RESULTS OF A HYDROGEOLOGICAL STUDY OF A PRECAMBRIAN KARST AQUIFER IN A SEMI-ARID REGION FROM MINAS GERAIS, BRAZIL

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ABSTRACT A Precambrian karst aquifer located in a semi-arid region in eastern central Brazil was studied to determine its hydrogeological characteristics. Several field methods were used, including environmental isotopes, artificial tracers, geophysical sensors, and satellite images. In addition, hydrochemical, hydroclimatological, geomorphological and piezometric data were collected. A two-dimensional, unsteady-state, finite-difference flow model was also employed. The transmissivity of the aquifer varied considerably from 5 m²/day to 500 m²/day with an average value of approximately 40 m²/day. The piezometric surface also varied with gradients on the order of 0.002 to 0.004 in the northern part of the aquifer and 0.003 to 0.005 in the southern portion. The lowest gradients (0.0004) were found in the central region. The hydrochemical data showed that bicarbonate and calcium ions strongly influenced the electrical conductivity which was found to vary with the lithology of the aquifer. The small amounts of chlorides found were dependent on climatic conditions, while sulfates and hardness were found to vary in the same manner as electrical conductivity. The isotope concentrations had irregular distributions which indicated local recharge and flow zones and little dispersion in the aquifer. The most important result of this study was the identification of the most favorable locations for developing significant water supplies.

RESUMO Um carste de uma região semi-árida no Brasil foi estudado com o objetivo de se conhecer as suas características hidrogeológicas. Foram utilizados isótopos ambientais, traçadores artificiais, sensores geofísicos, imagens de satélite e estudos hidrogeoquímicos, hidroclimáticos, piezométricos, além de um modelo matemático de simulação. A transmissividade desse aquífero varia muito: as áreas menos transmissoras têm valores da ordem de 5 m²/dia; áreas mais transmissoras podem atingir 500 m²/dia. A transmissividade média é de 40 m²/dia. A superfície piezométrica mostra duas elevações; uma ao norte, com gradiente da ordem de 0,002 a 0,004, e outra ao sul, com gradiente entre 0,003 a 0,005. Os menores gradientes são de aproximadamente 0,0004 e encontram-se na porção central da área. O estudo hidroquímico mostrou que a condutividade elétrica varia com a litologia do aquífero e que os íons bicarbonato e cálcio são os que mais influenciam nesta variação. As pequenas quantidades de cloretos encontrados dependem das condições climáticas, e o sulfato e a dureza apresentam variação semelhante à condutividade elétrica. A concentração isotópica tem distribuição irregular, o que indica recarga e fluxo locais e pouca dispersão da água. A interpretação dos dados permitiu identificar zonas com condições hidrogeológicas favoráveis à exploração de águas subterrâneas.

INTRODUCTION A series of studies and hydrogeological research were made during a five-year period on a Precambrian semi-arid region called Jaíba, in the state of Minas Gerais, Brazil. The object of this work was to evaluate and to compare techniques of prospection and exploitation of groundwater in this type of aquifer and to obtain its hydrogeologic characteristics.

In addition to the traditional techniques, the following methods were applied: environmental isotopes; artificial tracers; geophysical sensors; satellite images; hydrochemical, hydroclimatic, geomorphological and piezometric studies; and a mathematical simulation model.

The main results of the study are given in this paper.

GENERAL CHARACTERISTICS OF THE JAÍBA AREA The Jaíba area is about 5,150 km² and is bordered on the west by the São Francisco River, on the east and north by the Verde Grande River and on the south by the Sabonetal Mountain. The Jaíba area is generally flat, with the highest topographical elevation equal to about 50 m above the alluvial plane of the São Francisco River (440 m altitu-

de). To the south, the Sabonetal and Azul mountains rise to an altitude of 840 and 720 m respectively, and in the north, the Catarino Hill rises to 598 m.

The São Francisco River has an average flow of 1,850 m³/s, with a minimum of 225 m³/s. The level of the São Francisco River creates a constant boundary condition for the Jaíba aquifer. Floods up to 10,000 m³/s occur with a flood depth of 15 m. On the other hand, the Verde Grande River is small and has an average flow of 14 m³/s at its southern point and 28 m³/s in the north, where it intersects the São Francisco River. The minimum flow is between 0.1 and 0.5 m³/s. The other streams within the Jaíba area are intermittent.

The average rainfall is about 800 mm/year, the dry season being between July and September. The average annual temperature is 23.5°C with a variation between 17 to 33°C and a potential evapotranspiration demand of 1,300 mm/year. From a hydrometeorological balance, the net infiltration was calculated to be 35 mm/year, in general concentrated in January (the rainy season).

