Geofísica Internacional (2016) 55-2: 119-129

Original paper

Comparative analyzes among electrical resistivity tomography arrays in the characterization of flow structure in free aquifer

César Augusto Moreira, Marcelo Montenegro Lapola and Alan Carrara*

Received: May 11, 2015; accepted: November 27, 2015; published on line: April 01, 2016

Resumen

En este trabajo se hace un análisis comparativo entre los arreglos Dipolo-dipolo, Wenner e Schlumberger por medio de pruebas de Tomografía de Resistividad Eléctrica (TRE), como la sensibilidad y la resolución en la caracterización espacial de la infiltración de contaminantes en un tanque séptico y cono de depresión en el pozo de captación de agua; ambos contenidos en acuífero libre. La adquisición de datos consistió en lecturas de resistividad utilizando cinco líneas paralelas con 105 m de largo espaciado, 5 m entre los electrodos y líneas. Los datos de cada línea se sometieron a la inversión 2D, posteriormente interpolado para la generación de bloques 3D, de la cual se extrajo una isosuperficie de resistividad fija (620 Ω.m), lo que permitió el modelado de las estructuras de volúmenes de flujo relacionados. Los resultados para el arreglo Dipolo-dipolo permite el modelado de la estructura asociada con el eje cilíndrico, y un isosurface de la cavidad asociada con la deformación, pero que no permitirá que el modelado de la pluma. Los datos para la disposición Schlumberger no pueden ser reconocidos cono, pero dieron lugar a un modelo de forma de lágrima asociado con el tanque séptico, como una pluma de contaminación. El arreglo Wenner resultó en un modelo con estructura en formato de quilla alargado asociado con el cono de depresión, y uno en formato caída similar también asociado con el tanque séptico. El análisis comparativo muestra que la disposición Dipolo-dipolo se recomienda en las obras de modelado de estructuras tridimensionales de alta resistividad verticales en la zona saturada. La disposición Wenner y Schlumberger se recomiendan en estructuras de modelado en tres dimensiones verticales de baja resistividad en zona no saturada, con énfasis en la disposición Schlumberger.

Palabras clave: Dipolo-dipolo, Schlumberger, Wenner, pluma de contaminación, cono de depresión.

Abstract

This paper makes a comparative analysis between the Dipole-dipole, Wenner and Schlumberger arrays through electric resistivity tomography (ERT), about the sensitivity and resolution in the spatial characterization of infiltrating pollutants in septic tank and cone of depression in supply well, both contained in unconfined aquifer. Data acquisition consisted of electrical resistivity readings using five parallel lines with 105m long, electrode spacing and lines of 5m. The data from each line were subjected to 2D inversion and then interpolated to generate 3D blocks, which were extracted from a fixed resistivity isosurface (620 Ω.m), which enabled the modeling of volumes related to the flow structures. The results for the Dipole-dipole array allowed the modeling of the cylindrical structure associated to the supply well, and an isosurface deformation associated to the septic tank, but did not allow the modeling of the plume. The data for the Schlumberger array cannot allow for the cone recognition, but resulted in a drop shape model, associated to the septic tank and similar to a contamination plume. The Wenner array resulted in a model with structure in elongated keel format associated to the cone of depression, and another that is similar to the drop shape model, also associated to the septic tank. The comparative analysis shows that the Dipole-dipole array is recommended in works of modeling vertically integrated three-dimensional structures of high resistivity in the saturated zone. The Wenner and Schlumberger arrays are recommended for modeling vertically integrated three-dimensional structures of low resistivity in unsaturated zone, with emphasis on the Schlumberger array.

Key words: Dipole-dipole, Schlumberger, Wenner, contamination plume, cone of depression.

C. Augusto Moreira
Applied Geology Department

M. Montenegro Lapola
Graduation in Physics

A. Carrara*
Graduation in Environmental Engineering
Geoscience and Exact Science Institute
Univ. Estadual Paulista, UNESP, Rio Claro Campus
24-A Avenue, 1515, PO box 178 – ZIP 13506-900
São Paulo State, Brazil
**Corresponding autor: alancarrara05@gmail.com*

Introduction

The availability of hydric resources is something that requires growing attention by public management, in face of the demand increase and the even more restrict offer in terms of quality, availability and flows enabled by superficial hydric resources.

In face of the Brazilian hydric potential, its energetic matrix is historically based in the generation of electricity in ramps enabled by dams, which, among many other aims, also represent an available resource to public service (MME, 2013). Under a context of long drought periods, as in the case of the present Southwest Region of Brazil, it is natural the emergence of a standstill about the energetic needs and public supply.

In other view, it is still incipient the adoption of measures that aim to mitigate questions like the wastage in leakages in distribution lines, clandestine connections or the reuse of water coming from the waste treatment in distribution lines in specific activities. This set of factors, allied to the present hydric crises, indicates a scenario of energetic rationing and of public supplying.

The underground hydric resource is always an alternative considered in many cases, preferably in cities where the superficial resource availability is scarce or in a way to supplement the superficial capture (Balek, 1989). Particularly relevant in economic terms, underground capture is a growing resource in the capture by industries, agriculture, and in cases of communities distant from distribution networks (Hiscock, 2005; Elgzeli *et al.*, 2013).

