

Natural and artificial recharge investigation in the Zéroud Basin, Central Tunisia: impact of Sidi Saad Dam storage

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Abstract Hydrochemical and isotopic data of waters from the Zéroud aquifer have been used to potentially provide a means for locating occurrences and to trace movements of a variety of natural and anthropogenic recharge waters in the Zéroud Basin, Central Tunisia. Geochemical data have been measured during the dam water release, from May to September 2005, with a sampling time step of 15 days. An implication of dam water has been demonstrated that is noticeable up along the main flow path to a distance of 10 km far from the injection site. Environmental isotopes ^2H , ^{18}O and ^3H of water molecule were studied to investigate the effect of dam water on the hydrological system, and an isotope balance was established to compute the contribution of water storage component in groundwater. Based on isotopic mass balance, we assess that an average of 13% of total groundwater in the upper aquifer came from dam water storage. Three distinctive recharge waters in the aquifer can be determined. Water from local rainfall (pre-dam Zéroud River) that infiltrated into the boundaries of the Draa Affane Mountain was easily distinguished from the water influenced by

anthropogenic recharge located in the Zéroud right rivulet. Distinguishable isotopic signatures of native wadi Zéroud recharge due to “recent lineal recharge” through the riverbed were also identified.

Keywords Dam storage · Groundwater recharge · Chemical tracers · Isotope tracers · Ground water/surface water interaction

Introduction

Most of the south Mediterranean countries are characterized by the scarcity of water due to low and erratic rainfall. Though various studies on climatic fluctuations in the Mediterranean Basin suggest that the variation of precipitation does not show any decreasing trend (Leduc et al. 2007), high water needs during crop growing season coinciding with the dry period of the Mediterranean climate has resulted in the depletion of groundwater resources in some areas.

The low renewal rate of groundwater resources and the poor water quality of permanent rivers in the Mediterranean Basin make it necessary to improve water management efficiency to secure water supply for different socioeconomic sectors. Since the early 1980s, the Tunisian government has undertaken the implementation of the “National Strategy of Surface Runoff Mobilization”, by building numerous large and small dams and carrying out several soil and water storage works for irrigation and artificial recharge aims.

In many studies, the impact of water storage structures on groundwater recharge and on the riverbed has not been properly understood, except through crude methods based on fluctuations in water level in the aquifer. No generalized

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approach or solution has been presented to decide on the location and size of water storage structure in a micro-watershed and its efficacy in increasing groundwater table in a quantifiable manner. More recent studies suggest the interaction between surface and groundwater (SW–GW) systems including surface water storage structures and artificial recharge systems. Some of these studies described the advantages and the benefits of using hill reservoirs in the recharge of adjacent groundwater, which act as efficient mechanisms for preserving water resources compared with separate water storage facilities that allow evaporation but not groundwater recharge (Montoroi et al. 2002). Indeed, in El Gouazine watershed (Central Tunisia) after the building of dams, the water table has risen and has become accessible for pumping. This prediction was partly confirmed by the quantification of groundwater balance surrounding a hill reservoir using a water budget modeling (Grünberger et al. 2004).

The importance of groundwater recharge dams has been identified by many other authors. Haimerl 2006 evaluated the efficiency of this recharge process and used the results to develop a method for calculations of recharge efficiency downstream of dams. A case study and a comparison of the situation without and with a dam prove the benefit of the artificial groundwater recharge. Zammouri and Feki (2005) described the methodology used to estimate the competence of a small upland reservoir of Olga in the Nadhour–Sisseb Basin, built for artificial groundwater recharge. In this study, the water balance of artificial recharge operations indicated the infiltration of about 96% of the released water volume. The simulation of an additional water release of 51% over a decade showed an additional rise of the water table of about 7.5 m. The computed mixtures using isotopic mass balance techniques in this basin reveal that the dam water contribution to the groundwater reservoir ranges between 42 and 86%. This evaluation was confirmed by ^3H contents and ^{14}C activities in groundwater downstream of the dam (Kacem 2008).

On the other hand, dams and other water projects have affected irreversibly the hydrology of many basins. Some of these impacts and disadvantages are the disturbance of natural recharge, the degradation of groundwater quality and the decrease of the river capacity downstream of the basin (Barbier 2002; Dassi et al. 2007). The aquifer of Zérout (southern part of the Kairouan Plain, Central Tunisia) has also undergone an imbalance of its hydrodynamic mechanisms and a modification of water quality during the last 30 years since the building of the Sidi Saad Dam (Nazoumou 2002; Jeribi 2004; Bel Haj Salem 2006). Therefore, the long-term withdrawal from these resources has already resulted in serious trouble: drop of the regional water table and intense mineralization of groundwater.

Though several dam water release operations have been made in this basin aiming at artificial groundwater recharge, a continuous decrease of the water table is still observed downstream of the basin. Moreover, irrigated agricultural areas have been created around the dam lake enhancing the constraint on water storage, which has to provide for irrigation needs and artificial recharge with a priority to agriculture.

In this paper, stable isotopic techniques have been applied to locate occurrences and trace movements of natural and artificial recharged waters in this basin. The concern of the present study is mainly the various aspects of recharge in the Zérout Basin and its goals are threefold: (1) to characterize the groundwater geochemistry; (2) to identify the recharge and discharge zones; (3) to plan water dam storage management to contribute to alluvial aquifer recharge.

This study analyzes the effect of the Sidi Saad Dam on the recharge of the Zérout aquifer. It may, in future, help decision makers and planners design in such a way to optimize artificial recharge regulations.

Site description

The Zérout Basin is located in Central Tunisia (southern part of the Kairouan alluvial plain) and extends over an area of 1,500 km². It is bordered by the Draa Affane Mountain and the Merguellil Basin in the north, by sebkhet Chrita and Mechertat in the south, by sebkhet Kelbia in the east and by the mountain chain of Siouf and Cherahil on the west (Fig. 1). This region is characterized by a semi-arid climate with a hot dry summer and a cold wet winter. The mean annual precipitation is 300 mm and the mean annual temperature is 20.4°C. The mean annual evaporation far exceeds the annual rainfall with a mean annual amount of approximately 1,600 mm measured from 1991 to 2006. This aridity increases toward the west and the south of the plain.

The hydrologic network in the Kairouan alluvial plain consists of two main perennial rivers (locally known as wadi): the Merguellil Wadi and Zérout Wadi (Bouzaiane and Laforgue 1986). The source of these wadis is located in the highland zones close to the Algerian border.

From a geologic point of view, the oldest outcrops in the study area are the Cretaceous deposits. These Eocene–Oligocene series are found in the surrounding mountain of Jebel Cherahil and Siouf. Limestone and marly limestone deposits of Neocene are located in Draa Affane. Inside the plain, Quaternary deposits are represented by alluvial and crust limestone. These deposits are covered by an eroded Quaternary fluvial crust of variable thickness composed mainly of coarse sand (Bedir 1995; Yaich 1984).

