The use of FDEM–GCM method in environmental investigation: coastal aquifer case studies

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Abstract

This work presents the results of a research project that it had as motivation to obtain a better knowledge of the seawater intrusion contamination problem of the coastal aquifers in Canoa Quebrada city at coastal zone. The water supply to the coastal zones comes mainly from the coastal aquifers that are represented in the Ceará State by a system composed of dunes/Barreiras Formation/ crystalline. Due to intensive use of these groundwater reserves in the last years as a consequence of accelerated population growth along the coast, these systems are beginning to present signs of exhaustion that are characterized by salt contamination. The geophysical applied method used in this research to identify the seawater wedge in the coastal aquifer bases on the electromagnetic induction law treated in the frequency domain. This method is known as **GCM** ("Ground Conductivity Meter") that uses the system EM34. The hydrogeological domain in the studied area is defined as sedimentary composed of the Dunes, Alluvia, Terraces (colluvium coverings), the Barreiras Formation and Apodi Group. The main beach of Canoa Quebrada is worldly known due the presence of cliffs of 20 m of height at the beach line. For information obtained in field, old groundwater exploitation wells in the beach close to the foot cliff produced potable water of good quality five years ago and now the water of these wells is totally salted. In this area, due to the fact that the crystalline basement is at a depth superior to the investigation depth of the FEM-GCM method it was made a Vertical Electric Survey. The results obtained by this investigation allowed identifying the crystalline basement depth and the thickness of the saturated water mud-sandy package that corresponds to the Barreiras Formation resting over the crystalline basement or over the Apodi Group sediments. The results of this model were used as *priore* information for the FEM-GCM data inversion. The acquisition of the conductivity data was made along three parallel profiles that were orthogonal to the beach line and in such direction that is approximately parallel to the main directions of the structural lineaments. The information of the crystalline basement depth was recovered performing the 1-D inversion that allows to obtain a model that best adjusts the data in the sense of the minima squared by the outline of adjustment "ridge regression". The final model obtained after having made the 1-D inversion is presented under Geoelectrical Section form where the conductivity values and correspondent depths were interpolated. The results obtained in this study demonstrate that the method FEM-GCM is efficient in characterizing geoelectrically the presence of seawater intrusion contamination in coastal aquifers. It is concluded from the obtained results that in fact the problem of seawater intrusion contamination already exists in the Barreiras aquifer.

Introduction

The Ceará State is located in north-eastern Brazil. Its coastal zone is approximately 572 km long and consists mainly of long sandy beaches occasionally interrupted by small rivers and rocky headlands. The State is constantly affected by periodic droughts; for this reason the use of water resources is fundamental to the State's developmental process (Lima and Maia, 2004; Maia and Lima, 2003). When the underground water is pumped from aquifers that are in hydraulic connection with the sea, the gradients that are established can induce a flow of salted-water of the sea in direction to the well. This migration of salted water inside of aquifers of fresh water under the influence of the urban development is known as *seawater intrusion.* The seawater intrusion can be induced so much in aquifer confined as in free aquifer.

The water supply to the coastal zones comes mainly from the coastal aquifers that are represented in the Ceará State by a system composed of dunes/Barreiras Formation/ crystalline. Due to intensive use of these groundwater reserves in the last years as a consequence of accelerated population growth along the coast, these systems are beginning to present signs of exhaustion that are characterized by salt contamination.

Geoelectrical techniques have been used with success to detect the interface fresh water - salted water in coastal aquifers as described in the works of: Flathe (1970) and Zohdy (1969) applying the direct current resistivity (DCR) method; Stewart (1982), Lima and Maia (2004) and Maia and Lima (2003) applying electromagnetic (EM) induction in the frequency domain method (FDEM) using the system EM34 (Geonics); Fitterman & Hoekstra (1984) applying transient electromagnetic induction method (TEM); Carrasquila et al. (1997) applying the two methods combined. All these techniques have been showing to be efficient in supplying valuable information concerning the interface fresh water–salted water. The interface can be vertical (a gradual increase in the salinity of the coastal aquifer) or horizontal (lens of fresh water inserting lens of salted water). The two situations are common in coastal areas and both can be mapped very well by DCR and /or FEM methods. The EM34 is the one of the most suitable tools for a fast and more sensitive data acquisition to identify lateral variation in the conductivity in geological situations of shallow crystalline basement, in other words, close of 60 meters of depth (McNeil, 1980; 1990). Besides, usually the spacing among the coils used in a lot of electromagnetic methods it is shorter than the length of the arrangement used in conventional electric surveys resulting in improvement of space resolution when used in the profile way. For these reasons it is increasing the interest in the use of EM techniques.

