

THE POTENTIAL OF THE BARREIRAS AQUIFER IN THE LOWER COURSE OF THE DOCE RIVER, RIO GRANDE DO NORTE STATE, NORTHEAST BRAZIL – INTEGRATION OF HYDROGEOLOGICAL AND GEOPHYSICAL DATA

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ABSTRACT. The present article is a synthesis of studies developed by the Fundação Norte-Rio-Grandense de Pesquisa e Cultura-FUNPEC and Universidade Federal do Rio Grande do Norte-UFRN for the Companhia de Águas e Esgotos do Rio Grande do Norte-CAERN, in the lower course of Doce River, RN. This paper also presents alternatives to increase the water supply from wells in the Barreiras Aquifer located to the north of Natal district, RN, considering the degraded water quality due to nitrate contamination from the right margin of Doce River. The methodology was based on the combined use of hydrogeological and geophysical techniques (gravity and electrical resistivity). The regional structure was previously characterized by morphotectonic analysis and gravimetric and geoelectric data interpretation. According to these data, two preferential fault directions (NW and NE) directly influence local geometry of the aquifer causing abrupt variations of the saturated thickness. The potential of the Barreiras Aquifer increases gradually on the left bank of Doce River from east to west, due to larger spacing between hydrogeological equipotential surface and larger saturated thickness. These observations provided the basis to locate a new water collection area, where new wells are going to be drilled with 300 m³/h estimated total discharge.

Keywords: Barreiras Aquifer, Doce River-RN, geophysical analysis, hydrogeological potential.

RESUMO. O presente artigo representa uma síntese de estudos desenvolvidos pela Fundação Norte-Rio-Grandense de Pesquisa e Cultura-FUNPEC e Universidade Federal do Rio Grande do Norte-UFRN para a Companhia de Águas e Esgotos do Rio Grande do Norte-CAERN, na área do baixo curso do Rio Doce-RN. O mesmo objetivou apontar alternativas para o incremento do abastecimento d'água proveniente de poços no Aquífero Barreiras na zona norte do município de Natal-RN, tendo em vista o agravamento da contaminação de captações da margem direita do Rio Doce por nitrato. A metodologia adotada foi fundamentada no emprego conjunto de técnicas de hidrogeologia e geofísica (gravimetria e eletrorresistividade). A estruturação regional, caracterizada previamente a partir de análise morfotectônica e interpretação de dados gravimétricos e geoeletrônicos, foi evidenciada nas direções preferenciais NW e NE, influenciando diretamente na geometria local do aquífero na forma de variações bruscas de sua espessura saturada decorrente dos falhamentos. A potencialidade do Aquífero Barreiras apresenta um acréscimo gradativo na margem esquerda do Rio Doce de leste para oeste, decorrente de maiores espaçamentos entre equipotenciais hidrogeológicas e espessuras saturadas maiores. Estas observações fundamentaram a locação de uma subárea a leste da captação Rio Doce da CAERN como bastante promissora para a execução de uma segunda bateria de poços, com descarga total estimada da ordem de 300 m³/h.

Palavras-chave: Aquífero Barreiras, Rio Doce-RN, Geofísica, potencialidade hidrogeológica.

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INTRODUCTION

The Water and Sewage Company of Rio Grande do Norte State (Companhia de Águas e Esgotos do Rio Grande do Norte – CAERN) has been facing lately increasing contamination of the water uptake wells by nitrate in the northern area of Natal, the state capital. Therefore, alternatives are being sought to meet the water demand while a definitive solution to this contamination is found (completion of a sanitation program, for example). Thus, the lower course of the Doce River (Fig. 1), especially the left bank, is quite promising due to its proximity to the northern Natal area and the apparent adequate levels of nitrate, when considering the low population density and low occurrence of potentially contaminating sources.

Studies developed in northeastern Brazil show signs that the regional geological structures have a strong influence on the hydrogeological and petrophysical context, particularly along the Cenozoic sedimentary terrains (Lucena & Queiroz, 1996; Lucena et al., 1999, 2006; Balsamo et al., 2010; Rodrigues et al., 2011). These studies show, among other aspects, the delimitation of areas with high transmissivity, resulting from increased saturated thickness caused by local structural compartmentalization of the Barreiras Aquifer (Tertiary-Quaternary age). This was suggested by the substantial increase of flows in wells within local structural grabens (Lucena & Queiroz, 1996; Lucena et al., 1999). These studies further suggest conditioning of the groundwater flow through semi-impermeable side barriers (Cretaceous aquitard), also caused by faults. Another aspect characterized was the prominent reduction of porosity in sandstones aquifers of the Barreiras Formation along fault zones (Balsamo et al., 2010).

Therefore, this work reports the exploratory hydrogeological study performed in the lower Doce River area (Extremoz-RN), in order to increase the volume and improve the quality of the water supply to Natal, RN. This mainly involved the identification of the most promising sub-areas for water collection, highlighting local positive anomalies of saturated thickness. This research was coordinated by the Rio Grande do Norte (RN) State Research and Culture Foundation-FUNPEC and Rio Grande do Norte Federal University-UFRN. The general methodology employed was based on a set of hydrogeological, structural and geophysical techniques (gravity and electrical resistivity), which enabled the creation of geological and hydrogeological sections, the potentiometry of the Barreiras aquifer and a geometry model of the local saturated zone. The gravimetric and electric geophysical models used were instrumental in obtaining the results. Previous surveys of adjacent areas evidenced a strong correlation between deep and shallow fragile structures from the interpretation of residual gravimetric fields (Lucena, 2005; Lucena et al., 2006) while electrical resis-

tivity is the most widely used geophysical methodology to study shallow aquifers, either in sedimentary or crystalline soils/terrains (Rubin & Hubbard, 2005; Kirsch, 2006; Feitosa et al., 2008).

METHODOLOGY

The methodology used was a combination of geophysical, structural and hydrogeological techniques (gravity and electrical resistivity). The geological characterization consisted on the revision and updating the bibliographical and cartographical material, as well as available remote sensing products, particularly including field surveys to detail the local geology of Natal area and its surroundings, based on the geological map of Rio Grande do Norte State published by the Brazilian Geological Survey (CPRM, 2006). Additionally, the interpretation of residual gravity field and vertical electrical sounding was used to define the fault distribution and orientation.

The potentiometric map of the lower Doce river area was prepared according to the classical procedures used in this type of survey (Castany, 1975). Initially, the wells in the area were registered and later identified in the field, and it was checked, among other features, whether they were drilled in the Barreiras aquifer. The selected water wells were topographically leveled for further measurements of their static levels. This had the objective of individualizing the recharge and discharge areas of local groundwater, locating the major surface water bodies in the regional hydrogeological context and defining the main flow fronts.

The analysis of the gravimetric geophysical data shows possible relationships between the deep structure (crystalline basement and Mesozoic basin) and the overlapping sequences, with ultimate implications in the geometry of the Barreiras aquifer and the tectono-structural control of river valleys. Consistent results have already been reported in previous studies of the eastern region of Rio Grande do Norte, by Lucena & Queiroz (1996) and Lucena et al. (2006). The gravimetric data used are part of the database of the Geophysics group of the Rio Grande do Norte Federal University-UFRN. The surveys were conducted using LaCoste & Romberg gravity meter and geodetic global positioning system. The residual gravimetric map (Fig. 2) was created after subtracting the regional anomalous field from the respective Bouguer anomaly map according to methodology proposed by Beltrão et al. (1991).

The residual field was interpreted based on a simple model, consisting of crystalline basement blocks covered by the sedimentary column, assuming that the density contrasts are laterally uniform within each unit. Thus, gravimetric highs and lows are associated with basement highs and lows, respectively, and these lows are associated with increased sediment thicknesses.

