Probing the relationship between surface waters and aquifers by ^{18}O measurements on the top of the Araripe Plateau/NE Brazil

Luiz Alberto Ribeiro Mendonça · Horst Frischkorn · Maria Marlúcia Freitas Santiago

Josué Mendes Filho

Abstract The Araripe Plateau in northeastern Brazil has an area of about 8,000 km^2, confined by 39°05′E and 40°55′E, and 7°10′S and 7°50′S. Due to high permeability of soils, a surface drainage system is practically inexistent. Water is stored in excavations with clayey soil, the "barreiros". Monthly samples were taken for ^{18}O measurements, from September 1999 to August 2000, from four barreiros, three dug wells and five drilled wells. Results show that (1) groundwaters in the eastern part of the plateau are derived from present-day rainfall ($\delta^{18}O \approx -3.2‰$), whereas groundwaters in the western portion are isotopically different ($\delta^{18}O \approx -5.0‰$); (2) barreiros are strongly marked seasonally by elevated $\delta^{18}O$ during the dry period due to elevated evaporation; (3) a dug well at a distance of ≈30 m from a barreiro exhibits $\delta^{18}O$ similar to that of the reservoir, indicating a strong interaction between groundwater and surface water; and (4) a tubular well of 242-m depth, located in a fault, exhibits strong seasonal changes in $\delta^{18}O$ and electrical conductivity, revealing downward leakage between aquifers.

Keywords Isotope hydrology · Oxygen-18 · Araripe Plateau · Hydraulic connections · Brazil

Received: 13 June 2003 / Accepted: 11 November 2003
Published online: 27 February 2004

L. A. R. Mendonça · M. M. F. Santiago · J. Mendes Filho
Departamento de Física da UFC, Caixa Postal 6030, CEP 60455-970 Fortaleza, CE, Brazil

H. Frischkorn (✉)
Departamento de Engenharia Hidráulica e Ambiental da UFC, Caixa Postal 6006, CEP 60455-970 Fortaleza, CE, Brazil
E-mail: cariri@ufc.br
Tel.: +85-288-9775
Fax: +85-288-9627

Introduction

The study of the interaction between surface waters and aquifers through oxygen-18 measurements was applied in the Araripe Plateau in the semiarid zone of the Brazilian Northeast. In spite of rainfall amounting to 1,000 mm, due to the high hydraulic conductivity of sandy soils there are practically no surface water resources on top of the Araripe Plateau, except for the water stored in excavations covered with clayey soil ("barreiros") trampled for impermeabilization by livestock during drought periods. Part of the rainfall water that infiltrates on the plateau is responsible for recharging the superior aquifer system. Main groundwater discharge from this system is through some 300 springs along the northern scarp of the plateau that produce about 40.5×10^6 m^3 per year (DNPM 1996). Groundwater exploitation through drilled wells in the superior aquifer system is difficult due to the average water-table depth of 120 m. However, the "Jardim" Fault, in the very east of the plateau, with an extension of about 34 km and 400 m in width in a topographic depression, defines a strip-like area where the water-table depth is only 3 m (Marques and others 1984), thus allowing the construction of dug wells.

At present, in the Araripe Plateau, there are five pioneer wells, recently drilled for exploiting the medium aquifer system with a static water level of 360 m.

The aquifers studied are subject to a regional climate that is characterized by two distinct seasons: rainfall is limited to the 5 months from February to June, and the rest of the year is practically dry.

Oxygen-18 has been used in recent years, e.g., by Matheney and Gerla (1996) and Yehdegho and others (1997), as a natural tracer to investigate the hydraulic relationship between surface waters and groundwater. McCarthy and others (1997) used deuterium and ^{18}O to study the dynamic relationship between groundwater and the Columbia River. The authors made simple mixing calculations for the determination of the contribution of the river to the water produced by five wells.

In the present study, investigating the hydraulic relationship between surface waters and groundwater, measurements of ^{18}O and electrical conductivity were used for the characterization of infiltrating, modern meteoric water, evaporated modern water from "barreiros", and aquifer water. These parameters and their seasonal variations permit the detection of mixtures and mixing ratios for these components.

