Regional Hydrological Impacts of Climatic Change—Hydroclimatic Variability
(Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 296, 2005.

Impact of a long drought period on a large carbonate aquifer: the Liassic aquifer of the Sais plain and Middle Atlas plateau (Morocco)

FOUAD AMRAOUI[1], MOUMTAZ RAZACK[2] & L. HOUSSAINE BOUCHAOU[3]

1 *Hydrogeology Laboratory, Faculty of Science Aïn Chock, Hassan II University, BP 5366 Maarif, Casablanca, Morocco*

2 *Hydrogeology Department UMR 6532, University of Poitiers, 40 Avenue du Recteur Pineau, F-86022 Poitiers Cedex, France*
moumtaz.razack@hydrasa.univ-poitiers.fr

3 *Applied Geology and Geo-environment Laboratory, Faculty of Science Ibn Zohr, BP 28/5, 80000 Agadir, Morocco*

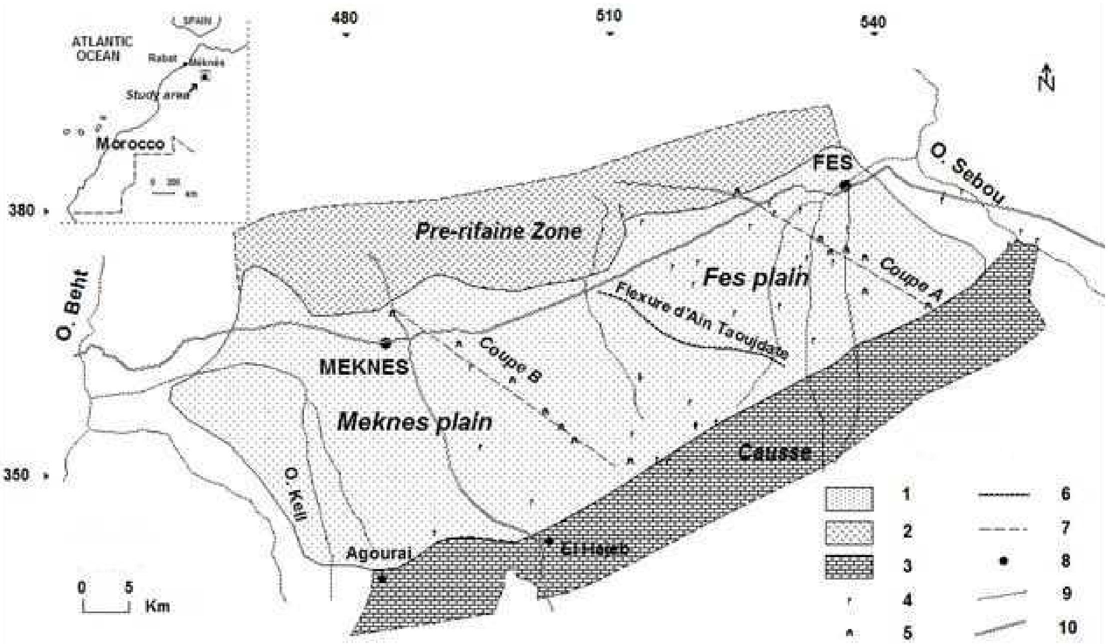
Abstract This article presents the results of a study into the behaviour of the large Liassic aquifer of the Sais plain (deep and confined aquifer) and of the Middle Atlas plateau (free and karstified aquifer), which has been subjected to a prolonged drought (>20 years). The methods of signal treatment, applied to two series (normal pluviometric period and drought period) of the Bittit spring discharges, show that the karstic system is inert with very significant reserves. However, in spite of the great regulating capacity of these reserves, the long drought period has resulted in a significant reduction in discharges, because of less diversified contributions and a reduction in the level of the reserves. A geographical information system (GIS) of the Liassic aquifer was compiled. The analysis shows that intensive exploitation coupled with the drought have significantly decreased the confined aquifer pressure and displaced down–stream the limit of appearance of the artesian characteristics in the plain.