The absence or scarcity of collection and treatment systems of sewage and liquid effluents and their direct throwing in rivers and lakes results in a direct impact of this superficial resource. However, in places where this procedure is economically unfeasible, the use of septic tanks is a very used alternative (Nemerow *et al*., 2009). The little visibility of this procedure and the hypothesis of depuration by filtering enabled in the geological environment, results in its indiscriminate use and not provided of any planning or technical procedures (König & Weiss, 2009).

The load of pollutants eventually present in streams and rivers is much attenuated in rainy periods, where the increase in flows enables for the dilution of liquid effluents and the increase in the outflow speed. However, the input of this kind of pollutant in soil and aquifers be it in accidental or purposeful form, results in long-term impacts due to the resident term by the infinitely lower speed in this environment (Peirce *et al*., 1998; Sara, 2003).

Obviously, it is essential the use of technical procedures that impair this kind of affect, besides the development and improvement of technologies that enable the diagnosis and the monitoring of ongoing situations (Lehr *et al*., 2001; Twardowska *et al*., 2005; Hernández-Soriano, 2014).

The use of geophysical methods is a rational possibility in this context. In face of factors like indirect measuring of physical factors that can be altered in face of the presence of pollutants in soil and underground water, wide coverage for investigation in spatial terms and the possibility of monitoring in a fast way at a relatively low cost, when compared to traditional techniques like installation and sampling of monitoring wells. (Knödel *et al*., 2007; Sara, 2003).

In this sense, the present work presents and discusses the results of the application of the geophysical method of electro resistivity, in an area with septic well upward an underground catchment well for public service. In this place, Electrical Resistivity Tomography (ERT) essays were performed in Dipole-dipole, Wenner and Schlumberger arrays. The main aim is an analysis of the most adequate array in terms of sensibility and resolution, in the detections of pollutants infiltrated in septic tanks and the identification of the depression cone in underground capturing systems.

Area of studies

The geophysical collection data was developed in the campus of the Universidade Estadual Paulista – UNESP, in the city of Rio Claro (SP), 190 km to the southwest of the state capital. The place consists in a terrain attached to a set of three didactic buildings with about 10 years of built, from where all water coming from restrooms was piped and conducted by gravity to a septic well located in the NW end of the site. About 5 years ago, a series of drillings and the installation of a interlinked chain of underground collection wells, among all these is a well located at 40m downstream the septic well, in the SSW direction (Figure 1).

In physiographic terms, Rio Claro is included in the São Paulo Peripheral Depression, geomorphologic unit characterized by lowered terrains and altitudes between 500 m and 700 m. The raising geological unit in the area of studies is the Rio Claro Formation, which in this region, presents an approximate thickness of 20 meters, placed beneath by siltstone of Corumbataí Formation and locally intruded by dams and sills of diabase related to the event Serra Geral (Oliva *et al*., 2005).

The Rio Claro Formation is made up of Neocenozoic deposits and is part of a set of units that cover large areas of the State, which occur in sloped levels in the relief and linked to planning phases. The work of Melo *et al*. (1997) proposes the division of this unit in four great lithofacies in the basis of granulometric and textural criteria. The laminate bed is originated from gravitational processes, gravel and sand from channels and river estuaries, fine sandstone occurring from the breaking of marginal dams and sedimented argilites in flooded plain areas. This set covers a basal horizon made up of conglomerates derived from erosion processes of the substrate during the initial phases of deposition of this unit, with emphasis to the Corumbataí Formation (Oliva & Chang, 2007).

This unit is characterized as a free aquifer in the region of Rio Claro, with high elevated transmissivity (upper 50 m^2/day) and wells with outflow of between 17m^3/h and 25 m^3/h. A second system of confined aquifer is represented by lithotypes of the Tubarão Group, with depths over 200 m and flow between 20 m^3/h and 37 m^3/h (DAEE, 1981).

In the area of studies, the Rio Claro Formation is represented by soil of arenite alterations, with predominance of fine to medium sand fraction. Based on the descriptive profile of the supply well in the site of studies, the first 10 m deep are constituted by a low consolidated arenite and of silt matrix, with sandy fractions absent of fine matrix below this depth.

This well is 20 m deep and presented a groundwater level positioned at 12.3 m during the performance of the geophysical essays, with a production of 8 m^3/h. The studies developed by Oliva *et al*. (2005), a few tenths of meters from the site of studies, revealed values of hydraulic conductivity for 2 m depth of 9,6x10^{-3} cm/s and of 6x10^{-3} cm/s for 14 m depth (saturated zone).