Area of study

The area of study consists of a plateau, the "Chapada do Araripe", and a valley, the "Vale do Cariri", north of it (Fig. 1). The Araripe Plateau, in the interior of the Brazilian Northeast, covers an area of about 8,000 km^2, has an average altitude of 800 m, and is partitioned between the three states of Ceará, Pernambuco and Piaui. This area is delimited by the following geographical coordinates: 39°05′E and 40°55′E, and 7°10′S and 7°50′S. The Araripe Plateau coincides with the outcropping area of the Exu Formation. A schematic profile is depicted in Fig. 2.
According to Ponte and Appi (1990), the sedimentary sequence is composed, from the top to the crystalline base, by the formations Exu, Arajara, Santana, Rio da Batateira, Abaiara, Missão Velha, Brejo Santo and Mauriti. The Exu and Arajara formations compose the superior aquifer system, the Rio da Batateira, Abaiara and Missão Velha formations the medium aquifer system, and the Mauriti F. the inferior aquifer system. The first system is separated from the second by the Santana aquitard, and the inferior aquifer system is separated from the medium aquifer system by the Brejo Santo aquitard.
In the northern margin of the superior aquifer system, there is an average hydraulic gradient of $-7‰$ that induces a groundwater flow to the scarp in the Cariri Valley, where a large number of springs emerge from the geological contacts Exu/Arajara and Arajara/Santana. In the central part, groundwater flow is from east to west (SUDENE 1967; Mendonça and others 2001a), driven by a gradient of about $-2‰$. On this pathway, flow is being intercepted by manifold tectonic features.

Methodology

The $^{18}O/^{16}O$ ratio in rainfall water of a specific region depends on several factors, distance to the coast, altitude, atmospheric temperature and the amount of rainfall being the most important. Furthermore, seasonal variations and latitude dependence also are observed to affect the $^{18}O/^{16}O$ ratio. Surface water is enriched in ^{18}O due to evaporation and, therefore, in the semiarid Brazilian Northeast exhibits a strong seasonal variation in its isotopic composition. In deep groundwaters, $^{18}O/^{16}O$ is conserved and characterizes the recharge water.
Isotopic ^{18}O measurements are expressed in units of $\delta(‰)$, defined as the relative permil deviation of the isotope ratio $^{18}O/^{16}O$ in a sample from that of a standard:

$$\delta^{18}O(‰) = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} * 10^3$$

Samples were collected monthly, from September 1999 to August 2000, in four barreiros, three dug wells, and five tubular wells indicated in Fig. 1.
$\delta^{18}O$ (‰) measurements were performed at the Centro de Energia Nuclear na Agricultura (CENA) in Piracicaba/São Paulo, with a precision better than ±0.15‰, in relation to the standard VSMOW (Vienna Standard Mean Ocean Water).

Results

Barreiros and dug wells

Results for ^{18}O and electrical conductivity (EC) on samples from four barreiros and three dug wells in the east of the Araripe Plateau (see Fig. 1) are listed in Table 1, and plotted in Fig. 3b, c together with precipitation (Fig. 3a).

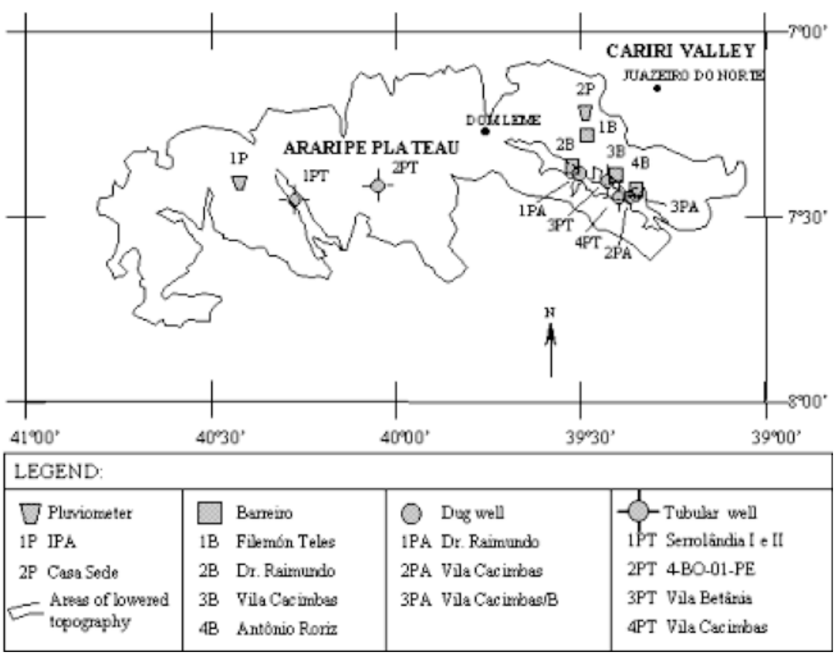

Fig. 1
Location map of the Araripe Plateau, along with pluviometer locations and sampling points