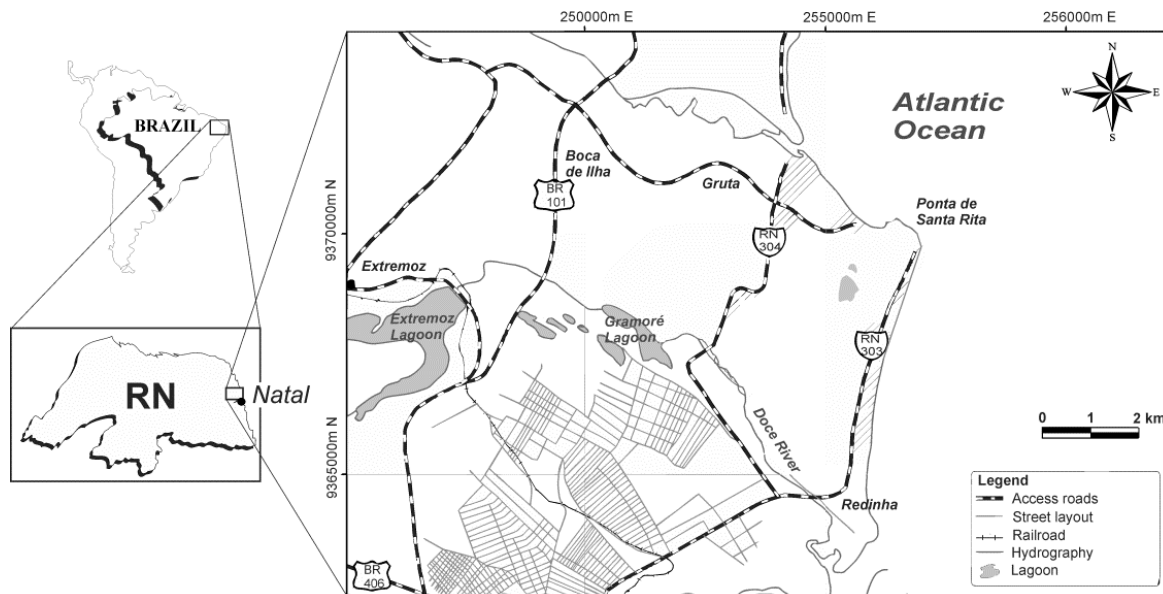


Figure 1 – Study area location.

The geoelectrical survey was aimed at providing local information where the well data, when available, were not sufficient for the development of a preliminary geometric model for the Barreiras aquifer in the area. Therefore, the most important information sought was the depth of the aquifer base, indicated regionally by the top of the non-outcropping Mesozoic carbonate sequence (sandstones to calcareous shales, according to well-known and historically used terminology in this region). The Vertical Electrical Sounding (VES) with an array of Schlumberger electrodes (Astier, 1975) was used. This technique allows characterizing how resistivity changes with depth in plane-parallel horizontal layer model settings.

The GEOTEST R85 resistivity meter was used. This equipment minimizes instability of the readings due to electrode polarization phenomena and filters the signal, attenuating noise caused by telluric currents. Noise attributed to possible electromagnetic inductions was controlled by keeping a suitable distance between the transmission and reception cables.

Other operational procedures involved a careful choice of the survey area and reducing contact resistances. We searched for low populated areas, by either humans or animals, to avoid damages and accidents with the equipment, and gentle topography to allow a electrodes spacing compatible with the depth of exploration. The contact resistances were reduced by using salty water around the electrodes and periodical cleanings, as well.

The clutch technique (Orellana, 1972) was used during each survey. This technique consists of performing the readings with the same AB (electrodes and current) while using different MN

openings (potential electrodes). These changes seek to improve the signal/noise ratio and enable to identify the lateral variation effects of the resistivity near the potential electrodes.

RESULTS

Residual Gravimetric Field

Two aspects are prevalent in the interpretation of the residual gravimetric map. The first is the occurrence of gravimetric highs and lows, with some in the form of extensive continuous surfaces, representing the structural internal highs and lows of the coastal basin, respectively. However, certain gravimetric highs do not fall, in principle, within the specific concept of internal structural high, that is, they do not fit the adopted interpretive model. This seems to be the case of the positive anomaly of 2.5 mGal east of Extremoz lake (Fig. 3). Such feature would be related to basic intrusions in the crust, such as that described by Rand & Manso (1990) for the Tabatinga beach latitude (approximately 25 km south of Natal), although the joint occurrence of horsts should not be ruled out in these sites. Another important feature concerns the gravimetric low of -3 mGal, immediately adjacent to the reported positive anomaly located southeast of the Extremoz lake. This gravimetric low shows the density contrast resulting from the increase of the sedimentary column in this structural block and is associated with the local graben configuration.

The sharp west-east gradient, with the isogalic curves approximately parallel to the coastline, is caused by the decreasing depth of the Mohorovicic discontinuity close to the coast (Lucena,

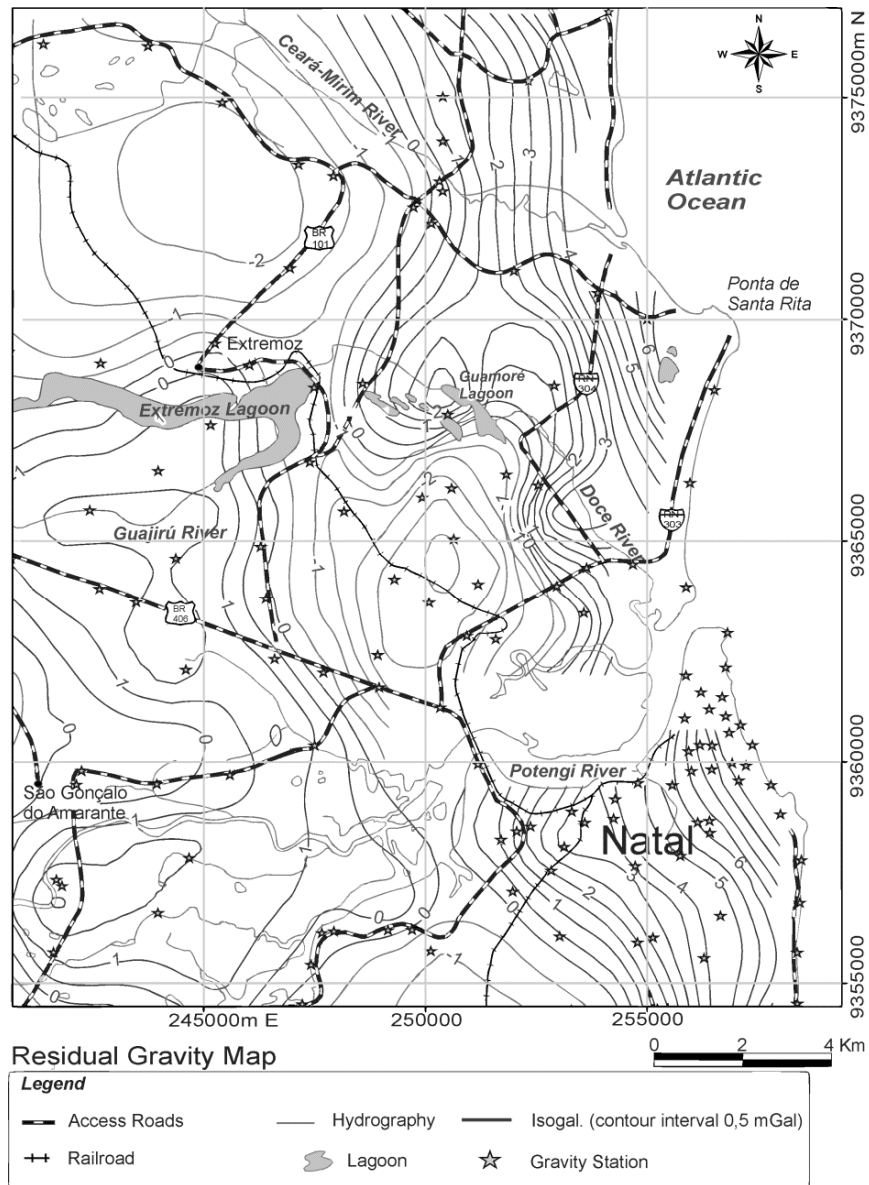


Figure 2 – Residual gravity map of northern Natal, RN, including Doce River lower course. Contour interval: 1 mGal (modified from Duarte, 1995).