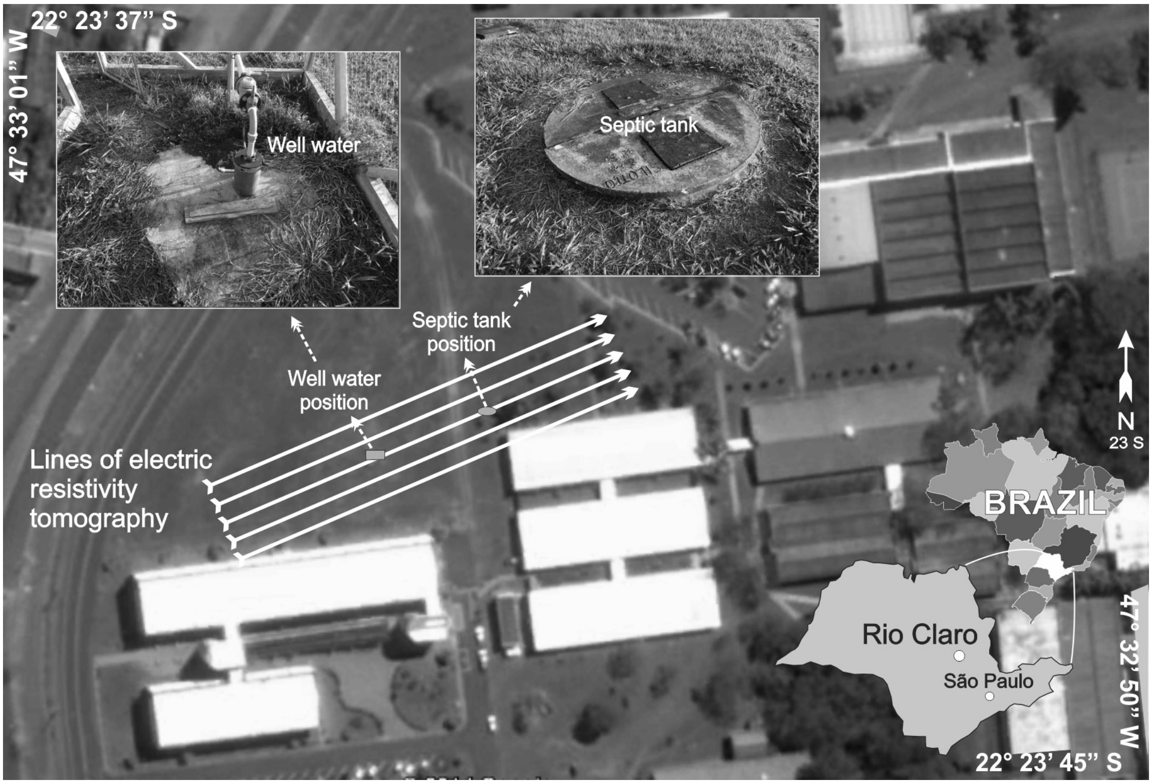


Figure 1. Location of the area of studies, with lines of the electrical resistivity tomography lines and detaching the investigated targets.

The septic tank located in the area of studies is 2 m in diameter and 3 m in depth, with a lining of concrete piping and open base, enabling the filtering of effluents directly into the soil. The area of studies has very plane topography, with a slope of approximately 1° in the SW direction of the area

Materials and methods

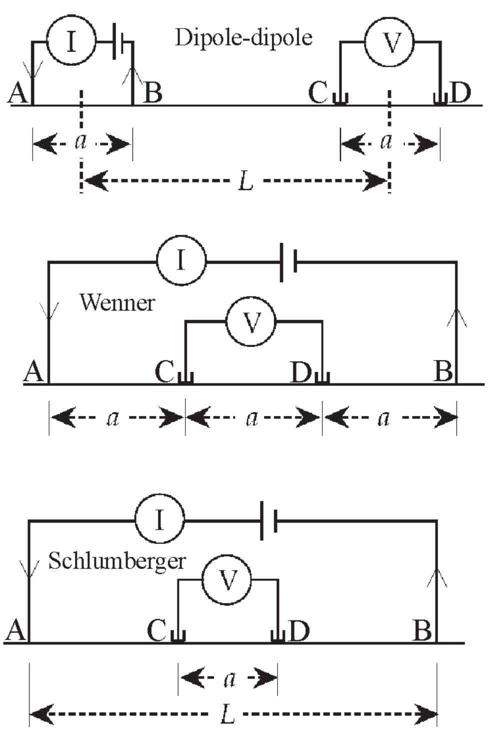
The acquisition of data in the field consisted in the performance of electrical resistivity readings applying the electrical tomography (ERT), in 5 lines of investigation with individual length of 105 m and spacing between electrodes of 5m, placed parallel and separated 5 m each (Figure 1).

The septic tank and the supply well, targets of the studies in this research, were placed in the center of this data acquisition scheme, with the aim of detecting eventual lateral alterations or in depth, related to the infiltration of effluents or by the artificial lowering of the aquifer, respectively.

In this work, acquisitions from Dipole-dipole, Wenner and Schlumberger arrays were performed (Figure 2), for the comparative evaluation of the individual sensibility and possibility of modeling of the contamination plume generated by infiltration of inorganic effluents of the septic tank and of the depression cone in supply well.

The geophysical equipment used was the Terrameter LS resistivity meter, manufactured by ABEM Instrument (Sweden), which consists in a single module of transmission and reception of signals, automated from previous programming, with 250 W, resolution of 1 μV and maximum current of 2,5 A. It enables the performance of spontaneous potential essays (SP), electro resistivity (ER) and induced polarization (IP) by means of periodic cycles of transmission and reception of signals, automated calculation of the contact resistivity and standard deviation from the measurement set.