The Jaíba aquifer consists of a sequence of Precambrian limestone layers, called the Bambuí Group, that lies di-

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rectly over a Precambrian gneiss basement. The limestone is covered, in a large area, by a layer of Tertiary-Quaternary detrital sediments and by recent alluvial deposits along the São Francisco and Verde Grande rivers.

From a structural point of view, the Jaíba area corresponds to a block that has been lowered by a fault that runs parallel to the São Francisco River. The limestone beds have a subhorizontal dip and are crossed by large fractures with strikes of N40-50°W and N30-40°E. Cenozoic karstification produced a typical topography, being characterized by a high density of sinkhole and some oriented longitudinal fractures. The surface lithological and structural properties of the Jaíba area have been thoroughly studied and mapped to a scale 1:100,000 by Costa (1978). However, little geologic information exists about the subsurface properties of the Jaíba aquifer.

The thickness of the limestone sequences and the depth of the crystalline basement are not known. The depth of karstification is, in general, less than 100 m, with most of the fissures about 30-40 m in depth. The fissures lie slightly above the level of the São Francisco River, this being confirmed by isotopic well logs (bromine-82) in 42 wells (Plata *et al.* 1980); the layer of Tertiary-Quaternary detrital sediment is very thin, with an average thickness of 15 m and a maximum thickness of 65 m. This has been confirmed by resistivity and from well logs (Escodino & Silva 1981).

HYDROLOGIC PARAMETERS Transmissivity data from the aquifer were obtained through 60 pumping tests, 55 specific capacity tests, and 10 chemical and radioactive tracer dilution tests.

The pumping tests could only be used to compute a rough estimate of the transmissivities because of: the presence of fissures, the different potentials in the fissures (verified in the tracer tests), the nonradial flow and heterogeneous conditions of the aquifer. The specific capacity of a well is greatly influenced by well losses, particularly when the well water drains from small and short fractures. In this case, the specific capacity method gives a minimum local transmissivity value. The transmissivities varied greatly, from a low value of 5 to 10 m²/day, to a high value of 500 m²/day, with an average transmissivity about 30 to 50 m²/day. In the upper portion of the aquifer (the karst region), the transmissivity ranges between 100 and 300 m²/day.

Due to noise in the short term drawdown data, only the long term drawdown data were used to compute the storage

coefficient, using the hydrogram method. The storage coefficient using discharge data from Verde Grande River (upstream, near the village of Colônia do Jaíba) was to be between 0.01 and 0.001. However, a study of the fracture frequencies by the radioactive tracer method gave a much higher storage coefficient than the one obtained by means of the by than the one obtained by means of the hydrogram method.

Finally, a hydrogram method, using the water level response to rain in 36 wells, gave a storage coefficient that ranged between 0.005 and 0.02. From these same 36 wells, it was also possible to compute the hydraulic diffusivity (T/S), which varied between 13 and 700 x 10³ m²/day.

The results of the above tests are listed in Tab. 1.

WATER TABLE The variations in the water table were measured monthly in a network of 98 observation points between October, 1977 to May, 1979. After 1979, the observation network was reduced to 25 points and these were measured until August, 1981. Water level recorders were installed in 6 additional wells from October, 1977 to August, 1981.

The water table contour map of the Jaíba area in the end of the rainy season of 1981 is shown in Fig. 1, where there are two zones with large water table gradients located at the Sabonetal Mt. and the Caratino Hill regions. Between these two zones, the water table gradient is very flat. Also note that there is no water table divide between the Verde Grande and São Francisco rivers. This indicates that the Verde Grande River is not hydrologically connected to the Jaíba aquifer, however water can pass under the Verde Grande River.

Various stream-gauging stations were installed in the Verde Grande River in order to measure the flow rate during 1978 and 1979. Custódio *et al.* (1981) showed that in the dry season the Verde Grande River is effluent until Colônia do Jaíba but, farther than this, it neither gains nor loses water until the Verde Grande joins the São Francisco River.