2005), and associated with the transition from the continental to oceanic crust. This gradient is locally very steep, considering that this region has a continental shelf of comparatively reduced width with respect to the southeastern and southern regions of Brazil, which masks the negative residual anomalies caused by the local sedimentary column. This aspect is well evidenced at Ponta de Santa Rita and to the south of the Potengi river mouth (Fig. 3).

The second important aspect of the residual map interpretation involved the characterization of gravity alignments, defined based on isogalic continuity and/or limits between positive and

negative anomalies, and traced approximately around the edges of such anomalies. These alignments are configured according to the northwest and northeast directions, supporting the analysis of tectonic and structural framework predominant in the crystalline basement and overlying Mesozoic sedimentary sequence. This assessment is supported by field observations in outcrops of crystalline basement to west and southwest of the area, as well as in studies involving branches of the Patos lineament on the coast of Rio Grande do Norte and Paraíba States (Bezerra et al., 1994; Bezerra, 1998).

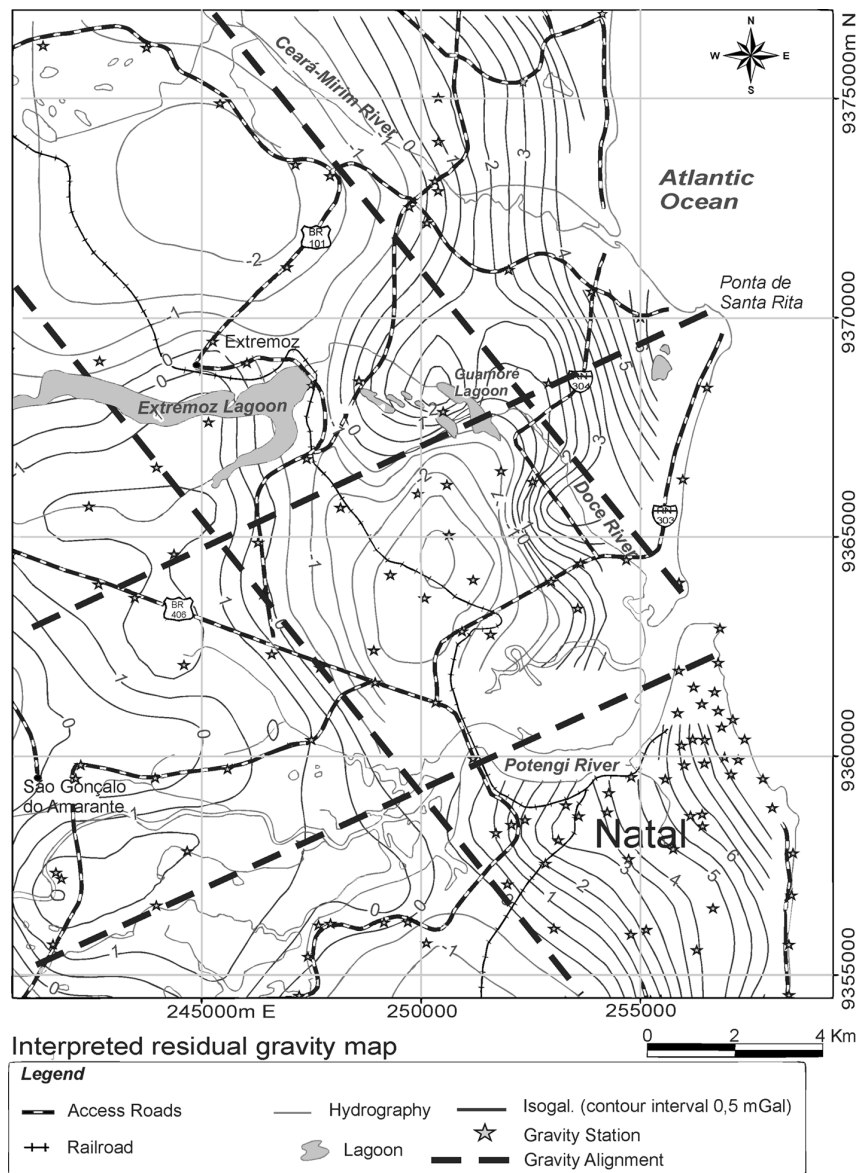


Figure 3 – Interpreted residual gravity map of northern Natal, RN, including Doce River lower course. Contour interval: 0,5 mGal (modified and interpreted from Duarte, 1995).

Regional Geological Context

Stratigraphically, the regional geology consists of two basic sequences: first, the subsurface Precambrian crystalline basement and Mesozoic sedimentary units, both identified in regional geophysical well logs. The second unit is represented by outcrops of Cenozoic sediments (Nogueira, 1982; Bezerra et al., 1993; Lucena, 2005). The latter includes clayey sands to conglomerates of the Barreiras Formation and sands of the Potengi Formation, below the quaternary sediments, which include beachrocks and several generations of mobile and fixed dunes.

Specific structural studies on the east coast of Rio Grande do Norte State date back to the 70s, including geophysical and lithological well correlation conducted by CAERN. These studies showed tectonic reactivation, with gravity faults oriented in the northeast direction of the Potengi River estuary (delimiting the so-called Natal Graben) and northwest oriented structures in Parnamirim-RN (Parnamirim Graben). Similar results were obtained by Salim et al. (1974) while studying the occurrence of structural valleys on the east coast.

This structural pattern, with NE and NW faults, is consistent with later published works (Lucena & Queiroz, 1996; Bezerra,

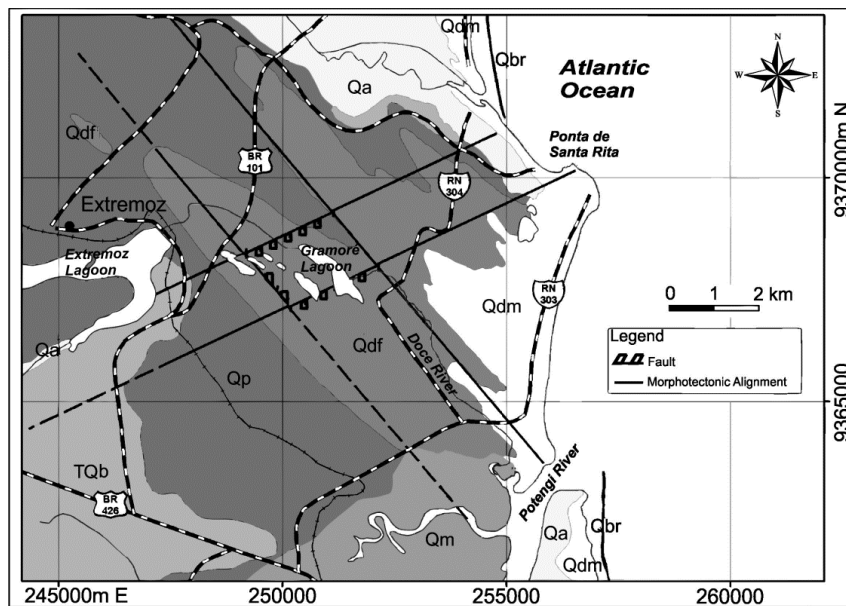


Figure 4 – Geological sketch of the northern Natal, RN, including the lower Doce River area (TQb – Barreiras Formation; Qp – Potengi Formation; Qdf – Fixed Dunes; Qdm – Mobile Dunes; Qbr – Beachrocks; Qa – alluvium and Qm – mangrove sediments).