APPLIED METHODOLOGY

The applied method bases on the EM induction law treated in the frequency domain. Considering two circular coils where the first is the transmitter and the second is the receiver it is then applied an alternating current in the transmitter coil. The two coils stay separate to a certain distance and they are positioned on the soil in two different configurations: (1) aligned in the same way in the vertical plan called Horizontal Dipole and (2) the two placed on the soil aligned in the horizontal plan called of Vertical Dipole. This method is known as “Ground Conductivity Meter” **(**GCM) that uses the system EM34, which is a variant of the Swedish Slingram EM induction method.

In general the secondary magnetic field is a complicated function of the spacing *s* between the coils, of the operation frequency, *f* and of the conductivity of the soil, σ. The value measured in the receiving coil it is the ratio H_s and H_p, the field when the coils positioned on a surface of homogeneous semi space with conductivity σ and the field when the two coils in the free space, respectively. The ratio is given as over homogeneous unit,

$$\left(\frac{H_s}{H_p}\right)_V \cong \left(\frac{H_s}{H_p}\right)_H \cong \frac{iB^2}{2} = \frac{i\omega\mu_0\sigma s^2}{4} \qquad (1)$$

where $\omega = 2\pi f$, μ_0 = free space permeability, i = $\sqrt{-1}$, B is induction number and much smaller than 1, and defined in terms of the skin depth δ as:

$$B = \frac{s}{\delta} << 1 , \quad \text{where} \quad \delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} \qquad (2)$$

So that the reading of the instrument is carried out in terms of the apparent conductivity σ_a, defined by (e.g. McNeil 1980, Parasnis 1986):

$$\sigma_a = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right) \qquad (3)$$

STUDY AREA

It was selected the beach of the Canoa Quebrada city in the municipal district of Aracati of Ceara State. The beach of Canoa Quebrada city is characterized for being a resort in frank expansion of tourist development (Figure 1).

Figure 1 - Study area: the beach of the Canoa Quebrada city.

GEOLOGY

According to Veríssimo et al. (1996) the regional geology is understood in three different groups: The first group constituted the crystalline basement identified as Complex Caicó / Northeasterner. The second litostratigraphical unit is identified as Orós Group, it is still part of the crystalline rocks identifies as plutonovulcano-sedimentary sequence. The third group embraces all the non-metamorphic sedimentary coverings including the Barreiras and Apodi (constituted by the formations Açu and Jandaíra) Groups, the tercio-quaternary coverings (terraces) outlying of the Jaguaribe river, the alluvia and at last the Dunes (coastal eolic sediments).
In the studied area the crystalline basement depth is about 100 meters (Maia et al., 1993). Above the crystalline basement occurs to east of the Jaguaribe river the Açu arenitic formation and to west the Barreiras Formation.

HIDROGEOLOGY

The hydrogeological domain is defined as sedimentary composed of the Dunes, Alluvia, Terraces (colluvium coverings), the Barreiras Formation and Apodi Group.
The dunes occupy a surface of 80 km^2 tacking the coast line having medium width of 2 to 3 km and thickness of the order 5 to 30 m. In this unit are included the recent dunes so much as the fixed paleo-dunes and the beach sediments constituted by selected homogeneous sands

that are high permeability free aquifers with yields reaching 15 m^3/h. The recharge is made predominantly by direct rain infiltrations. The sea, rivers, streams, interdunares ponds and the evapotranspiration represent the discharges. The waters of the aquifer Dunes are predominantly chlorite-sodium and have excellent physical-chemistry quality.