The measurements acquired in the field were processed in the Res2dinv program and resulted in sections of resistivity in terms of distance x depth, with a logarithmic graphic scale and interpolation intervals of values in colors. This is a program that automatically determines a two-dimensional model of



$r_{AC} = L \quad r_{AD} = L + a$

$r_{CB} = L - a \quad r_{DB} = L$

$$\rho_a = \pi \frac{V}{I} \frac{L(L^2 - a^2)}{a^2}$$

$r_{AC} = a \quad r_{AD} = 2a$

$r_{CB} = 2a \quad r_{DB} = a$

$$\rho_a = 2\pi \frac{V}{I} a$$

$r_{AC} = (L - a)/2 \quad r_{AD} = r_{CB}$

$r_{CB} = (L + a)/2 \quad r_{DB} = r_{AC}$

$$\rho_a = \frac{\pi}{4} \frac{V}{I} \frac{(L^2 - a^2)}{a}$$

Figure 2. Dispositions of current and potential electrodes for the Dipole-dipole, Wenner and Schlumberger array (Lowrie, 2007).

subsurface, from resistivity or chargeability data acquired in electrical routing essays (Griffiths & Barker, 1993).

The 2D model used in the program divides the pseudo-section in rectangular blocks that will represent the pseudo-section by the field adjustments. This optimization aims to reduce the difference between the values of apparent resistivity, calculated and measured in the field, by the adjustment of the resistivity in the model of blocks, which difference is expressed by the RMS (Root Mean Square) error (Loke & Barker, 1996).

The numeric product of two-dimensional inversion of data of each section was gathered in a single spreadsheet, which unites the position of the readings along the lines (variable "x"), spacing among lines (variable "y"), depth modeled by the inversion (variable "z") and the value of electrical resistivity (variable "R").

This spreadsheet was used for the generation of 3D viewing models, in a routine of basic steps adopted in mineral research. In this case, the sampling plan is frequently defined from statistic, structural criteria, spatial placement of a mineral accumulation, among other (Moon *et al*., 2006). A simple procedure consists in sampling by a set of perforations perpendicular to the main axis of the structure, followed by a parallel set of perforation lines.

The resolution of the sampling mesh is conditioned to the spacing among the perforations, among lines of perforations and among the amount of samples collected in each perforation. Anyway, the analytical result of the samples is plotted and modeled in two-dimensional terms and later interpolated in three-dimensional terms. Each point of the final 3D model is transformed in a block, with dimensions conditioned to statistical criteria and sampling mesh, to which a grade is attributed, based in chemical analysis and in an average value of density related to the rock that hosts the mineral. The relationship between content and volume enables the calculation of reserves and economic feasibility of the enterprise (Moon *et al*., 2006).

Geophysical models of 3D viewing generated from 2D sections provide a very wide comprehension of the complexity of geological and hydrogeological structures, as the pollutant flow and the modeling of lithotypes or mineral deposits (Chambers *et al*., 2006; Aizebeokhai *et al*., 2011; Moreira *et al*., 2012).

Results and discussions

Based in the principle of direct sampling in mineral research, the sampling mesh of geophysical data was planned with the aim of lateral interpolation of lines from 2D inversion models, by means of the minimum curvature, with the aid of the Oasis Montaj software, for the generation of 2D horizons or softening surfaces for several depths.

From the blocks with interpolated resistivity surfaces, isovalues resistivity surfaces were modeled for each block, representative of an acquisition array, which would reveal the structures studied in this paper (contamination plume and depression cone). The value of 620 Ω.m was adopted as the most adequate in individual terms and for comparative terms, which corresponds approximately to the capillary fringe of the free aquifer.

The analysis of resistivity models must consider the behavior of the analyzed structures in terms of contrast of resistivity in relation to the soil.

The effluent arising from the septic tank is chemically characterized in a simple form as inorganic compound, enriched in mineral salts (ammonia, nitrates) and solute organic matter (faeces) (Sara, 2003). The basal interface of the septic tank allows for the direct contact with the soil, where filtering of organic mass an infiltration of water in mineral salts occurs. Their flow into sandy material with incipient humidity results in a contrast and low resistivity values (Figure 3).

The pumping out of the water from the supply well causes a localized decrease in the groundwater level in the influence area of the well, namely depression cone (Fitts, 2002). The sandy material contained in the inner portion of this structure is relatively drier when compared to the material laterally present in the outer portion, which results in a contrast and high resistivity values (Figure 3).

The analysis of the data regarding the Dipole-dipole array clearly reveals a cylindrical structure of open upper extremity, indicating the increase in resistivity from the borders to the center, placed beneath the supply well (Figure 4). This structure shall be produced by the depletion of the aquifer level around the influence zone of the suction pumping system. Associated to the septic tank, there are also alterations in resistivity, although they do not enable the surface modeling with any relation to the flow of liquids of low resistivity in sandy environment or something similar to a contamination plume.

The data related to the Schlumberger array do not present any structure that brings reference to the depression cone of the supply well (Figure 5). The conic structure modeled below the position of the septic tank probably reflects the infiltration of effluents of low resistivity. The upper end of the cone is closed, indicating an increase in resistivity above that depth, and coincides with a punctual source (base of the tank), whereas its lower end presents a relatively smaller diameter, a reflex of the vertical and lateral percolations of effluents until the contact with groundwater level, under the form of a drop in tridimensional terms.