1998; Coriolano et al., 1999; Nogueira et al., 2006). These structures result in structural grabens and horsts that control the main valleys and the disposition of the quaternary stratigraphic units according to preferential directions. A brief morphotectonic analysis of the lower course of Doce River, based in remote sensing and field investigation, revealed certain anomalies in the drainage network. The Doce River, starting at Extremoz lake, has at least two prominent deflections at 90° angles, with drainage segments that change direction abruptly from NE to SE, repeating the behavior of other river valleys on the east coast of Rio Grande do Norte State, clearly under structural control. Another important observation is the presence of linear small water bodies and wetlands, located at 0.8 km to the northeast of the current Doce river channel, although parallel to it, suggesting that the old course (paleo-channel) of Doce river underwent a drowning process, probably due to the migration of local dune fields, although it remained a signature of the SE direction in its low area, associated with the regional structures.

The integration of geological, geophysical and geomorphological data (slopes and alignments of drainages and river valleys) of previous studies is consistent with an extensional regime, where the main faults are classified as normal. The probable transcurrent components while incorporating almost all the speculation about the acting stress field have not yet been evaluated consistently as well as the variations of the stress field over geologic time. Figure 4 shows the regional geology summary of the study area.

Hydrogeological Context – The Barreiras Aquifer

The hydrogeological context consists of two zones, unsaturated and saturated, with water that is usually of excellent physico-chemical and bacteriological quality. The unsaturated zone is predominantly represented by sandy sediments from the dunes and, secondarily, by the upper portion of Barreiras Formation. The saturated zone is represented mainly by the accumulation of water in the sediments of the lower portion of the Barreiras Formation. According to Melo (1995), such hydro-stratigraphic units together form the single predominantly free Dunas-Barreiras Aquifer System, with localized semi-confinements.

This aquifer is responsible for the water supply of most coastal cities of Rio Grande do Norte State, including the capital Natal. Its lithology is quite diverse, ranging from clays to conglomeratic sandstones, although argillaceous sandstones predominate. The lower boundary of the aquifer is the top of the non-outcropping Mesozoic carbonate sequence in the region, which has been individualized in well drillings as consisting of sandy-clayey to sandy calcareous and low hydrogeological potential, or even the crystalline basement in areas near the contact of the latter with the coastal sedimentary basin (Lucena & Queiroz, 1996; Lucena et al., 2004). Regarding hydrodynamics, the Barreiras aquifer also varies considerably, particularly in the southern region of Natal all the way to the border with Paraíba State. The aquifer behavior varies from free to semi-confined, with localized confinements where the semi-confining or confining layer, when present,

is represented by clay horizons or lenses of the Barreiras Formation itself (IPT, 1982).

The potentiometric map of the Doce river lower course area (Fig. 5) shows an underground main flow from SSW to NNE, reflecting ultimately, its minor influence, in terms of capacity to delineate the local hydrogeological sub-basin, when compared to the basins of Potengi (south) and Ceará-Mirim (north) rivers. In this respect, it is remarkable the equipotential asymmetry on the margins of the Doce river, the right margin (extreme SW of the map) being the main recharge area. A secondary recharge zone is observed on the left margin of the river (east-central map), already in the context of the dune string area that represents the Environmental Protection Area (EPA) of Genipabu. This EPA is limited to the west by the RN-304 highway, to the east and north by the ocean and to the south by the Doce river (see Fig. 1). The regional discharge zone is the Ceará-Mirim river (north), and a secondary discharge is found in the Doce river lower course area, starting at the Gramoré lagoon. In addition, smaller hydraulic gradients and larger spacing of the equipotential surfaces in the east-central map indicate a more promising area in terms of hydraulic transmissivity, given by the inverse relationship of these two parameters (Feitosa et al., 2008). The density of the water points considered did not allow, however, configuring prominent hydrogeological dividers, including a possible divisor of the groundwater of the Barreiras Aquifer between the Doce River and Rio Ceará-Mirim. The hydraulic gradients vary from 5×10^{-3} (SW quadrant of the map) to 2×10^{-3} (east-central map), showing higher hydraulic transmissivity on the left margin of Doce River (from the Doce River water capture of CAERN towards NE).

In general, the Barreiras Aquifer influences the whole surface hydric context, including local lakes. In the latter case, the discharge or underground contribution entering the left margin of the Gramoré lake can be estimated (according to the potentiometric map of Fig. 5) by the expression of Eq. (1) (Feitosa et al., 2008):

$$Q = T \times I \times L \tag{1}$$

where:

T = hydraulic transmissivity;

I = hydraulic gradient;

L = water flow front.

By adopting a hydraulic transmissivity (T) of $3.03 \text{ m}^2/\text{h}$ (according to CAERN capture production test of Doce River, Pt-47RDO), a hydraulic gradient (I) of 0.0025 and a water flow front (L) of 4,000 meters, the groundwater discharge entering the right margin of the Doce River is approximately $30.3 \text{ m}^3/\text{h}$.

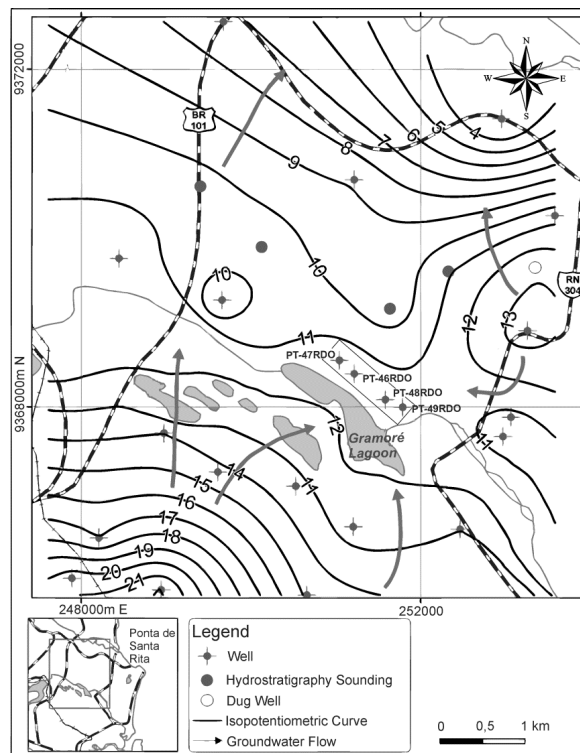


Figure 5 – Potentiometric map of Barreiras Aquifer in the lower Doce River area.

Due to the lack of piezometers that would enable the aquifer tests, the reassessment on the left bank of the lower Doce River consisted of reevaluating four capture production tests previously performed by CAERN, of four tubular wells Pt-46 RDO, Pt-47 RDO, Pt-48 RDO and Pt-49 RDO with the following UTM coordinates 251219/9368396, 251043/9368556, 251584/9367087 and 251790/9367999, respectively (marked on the Gramoré Lagoon left bank in Fig. 5). These 12" diameter wells were drilled from 07/12/04 to 06/04/05, coated with standard ribbed PVC pipes and filters (Pt-47 and Pt-49 RDO RDO) and stainless steel filters with 1-mm openings (Pt-46 and Pt-48 RDO RDO). The diameter of the pipes and filters was 8" for all wells. The tests lasted 12 hours and were performed using a submerged pump. The flow rates were measured as free discharge flow via a 200-liter barrel, while the water level measurements were made in relation to the mouths of the wells. The results of the tests are shown in Table 1.

