floods of Wadi Merguellil infiltrated into the Kairouan plain and recharged the phreatic aquifer, and the largest floods reached the sebkha el Kelbia, a large salt lake that often dried up.

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 (Fig. 2) 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.

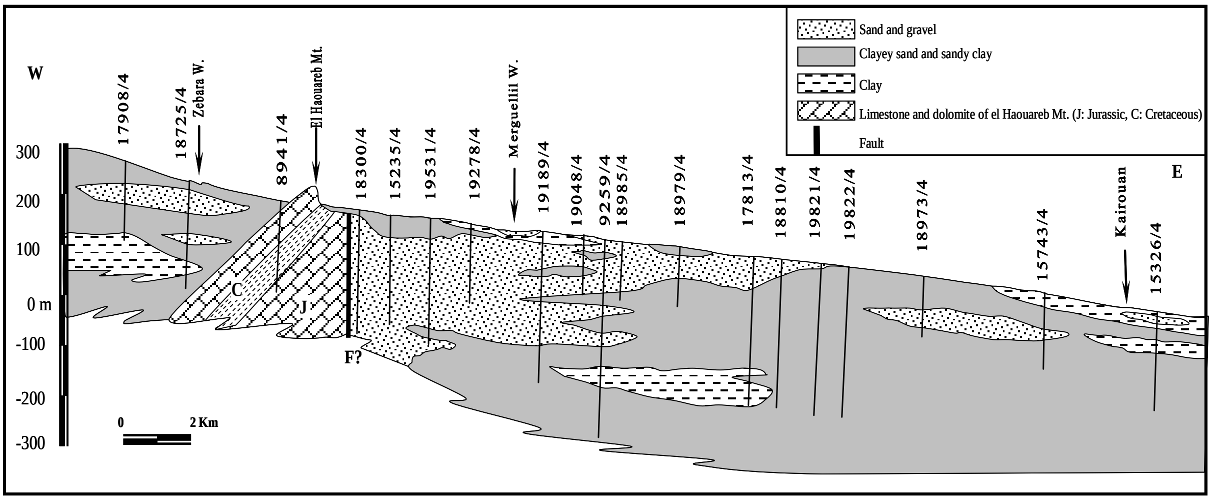

Fig. 2 W–E geological cross-section along Wadi Merguellil: the Tertiary and Quaternary Ain el Beidha aquifer to the west; the Mesozoic karst of Jebel el Haouareb; the thick Quaternary aquifer of the Kairouan plain to the east (whole thickness not represented).

CHANGE PROCESSES AT WORK

Climate variability

The contradictory results of analyses of the rainfall data sets at the Mediterranean scale have been mentioned above. 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-

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term steadiness, the high variability typical of the Mediterranean precipitation can be observed.

Kingumbi *et al*. (2005), who dedicated most of their study to the Merguellil catchment, identified slight modifications in the period 1976–1998: the years between 1976 and 1989 were dryer; the area covered by rain events of more than 30 mm d^{-1} decreased after 1976; the number of rain events over 30 mm d^{-1} was higher after 1989 (even when compared with the years before 1976). However, according to Kingumbi *et al*. (2005), the increase in the number of rainfall events exceeding 30 mm d^{-1} (from 11 days per year in 1966–1989 to 16 days in 1989–1998) did not counterbalance the decrease in their spatial extent (median of 7.6, 2.2, 2.9% of the upstream catchment for the periods 1966–1976, 1976–1989, 1989–1998, respectively). Lacombe *et al*. (2007) completed the rainfall study with data for the period 1998–2005. There was no change in rainfall intensity between the two periods 1989–1996 and 1997–2002, but other variations appeared, for instance in the link between rainfall and altitude.

Change in land use/land cover

Over the last two millennia, the vegetation in the Kairouan region has undergone significant changes, in particular due to human activities. It changed from a nearly natural state in the Iron Age to intensive agriculture during Roman times, which were more humid than now. Then, the decrease in population after the Arab invasions (647–1052 AD) coincided with a more arid steppe grazed by migratory herds. In the last 50 years, the region has returned to more intense agriculture. These changes concern the whole Merguellil catchment, but take different forms. In the very flat Kairouan plain, cultivated areas became larger and traditional crops (rainfed cereals and olive trees) were rapidly replaced by large irrigated fields. In the upstream catchment, available resources in land and water (both surface water and groundwater) are unevenly distributed and the pattern of extension of irrigation is fragmented and varied.