Key words artesian characteristics; correlation analysis; drought; karstic spring; Liassic aquifer; Middle Atlas; Morocco; Sais plain; spectral analysis

INTRODUCTION

The object of this paper is to characterize, from a general point of view, the hydro-dynamic behaviour of large aquifers that are subjected to drought. The understanding of the evolution of such systems in a context of drought is particularly significant at a time when one speaks more and more about climatic changes, which are evolving in the studied area towards aridification. The study site is represented by the Liassic aquifer of the Sais plain and the Middle Atlas plateau, located in the north of Morocco. The site was chosen because of the large size of this aquifer and its complexity, and the availability of long series of both rainfall in deficit and discharges of the principal springs, and data of deep drillings of which several are artesian.

The Sais plain has an area of 2200 km^2 and is one of the principal agricultural areas of Morocco. Its water resources are provided mainly by the karstic Liassic aquifer of the Middle Atlas plateau (Fig. 1). This plateau is drained by a group of springs of which the most significant is the Bittit spring (average annual discharge



1: Sais plain. 2: Pre-Rifian zone. 3: Middle Atlas plateau. 4: Springs from Lias. 5: Wells. 6: Important flexure. 7: Cross-sections (not shown) . 8: Town. 9: River. 10: Road.

Fig. 1 Location and geological map of the study area.

Q = 1.3 m^3 s^{-1}). The Bittit spring is currently exploited to partly supply the town of Meknes with drinking water. It rains abundantly on the plateau (600–1000 mm, depending on altitude) and moderately on the plain (490–560 mm). The area of study has been subjected to a regular rainfall deficit for almost 20 years.

AREA OF STUDY

The Sais plain is framed by pre-Rifian ridges to the north, and the limit of the Middle Atlas plateau to the south (Fig. 1). The flexure of Aïn Taoujdate divides the plain into two structural parts: the Meknes plateau to the west and Fes plain to the east. The Sais basin is a vast sedimentary structure. The following formations occur (Chamayou *et al.*, 1975): a Palaeozoic basement; a Triassic substratum composed of red clays and basalts; carbonate Lias containing the deep aquifer; the Miocene made up of molasse, and a thick layer of gray marls which overlays the deep confined Liassic aquifer in the plain; and the Plio-Quaternary composed of sands, lake limestones, silts, travertines and basalts.

The basin becomes increasingly thick northward. The marly formations of the Miocene also thicken northwards. The thickness of the Lias aquifer varies in the same direction as normal faults. A database was prepared which includes more than 200 deep drillings on the Sais plain that reached or crossed the Lias. Among these wells, 58 are artesian and used for drinking water supplies.

Figure 2 represents the rainfall variations compared to the average annual rainfall from 1934 to 2000. This figure shows the irregularity of the rains and highlights a significant reduction since 1980, except for two rainy episodes in 1982 and 1996. The

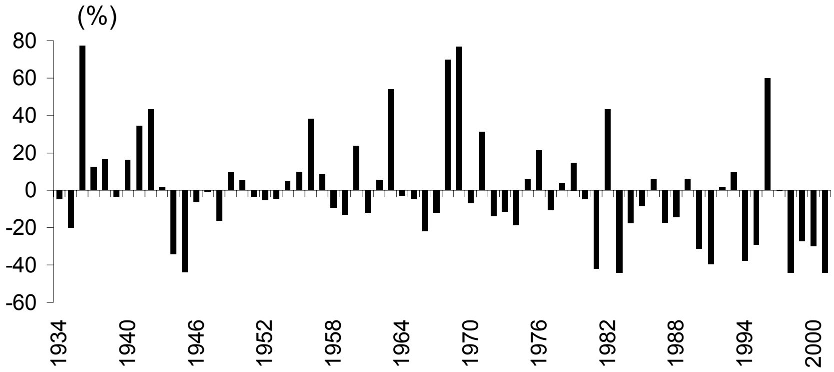


Fig. 2 Relative deviation (*RD*, %) from average annual rainfall at El-Hajeb station. $RD = ((P_i - P_m)/P_m) \times 100$ where P_i is annual precipitation and P_m is average precipitation.