The isosurface for the Wenner array resulted in the modeling of a long structure towards the data acquisition of the central line and narrow right below the supply well, tending to close in depth, indicating an increase of resistivity in its central part (Figure 3). A conic structure also occurs below the septic tank, to which the same interpretations attributed to the Schlumberger array are valid in face of the similarities, although in this case the structure is less pronounced vertically.

Intrinsic characteristics in terms of electric field and potential propagation produced by the use of each array can be used to understand the comparatively discrepant results in relation to the same targets investigated.

The Dipole-dipole array of characterized by the increasing separation between electrodes or dipoles of current and potential (Mussetti & Khan, 2000). Several papers describe its applicability in the study of organic and inorganic contaminations in saturated zone conditions, proved by chemical analysis (Moreira *et al*. 2006; Arango-Galván *et al*., 2011; Belmonte-Jiménez *et al.*, 2012; Delgado-Rodríguez *et al*., 2014).

In Nyquist *et al*. (2007), the authors demonstrate the lack of sensibility in the Dipole-dipole array my means of 2D sections, in the detection of a zone of verticalized fault filled with water, later confirmed by probing. This array was very susceptible to noises in detailed study performed by Furman *et al*. (2003), due to its high sensibility in shallow levels, where spacing below 1m was adopted between electrodes.

Something inherent to this array is the lateral distortion in the field and potential propagation under small separations of

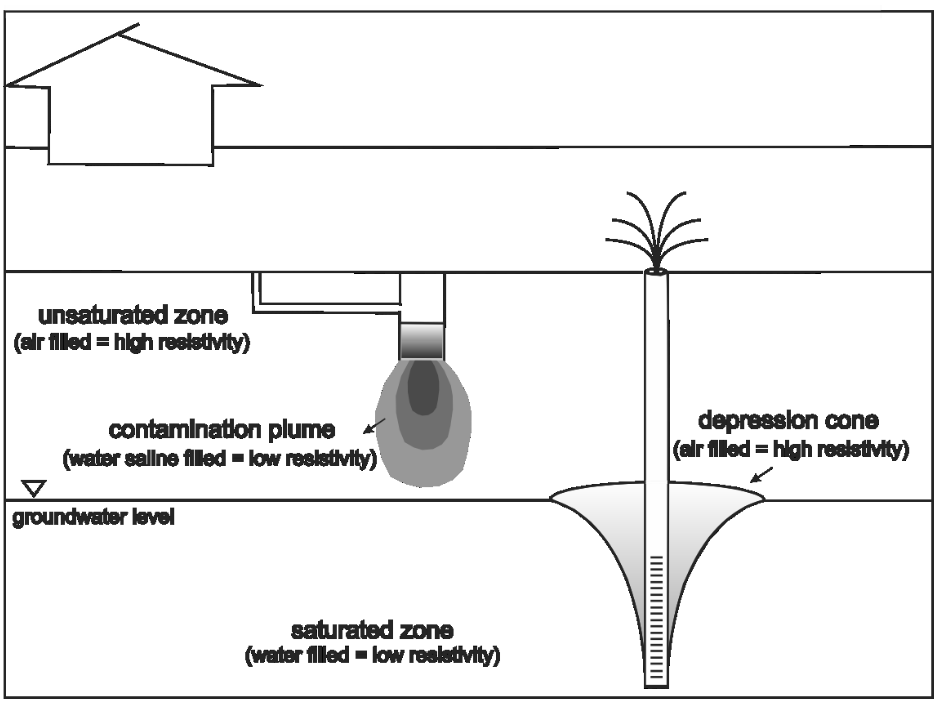


Figure 3. Model of gravitational dispersion of contamination plume arising from septic tank and depression cone in supply well (Based in Sara, 2003).