Table 1 – Results obtained from CAERN pumping tests at the Doce River production wells.

Well	NE (m)	ND (m)	Q(m ³ /h)	q(m ² /h)
Pt-46 RDO	29.60	32.30	45.00	16.69
Pt-47 RDO	30.50	35.01	48.00	10.65
Pt-48 RDO	29.75	34.25	49.66	11.03
Pt-49 RDO	29.10	39.12	39.56	3.95

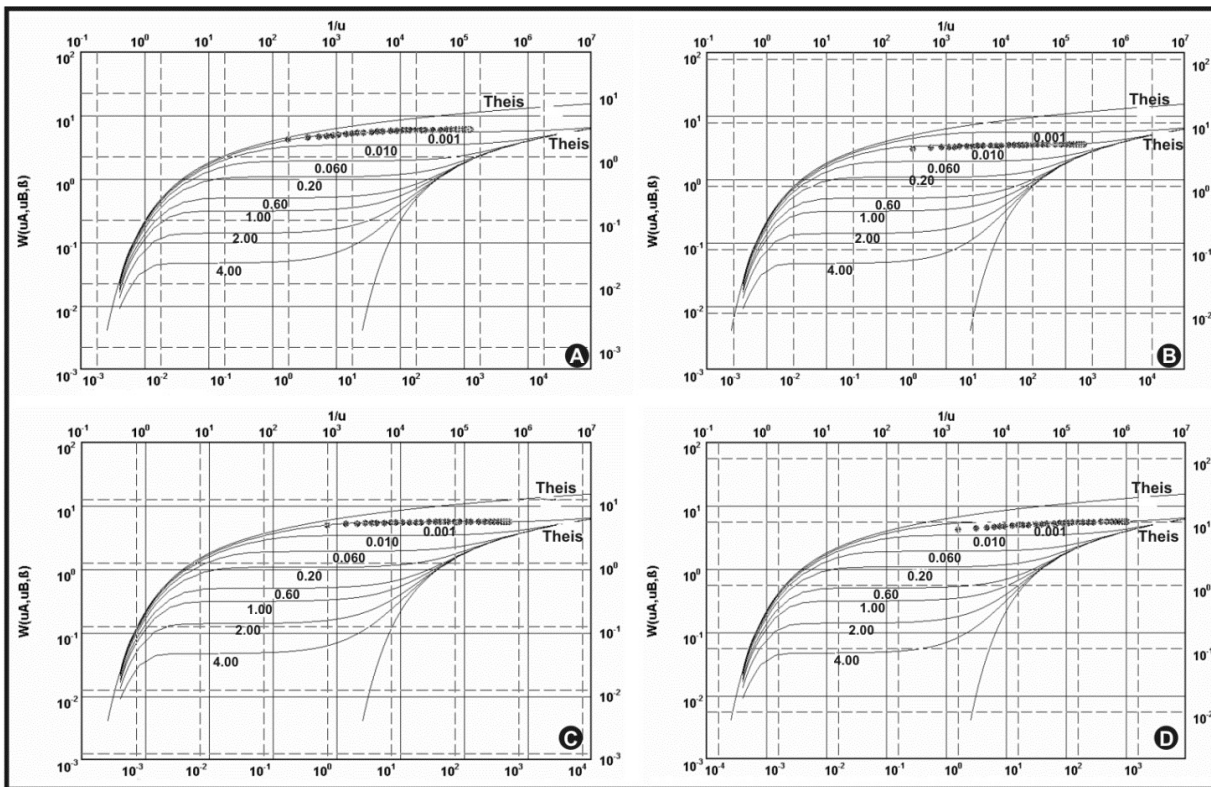


Figure 6 – Drawdown curves and respective fittings, according to Neuman’s method, for the Doce River wells – CAERN (A–Pt-46 RDO, B–Pt-47 RDO, C–Pt-48 RDO and D–Pt-49 RDO).

From these results, drawdown curves were constructed for each test and further adjusted according to methodology appropriate to the local hydrogeologic environment. In this case, the Neuman’s method (Feitosa et al., 2008) provided the best fit to the drawdown curves (Fig. 6), assuming the aquifer in the area as free and of delayed drainage. The hydrodynamic parameters, obtained using the AquiferTest software, are summarized in Table 2.

These parameters, however, differ substantially from other values obtained by CAERN for producing wells on the right margin of the lower Doce River, revealing how heterogeneous the two marginal plains of the aquifer are. Such heterogeneity must be credited to the tectonic-sedimentary evolution of the area. In this

respect, localized small grabens have been subjected to late eolian sedimentation after Cenozoic structural-tectonic events, with subsequent readjustment of local potentiometric loads. Thus, there are localized positive anomalies of hydraulic conductivity, which ultimately reflect also in elevated exploitable discharges. This observation is supported by descriptions of well logs and drilling information, which showed the presence of thick layers of sand only in the aquifer, consistent with a eolian deposition in structural lows and subsequent reworking. The changes in the lower Doce River, resulting from human activities (urbanization) coupled with the evolution of eolian sedimentation also corroborate this context. Contemporary remote sensing images reveal segments

Table 2 – Hydrodynamic parameters obtained from CAERN pumping tests at the Doce River production wells.

Wells	T (m ² /min)	K (m/min)	Thickness (m)	Tm (m ² /min)	Km (m/min)
Pt-46 RDO	1.33×10^{-1}	2.56×10^{-3}	52.00	7.397×10^{-2}	1.634×10^{-3}
Pt-47 RDO	5.05×10^{-2}	1.17×10^{-3}	43.00		
Pt-48 RDO	8.29×10^{-2}	2.07×10^{-3}	40.00		
Pt-49 RDO	2.95×10^{-2}	7.37×10^{-4}	40.00		

Table 3 – Electric sounding performed on the left margin of Doce River lower course.

ES's	Location	Coordinates UTM		AB/2 (m)	Altitude (m)	Aquifer thickness (m)
		mW	mN			
1	Close to the Doce River bank (Extremoz)	253020	9367030	500	16.00	55.0
2	Bank along the Genipabú road (Extremoz)	253742	9369464	600	34.00	50.0
3	BR-101 Pq. Vaquej. (Extremoz)	250079	9369846	600	48.00	30.0
4	BR-101 bank (Extremoz)	249352	9370378	500	55.00	40.0
5	Central green area (Extremoz)	252664	9369618	500	36.00	40.0

of abandoned river channels (with portions barred by dunes), and the old river mouth located about 1 km to the north of the current location.

Electrical-Resistivity Geophysical Survey

A total of five electrical soundings were performed in the lower Doce River (Table 3), with 1.2-km maximum spacing of electrodes ($AB/2 = 600$ m). Altimetry values were determined by topographic field survey and GP. The indicated thickness results refers only to the aquifer and not the entire Tertiary-Quaternary sedimentary column.

In order to interpret the geoelectrical data, it is necessary to adopt a model consistent with the geological environment, which, in the study area is represented by approximately horizontal sedimentary layers. In addition, the distances between the expressive horizontal discontinuities (faults) are much greater than the used maximum spacing between electrodes. Thus, the geoelectrical model adopted has the following characteristics:

- The subsoil consists of a sequence of layers with finite thickness (E_i), except the last one, which is assumed as infinite;
- Each layer is assumed to be electrically homogeneous and isotropic, characterized by a resistivity (ρ_i);
- The separation interfaces between the layers are flat and horizontal, and parallel to the Earth surface.