Such changes in vegetation obviously modified the hydrological cycle, but their impact is often difficult to identify from climatic fluctuations. In northern Tunisia, Zielhofer *et al*. (2002) observed substantial floods at the end of the Roman era, linked with intensive land use. No such detailed studies exist for central Tunisia and ancient descriptions (e.g. El Bakri in the 11th century AD) are often the only source of information, but similar processes can be assumed in a more arid, and thus more fragile, environment. In fact, during the last three decades, the most visible modifications have resulted from the conservation works in the upstream catchment. Aimed at fighting erosion and preventing silting up of the big El Haouareb Reservoir, they consist of bench terraces and 40 small- and six medium-sized earth dams. Bench terraces now cover 23% of the total area of the upstream catchment; they are yet to be completed in the places most sensitive to erosion (Fig. 3). The area controlled by the small and medium dams is 20% of the upstream catchment. One fifth of the bench-terraced area belongs to subcatchments controlled by these dams.

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

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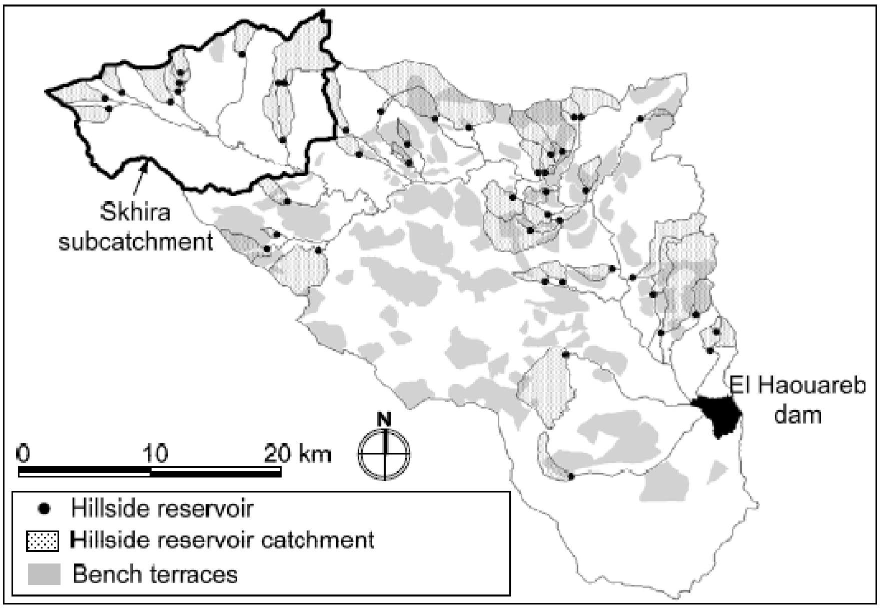

Fig. 3 Area controlled by soil and water conservation works in the Merguellil upstream catchment in 2006.

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

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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 under-estimated compared with the results of our detailed local field investigations. Over-exploitation 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 (Fig. 4). 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).

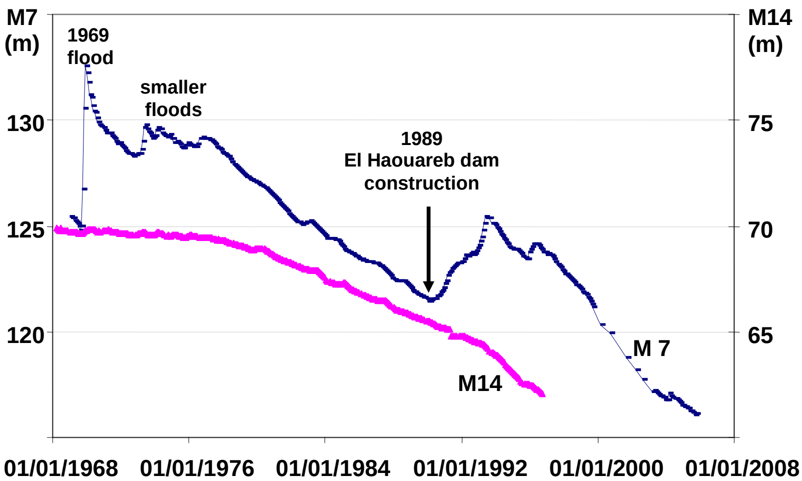

Fig. 4 Changes in the level of the water table of the Kairouan plain in recent decades: upstream (M7) recorded the main regional events while downstream (M14) seems to be only affected by pumping for irrigation (location of M7 and M14 is given in Fig. 6).