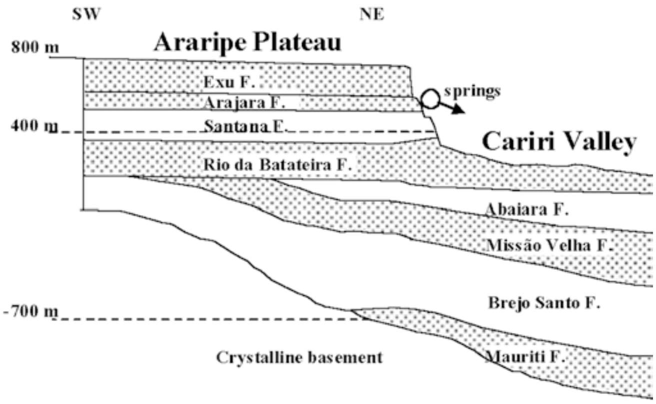

Fig. 2
Schematic profile of the Araripe sedimentary basin. *Shaded zones* are aquifers

Tubular wells

The $\delta^{18}O$ values for water samples taken from tubular wells in the eastern and western parts of the Araripe Plateau are listed in Table 2 and plotted in Fig. 4.
Figure 5 shows ^{18}O and electrical conductivity (EC) from February 1999 to September 2000 for the barreiro in Vila Cacimbas and for the dug well named Vila Cacimbas/B.

Discussions

Barreiros and dug wells

By analyzing Fig. 3 it is observed that all barreiros have a similar temporal behavior. In drought periods, from September 1999 to December 1999 and from June 2000 to July 2000, the concentration of ^{18}O increases due to evaporation. In rainy periods, from February 1999 to April 1999 and from January 2000 to May 2000, $\delta^{18}O$ decreases, thereby indicating the renewal of water through rainfall waters, which have lower $\delta^{18}O$ than the water in the reservoir. Small differences between these barreiros are due to their different usage and construction procedure.
The rainfall contribution to the barreiros is made through direct precipitation in the storage area, and mainly by temporary surface runoff guided into small drains known as "water pathways". The existence of such small creaks efficiently promotes the conduction of rainfall water that otherwise would infiltrate into the sandy soils of the plateau.
The barreiro Antonio Roriz does not dispose of an efficient clay revestment for keeping water stored during the dry season, thus drying up rapidly after its onset.
Contrasting with the barreiros Dr. Raimundo and Filemon Teles, the barreiro Vila Cacimbas presents smaller seasonal variations in $\delta^{18}O$. The fact that in the dry period $\delta^{18}O$ is less positive reveals that this barreiro is connected to the water of the aquifer. In the rainy season, $\delta^{18}O$ is less negative, indicating that the renewal through rainfall water is of less importance than in the barreiros Dr. Raimundo and Filemon Teles.
At the onset of the rainy period, $\delta^{18}O$ for the barreiros Dr. Raimundo and Filemon Teles reacts without delay, whereas barreiro Vila Cacimbas exhibits a 2-month delay (Fig. 3b). These differences in the behavior are certainly due the coupling of the latter water body to the much greater reservoir that the superior aquifer system represents. However, there are other reasons as well: the barreiros Dr. Raimundo and Filemon Teles constitute the exclusive source of water for the respective locations and are being used for small-scale irrigation and cattle breading; their runoff collecting "water pathways" are therefore maintained in good condition by permanent care. In contrast, the barreiro Vila Cacimbas is in a topographic depression where the water table is near

Table 1
Measurements of $\delta^{18}O$ (‰) and electrical conductivity (EC) for samples taken from barreiros and dug wells on the top of the Araripe Plateau (barreiros: *1B* Filemón Teles, *2B* Dr. Raimundo, *3B* Vila Cacimbas, *4B* Antônio Roriz; dug wells: *1PA* Dr. Raimundo, *2PA* Cacimbas, *3PA* Vila Cacimbas/B)

Year	Month	$\delta^{18}O$ (‰)							EC (μS/cm)	
		Barreiro				Dug well			Barreiro	Dug well
		1B	2B	3B	4B	1PA	2PA	3PA	3B	3PA
1999	Feb	−0.79	−0.12	−0.25	−0.51	−3.17	−1.79	–	83	–
	Apr	−0.25	−0.89	0.08	1.03	−3.16	−1.65	–	68	–
	Sep	5.12	5.35	4.3	Dry	−3.42	−3.4	–	93	–
	Oct	9.35	8.14	6.94	Dry	−3.58	−3.66	–	122	–
	Nov	8.66	7.83	6.78	Dry	−3.39	−3.54	–	124	–
	Dec	10.01	8.7	7.63	Dry	−3.49	−3.54	−0.34	139	152
2000	Jan	0.04	0.79	7.71	0.48	−3.55	−3.62	−0.76	190	140
	Feb	0.57	0.97	7.94	0.03	−3.53	−3.71	−0.86	210	156
	Mar	−0.93	0.46	3.18	−0.25	−3.47	−3.63	−0.66	127	164
	Apr	−2.3	0.34	2.29	−4	−3.63	−3.66	−0.6	126	164
	May	−0.9	−0.33	−0.54	Dry	−3.59	−3.66	−0.72	77	183
	Jun	0.11	0.41	0.29	Dry	−3.62	−3.68	−0.63	81	189
	Jul	2.44	2.47	2	Dry	−3.73	−3.73	−0.66	93	192