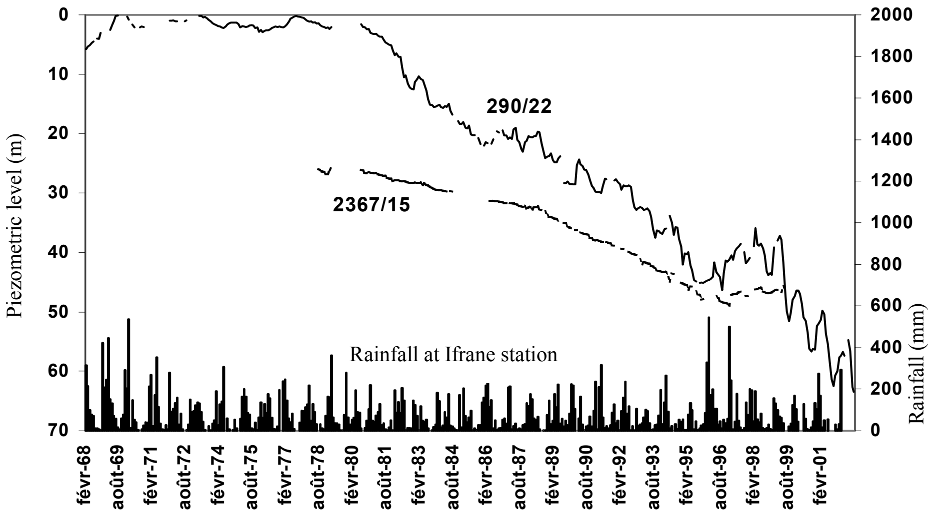


Fig. 3 Groundwater monitoring at wells 290/22 and 2367/15 showing a regular decrease in the water level due to the drought.

total rainfall deficit since 1980 at the El Hajeb station is equivalent to three years of average rainfall. Two piezometric series with a monthly time step account for the evolution of the aquifer piezometric level. The well 290/22, monitored since February 1968, controls the exploitation field located on the Meknes plateau. The well 2367/15, monitored between 1978 and 1999, controls the exploitation field located south of Fes. The graphs in Fig. 3 show a certain stabilization up to 1980, followed by a significant regular decline that ended in 1996/97 because of an exceptional rainfall distribution. During the last two decades, the average decline in piezometric level was 2.8 and 1.7 m year^{-1} for the Meknès plateau and for the Fes plain, respectively.

The Middle Atlas plateau is made up of limestone formations of Liassic age, which lie on argillaceous and basaltic Trias (Amraoui, 2003). Ten springs, of which Bittit is the principal one, are located along the contact between the carbonate plateau and the Sais plain. The plateau constitutes the recharge sector of the karstic system which is drained by the springs.

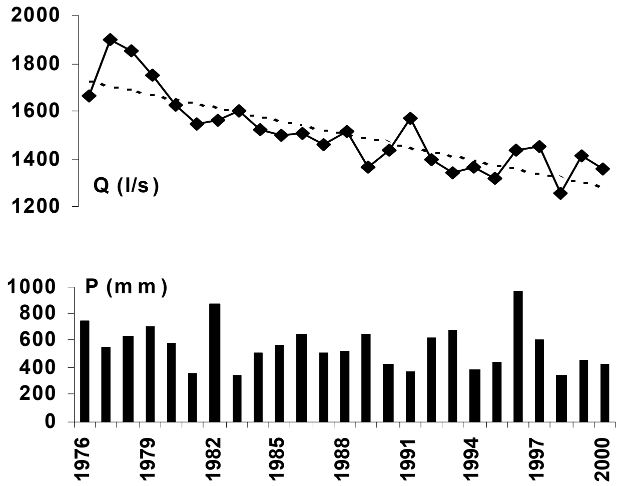


Fig. 4 Annual discharge evolution of the Bittit spring and annual rainfall at El-Hajeb station (1976–2000).

The emergence of the Bittit spring is located at the foot of a flexure within a flattening surface covered by Quaternary basalts. The hydrogeological system of Bittit has a very significant storage capacity, making it possible to store large amounts of recharge from rainfall and snowmelt, avoiding serious flooding. Indeed, the spring discharge is quite constant throughout the year. The presence of sandy dolomites at the base of the Liassic aquifer suggests the existence of an aquifer with intersticial porosity and relatively slow flow. The Bittit spring is characterized by a high average discharge (1510 l s^{-1} over the period 1975–2001) and a reduced statistical dispersion (SD = 186 l s^{-1}; *CV* = 12.3%). The relatively stable discharge indicates a good interannual regulation by the karst. Figure 4 illustrates the evolution of the spring discharge, which shows a regular decrease since the beginning of the drought. The discharge series of the Bittit spring, used in this work, cover the periods 1975–1977 and 1995–1998.