IMPACT OF CHANGES IN THE UPSTREAM CATCHMENT

According to Kallel *et al*. (1972), annual flows measured at Haffouz station (650 km^2) were 8.5 × 10^6 m^3 in 1966/67 and 1968/69, 146 × 10^6 m^3 in 1967/68 and 236 × 10^6 m^3 in 1969/70. Such high variability is common in Mediterranean environments and still exists. When referring to old time series of river flow measured at the different stations of the Merguellil upstream catchment (Bouzaïane & Lafforgue, 1986), the expected annual flow should be about 30 × 10^6 m^3 at the El Haouareb sill at that time. Because

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of many uncertainties (e.g. lack of stability of the river bed at some stations), this figure must be considered with caution but still it is much larger than the 17×10^6 m^3 actually observed for the period 1989–2005. A significant change has thus occurred in the surface hydrology of the region.

As mentioned earlier, the variability of rainfall is high in central Tunisia. Different authors, who worked on nearly the same data set (with or without the most recent years), pointed out distinct details but finally concluded that no significant change in rainfall has occurred in recent decades. Discrepancies between interpretations reflect the differences in methods and emphasize the unreliability of reasoning based on short time series. All the temporary changes in rainfall over the Merguellil catchment (especially the frequency, extent or intensity of the heaviest rains) may affect surface runoff. But even when considering the rainfall variability and the influence of topography on the production of surface runoff, as done by Cudennec *et al*. (2005, 2006) in the highest Merguellil subcatchment, the range of these limited changes in rainfall cannot explain the drastic decrease in surface runoff. As in many other semi-arid regions (e.g. Leduc *et al*., 2001), human activities are pre-eminent in explaining the hydrological changes.

Soil and water conservation works are the most visible reasons for the hydrological change in the Merguellil upstream catchment, especially due to their spatial extent. Depending on local conditions (topography, geology, soil thickness but also social traditions), they can take different forms. When they are new or well maintained, they completely stop the local runoff in the equipped area for all small rain events and some medium events. All authors agree that rainfall events lower than 10 mm do not generate significant surface runoff at the regional scale. The impact of the conservation works is proportionally lower for the most violent events. From a temporal point of view, their efficiency decreases with time, the highly variable rate of the decline depending on maintenance (Baccari *et al*., 2006). This decrease most often results from the development of hollows in unconsolidated parts of the contour ridges, rather than from complete silting up of the terrace itself.

At the small scale of the El Gouazine sub-catchment (18 km^2), Nasri *et al*. (2004) observed a change in surface runoff after the completion of bench terraces that cover 43% of the total area. The runoff coefficient calculated for each rain event decreased to below 10%, whereas it previously reached up to 30% for the autumn events. When small violent events were included, the annual mean runoff coefficient decreased from 4.5% to values that varied between 0.2 and 2.7% for the first three years after completion of the conservation works.

Considering the conservation works at the scale of the whole Merguellil upstream catchment (Fig. 3), Dridi (2000) noted that bench terraces covered 17% of the area in 1998 and that works older than 20 years had lost their efficiency. Their median retention capacity was 85 mm while the total capacity of the 43 artificial lakes was 5.8×10^6 m^3, i.e. a water height of 36 mm over the controlled area of 160 km^2. Dridi estimated that a runoff higher than 1 mm required an event rainfall exceeding a threshold of 10–17 mm, depending on the sub-catchment.

In contrast, Kingumbi (2006) confirmed that changes in rainfall were not sufficient to explain the decrease in the surface runoff and reported a very limited impact of conservation works (1% decrease in runoff). Using a coupled model of surface and

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groundwater flow, he concluded that this decrease was essentially explained by a much smaller baseflow, which was the consequence of the drop in groundwater levels induced by overexploitation of the Bou Hafna aquifer.

Lacombe *et al*. (2007) used a different approach. They compared the uppermost subcatchment of Skhira (194 km^2) and the rest of the Merguellil upstream catchment (Fig. 3) and did not observe any significant change in the uppermost subcatchment where conservation works are very rare (only 3% of the converted area). According to these authors, most of the decrease in runoff was explained by a drastic reduction in the lower remaining part of the upstream catchment. The change affected all categories of rain events of less than 40 mm (divided into 10 mm classes) in similar proportions. This seriously weakened the assumption of a smaller baseflow. In the Merguellil semi-arid environment, where most of the flow occurs during floods, the contribution of baseflow to total river flow is proportionately higher for small rainfall events, which implies differentiated sensitivity of different rainfall classes. Their conclusion was that an expansion of 21% in areas with conservation works in the remaining lower part induced an overall decrease in runoff of 41–50%.