The Barreiras and Terraces aquifers represent a clastic mud-silt-sandy sequence with predominance of the mud-silt fraction and it recover a 2.078 km^2 surface area and can be considered as an only hydrogeological unit. This unit is characterized as being a free aquifer having small permeability with variable thickness and groundwater exploitation essentially at the sandy levels (Gomes et al., 1981). The medium depth of the wells varies from 20 to 50 m some of them could reach up to 100 meters. The medium yield oscillates between 2 and 3 m^3/h reaching a maximum of 5,5 m^3/h (Bianchi et al., 1982). The recharge is accomplished essentially through the rainfall and secondarily by the influential drainages and covered formations (alluvia and dunes). The discharges are represented by the outflow drainages, evapotranspiration and covered formations that allow means of water transferring. In general, the waters are of good physical-chemistry quality happening occasionally with high concentration of oxide of iron (Bianchi et al., 1982).

RESULTS

The main beach of Canoa Quebrada is worldly known due the presence of cliffs of 20 m of height at the beach line. For information obtained in field, old groundwater exploitation wells in the beach close to the foot cliff produced potable water of good quality five years ago and now the water of these wells is totally salted. This fact was proven in field so much by flavor test as by conductivity measurements using a digital conductivity meter. While the conductivity values of the exploitation wells aligned at a distance of 100 m of the border of the cliff vary from 227 µS and 471 µS the well closer to beach line presents a conductivity value of 44.3 mS. This fact is already a strong indicator of the existence of the seawater intrusion contamination problem in the coastal aquifer.
In according on geology information and previous works using Vertical Electric Survey (Maia et. all, 1993) the crystalline basement depth in the Canoa Quebrada beach is expected as being 40 m until a maximum of 100 m of depth. In this area, due to the fact that the crystalline basement is at a depth superior to the investigation depth of the FDEM-GCM method it was made a DCR Survey. The results obtained by this investigation allowed identifying the crystalline basement depth and the thickness of the saturated water mud-sandy package that corresponds to the Barreiras Formation resting over the crystalline basement or over the Apodi Group sediments. The results of this model were used as *prior* information for the FDEM-GCM data inversion. The acquisition of the conductivity data was made along three parallel profiles that were orthogonal to the beach line and in such direction that is approximately parallel to the main directions of the structural lineaments. In such way it is ensured that the variation of conductivity values observed along the profiles it is only owed to the presence of seawater intrusion and not to the structural discontinuity.

Analyzing only the curves of apparent conductivity without perform the data inversion we didn't get to infer the crystalline basement depth. This information is then recovered starting performing the 1-D inversion that allows to obtain a model that best adjusts the data in the sense of the minima squared by the outline of adjustment "ridge regression" (Inman, 1975) using the commercial software EMIX34-Plus.
The final model obtained after having made the 1-D inversion is presented under Geoelectrical Section form in Figure 2 where the conductivity values and correspondent depths were interpolated.

The apparent conductivity curves for the profile 3 are illustrated in Figures 3, 4 and 5. Interpreting these curves without performing the data inversion suggests that exists a high degree of heterogeneity of the subsurface (Figure 3) and that the saturated water level of the aquifer is to an approximate depth of 30 m and that the presence of the saline wedge is only noticed starting from the configuration DH40 (Figures 4 and 5). However, being compared with the other two profiles the values of conductivity of the aquifer are a little smaller. This fact can be explained by the presence of another aquifer, the aquifer dunes. This interpretation is noticed analyzing the final inversion conductivity model. This model is illustrated in the figure 2 as Conductivity Geoelectrical Section. It is important to mention that for the illustrated model it was not taken into account the topography. In the model of the profile 3 at 150 m of distance begin the dunes with elevations of 40 m and accentuated inclination. Therefore in the model starting from 150 m comes in an area with conductivity values moderated that are represented in the blue color. This area was interpreted as the presence of the aquifer dunes, which has a conductivity value inferior of that Barreiras aquifer and it is identified the recharge flux connection between the two aquifers. Therefore the interpretation of this model indicates a package of recent sediments covered on the Barreiras aquifer in the beginning of the profile (close to the beach line) and at the end that it corresponds to the course on the dune it presents a layer of medium conductivity value corresponding to the aquifer dunes and a relative resistive interface that should correspond to a buried beachrock. Below this resistive layer there is a layer of low resistivity value that corresponds to the continuation of the aquifer Barriers. In this profile, the presence of seawater intrusion is indicated at a distance of 20 m starting from the border of the cliff.