METHODS

The following methods are used in this study: (a) study of the discharge distribution; (b) study of the recession curves; (c) correlation and spectral analyses; and (d) geographical information systems (GIS) analysis of the artesian nature of the deep aquifer. Detailed descriptions of these methods and their applications in hydrogeology may be found in the following references: Amraoui *et al*. (2003, 2004), Larocque *et al*. (1998), Mangin (1984), Labat *et al*. (2002), Padilla & Poulido-Bosch (1995) and Sinan *et al*. (2000).

RESULTS AND DISCUSSION

Discharge distribution analysis

Two curves of the Bittit spring discharge distribution are shown in Fig. 5, relating to normal rainfall distribution (September 1975–August 1977) and the drought period

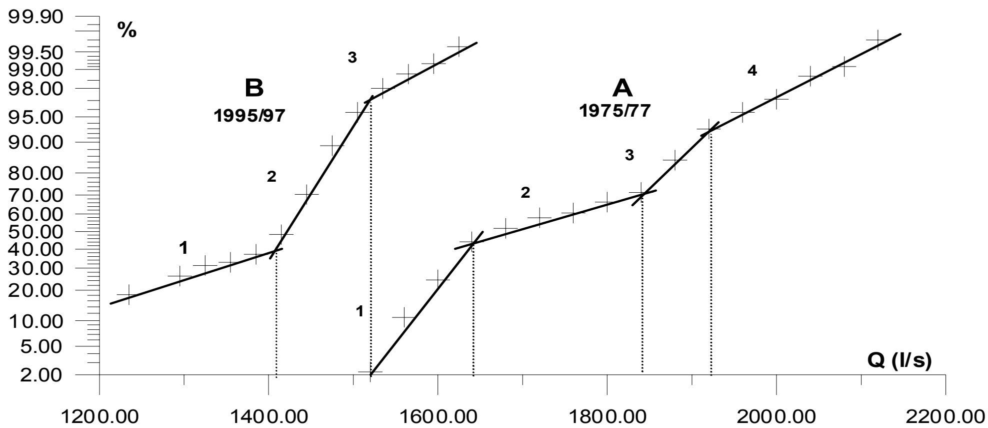


Fig. 5 Discharge distribution during a normal period (A) and a drought period (B).

(September 1995–August 1997). The diagrams show four segments for the period 1975–1977 and three for the period 1995–1997. This organization reveals a difference between the discharge evolution of the normal period and the dry period. The changes in the flow regimes depicted at weak discharge levels are explained by the passage from a flood recession (Fig. 5, Segment 2) to a baseflow (Fig. 5, Segment 1). The flow regime relating to this first segment corresponds to a Maillet law. The more significant slope of Segment 1 in the 1975–1977 period shows that, in a normal period, the baseflow discharges are less dispersed. Segments 2, 3 and 4 in the 1975–1977 period and segments 2 and 3 in the 1995–1997 period represent the flood recession discharges. The larger number of segments in the normal period is an indication of a more diversified origin of the contributions compared to the dry period. In the domain of high discharges, a discontinuity with increase in slope (segments 2 and 3, 1975–1977) means that water outlets exist outside the system and indicates the probable existence of overflows (for example a drain above the principal spring). In the dry period, one may observe a discontinuity with reduction in slope between segments 2 and 3. This characteristic means that water contribution occurs in the system, which can represent a temporary retention of a certain volume of water in additional structures at the time of floods and its release from the very start of the flood recession. Discontinuity between segments 3 and 4 of the 1975–1977 period represents the contribution of a volume of external water only during periods of floods (modification of the limits of the basin, rain, snowmelt). During the 1975–1977 period, the discharge levels of the spring were more significant than they are currently and they were organized in four segments. The supply of the source was more constant and was probably more diversified before the 1980s than during the period of current drought. Indeed, if the piezometric level of the aquifer drops because of a reduction in the contributions, secondary drains are found drained and the recharge surface is reduced. This is expressed in the graph of the discharge distribution by the reduction in flow regimes (three segments instead of four) and by a change towards lower values of the limits of the discharge intervals. The impluvium modifications considered above are assumptions, which could not be checked as no tracing tests were performed in the system.