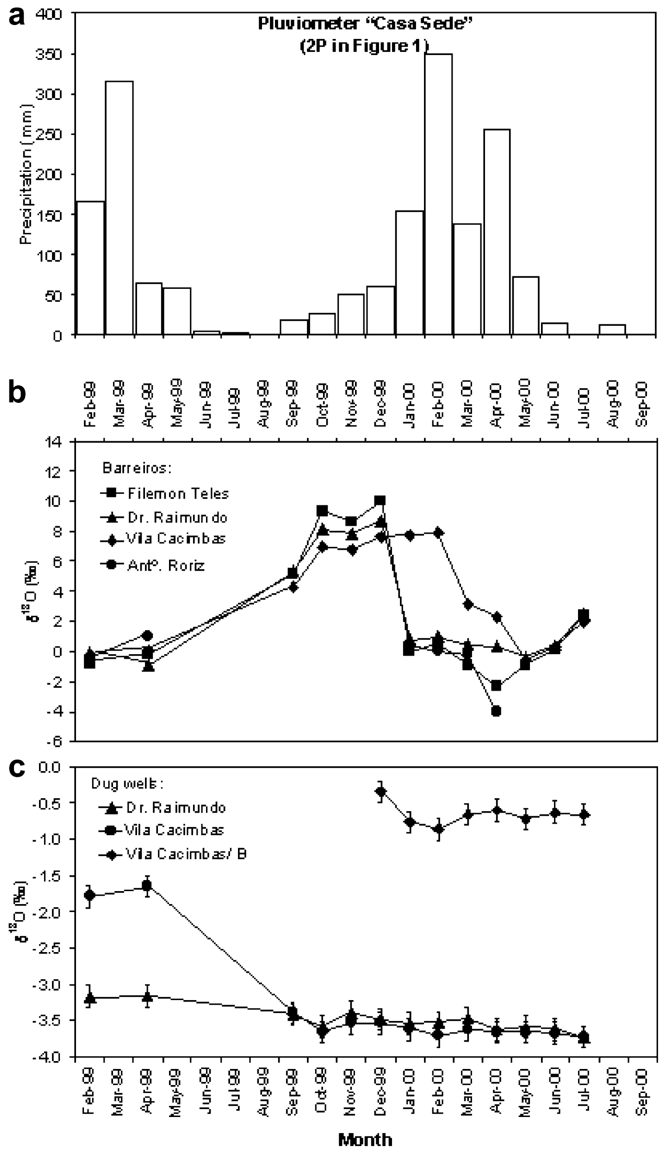

Fig. 3a–c
Monthly precipitation in the eastern part of the Araripe Plateau (**a**), and $\delta^{18}O$ for water samples taken from barreiros (**b**) and dug wells (**c**) in the period February 1999 to September 2000

surface and the population disposes of dug and drilled wells. Under these conditions, maintenance of the surface water reservoir is neglected and "water pathways" are taken over by vegetation.

$\delta^{18}O$ values for water collected from the dug wells Dr. Raimundo and Vila Cacimbas did not present significant variations from September 1999 to July 2000, scattering closely around an average of −3.58‰ (Fig. 3c). This is consistent with the average $\delta^{18}O$ value of −3.76‰ for wells exploiting waters from the Arajara aquifer in the eastern sector of the plateau (Mendonça and others 2001b).

The dug well Vila Cacimbas was not being pumped from February 1999 to April 1999. Thus, the water presented an average $\delta^{18}O$ value of −1.72‰ in this period, typical of evaporated water.

The dug well Vila Cacimbas/B, at a distance of 30 m from the barreiro Vila Cacimbas, produces water of $\delta^{18}O$=−0.67‰. This value is much higher than the average value for waters exploited by other wells in the neighborhood. However, it is similar to $\delta^{18}O$ measured in barreiros during the rainy period (Fig. 3), i.e., when the water level is elevated. This result indicates an injection of surface water into the groundwater. This assertion is further confirmed by comparing the temporal behavior of the electrical conductivity and $\delta^{18}O$ values for the barreiro Vila Cacimbas with those values for the dug well Vila Cacimbas/B. The barreiro exhibits strong changes in salt concentration and isotopic enrichment through evaporation. The highest $\delta^{18}O$ concentration occurred in February 2000, which also corresponds to the highest salt concentration (see Fig. 5). The minimum values for EC and $\delta^{18}O$ occur at the end of the rainy season in May. Similar variations in EC and $\delta^{18}O$ occur in the dug well, but with a delay of about 7 months corresponding to a groundwater flow velocity of about 4.5 m per month.