Hydrographs from the water level recorders between 1977 and 1979 (20 months in total) showed two regions in the Jaíba aquifer with large piezometric variations (a maximum of 15 m) and the rest of the Jaíba area with small variations (see Fig. 1). In the northern region of the Jaíba aquifer (at Catarino Hill) the piezometric gradient was around 0.002 to 0.004 and to the south (at Sabonetal Mt.) a gradient of 0.003 to 0.005. The above two locations represent recharge areas with low vertical permeabilities. In the

Table 1 – Transmissivity and storage coefficient of the Jaíba Aquifer

Zone	Transmissivity T (m ² /d)		Storage Coefficient (S)
	Average	Range	Range
Sabonetal Mt. to Colônia do Jaíba	25	from 15 to 40	from 0.002 to 0.005
Sabonetal Mt. W zone	200	80 300	0.005 0.010
Colônia do Jaíba, distant zone	70	40 100	0.002 0.005
Colônia do Jaíba, near zone	500	40 1,000	0.010 0.050
Central plain, E zone	100	50 500	0.010 0.030
Central plain, W zone	1,000	300 2,000	0.020 0.050
Catarino Hill, high zone	20	5 50	0.001 0.030
Catarino Hill, north plain	100	20 300	0.010 0.030
São Francisco River, flood plain	150	50 300	0.020 0.050

Figure 1 – Water-table contour map for the end of the rainy season (1981)

central zone of the Jaíba area, the piezometric gradient was the order of 0.0004. However the storage coefficient is greater in the central region than in other areas.

HYDROCHEMICAL STUDY Water samples were collected during four dry and rainy seasons. A total of 427 samples of groundwater and 254 surface-water samples were analysed.

Chemical analysis showed that the chemical composition of the water in the São Francisco River does not depend on the groundwater. In the dry season the elevated

concentration of HCO_3^- in the Verde Grande River between the villages of Colônia do Jaíba and Gado Bravo indicated that this river was chemically similar to that of the groundwater (Tab. 2). During the rainy season there was a notable decrease in the total dissolved solids downstream of Colônia do Jaíba, indicating a strong groundwater contribution to the river. However, the chloride concentration was much higher than that in the rainy water.

Using a modified stiff diagram map it was possible to identify areas with equal chemical facies and to make groupings according to the method of Schoeller, which orders the concentrations of the anions and cations (Custódio & Llamas 1976).

A study of the spatial distribution of the chemical characteristics of the groundwater showed: a) the electrical conductivity varied with the lithology of the aquifer and bicarbonate and calcium ions have the greatest influence on this variations (Fig. 2); b) the hardness is similar to the electrical conductivity and the alkaline-earth metals are the dominant cations (where elevated concentrations are dominated by limestone); c) the chloride concentrations are low and depend on climatic conditions (the concentrations range between 40 and 50 ppm at Sabonetel Mt. and Caterino Hill and are 80 ppm near Colônia do Jaíba); d) the zones of high chloride concentrations do not necessarily coincide with high electrical conductivity; e) the distribution of chlorides shows that there are two circulation paths, one along the Serraria stream to the São Francisco River and the other between Colônia do Jaíba to Mocambinho village (Silva *et al.* 1982); f) the sulfate concentration is normally low and is parallel to the electrical conductivity and hardness (suggesting that the same phenomenon that controls the variation in the electrical conductivity and hardness controls also the variation in the sulfate); g) the rSO_4/rCl ratio is similar to the hardness; h) the rNa/rCl ratio can be used to show that the solution preferentially dissolves Ca^{2+} and Na^+ .

A chloride balance was used to calculate the infiltration coefficient of the rain water into the aquifer. The infiltration coefficient was estimated supposing that the major part of the Cl^- ions of the groundwater came from the atmosphere (Tab. 3).

ENVIRONMENTAL ISOTOPES Water samples were analysed for natural isotopes [oxygen-18 ($\text{O}-18$), deuterium (D) and tritium (T)]; 127 samples were subdivided as follows: 63 groundwater and 11 surface water samples were analysed for O-18 and D; 49 groundwater and 4 surface water samples were analysed for T.

Table 2 – Chemical characteristics of the water of the Verde Grande River

The most representative range of chemical variation (ppm)								
Gauge	Ca^{2+}	Mg^{2+}	Na^+	Cl^-	SO_4^{2-}	CO_3H^-	rSO_4/rCl	$(\text{rCl}+\text{rNa})/\text{rCl}$
VG-11	40-75	5-7	8-14	10-15	11-20	150-300	1	0/(-)
VG-04	40-75	4-8	7-10	9-15	9-20	130-220	1	(-)
VG-14	40-75	5-9	10-13	10-15	13-18	150-250	0/21	(-)
VG-12	35-65	6-8	9-15	11-18	8-13	80-200	1	(-)
Groundwater	45-80	4-8	2- 5	30-40	25-30	300-400	—	—

Figure 2 – Spatial distribution of the electrical conductivity

Figure 3 – Distribution of the results of the tritium analyses

The following conclusions were obtained from the T, D and O-18 analyses (Plata *et al.* 1980, Custódio *et al.* 1981): a) evaporation of the rain water is negligible, except in a few localized areas (this allows us to do a chloride balance); b) the isotope concentrations have an irregular distribution which indicates that the recharge and flow are local and that the groundwater exhibits little dispersion; c) the tritium analysis confirmed the deuterium and oxygen-18 analysis (Fig. 3); d) the tritium concentration appears to decrease with the depth of the groundwater sample [the tritium concentration follows the relation: $T = 5.5 \times \ln(h) +$