Exchanges between surface water and groundwater have probably changed during recent decades, particularly because of the falling heads in aquifers and modified river regimes. An induced decrease in the Merguellil annual flow would thus be expected, but the present observation network is not dense enough to reveal a clear spatial and temporal pattern for these modifications. Like all semi-arid rivers, the Merguellil baseflow is limited (about one eighth of the annual flow). It is thus reasonable to explain the present hydrological changes essentially by the impact of conservation works (first-order, well identified); the change in flows between surface water and groundwater is a second-order phenomenon, which has not yet been quantified precisely. Future studies of hydrological changes in the Merguellil upstream catchment should pay closer attention to the loss of efficiency of the conservation works with age. Moreover, as areas with conservation works that are not properly maintained are more affected by erosion than “natural” areas, we face another difficulty in the upscaling of local observations to estimate their hydrological impact at the regional scale.

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.

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 water volumes. Even now, we were unable to find any traces of a possible return of irrigation water to the plain groundwater (a more

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detailed study based on ^{15}N 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 (Fig. 4).

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 (e.g. M14 in Fig. 4) 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 (Fig. 5). 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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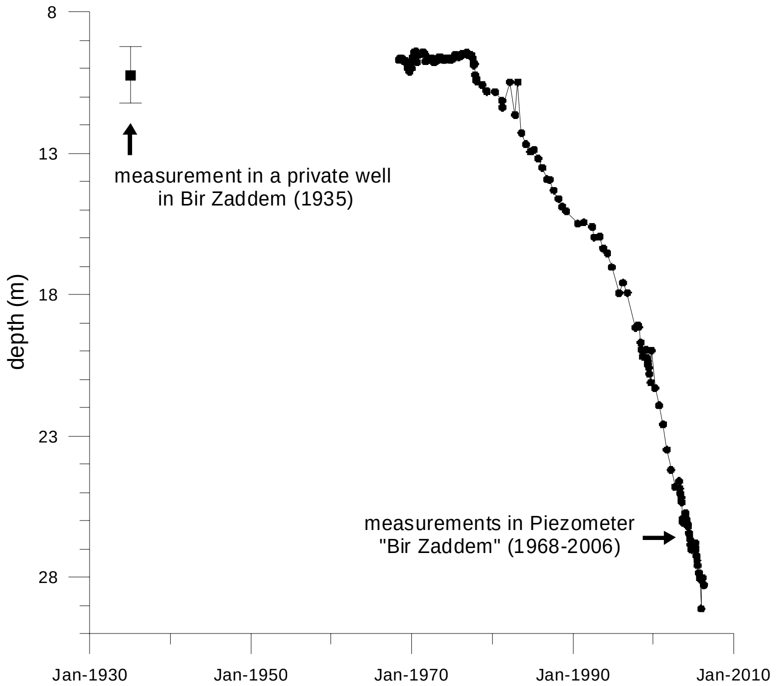

Fig. 5 Long-term changes in the water table of the Kairouan plain: comparison of levels in 1935 and in recent decades.

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 water level 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 4.6×10^6 m^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 (e.g. Nazoumou & Besbes, 2001). These models could be significantly improved in two ways: (a) 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); and (b) 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.