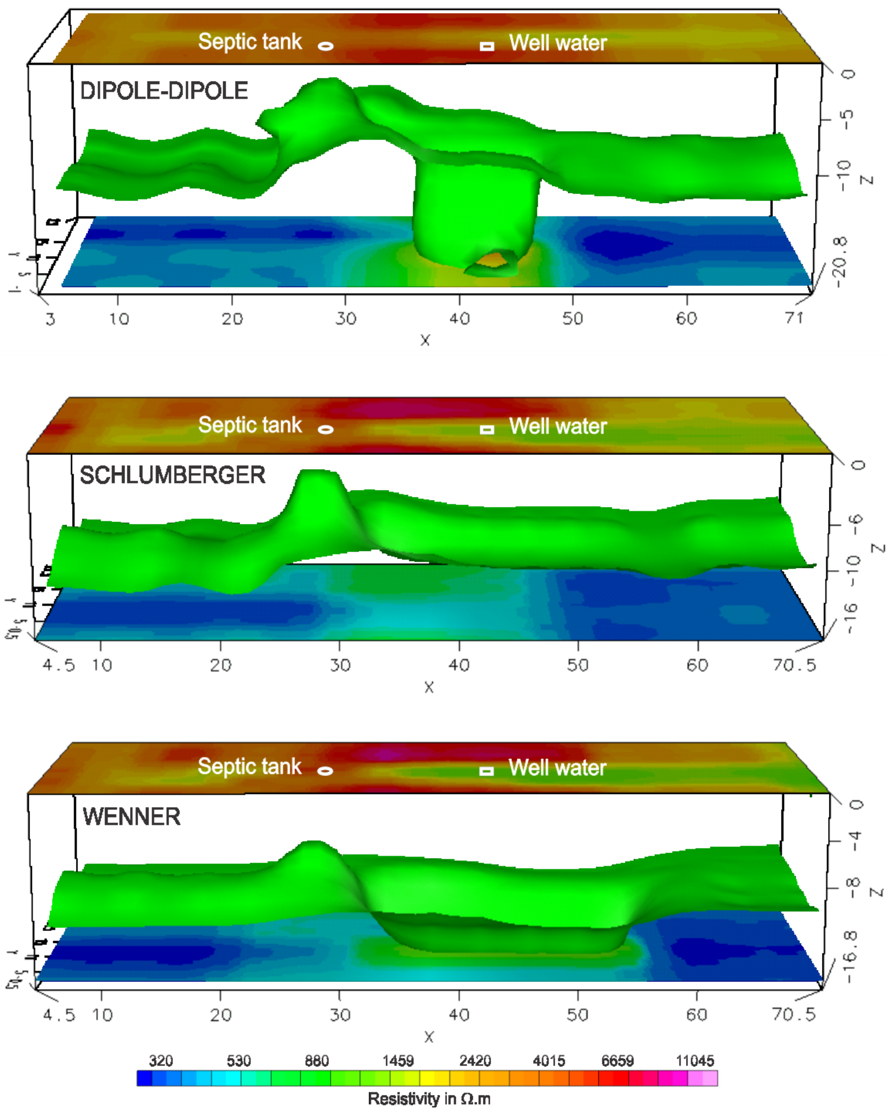


Figure 4. 3D Surfaces of isovalues of 620 W.m for the acquisition arrays in study, with position in the surface of the septic tank and of the supply well (distances in meters).

electrodes (shallow investigations). This tendency is attenuated as the spacing between dipoles increase, although at the same time there is a reduction in sensibility or signal/noise rate (deep investigations). In both cases, the main flow vector tends to be horizontal under small separations of electrodes, with gradual tendency to verticalization under large separation of electrodes (Figure 5).

About the depression cone around the supply well, lateral limits with the aquifer are sloped in high angle, in an inverted base cone with concave interface geometry, i.e., curve in its central axis direction. The distorted field propagation shape of the Dipole-dipole array is effective in the detection of this kind of structure, at least about its shallowest portion. The tendency to horizontalization of the field vector in short spacing allows for a high incidence angle in the interface in the cone of depression.

This situation enables the field refraction, although resulting in a partial characterization of the structure, as it is expected a conic geometry structure to the detriment of the cylindrical structure of the modeling. The concavity of the depression cone interface shall enable for low incidence angles in depth, allied to a reduction in resistivity contrast (increase in humidity content in the structure center). The beginning of the cylindrical structure at about 7m is very much far from the 14m depth of the aquifer level, because in this case the cone is started in the non-saturated zone, something far from reality.

The Schlumberger and Wenner arrays are characterized by current electrodes placed at the ends of the device, with potential electrodes fixed in the central position. The Schlumberger array enables for increasing and diverse readings of the current electrodes for the same opening of potential electrodes, whereas for the Wenner array increasing openings are needed in all electrodes at each reading (Mussetti & Khan, 2000). In the work of Furman *et al*. (2003), it is described the higher sensitiveness of these arrays for deep targets in relation to the Dipole-dipole array.

Regarding the Schlumberger array, the propagation of electrical field and potential for short spacing results in geometry of potential field similar to a drop, with main flow vector that has a tendency to verticalization with the increase in depth of investigation and incipient distortion in potential field (Figure 5). This array is very much applied in hydrogeological studies (Salem, H. S., 2001; Sequeira Gómez & Escolero Fuentes, 2010; Urrutia-Fucugauchi, 2014; Dena *et al*., 2012).

The tendencies of equipotential isosurfaces, parallel and horizontal in relation to the main vector of potential field are coincident with the fronts of liquid percolation originated from the septic tank, condition that shall enable for the field refraction in high angle. The geometries of potential field and contamination plume in the non-saturated zone are also very similar, something that provides a modeling very close to reality. The upper end of the isosurface located at 3m depth coincides with