The interpretation of the vertical electrical sounding (VES) experimental curve ($\rho_a \times AB/2$) basically consists of obtaining numerical estimates of geoelectric parameters, in this case, resis-

tivity and thickness, for the flat and parallel layers model. The fittings between interpreted and acquired curves were made by trial and error, varying the parameters of the initially proposed model until a satisfactory fit was reached at the same time that known constraints were incorporated to the geoelectrical model.

Since there were no electrical well logs determining the *in situ* resistivity values of the local stratigraphic horizons, we performed calibration electrical soundings, adjacent to wells with known stratigraphic profiles. These VES were interpreted by fixing the layer thickness values (provided by lithological profiles) and estimating the resistivity, so as to adjust the curve using intervals of characteristic values (literature data) of the respective lithology (Silva & Medeiros, 1996). We used the geoelectric inversion WINSEV software for the VES interpretations, including the calibration electrical soundings. This software is based on the calculation of theoretical curves using the methodology described by Mallick & Koefoed (1979).

The calibration (Fig. 7), located in the Sonho Verde lot area in Parnamirim-RN (UTM coordinates 250072 mW and 9341890 mN, about 25 km south of the study area) and adjacent to the recently drilled well, defined a bottom-up geoelectric stratigraphic model consisting of: limestone (referring to Cretaceous sedimentary basin), calcareous sandstone with resistivity of 30 Ω .m., clayey sandstone turning to fine and coarse sandstone with resistivity of 180 and 500 Ω .m, respectively, and sandy sediments with eventual clay and humidity, with resistivity between 1200-5500 Ω .m. The small total thickness variation of about 3 m (66 m in lithological well profile and 63 m in the geoelectric interpretation) up to the top of the Mesozoic sequence (calcareous sandstone) can be explained by the fact that the sounding was not performed exactly on the well site, due to operational difficulties in the field.

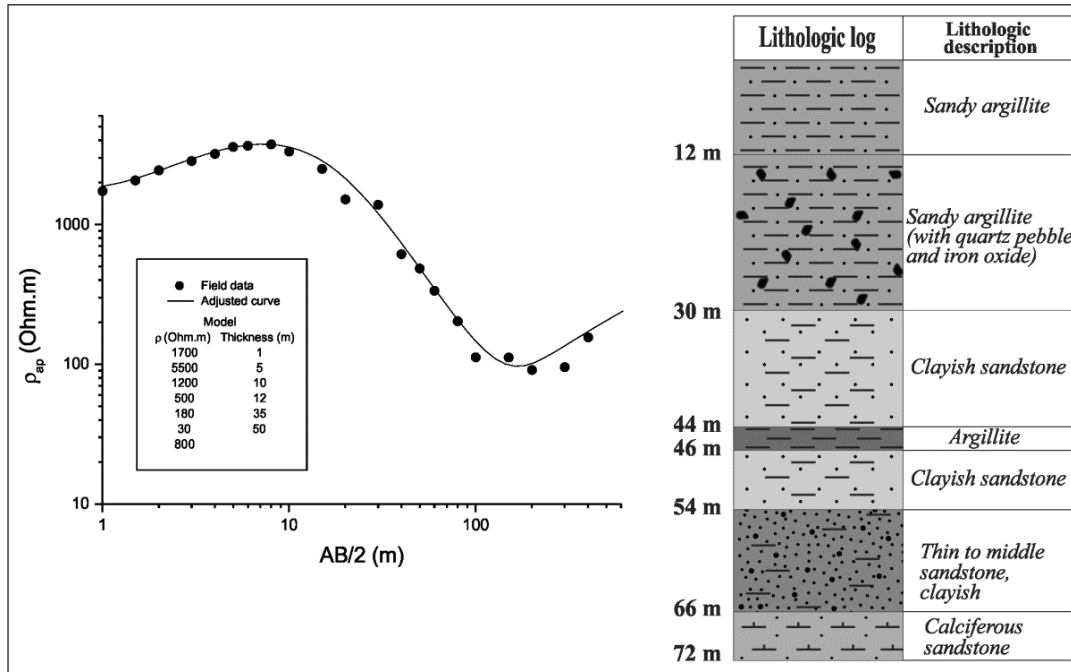


Figure 7 – Calibration electrical sounding, with “thickness × resistivity” geoelectrical model and the lithological profile from the well in the Sonho Verde area, Parnamirim, RN.

Figures 8-12 show the other soundings performed, including the geoelectrical models. Although the Cretaceous sequence limestone appears in the interpretation of some electrical soundings (resistivity of 800-1200 Ω.m. at the base of the stratigraphic column), it was not adequately characterized since it requires greater electrode spacing (deeper penetration of electric current), and is not included in the goals of this research.

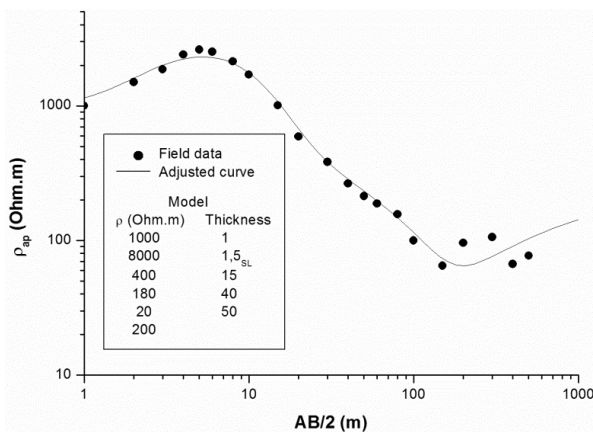


Figure 8 – Electric sounding 1 and its geoelectric model.

The Saturated Thickness Map

The interpretation and mathematical modeling of the geoelectric surveys, integrated with data from wells drilling the entire Bar-

reiras Formation, yielded a thickness map of the Barreiras Aquifer on the left margin of the lower Doce river (Fig. 13). The information of wells used herein was obtained from the database of CAERN and Autonomous Service for Water and Sewage-SAAE (Health National Foundation – FUNASA/City Halls). Data distribution and origin are presented in Table 4. This punctual information, involving XY coordinates (UTM) and their thickness values were interpolated and gridded using the Surfer software (Golden Software) Kriging method.

Table 4 – Origin of the data used to produce the Barreiras Aquifer saturated thickness map on the left margin of Doce River lower course.

Data/Orgin	Number of points
Coastline (zero saturated thickness)	06
Tubular wells	15
Electrical soundings	05
Total	26

The map of Figure 13 shows that the aquifer thickness varies between 30-35 m, mainly in the S-W sector, reaching about 60 m in the south-central sector. The well-defined E-W gradient noted in the eastern portion is due to the influence of the aquifer thickness values equal to zero taken along the coastline. The adoption of “zero” virtual values for the saturated thickness along the

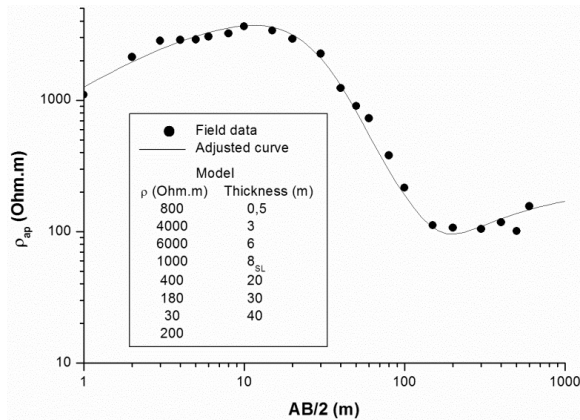


Figure 9 – Electric sounding 2 and its geoelectric model.