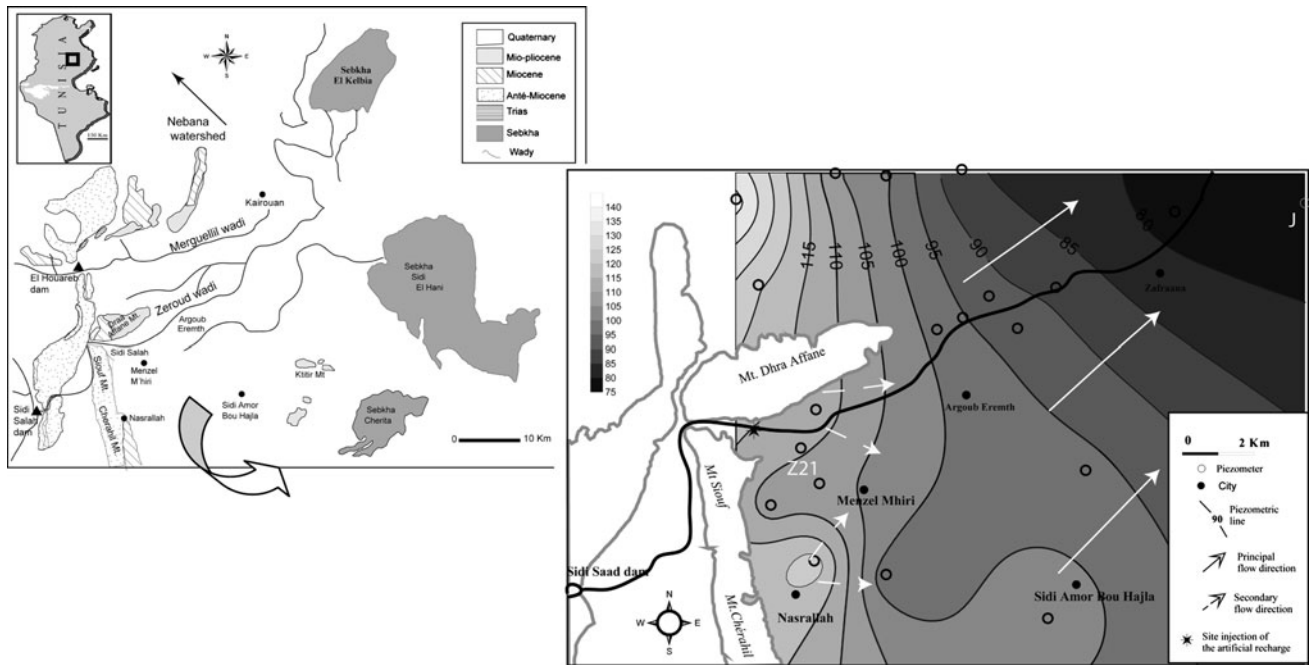


Fig. 1 Location of the study area

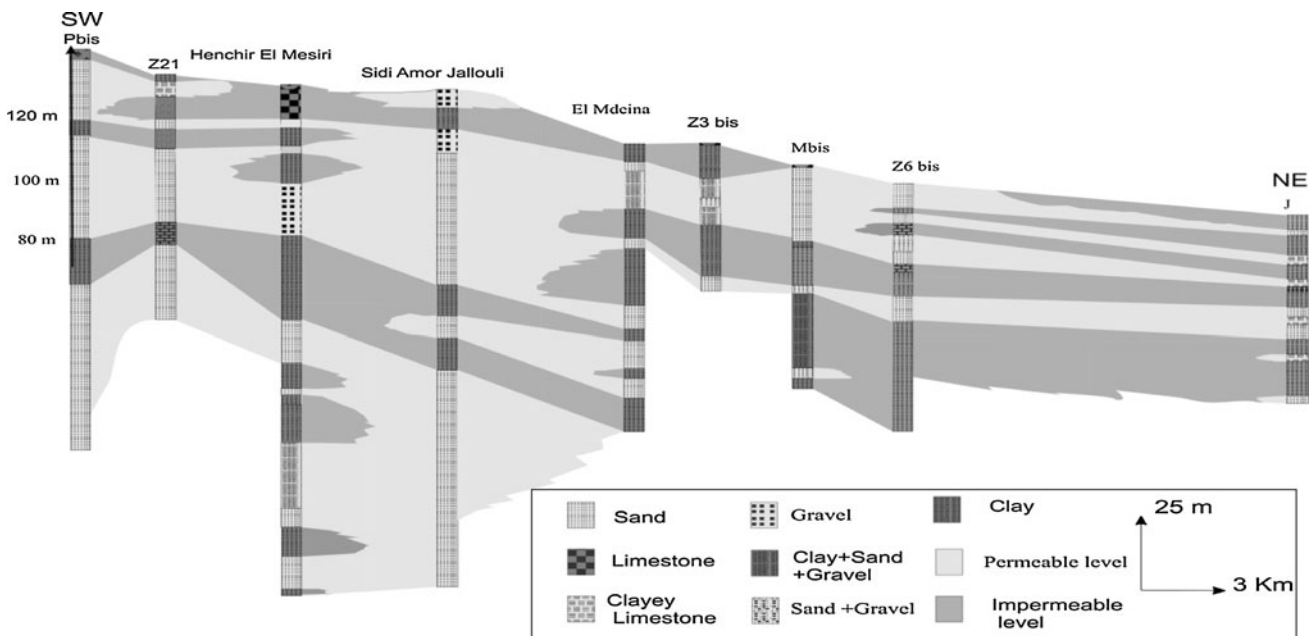


Fig. 2 Hydrogeological cross section in the Zéroud Basin

Hydrogeologically, the Zéroud aquifer basin is hosted in Plio-Quaternary continental detrital deposits marked by lenticular sedimentation of sand alternated with clays (Fig. 2). The first upper sandy level is capped by several wells (5,000 in the Kairouan Plain). Several boreholes capted the others levels until to 500 m of depth. The various superposed aquiferous horizons are separated by semi-permeable levels increasing from west to east. Under the

wadi's bed, the water level is located at more than 60 m of depth upstream and <10 m downstream. In the central and western parts of the plain, communication and mixture between groundwater levels seem to be possible.

The piezometric map of the water table shows that the groundwaters converge southwest–northeast parallel to the Merguellil and Zéroud Wadi courses (Fig. 1). In the western part of the basin, in the Argoub Eremth area, the

piezometric map shows concave lines and a divergence of flow lines from the Z eroud Wadi axis, which indicates a local contribution of surface water in recharging the aquifer system. This highlights the recharge of the aquifer in this region during the artificial recharge planning.

Toward the eastern part of the region, flow lines shift to the SSW–NNE direction, with a uniform hydraulic gradient, and groundwater discharges mainly in the Sebkhia Kelbia depression.