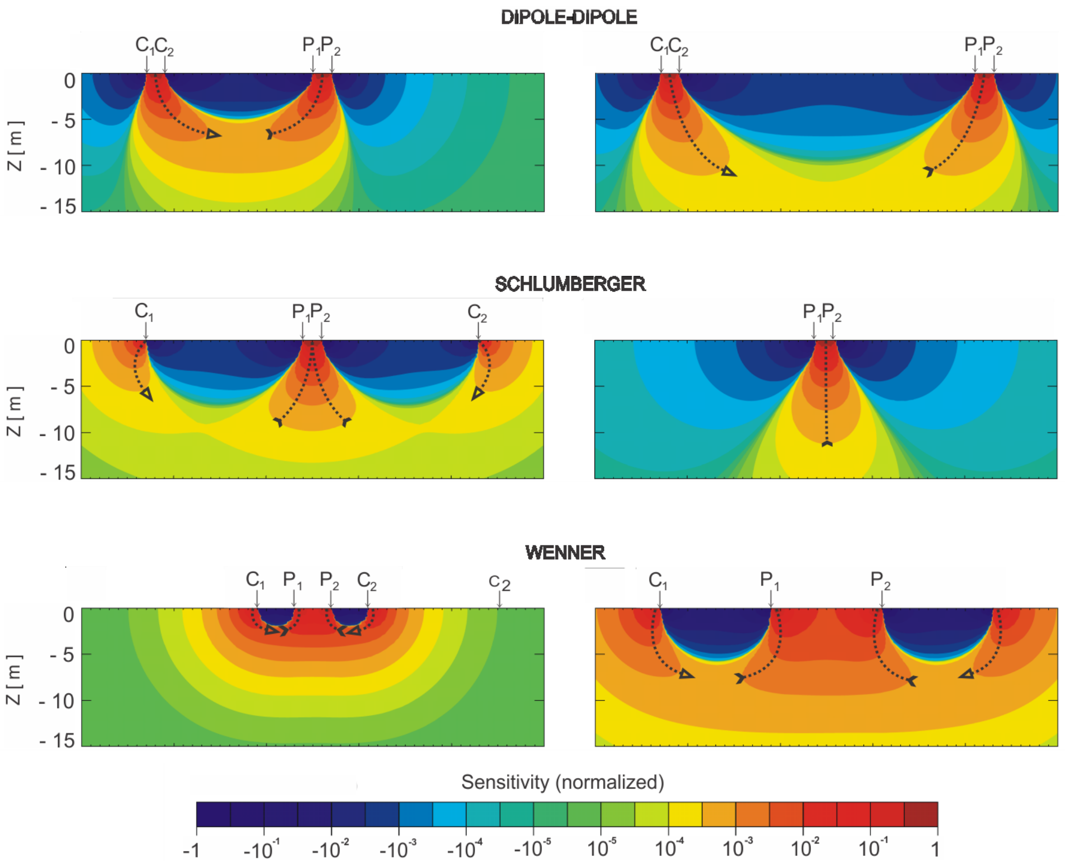


Figure 5. Sections of sensibility normalized for the arrays under study, with main vectors of electrical field propagation (Modified from Knödel *et al*., 2007).

the base of the septic tank, proved in field, other factor that corroborates the veracity of the model (Figure 4).

However, the complex geometry of the depression cone, hollow and with lateral limit in the slope angle, results in an interface almost parallel to the main vector of field propagation, condition that apparently blocks the detection of this kind of structure by means of the Schlumberger array.

The Wenner array presents a verticalized propagation of the field vectors, i.e., horizontalization of the electrical field and potential isosurfaces, slightly attenuated under high spacing between electrodes (Figure 5). Based in this characteristic and similarly to the Schlumberger array, it is possible to recognize in the isosurface model for the Wenner array the existence of a conic structure below the septic tank. In this case, the accentuated tendency for horizontalization of the field isosurfaces in comparison to the Schlumberger array caused some flattening of the conic structure.

This array presents speed and versatility in tomographic acquisition (ERT) due to the relatively reduced quantity in readings (Dahlin 2000; Zhou *et al*., 2001; Corwin & Lesch, 2003; Samouëlian *et al*., 2003). In a comparative study between the Dipole-dipole, Schlumberger and Wenner arrays, Zhou *et al*. (2002) affirm that the Wenner array was the least sensible in the detection of reduction faces in karst terrain (hollow cavity).

The structure placed below the supply well with a keel shape elongated in the central line direction, shall be related to the depression cone. The tendency of horizontalization of the field propagation vectors in higher spacing of electrodes result in high incidence angles with the interface of the depression cone, similar to the Dipole-dipole array, with field refraction and definition of lateral contrast.

However, apparently such conditions do not occur in lateral lines to the supply well, where certainly the resistivity contrast shall be lower, attributed to a peripheral position to the center of the depression cone. The procedure for data acquisition by means of laterally parallel lines, followed by 2D inversion and interpolation in 3D isosurface, generated a processing artifact very distant from the real conic format. Although distorted, this isosurface is initiated in 11m, initial depth of the capillary fringe, horizon able to depression by pumping in the supply well.

Conclusions

A comparison of results among geoelectrical data acquisition revealed the complexity of the study of dynamics targets in the geological environment. The elements analyzed are contained in dry sandy soil (inorganic contamination plume) and saturated (depression cone), both characterized by contrasts of low and high resistivity in relation to the surrounding materials, respectively.

The results demonstrate that in spite of the contrast in electrical properties existent among the studied targets and the surrounding environment, in some cases there simply was no recognizing of the structure by means of any set array, while some geophysical models were simply unreal. Besides all the care required for planning, acquisition and treatment of data, the choice for the array is notoriously relevant to the recognizing and modeling of structures bound to coherent analysis and interpretations.

The versatility of the Dipole-dipole array in terms of data acquisition logistics makes its use attractive to field acquisitions. Under conditions of non-saturated zone, however, the results acquired in this work demonstrate that although possible the definition of contrasts by the presence of contamination plume in this environment, the modeling of isosurface resulted in a product totally disconnected to the structure generated by the propagation of liquids in this environment. The data acquired by means of this array yet enabled for the modeling of the depression cone in very reasonable terms.

The data acquired by means of the Schlumberger and Wenner arrays resulted in a structure with the shape of a drop, below the septic tank, very close to the shape of a contamination plume in vertical flow. The modeling in Schlumberger array enabled for positioning the upper end of the structure right below the septic tank, at 3m depth. However, this same array showed to be ineffective in the detection and consequent modeling of the depression cone, possibly due to issues of propagation of electrical field and potential.