Analysis of the recession curves

The various floods which were used for the analysis of the recession curves were chosen in such way that they represent the maximum amplitudes of each hydrological cycle and precede long periods of low water stage (Fig. 6). The baseflow coefficients are low (1.5 10^{-4} day^{-1}) and seem similar from one baseflow to another, thus representing the slow draining of the reserves and consequently the tendency to storage. Dynamic volumes are considerable and can be estimated at nearly a billion m^3. The variation in the dynamic reserve of the spring between 1977 and 1996 should be noted. Indeed, over 19 years, the system lost 179×10^6 m^3, that is to say an annual average volume of 9.4 Mm^3. This loss is connected directly with the drought which had prevailed in the area since 1981. The flood recession is generally spread out (30–45 days for the studied spring). This expresses a delayed response to the input signal represented by the rain. The durations of the flood recession can vary from one hydrological year to another according to the quantity of rain.

The Bittit spring is a wide and complex hydrogeological system. The volume of water supporting the baseflow is very significant (907 Mm^3 in 1996), which implies an immense reservoir and places this aquifer among the little karstified domains. Sandy dolomites would constitute a porous system with very high regulating capacity. Finally the volume of flood recession (Vi = 0.5 Mm^3) is insignificant compared to the dynamic volume (Vr).

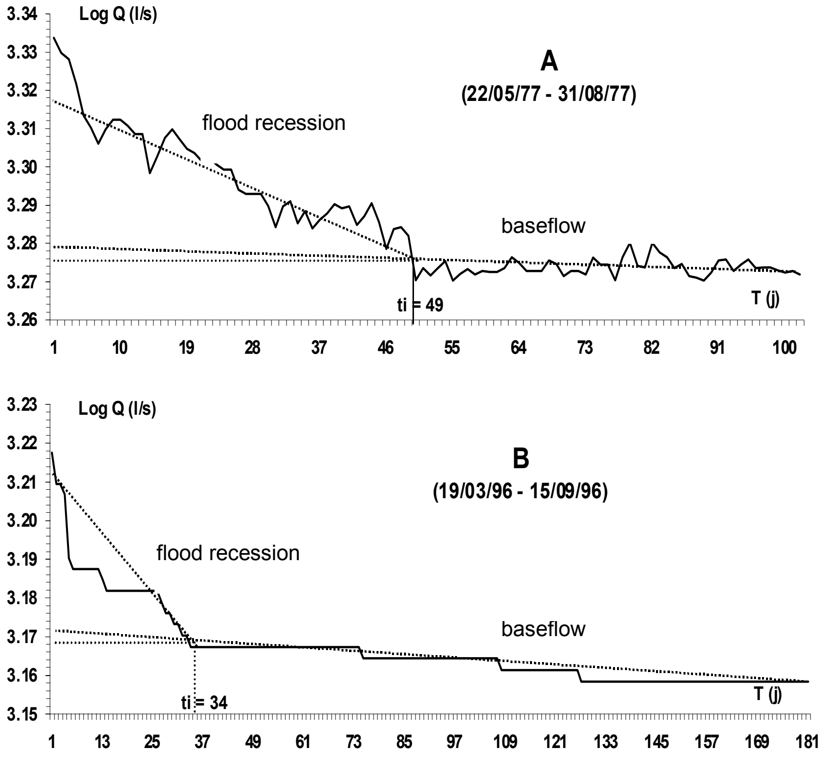


Fig. 6 Recession curves of the Bittit spring in (A) a normal period and (B) a drought period.