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

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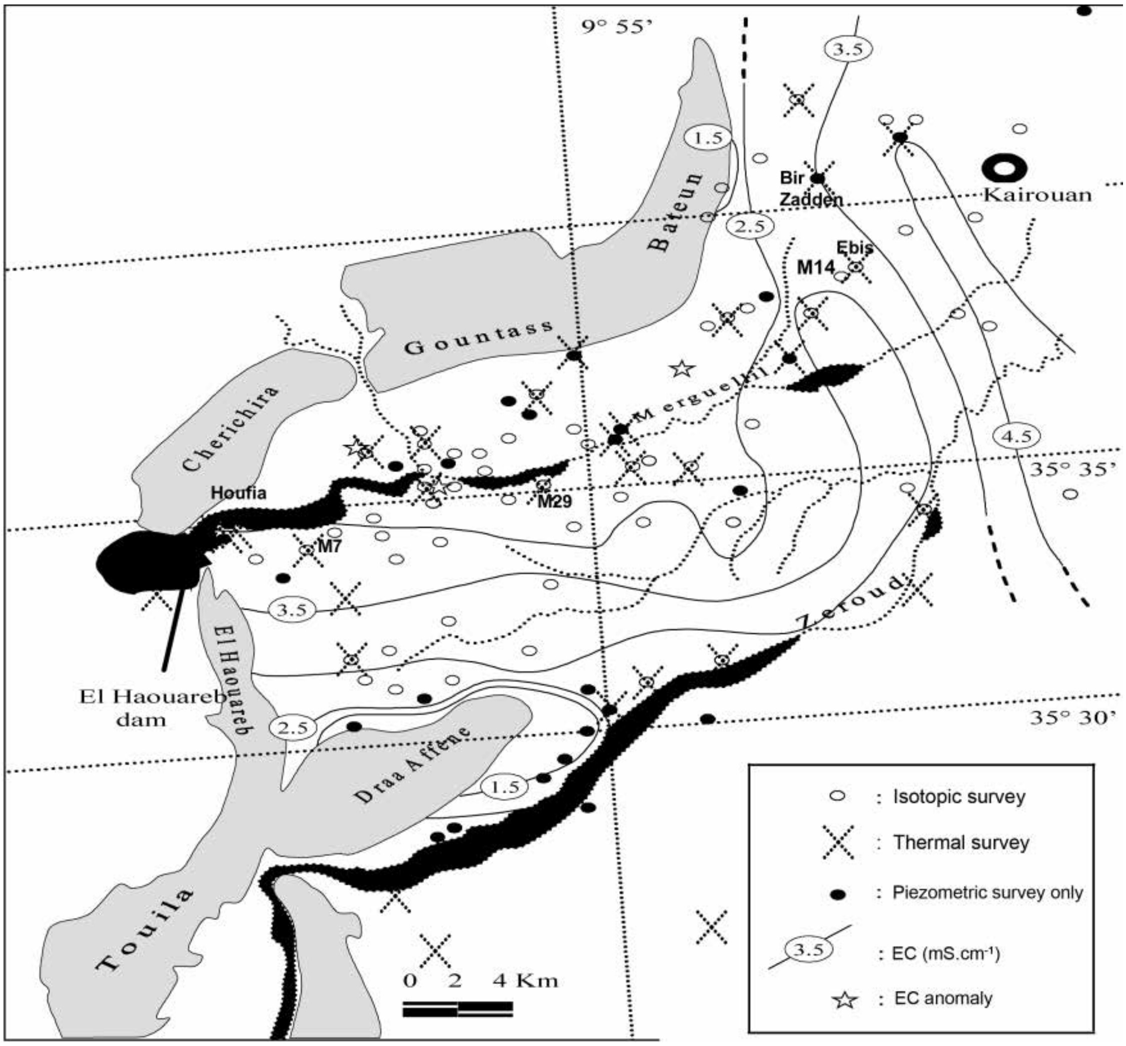

Fig. 6 Wells of the Kairouan plain aquifer surveyed for piezometry, geochemistry and thermics. Isolines of electrical conductivity (EC). river courses indicated by dotted lines, with areas usually covered by floods (before 1989) in black.

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 μS cm^{-1} (Fig. 6). Dominant ions are Ca^{2+}, Mg^{2+} and SO_4^{2-} as in the Wadi Merguellil water. The small reservoirs in the upstream catchment and the El Haouareb Reservoir 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 Reservoir, 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 greater in small dams where loss due to evaporation may be higher (Grünberger *et al*., 2004).

Electrical conductivity measurements were used to evaluate the mixing ratio of water coming from the reservoir 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 reservoir, estimated their respective contributions at 60 and 40%. This rough calculation will be repeated with similar more recent episodes.