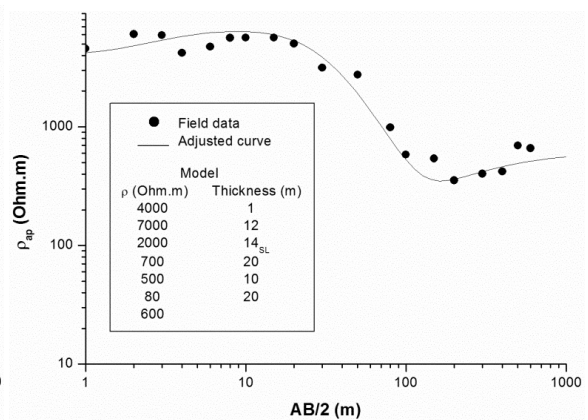


Figure 10 – Electric sounding 3 and its geoelectric model.

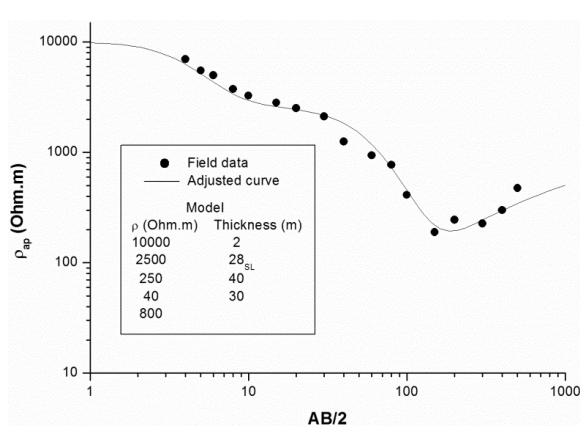


Figure 11 – Electric sounding 4 and its geoelectric model.

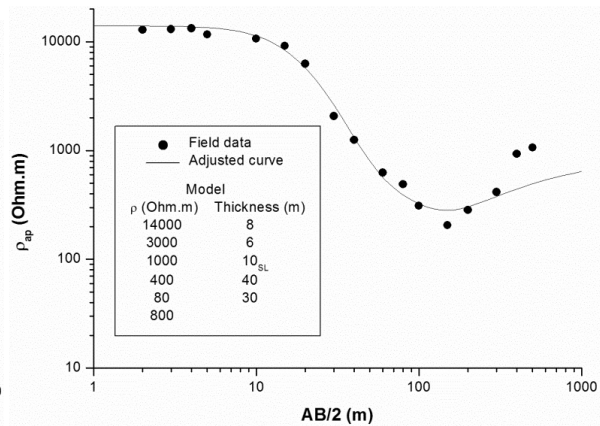


Figure 12 – Electric sounding 5 and its geoelectric model.

shoreline aimed to enhance the positive anomalies in the interior of the continent (by gridding and data interpolation), which constitute targets for water capture. In addition, it emphasizes the recommendation for not having high-flow producing wells near the sea due to the risk of salinization. Thus, the saturated thickness in this sector, also resulting from the interpolation and gridding of the source data must be viewed with reservations. Such variations in saturated thickness can also be viewed in the C-D hydrogeophysical section (Fig. 14), compiled from well log data (Pt-47RDO and Pt-49RDO) and SEVs (SEV 1 and 4).

DISCUSSION

The regional geology of the eastern coastal Natal reveals a lithostratigraphic context that consists, from bottom to top, of a Precambrian crystalline basement, Mesozoic sedimentary basin deposits, both non-outcropping sequences, in addition to all Cenozoic sedimentation. The latter outcropping throughout the study area, comprises the Barreiras Formation (Tertiary-Quaternary age)

and other Quaternary sedimentary units, composed by several generations of dunes and sandy covers and, alluvial and mangrove sediments. The tectonic and structural framework is formed by a complex regional structure, characterized in the main NW and NE directions. In this context, it is noteworthy that previous reported data show a correlation between a deep structure, supported primarily by gravimetric surveys, and a shallower structure, defined by geoelectrical surveys, morphotectonic analysis, stratigraphic correlation in well log profiles and field investigations.

The analysis of the residual gravity field was used to define the gravity alignments, which are set by the continuity of equipotential lines and demarcation between local positive and negative anomalies. Except for possible intrusions of basic rocks, negative anomalies are associated with greater thickness of the sedimentary package, reflecting particularly on the Cenozoic sequence. The results were consistent with gravimetric surveys of adjacent areas where the NW and NE directions were also evident, and are associated with the current regional stress field, which determines the maximum compression in the east-west direction and

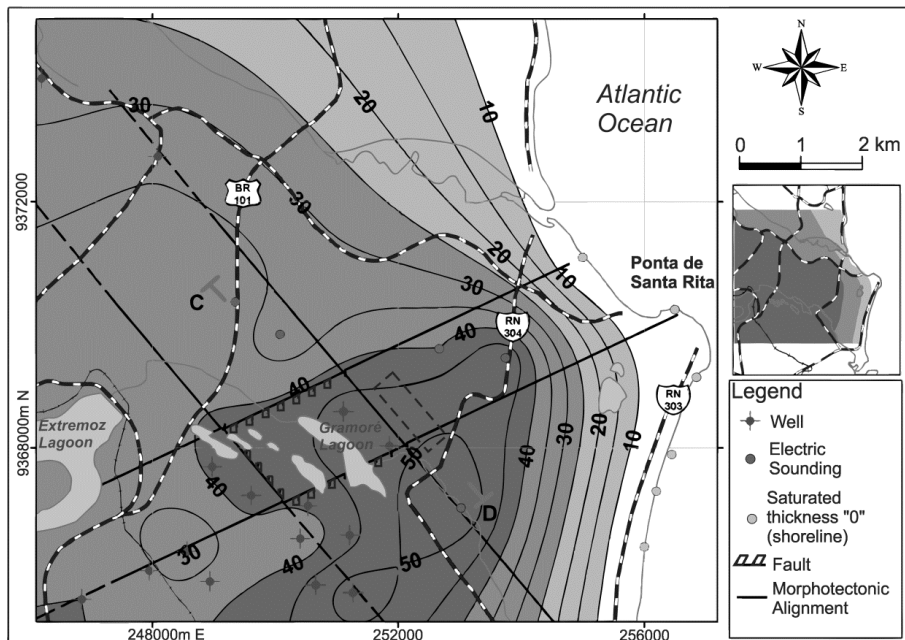


Figure 13 – Barreiras Aquifer thickness map and the structural sketch of the lower Doce River area.