Tubular wells

Figure 4 shows that the waters exploited in the eastern sector of the plateau are isotopically distinct from those exploited in the western sector.

$\delta^{18}O$ values for the tubular well Betânia, closest to the scarp, vary only slightly around an average of −3.15‰ (see Table 2). This is consistent with the average value of −3.24‰ for springs at the interface Exu/Arajara (Mendonça and others 2001b). Also, the EC of 30 µS/cm for the well is very close to that for waters from these springs.

The tubular wells Vila Cacimbas and Serrolândia I exploit water from the Arajara aquifer, presenting an EC of 85 µS/cm, exactly the same as observed for waters from springs at the Arajara/Santana contact of the scarp of the plateau (Santiago and others 1997). In spite of this chemical similarity, the waters from the two wells present $\delta^{18}O$ values completely different from each other, namely, −3.56 and −4.70‰. The former value agrees with that for the springs, −3.59‰ (Mendonça and others 2001b), the latter not.

The tubular well 4-BO-01-PE exploits the Rio da Batateira aquifer confined on its top by the Santana aquiclude. The average electrical conductivity is 1,098 µS/cm (Mendonça and others 2001b), and $\delta^{18}O$ remains practically constant, with an average of −4.70‰ (Fig. 4). The tubular well Serrolândia I also presents $\delta^{18}O$ values in the same range. It is noteworthy that these values are much lower than the average for modern rainfall in the region, which is between −3.20 and −3.70‰. Frischkorn and others (1984) have shown that significantly lower $\delta^{18}O$ in deep sedimentary aquifers of the northeast of Brazil is due to the presence of paleowaters older than about 10,000 years. These waters accumulated before a +5 °C climate change at the Pleistocene/Holocene transition.

The tubular well Serrolândia II (242 m in depth) produces water from a sandstone lens (9 m in thickness) inside the Santana Formation. In the dry period this well exhibits

Table 2
Measurements of $\delta^{18}O$ (‰) for tubular wells on the top of the Araripe Plateau

Year	Month	$\delta^{18}O$ (‰)				
		Tubular well				
		Western sector		Eastern sector		
		Vila Cacimbas	Vila Betânia	Serrolândia I	Serrolândia II	4-BO-01-PE
1999	Sep	−3.44	–	–	–	–
	Oct	−3.54	−3.12	−4.72	–	−4.55
	Nov	−3.46	−2.99	−4.54	−4.69	−4.51
	Dec	−3.49	−3.05	−4.64	–	−4.61
2000	Jan	−3.39	−3.14	−4.45	−4.46	−4.65
	Feb	−3.79	−3.37	−4.93	−4.32	−4.89
	Mar	−3.58	–	−4.65	−4.24	−4.74
	Apr	−3.62	−3.11	−4.66	−4.28	−4.67
	May	−3.57	−3.19	−4.72	−4.46	−4.59
	Jun	−3.65	−3.16	−4.68	−4.52	−4.6
	Jul	−3.68	−3.18	–	–	–
	Aug	–	–	−4.74	−4.84	−4.85
Average		−3.56	−3.15	−4.7	−4.48	−4.7