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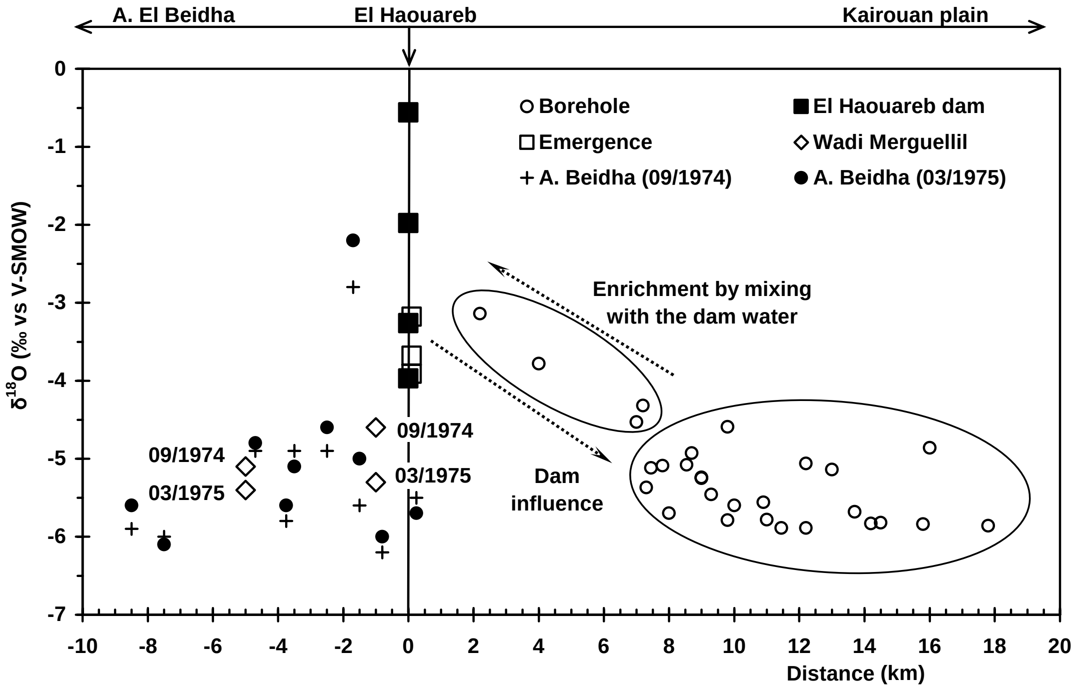

Fig. 7 Isotopic content ($\delta^{18}O$) of groundwater before (left, Aïn el Beidha aquifer), in (km 0) and after (right, Kairouan plain aquifer) the El Haouareb karstic sill.

Isotopic studies, firstly undertaken by Ben Ammar *et al.* (2006) and still ongoing, provide an efficient tool for estimating the origins and proportions of groundwater. 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. 7). Identical values are also observed in the Kairouan plain aquifer far from the dam. Observed ^{18}O values in the El Haouareb Reservoir varied between –6.54 and +7.41‰ *vs* VSMOW. The mixing of the evaporated reservoir water with the Aïn el Beidha unchanged water and the groundwater infiltrated in the Kairouan aquifer before 1989 is visible in the first 7 km downstream from the dam, with a proportion of recent evaporated water inversely proportional to the distance from the dam (Ben Ammar, 2007). Ben Ammar *et al.* (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 used (^{2}H, ^{3}H, ^{18}O), 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 reservoir water, which is in good agreement with results from other methods or periods.

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. 8 "type 3"),

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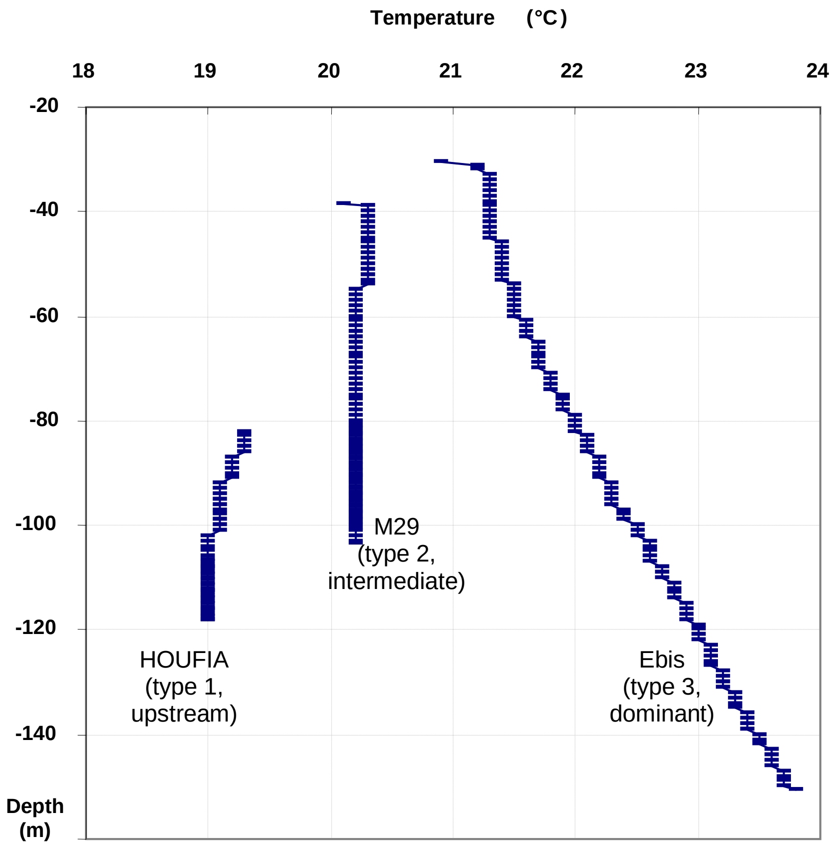