CONCLUSION AND SUGGESTIONS

The results obtained in this study demonstrate that the method FDEM-GCM is efficient in characterizing geoelectrically the presence of seawater intrusion contamination in coastal aquifers. The great advantage of using this method is the speed of the survey what results in reduction of costs in the field campaigns. Its limitation of investigation depth is compensated by the combined use with another method geophysical method that in the case of this study it was used the Vertical Electric Sounding method.

It is concluded from the obtained results that in fact the problem of seawater intrusion contamination already exists in the Barreiras aquifer. The progress of the saline wedge is shown accentuated taking in account the localization in the central beach of the main exploitation wells. As the area is in frank tourist expansion, what certainly it will result in more intensive use of groundwater exploitation, the progress of the saline wedge will be able to in a close future to contaminate the existent wells. This will bring immediate problems for the consumption and it will implicate in the need of new investments for construction of new exploitation wells more distant of the beach line. Therefore, it is suggested that are done new surveys in form of profiles and new measures of VES surveys in way to embrace a wider area so it can be possible to compose a monitoring database to check out the progress of the saline wedge in the area.

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References:

Bianchi, L. et al., 1982. Recursos hídricos das regiões do Baixo e Médio Jaguaribe - CE. Fortaleza: Secretaria de Agricultura de Abastecimento do Ceará / PROMOVALE, 1982, 61 p. il.

Carrasquila, A. A. G., Fontes, S.L., Lima, J. P. R., Laterra, E. F., Germano, C. R., Metelo, M., 1997. Geoelectrical and Magnetic Profiling for Fracture-Zone Aquifers in a Crystalline Basement Terrain in Piauí State, Northeast Brazil. In: 5th International Congress of the Brazilian Geophysical Society, Expanded Abstracts, v. II, p. 441-444.

Fitterman, D.V. and Hoekstra, P., 1984. Mapping of saltwater intrusion with transient electromagnetic soundings. In: Nielsen, D. M. and Curl M., Eds., Proceedings of the National Water Well Assn. Conference on surface and borehole geophysical methods in subsurface investigations, Santo Antonio, National Water Well Assn., p. 429-454.

Flathe, H., 1970. Interpretation of geoelectrical resistivity measurements for solving hydrogeological problems. In: Morley, L. W., Ed., Mining and groundwater geophysics, Geol. Surv. Can. Economic Geol. Rep., 26, p. 580-597.

Gomes, J.R. de C., Gato, C.M.P.P., Souza, G.M.C. de, Luz, D.S. da, Pires, J. de L., Teixeira, W., 1981. In: Projeto RADAMBRASIL (Programa de Integração Nacional, Vol. 23. Levantamento de Recursos Naturais), Folhas SB 24/25, Jaguaribe / Natal; geologia, p. 31-280. Rio de Janeiro, 1981.

Inman, J.R., 1975. Resistivity inversion with ridge regression. Geophysics, 40, 798-817.

Maia, L.P., Morais, J.O., Moraes, R.M, 1993. Geometria dos Pacotes Sedimentares da Borda Oeste da Bacia Potiguar. XV Simpósio de geologia do Nordeste - Natal, 1993. P. 355-356.

Lima, J.PR. and Maia, L.P., 2004. Estudos Hidrológicos e Geofísicos Integrados para Avaliação do Problema de Intrusão Marinha em Aqüíferos Costeiros na Região NE do Brasil. VII Simpósio de Recursos Hídricos do Nordeste, São Luís / MA, 30 nov a 03 dez de 2004, trabalho completo em forma digital em cd com 20 paginas e resumo em forma impressa no Livro de Resumos pg. 213.