The Sidi Saad Dam

In 1982, the Sidi Saad Dam was built, with a capacity of $154 \times 10^6 \text{ m}^3$, on the Z eroud Wadi to protect the town of Kairouan against floods as those of 1969, which caused more than 130 deaths, and also to develop irrigation in the downstream area. Before the dam building, runoff represented the major source of the aquifer recharge. An example of natural refill is given by the exceptional groundwater level rising up to 2–11 m, observed as a consequence of the 1969s flood, which was gauged in the Sidi Saad station as $17 \text{ m}^3 \text{ s}^{-1}$.

Since 1989, many artificial recharge operations from dam water have been organized to insure the groundwater recharge as major interventions in the massive watershed development program undertaken in the country. These dam releases are carried out during short-term recharge programs, according to water resources available in the dam lake. Most significant releases have been carried out after high precipitation rate of January 1990 (Table 1). Between 1991 and 1997, nearly 356 Mm^3 were mobilized from dam water storage. During the current period (1997–2007), release operations were realized with less significant volumes lower than 20 Mm^3 , through the Sidi Salah gate that transfers a flow ranging between 1 and $1.5 \text{ m}^3/\text{s}$ directly to a preferential infiltration zone in the Z eroud riverbed. Indeed, most of the released water can be lost by evaporation or by non-beneficial vegetation growth in the river. The injected volume during the dam water release of May 2005 was 13 Mm^3 . This artificial recharge operation continued until September 2005.

Sampling and analytical methods

Chemical analysis for major elements was conducted on 13 surface waters and 30 wells and drillings. Sampling has been carried out with a time step of 15 days during the release period of May to September 2005 and was continued monthly until December 2005.

Water temperature, pH and electrical conductivity (EC) were measured in the field. Water samples were filtered

Table 1 Hydraulic evolution of the Sidi Saad Dam

Years	Rainfall (mm)	Evaporation (Mm^3)	Irrigation (Mm^3)	Releases (Mm^3)
1981/1982	149.9			0.0
1982/1983	237.7			0.7
1983/1984	193.7			1.0
1984/1985	221.0	8.9		0.4
1985/1986	138.0	13.1	2.9	3.2
1986/1987	167.9	14.1	5.5	1.8
1987/1988	137.5	15.4	6.0	12.5
1988/1989	145.1	13.2	5.2	19.4
1989/1990	551.5	15.2	2.2	163.0
1990/1991	285.4	20.6	1.6	78.4
1991/1992	359.1	18.4	2.2	25.4
1992/1993	197.9	21.7	2.7	46.2
1993/1994	182.5	12.2	9.7	25.3
1994/1995	215.1	19.1	14.3	28.7
1995/1996	406.9	16.9	5.7	105.5
1996/1997	153.3	16.1	18.4	11.0
1997/1998	330.0	14.4	20.3	14.5
1998/1999	205.6	15.5	19.4	9.7
1999/2000	198.3	11.0	19.3	6.7
2000/2001	129.8	15.0	20.1	2.8
2001/2002	215.3	13.1	17.8	14.8
2002/2003	290.4	14.6	29.8	6.6
2003/2004	308.2	9.5	29.9	6.6
2004/2005	245.2	15.6	36.6	14.3
2005/2006	233.1	18.2	35.4	11.6
2006/2007	234.2	15.5	31.9	0.0

($0.45 \mu\text{m}$) and collected in 100-ml polyethylene bottles. Total dissolved solids (TDS) were determined by evaporating the sample and drying it at 105°C . Hydrochemical analyses were undertaken in the ‘‘Laboratoire de Radio-Analyses and Environnement’’ Sfax, Tunisia. Major cation concentrations were measured on a Waters ion chromatograph using IC-PakTM CM/D columns. Major anion concentrations were measured using a Metrohm ion chromatograph equipped with CI SUPER-SEP columns. The analysis of bicarbonate was undertaken by titration to the methyl orange end point.

Stable isotope ratio ($^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$) analyses were performed between May 2005 and April 2007 in 11 surface waters and 30 wells and drillings. These analyses were carried out with mass spectrometer and the results are expressed in ‰ compared to the international standard VSMOW. The measurement precision for stable isotope analysis is about of $\pm 0.15\text{‰}$ for oxygen 18 and $\pm 2\text{‰}$ for deuterium. In April 2007, 18 measurements (15 wells and 3 surface water) of tritium were conducted (Table 2). Tritium contents, expressed in units of tritium (TU), and stable