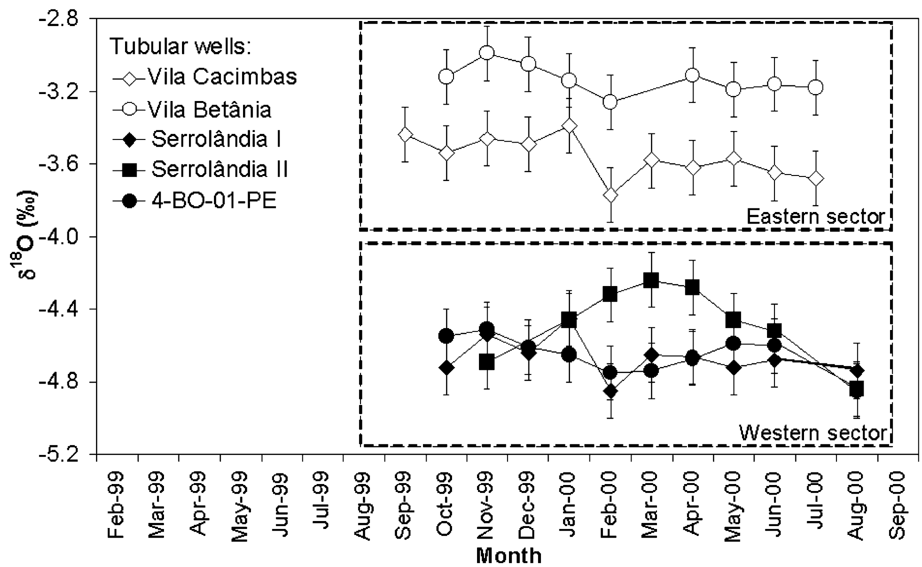

Fig. 4
$\delta^{18}O$ as a function of time for tubular wells located in the eastern and western sections of the Araripe Plateau

$\delta^{18}O$ similar to that of the wells Serrolândia I and 4-BO-01-PE. However, systematic changes are observed in the rainy season. Considering an error of 0.15‰ for these isotope measurements, the observed changes could seem to be negligible. However, systematic, simultaneous changes are monitored also in the water quality, as illustrated in Fig. 6. EC varies from over 1,000 μS/cm in the dry season to about 250 μS/cm at the end of the rainy season.

Lowest $\delta^{18}O$ values of −4.69 and −4.84‰, observed in November 1999 and August 2000, respectively, are marked by the presence of paleowaters in the superior aquifer system in the western sector of the plateau. The maximum $\delta^{18}O$ value of −4.24‰ was observed in March 2000, evidencing a contribution from waters isotopically very different, originating from modern waters in the superior aquifer system, indicating downward leakage. By plotting $\delta^{18}O$ vs. EC (Fig. 7), one observes a linear relation (R=0.941) that can be satisfactorily represented as a mixture of one component with high EC and low $\delta^{18}O$ with another one with low EC and high $\delta^{18}O$.

For a quantitative analysis of the mixture, the authors adopted end members of EC and $\delta^{18}O$ of 1,040 μS/cm and −5.00‰, respectively (for the paleocomponent), and of 85 μS/cm and −3.70‰. These latter values characterize the modern recharge waters in the superior aquifer system, as measured for the wells 1PA and 2PA (Table 1). The intermediate values are averages weighted with the concentration of each component.

The temporal variation of EC in the well Serrolândia II was used for the determination of the percent contribution of the modern component, by using the values predicted by the mixing line shown in Fig. 7. The calculated results are listed in Table 3.