Maia, L.P. and Lima, J.P.R., 2003. Hydrogeochemical Characterisation of Groundwater Saline Intrusion in the Western Shore of Ceará, North-Eastern Brazil. In: L..D. Lacerda; R. E. Santelli; E.K. Duursma; J.J. Abrao. (Org.). Facets of Environmental Geochemistry in Tropical and Sub-tropical Environments. Heidelberg, 2003, v. 1, p. 277-291.

McNeill, J.D., 1980. Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. Technical Note TN-6, Geonics Limited, Ontario, Canada.

McNeil, J.D., 1990. Use of Electromagnetic Methods for Groundwater Studies, *In*: Ward, S. H., 1990, Geotechnical and Environmental Geophysics, Vol. I: Review and Tutorial.

Parasnis D.S., 1986. Principles of Applied Geophysics, 4^{th} ed. London Chapman and Hall.

Stewart, M. T., 1982. Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers, *Ground Water*, 20, p. 538–545.

Veríssimo, L.S., Medeiros, M. de F., Souza, J.F. de, Andrade, F.T.B. de, 1996. Avaliação das Potencialidades Hídrica e Mineral do Médio-Baixo Jaguaribe - CE. CPRM, 1996; 115 p. (Série Recursos Minerais - Fortaleza - v. 4). "Programa Gestão e Administração Territorial - GATE".

Zohdy, A. A. R., 1969. The use of Schlumberger and equatorial soundings in groundwater investigations near El Paso, Texas, *Geophysics*, 34, p. 713-728.

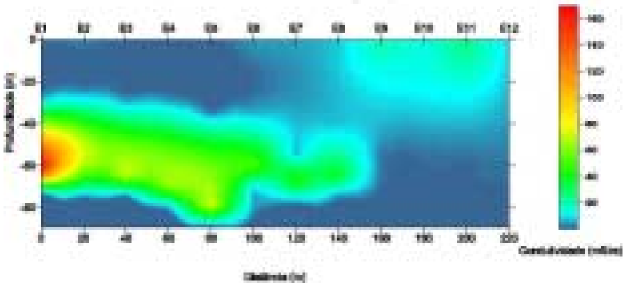

Figure 2 - 1D inversion result of the DCR data for profile L3 in Figure 1.

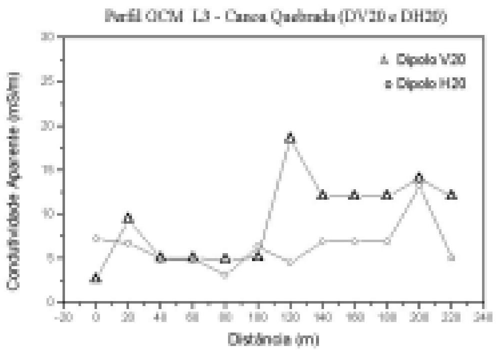

Figure 3 - Apparent conductivity data obtained from FDEM method for s=20m.

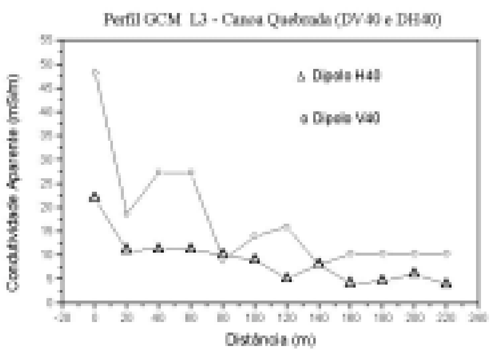

Figure 4 - Apparent conductivity data obtained from FDEM method for s=40m.

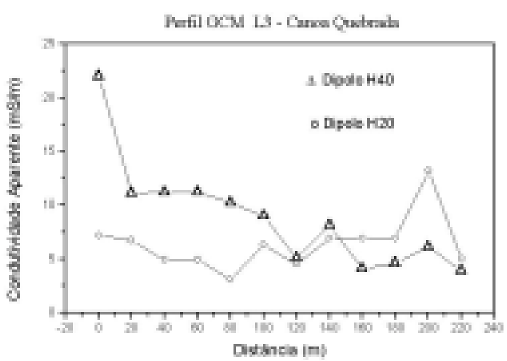

Figure 5 - Apparent conductivity data obtained from FDEM method for s=20 and 40m.