Table 2 Chemical and isotopic properties of selected groundwater samples

Samples	pH	EC (mS cm ⁻¹)	T (°C)	¹⁸ O‰ vs. V-SMOW	² H‰ vs. V-SMOW	³ H‰ (TU)	Cl (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)	CO ₃ (mg/l)	HCO ₃ ⁻ (mg/l)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	TDS (mg/l)	δ ¹⁸ O balance
w1	7.50	2.70	21.30	-5.98	-37.06	0	292.7	6.8	737.2	0.0	130.0	320.0	15.8	77.5	105.2	1,829.0	4.4
w2	7.90	3.03	20.70	-5.98	-36.47	0	541.1	4.3	813.2	0.0	127.0	350.0	17.9	102.1	144.5	2,100.0	4.4
w3	7.65	3.28	21.40	-4.90	-31.66	2	360.0	7.4	1,031.8	0.0	113.0	325.0	12.3	121.0	180.0	2,350.0	26.3
w4	7.50	3.28	21.50	-5.40	-34.82	0	417.2	5.3	834.5	0.0	169.0	350.7	12.4	101.2	157.5	2,232.0	16.2
w5	7.40	3.07	21.10	-5.68	-35.39	0	499.2	5.7	770.2	0.0	155.0	322.6	12.9	99.1	146.7	2,092.0	10.5
w6	7.40	2.71	21.70	-5.89	-36.93	0	412.9	6.4	713.9	0.0	149.0	238.5	10.0	74.0	300.0	1,886.0	6.3
w7	7.50	3.06	21.90	-6.10	-37.42	0	366.3	10.0	840.0	0.0	135.0	266.6	14.0	103.5	194.5	2,142.0	2.0
w8	7.50	3.23	22.00	-4.40	-27.35	6	278.8	2.1	1,100.0	0.0	115.0	317.4	9.2	85.6	242.0	2,386.0	36.4
w9	7.70	2.73	20.10	-5.78	-35.80	0	444.7	6.4	730.5	0.0	143.0	304.2	12.7	83.0	148.3	1,875.0	8.5
w10	7.52	3.31	21.80	-5.61	-34.48	0	347.0	7.0	882.2	0.0	195.0	160.0	12.2	187.4	116.3	2,277.0	11.9
w11	7.63	3.36	21.60	-5.49	-35.14	0	309.4	5.8	954.4	0.0	185.0	369.3	12.1	105.0	102.7	2,355.0	14.3
w12	7.65	2.04	21.00	-6.20	-38.51	7.2	134.3	5.0	625.0	0.0	175.0	195.0	8.3	54.8	132.5	1,427.0	0.0
w13	7.60	2.59	21.50	-5.61	-34.19	15.2	264.6	3.7	772.5	0.0	122.0	277.8	12.3	78.5	146.2	1,889.0	11.9
w14	7.53	3.14	21.70	-5.65	-35.68	2.5	294.6	6.7	949.2	0.0	140.0	321.7	13.0	108.3	167.5	2,240.0	11.1
w15	7.49	3.20	22.10	-5.80	-35.70	0	443.2	9.8	900.0	0.0	201.0	341.0	11.2	99.5	177.7	2,218.0	8.1
w16	7.52	3.15	21.80	-5.84	-35.44	0	371.7	10.4	954.9	0.0	180.0	298.4	13.8	112.6	176.2	2,303.0	7.3
w17	7.55	2.82	21.90	-5.75	-35.70	0	622.8	6.6	600.0	0.0	129.0	350.0	4.0	92.5	242.5	1,972.0	9.1
w18				-4.25	-29.75		1,744.0	10.4	1,384.3	0.0	189.0	815.0	21.1	180.0	658.0	5,063.0	39.4
w19	7.48	2.82	21.90	-5.47	-33.90	0	525.0	1.8	614.3	0.0	209.0	275.3	9.3	99.5	162.8	1,919.0	14.7
w20	7.45	2.41	21.20				347.6	1.9	685.2	0.0	174.0	189.6	7.6	86.8	177.2	1,676.0	
w21	7.21	2.95	17.70				529.3	1.6	816.7	0.0	124.0	346.0	14.1	92.0	160.0	2,002.0	
w22	7.54	4.03	20.40	-5.34	-34.01	0	700.0	2.3	1,010.8	0.0	118.0	482.6	15.7	114.1	166.7	2,757.0	13.9
w23	7.70	2.72	18.20				430.0	2.1	770.0	0.0	134.0	264.5	12.2	77.5	191.5	1,867.0	
w24	7.83	3.19	18.90	-6.14	-38.19	0	393.0	1.9	885.9	0.0	111.0	337.1	13.9	93.5	175.1	2,186.0	1.0
w25	7.60	2.83	22.90				304.9	4.4	812.6	0.0	201.0	349.9	12.2	80.2	121.1	1,926.0	
w26	7.47	2.68	22.00				362.5	3.2	743.1	0.0	139.0	266.2	12.5	85.6	146.3	1,863.0	
w27	7.45	3.90	22.70	-4.97	-31.77	0	842.3	1.4	581.1	0.0	182.0	410.1	11.2	114.2	185.7	2,625.0	24.8
w28	7.67	2.94	22.40	-5.57	-35.55	1.1	296.7	4.6	1,025.0	0.0	160.0	310.4	13.0	99.5	151.4	2,070.0	10.2
w29	7.65	1.59	19.90	-5.46	-36.55	0	121.3	0.8	288.9	0.0	258.0	240.9	7.3	27.6	42.0	985.0	
w30	7.55	2.74	22.90	-5.26	-34.28	0	362.5	3.7	640.0	0.0	170.0	425.0	11.4	67.5	94.9	1,852.0	15.2

isotopes were analyzed by the Laboratory of Hydrogeology of Avignon in France (Table 3).

Results and discussion

Hydrodynamic response to artificial recharge

Most of the release operations in the studied area took place after irrigation supplies were scarce, in summer periods during which a high amount of water could be lost by evaporation. In order to quantify the actual evaporated volume during groundwater recharge, daily water level of the lake dam were measured and assumed as an approximate evaporation rate for the evaporating surface (mm). Given the extension of the wet area in the riverbed, a daily evaporated amount could be estimated and cumulated over the recharge period.

This approach allowed calculating that about 0.15 Mm³ of the 13 Mm³ released in the riverbed was lost by direct evaporation. The remaining volume was assumed to infiltrate through the soil. However, another evaporation process through the unsaturated zone has to be considered after the submersion period.

Indeed, summer is probably not the best period for the practice of artificial recharge, when high quantity of injected water could be lost in the unsaturated zone and the response of the table water would be very low.

Many studies have demonstrated that the infiltration rate, during groundwater recharge, depends also on the soil type, the water level of the submersed area, the wet area and the duration of surface wetting (Haimerl 2006). During 5 months of this release, an area 5 km from the site injection in the Z eroud riverbed was continuously submersed, which could increase the percolation rate by reducing the evaporation through the vadose zone, and was probably the area most influenced by dam water (Fig. 3).

Water table response to dam water releases was investigated in 16 boreholes in the studied zone. The mapping of groundwater level response (Fig. 4) shows that the rise in table ranged between 0.2 and 5.25 m up to a distance of 8 km away from the injection site along the main flow path, and up to 4 km toward the south of the basin along a secondary flow path. Consequently, we can consider this area to be part of the basin that is largely influenced by dam water. As shown also by this map, the response is more significant in the right rive of the Z eroud Wadi, which is in part explained by the slope and the type of the sediments traversed by the water.

The response time lags (in days) yield significant correlations with the distance to injection site (Fig. 5). Most important responses of the water table were observed during August and September 2005 when the release flow

Table 3 Chemical and isotopic proprieties of selected surface water samples

Samples	pH	EC (mS cm ⁻¹)	T (�C)	¹⁸ O‰ vs. V-SMOW	² H‰ vs. V-SMOW	³ H‰ (TU)	Cl (mg/l)	NO ₃ (mg/l)	SO ₄ (mg/l)	CO ₃ (mg/l)	HCO ₃ (mg/l)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	TDS (g/l)
Sidi Saad Dam June	8.0	2.4		-1.6	-13.4		749.0	0	1,521.0	0	170.8	426.4	0	107.4	519.6	3.5
Injected water June	7.6	3.6		-1.8	-15.5		572.8	0	1,221.1	0	244.0	387.3	0	84.6	396.9	2.9
Injected water July	7.8	2.8	26.1	-1.5	-13.2		680.7	0	1,009.2	0	97.6	426.1	0	85.8	411.8	2.7
Sidi Saad Dam September		3.2		-0.8	-9.5		618.4	0	1,029.9	0	97.6	457.9	0	78.9	355.0	2.6
Injected water October	7.2	3.8	23.1				665.5	0	991.3	0	122.0	405.5	0	92.4	408.6	2.7
Sidi Saad Dam October	7.8	3.8	22.3	-0.9	-9.3		575.3	0	1,168.4	0	176.9	459.1	0	88.4	395.2	2.9
Sidi Saad Dam January	7.5	3.5		-2.1	-14.6		440.8	0	1,181.2	0	73.2	332.3	0	72.5	400.5	2.5
Injected water December	7.1	4.0	8.3				449.1	0	1,285.7	0	97.6	358.3	0	82.3	455.8	2.7
Sidi Saad Dam December	7.2	3.8		-0.9	-9.3		459.2	0	1,355.3	0	122.0	370.2	0	80.1	462.6	2.8
Sidi Saad dam April	8.2	4.1	16.5	-1.1	-13.4		640.3	0	1,478.2	0	87.0	430.5	11.1	98.6	368.5	3.1
Injected water April	7.7	4.1	17.2	-1.3	-14.1	3.9	404.4	0	1,453.1	0	100.0	437.4	12.7	99.4	385.0	3.1
Sidi Saad Dam March	8.1	5.0	13.8	0.0	1.9	2.9										
Injected water March	8.0	5.0	14.5	-0.4	2.4	3.9										

exceeded 0.1 Mm³/day. Besides, injected water needs more than 4 months to reach the aquifer.