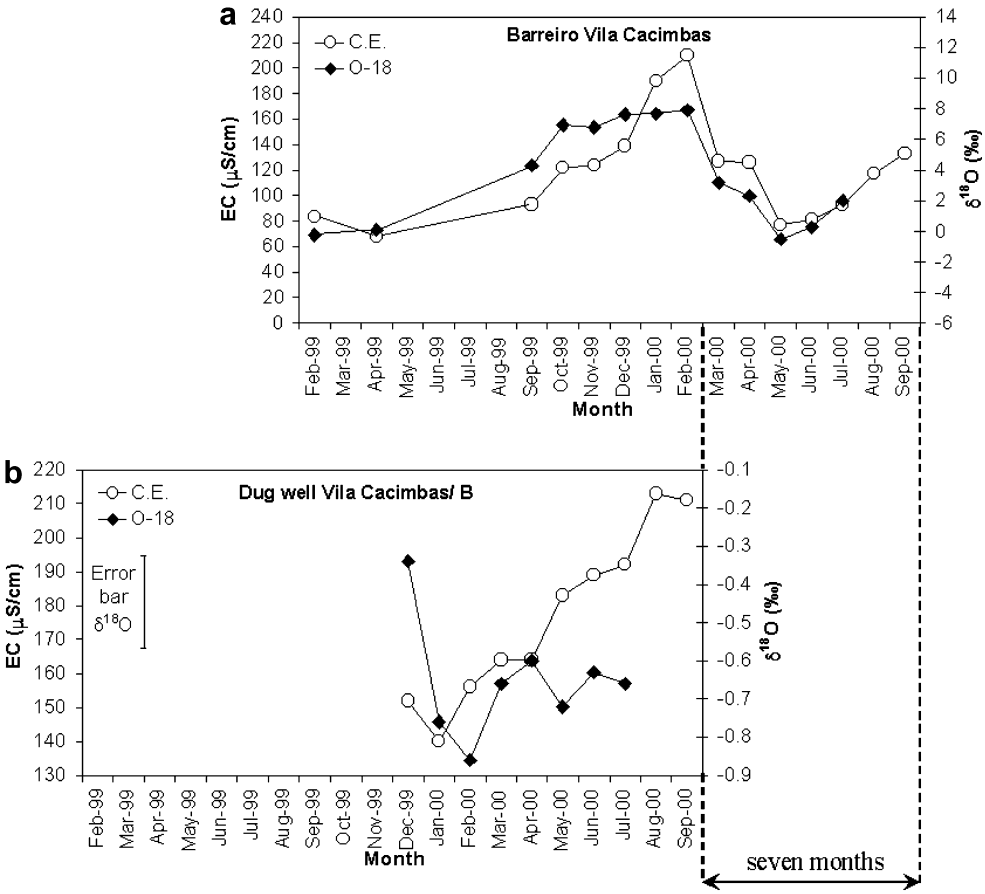

Fig. 5a, b
Electrical conductivity (EC, *left axis*) and $\delta^{18}O$ (*right axis*) as a function of time for the barreiro in Vila Cacimbas (**a**) and for the dug well Vila Cacimbas/B (**b**)

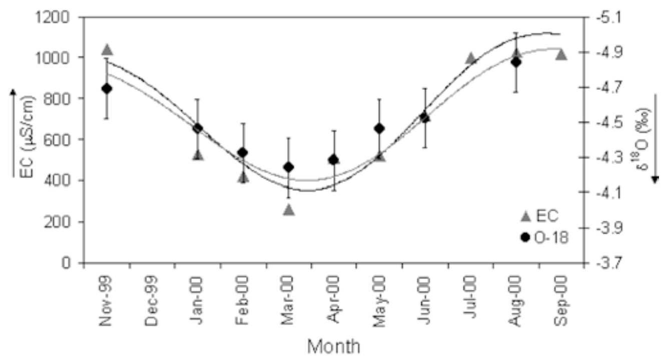

Fig. 6
Electrical conductivity (EC, *left axis*) and $\delta^{18}O$ values (*right axis*) for the water samples taken from the tubular well Serrolândia II

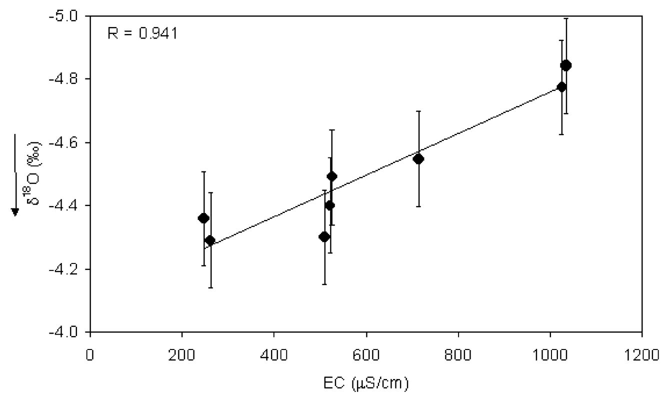

Fig. 7
Linear plot of EC vs. $\delta^{18}O$ for samples from the well Serrolândia II

A comparison of the percent contribution from the modern component with rainfall (Fig. 8) illustrates the fast reaction of the well to recharge to the upper aquifer system with a delay of about one month only. This may occur either due to leaks in the well sealing or to deep, open faults in the sedimentary package.
Hydraulic connections through geologic faults in the Santana aquiclude were recently discussed by Santiago and others (1997), using a phenomenological model for groundwater circulation in the Araripe sedimentary basin, and by Mendonça and others (2001c), reporting on MODFLOW simulation of the depression cone for well 4-BO-01-PE on the top of the Araripe Plateau.

Conclusions

Oxygen-18 and EC measurements permit the characterization of surface waters and groundwater in the Araripe Plateau, and an understanding of the relationship between them.

Table 3
Percent contribution, X, from the modern component to the water produced by well Serrolândia II, together with measured and calculated EC and $\delta^{18}O$

Month	Measured		X (%)	Calculated	
	EC (µS/cm)	$\delta^{18}O$ (‰)		EC (µS/cm)	$\delta^{18}O$ (‰)
Nov 1999	1,039	−4.69	12	925	−4.84
Jan 2000	526	−4.46	41	650	−4.47
Feb 2000	420	−4.32	55	510	−4.28
Mar 2000	262	−4.24	68	390	−4.12
Apr 2000	510	−4.28	66	410	−4.14
May 2000	522	−4.46	51	550	−4.33
Jun 2000	714	−4.52	34	714	−4.56
Aug 2000	1,026	−4.84	1	1,026	−4.98