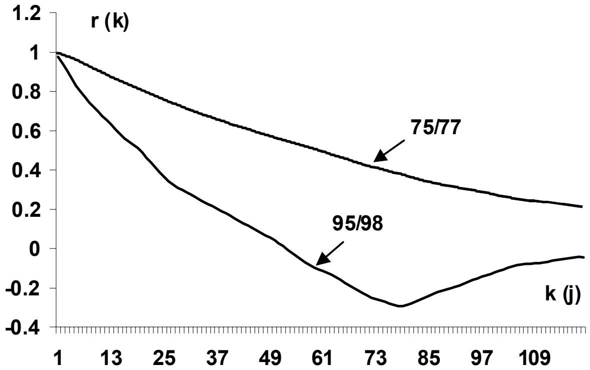


Fig. 7 Simple correlograms of the Bittit spring discharges (m = 120 days) (September 1975–August 1977: n = 731; and December 1995–February 1998: n = 770); the horizontal axis is in days.

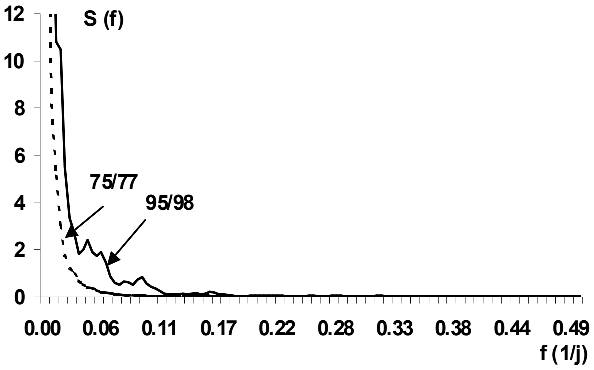


Fig. 8 Spectral density functions of the Bittit spring discharges (m = 120 days) (September 1975–August 1977: n = 731; and December 1995–February 1998: n = 770); the horizontal axis is in days^{-1}.

Spectral and correlation analysis

The analysis was carried out in a short run with a daily time step and truncation after 120 days. Figure 7 shows simple correlograms of the spring discharges during the two periods of observation. A rather slow decrease may be noted, which indicates the presence of a significant memory effect. The system modulates the input signal and has a memory effect which is in relation to the regulating role of the reserves. During the 1975–1977 period, the decrease is much slower (r_k = 0.2 for k = 117 days) than that during the 1995–1998 period (r_k = 0.2 for k = 37 days). This indicates the effect of the reduction in the groundwater reserve on the damping of the input signal. This result underlines the vertical heterogeneity of the karstic systems and shows the significant influence of their storage levels on input–output relationships.