Fig. 8 Thermal gradients measured in piezometers in the Kairouan plain. Most of the profiles show increasing temperature with depth (type 3).

with an average value of +0.018°C m^{-1}. This is less than the local geothermal gradient (+0.029°C m^{-1}) calculated from measurements in three oil boreholes located in the plain (Ben Dhia, 1991) and values of the regional heat flux (Bouri *et al*., 1998) and thermal conductivity of the Kairouan plain sediments (Ben Dhia, personal communication). 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. 8, “type 1”) attesting to an upwards flux of freshwater. 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 reservoir 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 hydrodynamic 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.

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CONCLUSION

The Merguellil catchment is apparently rich in hydrological data. The frequency of surveys has varied over the past 40 years, and gaps remain, but the total number of measurements is impressive. Thus, for many technical or political managers, water resources in the Merguellil catchment were assumed to be satisfactorily identified. But because of the rapid changes affecting the whole water cycle, the spatial and temporal density of the data is not sufficient to design efficient water management systems. Moreover, there are many sources of potential errors in the field measurements and a time-consuming preliminary analysis was required. It revealed a heterogeneous data set in terms of representativeness and reliability, which had a direct impact on the overall quality of further interpretations. One important result was that the spatial and temporal distribution of water in the Merguellil upstream catchment has been seriously modified by the numerous soil and water conservation works. In the areas influenced by these works, the surface runoff may have been reduced by up to 50%.

Most previous studies in the region considered only the hydrodynamic aspect, but were not able to reach an operative level. The comparison with other approaches (hydrochemistry in particular) enabled substantial progress in the surface hydrology of the upstream catchment, in the groundwater dynamics of the Kairouan plain and, last but not least, in our understanding of the complex processes that transfer upstream water to the plain through the karst. With a thorough survey of major ions and stable isotopes, we were able to estimate the infiltration beneath the dam reservoir (10×10^6 m^3 on average, with very large variability), the signal transformation in the karst (transfer time longer than two weeks, buffer volume greater than 5×10^6 m^3) and the progress of new groundwater in the Kairouan plain aquifer (7 km in 15 years). Uncertainty, often high, still exists at every step of the water balance calculation, and additional studies are necessary. The present Merguellil hydrological system is clearly unsteady, whatever the time step, from the rain event to the decade. Previously-used numerical models should be improved by accounting for various human activities; the new models should then be capable of checking the coherence of the different calculations.

In many other Mediterranean areas where information is sparser and less reliable, estimates of available water resources should be very carefully reassessed. But this study also provides other lessons. Water management in the Merguellil catchment has little freedom of action. If soil and water conservation works increase in the upstream catchment, surface water reaching the El Haouareb Reservoir will decrease and consequently so will recharge of the Kairouan aquifer. The only way of saving water would be to manage dam releases to enhance recharge and reduce evaporation losses, but this would be a second-order answer to the problem, as would be the construction of desalination plants close to tourist facilities or the re-use of wastewater. The regional water shortage could also be temporarily solved by the long-distance transfer of water through channels from the more humid north, but the increasing demand for water applies to the whole country.

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

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irrigated agriculture is, therefore, 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 stakeholders; 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 *et al*. (2007). In Morocco, the aquifer of the Haouz plain near Marrakech studied by Abourida *et al*. (2003) has experienced both a lowering of the water table (by as much as 12 m in 6 years) because of pumping and a rise 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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