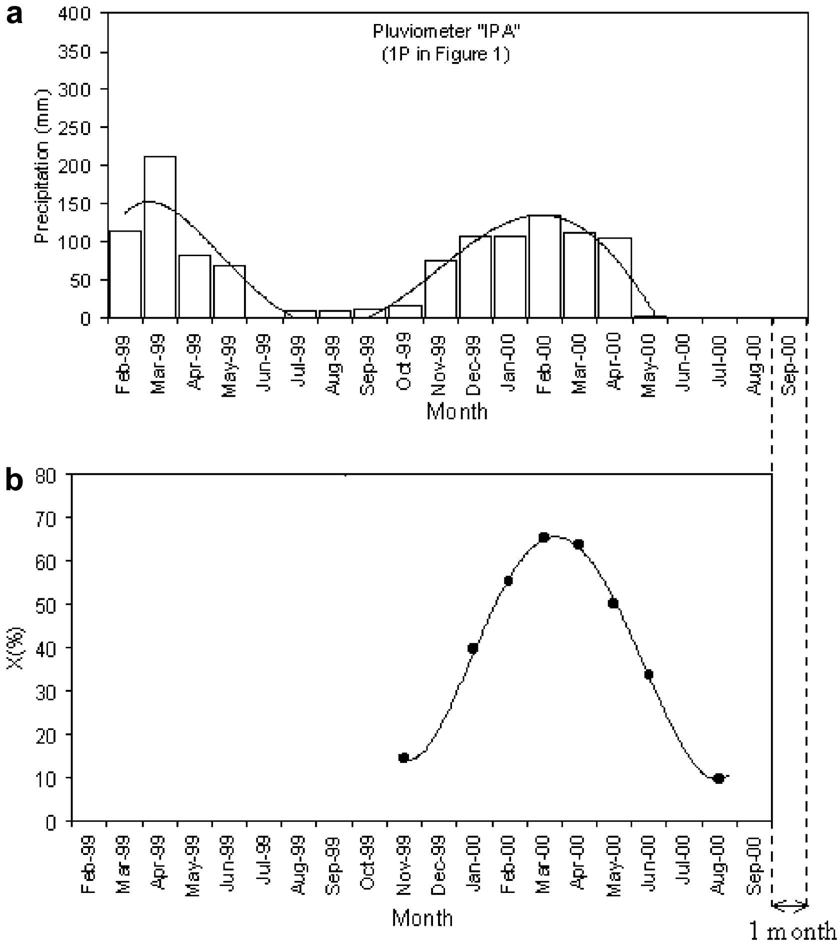

Fig. 8a, b
Comparison between precipitation (**a**) and the modern contribution, X, to samples from well Serrolândia II (**b**)

Measurements of ^{18}O in samples from four "barreiros", three dug wells and five drilled wells reveal that groundwaters from the eastern part of the Araripe Plateau are derived from present-day rainfall, characterized by $\delta^{18}O$ between −3.2 and −3.7‰, while groundwaters from the western portion are isotopically different, with $\delta^{18}O$ approximately −5.0‰, revealing the presence of paleowaters. Due to elevated evaporation, the surface reservoirs "barreiros" are strongly marked seasonally by elevated ^{18}O and EC during the dry period. The dug well Vila Cacimbas/B, at a distance of approximately 30 m from a "barreiro", exhibits $\delta^{18}O$ and EC similar to that of the reservoir in the rainy season, indicating strong interaction between groundwater and surface water. Thus, special care should be taken with respect to water quality of these surface reservoirs, as they constitute a risk to groundwater contamination. Despite a depth of 242 m, the tubular well Serrolândia II, located in a fault, exhibits strong seasonal changes in $\delta^{18}O$ and EC, revealing downward leakage between aquifers. As the waters from the two aquifers involved are different in terms of isotope composition and salinity, the water produced by this well may be identified as a mixture of two components: an older one, of high EC (1,040 μS/cm) and low $\delta^{18}O$ (−5.00‰), and a younger component, of low EC (85 μS/cm) and high $\delta^{18}O$ (−3.70‰). Mixing calculations (Table 3) reveal that the Serrolândia II well receives a contribution of up to 68% from the young component in the rainy period (March 2000), whereas this contribution amounts to just 1% in the dry period (August 2000).

Acknowledgements The authors express their gratitude to José Yarley de Brito, Walber Cordeiro and Antônio Ribeiro Zaranza from COGERH for logistic support; to professors Plínio Barbosa de Camargo and Marcelo Zacarias Moreira from CENA/USP–Piracicaba for isotope measurements; to Rodolfo José Sabiá, Danielle Inácio Magalhães, Raimunda Moreira Franca, Francisco Ramis da Silva, and Vanda Alves Feitosa from Núcleo de Estudos dos Recursos Hídricos da Chapada do Araripe/URCA for helping in sampling; to Antônio Gomes de Sousa Filho for translating this paper; and to FUNCAP for financial support.

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