Geochemical response to release operations

The overall chemical characteristics of water show a contrast between reservoir water and groundwater. TDS and the electrical conductivity (EC) of surface water range from 2.5 to 3.7 g l⁻¹ and from 2.4 to 5 ms cm⁻¹. Reservoir water is highly sulfated with contents ranging from 1,020 to 1,520 mg l⁻¹ and weakly carbonated with a mean alkalinity equal to 128 mg l⁻¹. All pH values are weakly basic in surface water including dam water and nearly neutral for groundwater. TDS and EC of groundwater vary from 0.985 (w29) to 5,063 (w18) g l⁻¹ and from 1.6 (w29) to 6.7 (w18) ms cm⁻¹. Alkalinity in all groundwater samples is highly variable ranging from 111 (w24) to 258 (w29) mg l⁻¹. Moreover, chemical signals of dam water and groundwater are distinctive and can serve as ideal tracers of water origins in the aquifer.

To distinguish water types and to discern processes that control groundwater chemical properties, an expanded Durov diagram, developed by Lloyd and Heathcote (1985), was applied on data obtained by chemical analysis performed on a representative number of groundwater and surface water samples (Fig. 6). Many authors have discussed the significance of the nine subfields on the expanded Durov diagram. In general, samples falling in field 1 indicate recharging waters of the HCO₃-Ca hydrochemical type; fields 2 and 3 indicate ion exchange and tendency to water mineralization by enrichment of Na, HCO₃. Samples collected from the Zéroud River and El Houareb Dam (north part of the Kairouan Plain) are located in field 4, which indicate dissolution of carbonate minerals. Sidi Saad Dam water and rainfall samples are located in field 5, reflecting sulfate type of recharging water. Most of the groundwater samples are also plotted in this field showing mixture processes with surface water. These groundwaters are located near the wadi in the upstream zone and in the central basin and could be influenced by recharging waters, indicating the role of liner recharge in the upstream and the center of the basin in the alimentation of the upper aquifer. Samples in field 6 indicate probable composite influences of different water origins; these waters are sampled from the southwestern basin where the most irrigated zones are located. In fact, different waters are used in this district for irrigation: they are represented by the dam water and the groundwater. Groundwater samples falling in fields 8 reflect reverse ion exchange of Na⁺-Cl⁻-waters. Reverse ion exchanges is a common feature of waters characterized by high mineralization, and this process typifies wells situated in the downstream and southern basins.

During groundwater recharge of May 2005, the chemical signature of groundwater has been trending to dam water facies. Sulfate concentrations in recharge area increased. The majority of the significant responses were observed in September 2005, which marked the dam water percolation in the aquifer characterized by increased sulfate concentrations, while variation in the other wells was weak (Fig. 7). Consequently, it can be suggested that given a volume of 13 Mm³ and a flow of 1 m³s⁻¹, dam water needs at least 4 months to reach the aquifer. However, the variation of groundwater mineralization at this recharge period was minute, which indicates that actually aquifer salinization by injected dam water is weak, but if volumes injected from the evaporated water dam into the aquifer become more significant, we may possibly confront this problem.

Recharge tracing based on CO₂ pressure

Surface water exchanges gases with the atmosphere, which makes its CO₂ pressure (*p*CO₂) lower, ranging around 10^{-3.5}. However, *p*CO₂ values in groundwater are, in general, significantly higher than that of the atmosphere. The CO₂ partial pressure in water is strongly related to the respiration of plant roots and microbes in soils. Indeed, when the aquifer is open to the atmosphere, the exchange is possible and *p*CO₂ in groundwater can vary mainly according to exchange of fluxes and temperature. *p*CO₂ commonly decreases after heavy rainfalls and shows reverse variation with groundwater level elevation (Macpherson et al. 2008).

In this study, *p*CO₂ data are used to identify modern recharge and groundwater mixing in the Zéroud Basin. The difference between CO₂ pressure values of dam water and those of groundwater can give invaluable indications on recharge mechanisms. This method consists of comparing calculated *p*CO₂ in groundwater samples at the recharge period with those at the natural stage.

The temperature, pH and geochemical composition of the waters were treated with PHREEQC (Parkhurst and Appelo 1999) to calculate the partial pressure of CO₂ (log *p*CO₂) and saturation state of the water.

Spatial distribution of *p*CO₂ during artificial recharge (recharge operation of May 2005) indicates that the injection of dam water controlled carbonates balance in the aquifer. During June, when dam water had not yet arrived at the aquifer and biological activities had enriched groundwater with CO₂, the CO₂ pressure values remained high ranging between -1.5 and -1.6 downstream of the Zéroud River (Fig. 8a). After 4 months, beginning from September, groundwater CO₂ pressure values near the site injection were reduced due to the percolation of dam water, characterized by a low *p*CO₂ (Fig. 8b, c).

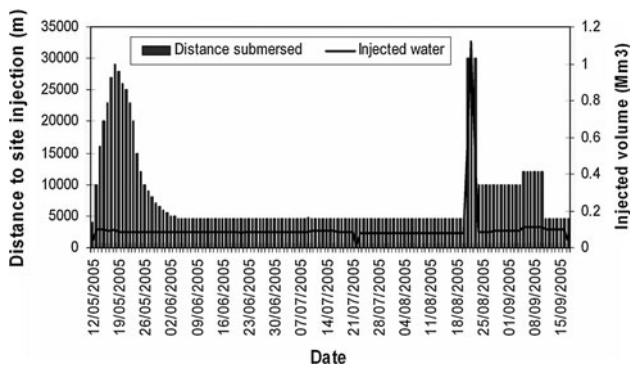


Fig. 3 Relationships of submersed distance/time at the groundwater recharges operation of May 2005