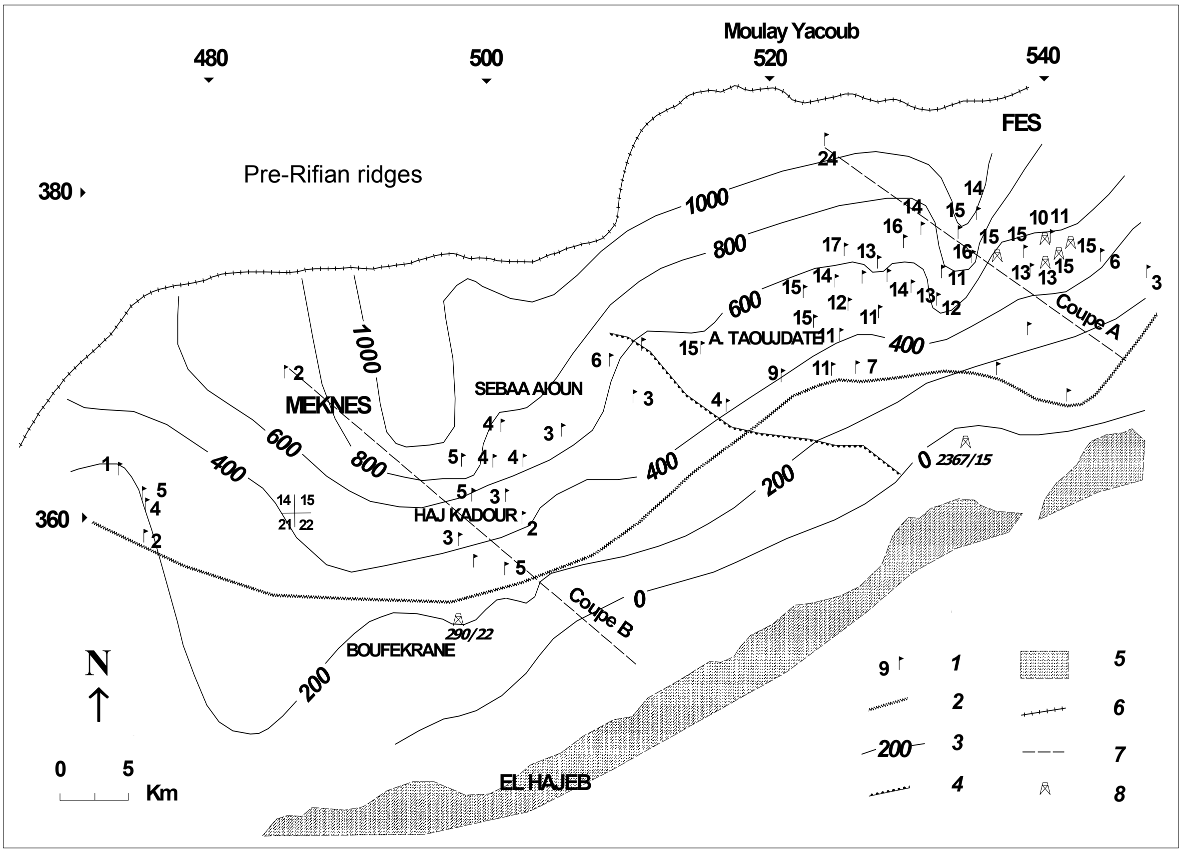
The spectra of the variance density of the spring discharges (Fig. 8) show narrow cut-off frequencies (0.11 day^{-1}), and confirm that the system is inert. Calculated times of regulation are 53 days over the 1975–1977 period and 37 days over the 1995–1998 period. This result shows a significant reduction in the inertia of the system during the period of drought due to the decrease in the reserves.

The parameters obtained by analysing the spring discharges show a great memory effect (37–117 days), a narrow spectral band (0.11 day^{-1}), and a time of regulation from 37 to 53 days. These data can be compared with those of carbonated aquifers studied elsewhere. The Bittit spring can be classified among the aquifers with significant memory effect.

Study of the artesian characteristics

The artesian pressure in the Sais basin was measured at 58 deep wells of which several are used for the drinking water supply of the two large towns of Fes and Meknes (Fig. 9). The pressure recorded at these wells at the time of their realization varies between 1 and 24 bars. The flexure of Aïn Taoujdate constitutes a very clear limit between two compartments of the aquifer, where the difference in pressure between the wells is very significant. Indeed, in the Fes plain, the pressures vary between a few bar in the south and 24 bar in north (well 2370/15), whereas on the Meknes plateau, the pressure only varies between 1 and 6 bar (northeast of Sebaa Aioun). In Fig. 9, the southern limits of the Miocene transgression (thickness of the Miocene marls = 0 m) and of the artesian features are indicated.

The average increase in the thickness of the marls from south to north is between about 40 and 50 m km^{-1}. This average value can be much greater, as is the case to the



1: Artesian well (pressure in bar); 2: Southern limit of the artesian nature of the aquifer; 3: Contour lines of thickness (m) of Miocene marls; 4: Aïn Taoujdate flexure; 5: Middle Atlas plateau; 6: Limit of the pre-Rifian ridges; 7: Cross sections (not shown); 8: Monitored wells.

Fig. 9 Map of the artesian characteristics of the deep Liassic aquifer in the Sais plain.