28.1, where T is in TU (tritium units), h (depth) in meters and $\ln$ indicates natural logarithm]; e) the tritium analysis indicate that the aquifer is well mixed and has an average residence time of 50 years. The highest residence times were found in the west Sabonetal Mt. and Colônia do Jazba areas (80 to 100 years), the N-NW sector (160 years) and the central zone (200 years). The smallest residence times were found in the central Sabonetal Mt. and the E-NE area (20 years), Catarino Hill (6 to 20 years) and north plain (910 years). These last areas have the smallest storage coefficients and the greatest circulation.

Table 3 – Average annual infiltration coefficient of the rain water

Zone *	Concentration of Cl^- in Groundwater (ppm)	Infiltration Coefficient (I)**		Deep Infiltration for P - E = 800 mm/yr	
		Average	Extreme	AVG	Range
Flood plain of the São Francisco River	10	0.020	0.010-0.030	16	(8 to 24)
Drainage area of the Serraria stream	40	0.005	0.002-0.007	4	(2 to 6)
Sabonetal Mt. high zone	10	0.020	0.010-0.030	16	(8 to 24)
Sabonetal and Azul Mts. North	15	0.015	0.007-0.020	12	(6 to 16)
Colônia do Jazba	15	0.015	0.007-0.020	12	(6 to 16)
Central plain	45 (?)	0.004	0.002-0.006	3	(2 to 5)
North plain	5(?)	0.040	0.040-0.060	24	(12 to 48)

* Range of the rain Cl^- is from 0.10 to 0.30 ppm

** The infiltration coefficient is defined as the percent of precipitation which actually reaches the aquifer

Figure 4 – Finite difference grid used in the Prickett and Lonquist model

MATHEMATICAL MODEL The objective of the simulation model was to integrate the different data into a coherent system which would be able to reproduce the observed data and hence to verify the methodology applied to this study. The Prickett & Lonquist (1971) finite difference model was used. A grid with 13 columns and 19 rows was used, with a total of 206, with $5 \times 5 \text{ km}^2$ each elements (Fig. 4). The São Francisco River was treated as a constant head boundary condition. The observed piezometric surface at the end of the 1977 dry season was used to specify the initial condition.

The simulations showed that the water accumulated in the aquifer after two to four years created a steady state piezometric surface with gradients greater than those observed (Fig. 4). The simulation showed that it was more reasonable to have small values of recharge (1 to 2%) and large values of transmissivity ($500 \text{ m}^2/\text{day}$), specially in the central zone (Cruz & Silva 1980). The hydrologic balance was approximately in equilibrium after the fourth year of simulation and revealed that the aquifer had a high flood control capacity. This was because the aquifer absorbed infiltrating water during the first five months of the hydrologic cycle and slowly liberated it later in the year.

HYDROGEOLOGIC CHARACTERISTICS OF THE AQUIFER

An interpretation of the hydrologic, hydrochemical, and environmental isotopes data and the results of the simulation model identified six zones with different hydrogeologic characteristics (Fig. 5): a) *flood plain of the São Francisco River* – this zone is influenced by the variation of the river level and has a width of about 2 to 5 km; b)

Figure 5 – Delineation of the Jatba Karst aquifer

north plain — this zone has a moderate hydraulic diffusivity that stores water during the rainy season. This stored water is then discharged into the Verde Grande River and São Francisco River with gradients less than 0.0004; c) *Catarino Hill* — has moderate very diffuse recharge, and a very low storage coefficient. The recharge water is rapidly transferred to the north and central plains; d) *central plain* — this zone probably has the greatest reserve of groundwater and highest transmissivities. It discharges water to the São Francisco River and it can receive water from the Verde Grande River. There appears to be two preferential circulation zones; one that begins near Colônia do Jaíba, and the other, upgradients of the confluence of the Verde Grande River with the Gurutuba River; e) *Sabonetel Mt.* — has moderate and very diffuse recharge, with a reduced storage

coefficient and little hydrologic significance. It discharges to the E-NE (colônia do Jaíba) and to the NW (São Francisco); f) *area of Colônia do Jaíba* — it is a very heterogeneous zone. There appears to exist a preferential permeable zone to the NW that conducts water to the central plain. It can receive water from the southern side of the Sabonetel Mt. and perhaps from the Verde Grande River.

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MANUSCRITO

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