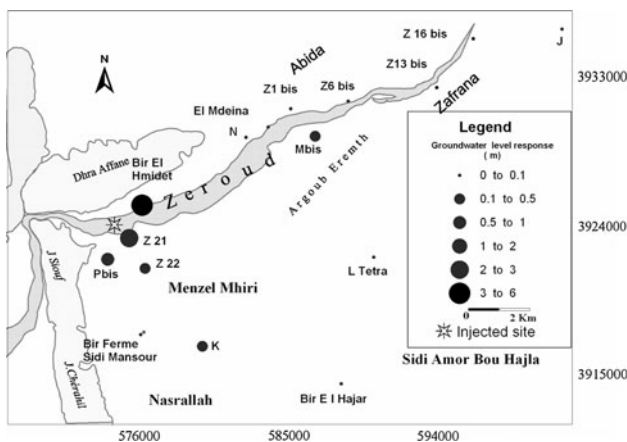


Fig. 4 Mapping of groundwater level response to artificial recharge

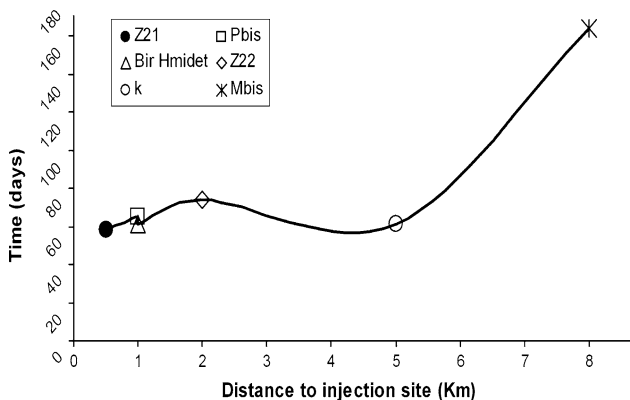


Fig. 5 Relationships of distance to injection site/time

The artificial recharge influence could be identified according to the extension of pCO_2 decrease between June and December. The Argoub Eremth area where this influence is well defined extends over a length of ten km and an average width of about 4 km, upstream of the plain, directly downstream of the injection site.

Spatial distribution of pCO_2 during April 2007 (Fig. 9) has been considered as a reference state. This clearly

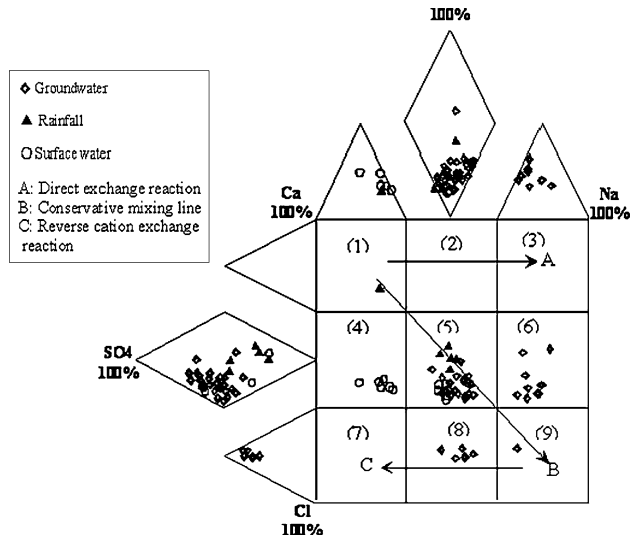


Fig. 6 Expanded Durov diagram of groundwater and surface water samples in the study area

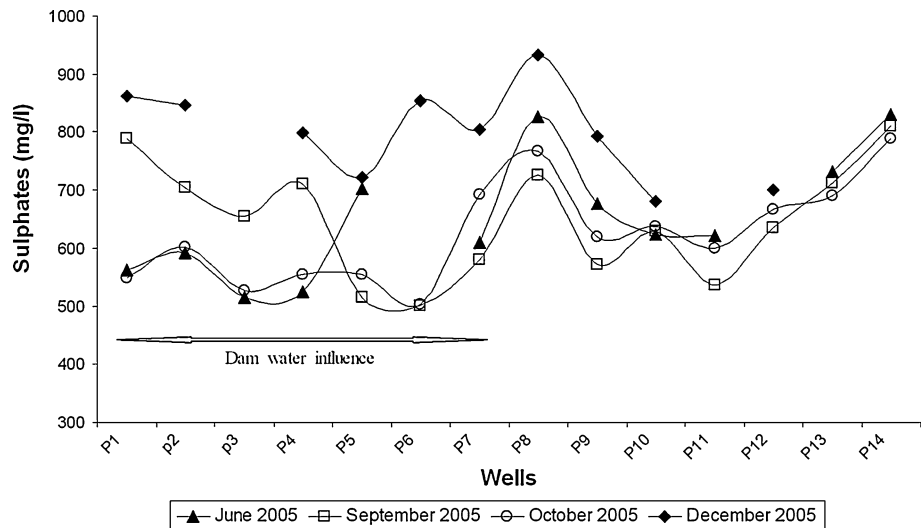
indicates that the high contents of pCO_2 are related to old waters; however, the low concentrations lead to recharge process. Three types of groundwater could be distinguished: (1) fresh groundwater with lower pCO_2 levels upstream the plain close to the injection site and that could be explained by the influence of the recharge operations; (2) groundwater with higher pCO_2 levels reflecting longer residence times in the downstream part and (3) mixed groundwater with low pCO_2 values located in the most irrigated zone, such as the Menzel Mhiri area. In the later district, pCO_2 values fluctuate slightly from a month to another according to the exploitation. In fact, this return flow is strongly suggested considering the relatively low depth of the upper aquifer water table in the mentioned region.

We can assume according to the chemical study that the sulfates and pCO_2 can be considered as good tracers to identify different water origins and are useful in the comprehension of the recharge process in the Zéroud Basin.

Stable isotopes (^{18}O and 2H)

The local meteoric line calculated from precipitations higher than 5 mm in El Ogla (60 km in the north of Kairouan) by imposing a theoretical slope of 8, reflecting the equilibrium thermodynamic conditions during condensation is $\delta^2H = 8 \times \delta^{18}O + 10.75$ (Gay 2004; Jeribi 2004; Ben Ammar et al. 2006). This local meteoric water line (LMWL) is relatively similar to that of Tunis and Sfax, as in, whose deuterium excess calculated for a slope of 8 is 11%. Sidi Saad dam water has been monthly sampled and analyzed at the recharge period. Stable isotope values

Fig. 7 Evolution of groundwater sulfate contents during artificial recharge



range from 0 to -2.1‰ for oxygen 18 and between -1.9 and -14.6‰ for deuterium, indicating the effect of the evaporation process. Even if stable isotope contents show seasonal variations, they remain in the same range and we assume a mean value of -1.25‰ for oxygen 18 and of -11.41‰ for deuterium.

Values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for dam water and groundwater samples are plotted in Fig. 10. Most of the groundwater samples are located near the global meteoric water line ($\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 10$) and the LMWL suggesting that they are derived from infiltrated precipitation, which had not been subjected to surface or subsurface alteration. Dam water samples show ^2H and ^{18}O enrichment, which is typical for water that has been submitted to open surface evaporation (AIEA 2004; Blavoux 2000). The slope of the trend line is nearly 5 as recognized for evaporation effect. Groundwater sampled in the right rive of the Z eroud Wadi are plotted along this evaporation line suggesting mixture with enriched dam water (Fig. 10).