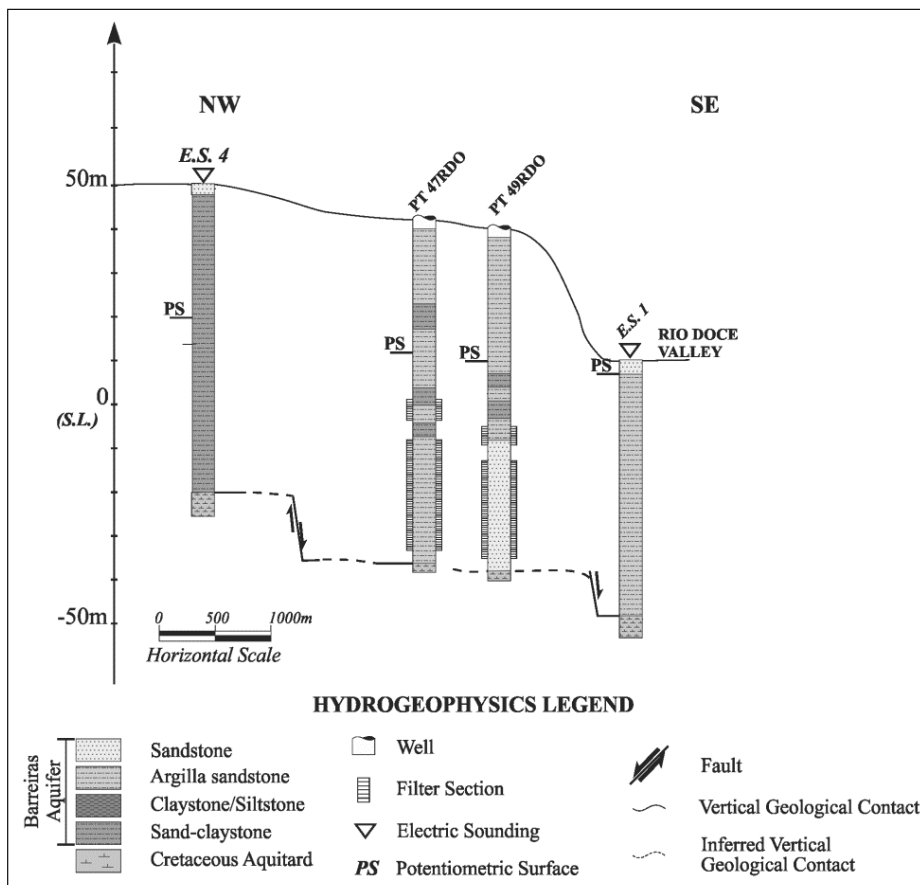


Figure 14 – C-D hydrogeophysical section derived from wells and electric sounding data (see location in Fig. 13).

maximum strain in north-south direction (Ferreira, 1997; Bezerra, 1998, Nogueira et al., 2010).

It can be suggested that the shallow structures are “rooted” in ancient and deep lineaments; considering that the fault displacements were determined by the correlation between well logs and vertical electrical soundings interpretation within the Cenozoic stratigraphy and the top of the non-outcropping Mesozoic sequence (carbonate rocks), as well as field investigations. Similarly, the faults are affecting the Cenozoic stratigraphic column and structurally conditioning river valleys (Doce River), and the morphotectonic (shallow crustal investigation) and the gravimetric (deep crustal investigation) alignments, are consistent with the reactivation of preexisting faults, rather than a strictly neoformed structure. This regional structural re-activation becomes important since it strongly influences various hydrogeological aspects, particularly the occurrence of positive anomalies of saturated thickness, resulting usually in locally high hydraulic transmissivity of the Barreiras Aquifer, as shown in Table 2.

In this context, the aquifer thickness anomaly up to 60 meters in the south-central sector (Fig. 13) is associated with NW and NE trending gravimetric alignments, identified on the residual gravity anomaly of up to -3 mGal south of Gramoré Lagoon (Fig. 3). In addition, morphotectonic alignments occur in the same directions, and at least two coincide with gravimetric alignments, particularly the NE trend that intersects the Gramoré Lagoon and the other alignment immediately NE of the lagoon. The recognition of these faults resulted from the identification of subsurface displacements, which are enhanced in the hydrogeophysical section of Figure 14. This section shows the composition of a stepped fault system, where the greater thicknesses of the aquifer are associated with the negative displacement of the Mesozoic carbonate sequence top.

It is noteworthy that the higher productivity of the wells should not be understood only as the result of saturated thickness increases, caused by local faulting. These positive changes in saturated thickness increase the capture probability of more hydraulically transmissive horizons, resulting from accumulation of sandy sediments, considering part of the regional tectonic-structural conditioning synchronous with the deposition of the Barreiras Formation (Lucena et al., 1999). The present local hydrogeological characterization, although preliminary, suggests that the “saturated thickness” parameter would be more valuable than the hydrogeological parameters “Hydraulic conductivity and transmissivity”, when searching for the most promising capture areas. Although the latter reflects the influence of saturated thickness, it is routinely obtained from the aquifer testing as opposed

to positive changes of saturated thickness that can be determined with the help of existing well logs and geoelectrical surveys. It also emphasizes the direct proportional relationship between hydraulic transmissivity and transverse electrical resistance, considering a similar relationship between the hydraulic conductivity and resistivity in the saturated zone (Henriet, 1975; Griffiths, 1976).

Regarding other aspects of the area hydrogeological context, the potentiometry revealed an asymmetrical potential of the Doce River. The main recharge area is situated on the right margin of the drainage and the great discharge zone towards the lower Ceará Mirim River. The greater distance between equipotentials, especially NE of Gramoré Lagoon, reflects higher hydraulic transmissivity also highlighted on the aquifer saturated thickness map (Fig. 13). A secondary recharge area is characterized in the center east of Figure 5, coincident with a local Environmental Protection Area (EPA of Genipabu-RN), although it does not configure a flow converging to the Doce River lower course. This regional potentiometric setting reveals, ultimately, the low expression of the Doce River as hydrogeological sub-basin unit, when compared with the adjacent basins of the Potengi (south) and Ceará-Mirim (north) Rivers. The main regional SSW to NNE flow increases, however, the risk of contamination of the left margin area of the river, since several producing wells located on the right margin have high nitrate levels, resulting from the infiltration of served water (poor sanitation system), plus chemical fertilizer used by the fruit and vegetable producers of the area.

The analysis and interpretation of CAERN capture production tests of the Doce River wells revealed transmissivity values from 1.33×10^{-1} to 8.29×10^{-2} m²/min and hydraulic conductivity from 1.77×10^{-3} to 7.37×10^{-4} m/min. These data, together with the local potentiometry and saturated thickness map indicate an optimized location of a string of wells, aimed at increasing the water supply to northern Natal, approximately parallel to the current Doce River capture, displaced about 1 km towards E-NE.

CONCLUSIONS

The integration of shallow and deep geophysical data in the hydrogeological context of the Barreiras Aquifer was very effective in developing a local hydrogeological conceptual model that emphasized the geometry of the aquifer. The regional structure reported herein, whether modern or from reactivated ancient and deep lineaments was determinant in the aquifer compartmentalization, especially by defining the positive thickness anomaly of Barreiras Aquifer of up to 60 meters in the vicinity of Gramoré Lagoon. In this respect, there was a similarity between some

gravimetric alignments (deep investigation) and local morpho-tectonic alignments (shallow investigation), indicating that this saturated thickness anomaly resulted from the kinematic evolution of deeper structures (rooted) in the basement. This structural kinematic evolution led, ultimately, to the delineation of more promising subareas in terms of hydraulic transmissivity, taking as reference the aquifer thickness and assuming an average hydraulic conductivity representative of the left margin area of the Doce River (about 1.63×10^{-3} m/min for the CAERN capture in the Doce River). Thus, it is noteworthy that the electrical resistivity survey has confirmed to be an essential prospecting methodology, to determine the top and bottom of the Barreiras Aquifer since the saturated thickness parameter prevails at the expense of other hydrogeological parameters obtained for the same location.

Future well locations on the left margin of the Doce River should prioritize the interception of the reported geological/hydrogeological feature, even more due to the proximity of a secondary recharge zone. This determines a zone roughly parallel to the current Doce River capture and displaced about 1 km towards E-NE.

Given the results of this research, the first of the new water captures drilled by CAERN in January 2009 with 8" pipe, located within the selected area of saturated thickness positive anomaly (indicated by the dashed line NE of the Gramoré Lagoon), gave a specific flow of 14 m²/h, with recommended exploitable flow of 100 m³/h. Such values result in a total discharge estimative of not less than 300 m³/h for all four wells.

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