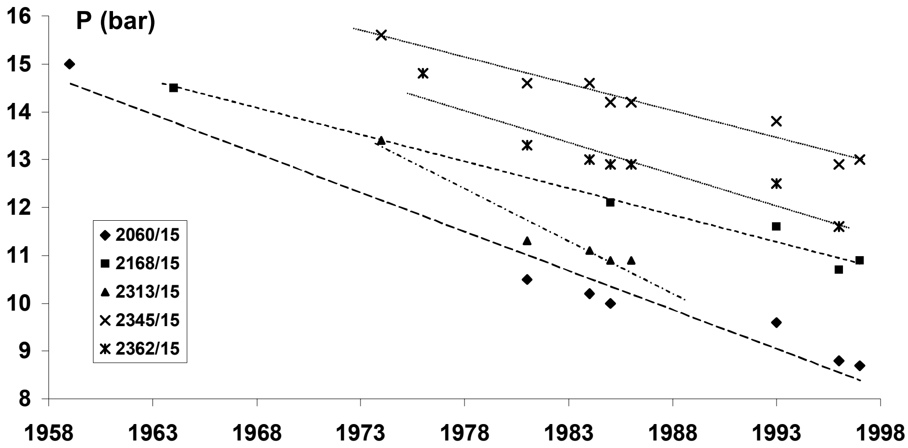


Fig. 10 Evolution of the pressure (*P*, bar) in the artesian wells located south of Fes.

southwest of Fes town or to the north of El Haj Kaddour. These marls are responsible for loading of the deep Liassic aquifer and one can trace the limit from which the aquifer becomes artesian from the drilling data. At the time of the realization of the wells (Fig. 9), this limit corresponded to a thickness of the marls varying from 150 to 300 m. Currently, because of the drought and the intensive exploitation, this limit, which is in fact dynamic, would have probably moved northwards in response to the decline in the aquifer piezometric level and the decrease in pressure in the wells.

For five artesian drillings exploited by the Fes Water Management, a long series of 40 years of pressure measurements at the head of the wells has been obtained. Figure 10 accounts for the continuous downward evolution of the Liassic aquifer loading. The average decline in groundwater piezometric levels deduced from these drillings varies from 1.1 to 2.1 m year^{-1}.

CONCLUSION

The various methods used in this study show that the Bittit hydrogeological system has significant storage capacity, discharges controlled and supported throughout the year, relatively slow flow because of its presence at the base of a sandy dolomite base, and little developed karstification. However, in spite of the great storage capacity of this karstic aquifer, the discharge of this system indicates a regular and significant tendency to decline, due to a long period of drought which has reduced the recharge of the aquifer considerably. The methods implemented in this work (study of classified discharges and recession curves; correlation and spectral analysis; study of artesian characteristics/pressure have enabled us to better understand the evolution of a great karstic system such as that of Bittit.

Thus, the phenomenon of drought has become a parameter which needs to be accounted for in the sustainable management of the water resources, in particular in semiarid zones with irregular climate, where the climatic changes tend towards aridification. This report pleads for a suitable management of the water resource to guarantee its durability.

REFERENCES

Amraoui, F. (2003) L'aquifère karstique du moyen atlas tabulaire: problème de la turbidité affectant les sources du complexe Ribaa–Bittit (Maroc). *Cah. Recherche, Rectorat de Casablanca (Maroc), Série A Sciences et Technique* **5,** 81–92.

Amraoui, F., Razack, M. & Bouchaou, L. (2003) Turbidity dynamics in karstic systems. Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). *Hydrol. Sci. J.* **48**(6), 971–984.

Amraoui, F., Razack, M. & Bouchaou, L. (2004) Behaviour of a karstic spring subjected to a long drought: Bittit spring (Morocco). *C. R. Geosci.* **336**(12), 1099–1109.

Chamayou, J., Combe, M., Genetier, B. & Leclerc, C. (1975) Le bassin de Méknès–Fès. Ressources en eau du Maroc. In : *Plaines et bassins du Maroc Atlasique*, tome 2, 41–71. Service Géologique du Maroc.

Labat, D., Ababou, R. & Mangin, A. (2002) Analyse multirésolution croisée de pluies et débits de sources karstiques. *C. R. Geosci.* **334**(8), 551–556.

Larocque, M, Mangin, A, Razack, M & Banton, O. (1998) Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *J. Hydrol*. **205**(3–4), 217–231.

Mangin, A. (1984) Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoires et spectrales. *J. Hydrol.* **67**, 25–43.

Padilla, A. & Pulido-Bosch, A. (1995) Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *J. Hydrol.* **168,** 73–89.

Sinan, M., Haddouchi, B., Razack, M. & El Hebil, A. (2000) Évaluation et gestion des ressources en eau souterraine des aquifères régionaux à l'aide des systèmes d'informations géographiques. *Hydrogéologie* **4**, 89–100.