The average studied groundwater isotopic contents is about $-5.6 \pm 0.33\text{‰}$ for oxygen 18 and $-34.6 \pm 2.96\text{‰}$ for deuterium. Indeed, moving from the site of injection of dam water, groundwater becomes more and more depleted in isotope signatures, indicating a strong influence of dam water up to a distance of about 10 km, beyond of which oxygen 18 contents remain constant marking the isotopic groundwater signature (-6.1‰).

Based on ^{18}O contents, dam water contribution to the aquifer recharge has been quantified. Indeed, groundwater in the Z eroud Basin represents mixtures of the deep aquifer component with the recent dam water. Isotopic compositions can permit mass balance quantification of each involved component and the equation of the mass balance is therefore formulated in the following equations

$$X_1\delta_1 + X_2\delta_2 = (X_1 + X_2)\delta_3$$

where X_1 and X_2 represent the contribution fraction of the deep groundwater and the dam water, respectively. These two waters are taken as end members where the resulting mixed waters should plot at intermediate positions between the two poles.

δ_1 , δ_2 and δ_3 represent the isotopic compositions (^{18}O) of the deep groundwater, dam water and the mixed water, respectively. Knowing that $X_1 + X_2 = 1$ and by rearranging the mass balance equation, we get $X_2 = (\delta_3 - \delta_1 X_1) / \delta_2$, which represents the dam water contribution fraction.

Average computed mixing values obtained for $\delta^{18}\text{O}$ were consequently used as a convenient way to approach the resulting mixed waters with variable isotopic signature plots along the mixing line at a distance proportional to the dam water contribution fraction (Fig. 11).

This contribution decreases from 39% near the injection site to 0% up to 20 km away. Hence, we assume that an average of 13% of total aquifer volume in the sampled area comes from dam water through the Sidi Salah gate, which is 152 Mm^3 .

Since 1982, 390 Mm^3 has been released from the dam. Only 39% of the released water had reached the water table, while the remaining amount evaporated and/or was stored in the unsaturated zone. This suggests that after the building of the Sidi Saad Dam, the recharge will be more localized and more than half of the low volume injected during the groundwater recharge operations is lost by the evaporation process. This evaluation was confirmed by the spatial distribution of the ^3H contents in the groundwater downstream of the dam (Argoub Eremth area).

Tritium content

Tritium is a reliable tracer of water flow, which provides an indication for average residence time of water. Its short

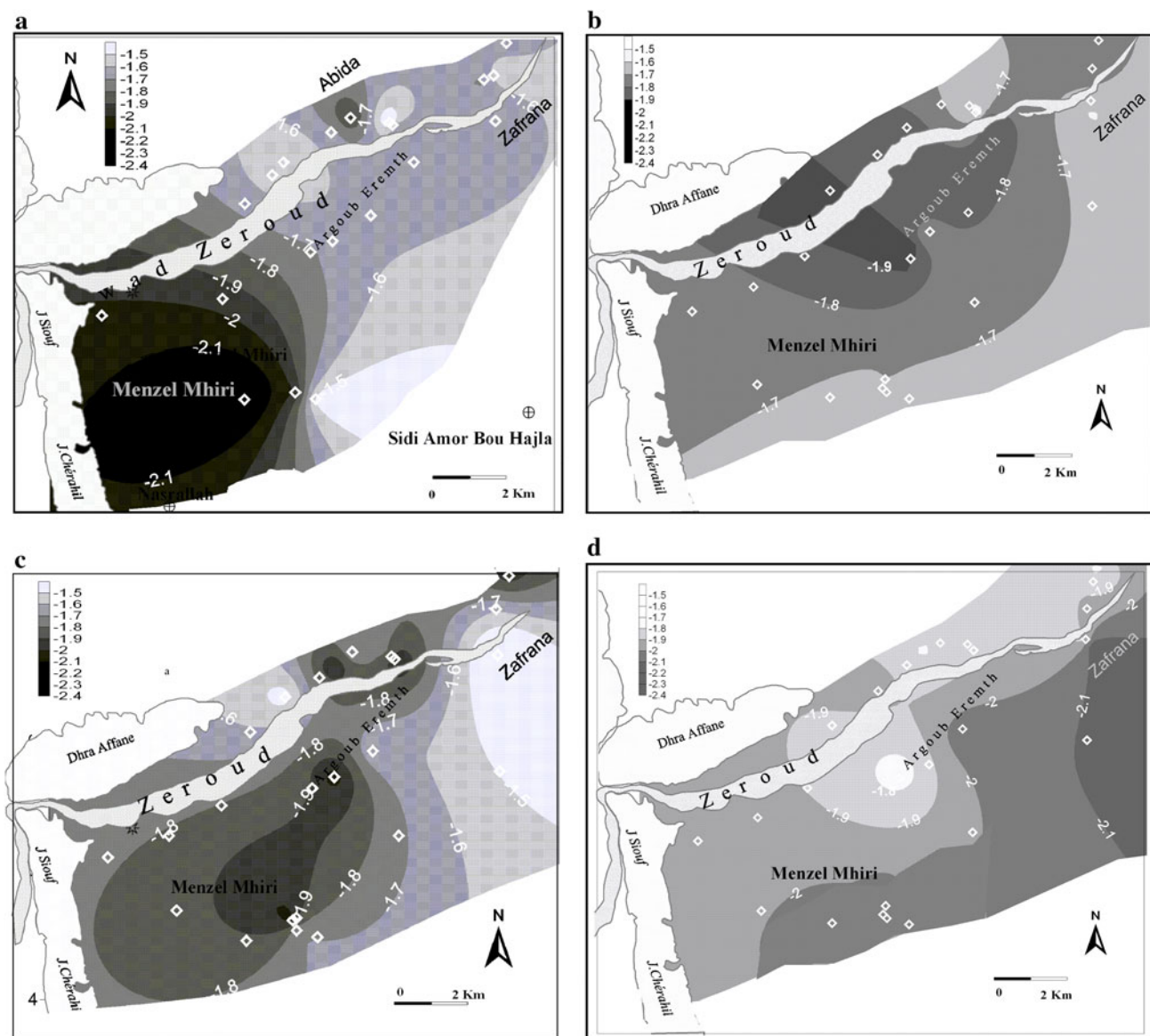


Fig. 8 $p\text{CO}_2$ spatial distributions in June 2005 (beginning of the recharge) (a), September 2005 (b), October 2005 (c) and December 2005 (d)

half-life (12.4 years) allows it to be used for relatively young waters, i.e., waters recharged <60 years ago. Estimation of relative age and evidence of the mixing process have been obtained by comparing the measured ^3H contents in the groundwater system with the long-term monitoring of rainfall ^3H input at the Sfax station where the ^3H concentrations measured during 1992–2007 varied between 2.1 and 11 TU. Indeed, recent precipitations recorded during the last 5 years have ^3H contents lower than 6 TU.

Groundwater tritium contents measured in the study area during the sampling campaign of 2007 vary in a relatively large range between 0 and 15.2. The high contents were measured along the Draa Affane relief, indicating probably that it was the signature of the rainfall that infiltrated

during post-nuclear periods, and this water had slight exchanges with the recent precipitations.

The relationship between tritium and ^{18}O contents (Fig. 12) allows identifying four types of groundwater that could be related to various recharge areas:

- The first group encloses wells influenced by dam water, located in the right rive of the Zéroud Wadi, in Argoub Eremth. These samples are characterized by strong sulfate contents (1,000 mg/l), the most enriched ^{18}O values and tritium contents ranging between 2 and 6 TU.
- The second group characterizes groundwater situated close to the wadi path, where geochemical signals are quite similar to those of the first group, but with lower ^{18}O

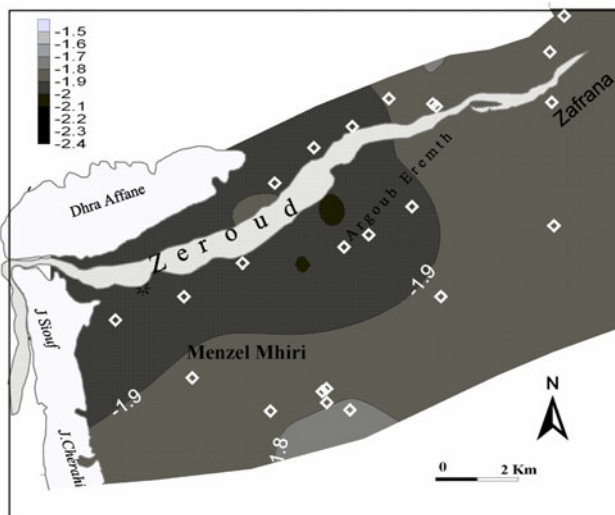


Fig. 9 Spatial distributions of pCO_2 in April 2007

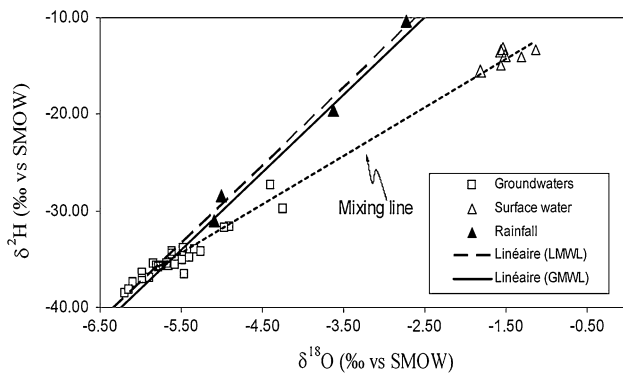


Fig. 10 Relationships $\delta^{18}O/\delta^2H$ of the groundwater in the Zéroud Basin

and sulfate ranges that have been interpreted as being indicative of the significant role of the lineal recharge through the Zéroud River during rainy periods.

- The third group involves groundwater with higher tritium contents exceeding that of recent precipitations and related to post-nuclear periods, mainly those of the late 1960s and early 1995s flooding. These groundwaters are sampled from wells located in the same area as the first group, but in the wadi's left river, and seem to be more recharged by rainfall that infiltrated along the Draa Affane relief.
- A fourth water type is located downstream of the basin toward the Zaafrana bridge and overall the southeastern part of the basin, which is marked by depleted stable isotopes contents and low 3H contents below detection limit indicating inexistent or insignificant recent water recharge.

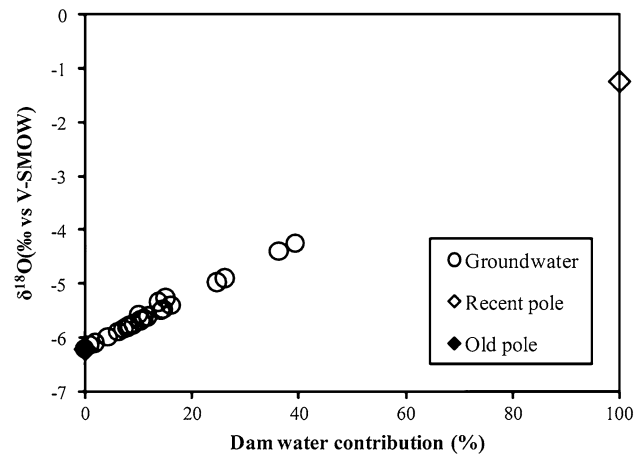


Fig. 11 Dam water computed contribution versus ^{18}O contents

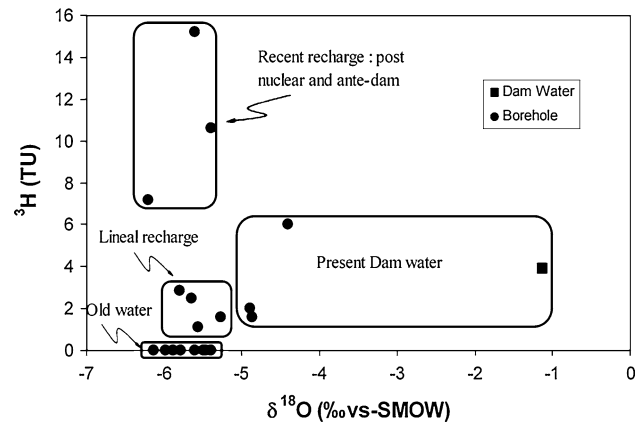


Fig. 12 Relationships of $\delta^{18}O/^3H$ of the groundwater in the Zéroud Basin

Conclusions

An attempt has been made to examine the effect of water storage structures on groundwater recharge in a semi-arid agroclimatic setting. Geochemical and isotope contents of the dam water and groundwater in the Zéroud Basin, recorded during an artificial recharge operation, have provided useful information regarding the mechanism of recharge and residence time of groundwater. The time for the water table response to dam water injection has been found to be more than 4 months according to chemical evolution of groundwater. On the other hand, the spatial contribution of dam water in recharging the groundwater has been evaluated by $\delta^{18}O$ values variation along a flow line. Results indicate a significant influence up to a distance of 10 km. Stable isotope ratios in combination with dissolved ions and tritium contents allowed tracing several distinctive recharge waters in the studied zone. The influence of dam water in the aquifer recharge is clearly

observed in the right rive of the river, in Argoub Eremth area. While, the local meteoric recharge is restricted to the left rive along the Draa Affane relief. Distinctive isotope signatures highlighted the significant role of lineal recharge insured by the Zéroud Wadi during rainy periods. The computed mixtures using isotopic mass balance techniques demonstrate a contribution of about 13% of the dam water to the aquifer water suggesting that only 39% of the released water percolates to the aquifer.

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