Results referring to the Wenner array enabled for the recognition of a structure in the shape of a keel, elongated along the central line, associated to the depression cone. This shape is attributed to issues of lateral sensibility and procedure of acquisition/interpolation of data, quite far from the inverted cone shape.

In face of the results of this research, the Dipole-dipole array is recommended in works of modeling of verticalized three-dimensional structures of high resistivity. The Wenner and Schlumberger arrays are recommended to modeling of low resistivity verticalized three-dimensional structures, with emphasis to the Schlumberger array.

References

Aizebeokhai A.P., Olayinka A.I., Singh V.S., Uhuegbu C.C. 2011. Effectiveness of 3D geoelectrical resistivity imaging using parallel 2D profiles. *International Journal of the Physical Sciences*, 6, 5623-5647.

Arango-Galván C., Torre-González B., Chávez-Segura R.E., Tejero-Andrade A., Cifuentes-Nava G. Hernández-Quintero E. 2011. Structural pattern of subsidence in an urban area of the southeastern Mexico Basin inferred from electrical resistivity tomography. *Geofísica Internacional*, 50, 401-409.

Balek J., 1989, Groundwater resources assessment – Developments in water, *Science,* 38. Elsevier, Praga, 251p.

Belmonte-Jiménez S., Jimenez-Castañeda M.E., Pérez-Flores M.A., Campos-Enríquez J., Reyes-López J.A., Salazar-Peña L., 2012, Characterization of a leachate contaminated site integrating geophysical and hydrogeological information. *Geofísica Internacional*, 51, 4, 309-321.

Chambers J.E., Kuras O., Meldrum P.I., Ogilvy R.D., Hollands J. 2006. Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. *Geophysics*, 71:231-239.

Corwin D.L., Lesch S.M., 2003, Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agronomy Journal*, 95: 455-471.

Dahlin T., 2000, Short note on electrode charge-up effects in DC resistivity data acquisition using multi-electrode arrays. *Geophysical Prospecting*, 48, 181-187.

Delgado-Rodríguez O, Flores-Hernández D., Amezcua-Allieri M.A., Shevnin V., Rosas-Molina A., Marín-Córdova S., 2014, Joint interpretation of geoelectrical and volatile organic compounds data: a case study in a hydrocarbons contaminated urban site. *Geofísica Internacional*, 53,183-198

Dena O.S., Griselda Obeso C., Doser D., Leyva J.E., Rascon E., Gómez, F., Domínguez M.A., 2012, Using subsurface geophysical methods in flood control: A resistivity survey to define underground storage capacity of a sand body in Ciudad Juárez, Mexico. *Geofísica Internacional*, 51, 225-249.

Departamento de Águas e Energia Elétrica do Estado de São Paulo - DAEE. 1981. Estudos de águas subterrâneas, Região Administrativa 5 - Campinas. São Paulo, 607 p.

Elgzeli Y.M., Ondovčin T., Zbyněk H., Jiři K., Jiři M., 2013, Impact of heavy grondwater pumping on hydrogeological conditions in Lybia: Past and present development and future prognosis on a regional scale. *Acta Geologica Polonica*, 63, 283-296.

Fitts C.R., 2002, Groundwater Science. Academic Press, London, 450p.

Furman A., Ferre T.P.A., Warrick A.W., 2003, A sensitivity analysis of electrical resistivity tomography array types using analytical element modeling. *Vadose Zone Journal*, 2, 416–423.

Griffiths D.H., Baker R.D., 1993, Two-dimensional resistivity imaging and modeling in areas of complex geology. *Journal of Applied Geophysics*, 29, 211-226.

Hernández-Soriano M.C., 2014, Environmental risk assessment of soil contamination. InTech, New York, 905p.

Hiscock K.M., 2005, Hydrogeology: principles and practice. Blackwell Publishing, Oxford, 405 pp.

König L., Weiss J.L., 2009, Groundwater: modelling, management, and contamination. Nova Science Publishers Inc., New York, 422 pp.

Knödel K., Lange G., Voigt H., 2007, Environmental geology: handbook of field's methods and case studies. Springer, Hannover, 1374 pp.

Lehr J., Hyman M., Gass T.S., Servers W.J., 2001, Handbook of complex environmental remediation problems. McGraw-Hill Handbooks, 606 pp.

Loke M.H., Baker R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by quasi-Newton method. *Geophysical Prospecting*, 44, 131-152.

Lowrie W., 2007, Fundamentals of Geophysics. Cambridge University Press, New York, 393 pp.

Melo S.M., Coimbra M.A., Cuchierato G., 1997, Fácies Sedimentares da Formação Rio Claro, Neocenozóico da Depressão Periférica Paulista. Revista IG. São Paulo (SP), 18, 49-63.

Ministry of Mines and Energy – MME. 2013. Brazilian Energy Balance – final report. Empresa de Pesquisas Energéticas, Brasilia, 284 pp.

Moreira C.A., Dourado J.C., Braga A.C.O., 2006, Aplicação da técnica de caminhamento elétrico em área contaminada por derivados de petróleo. *Brazilian Journal of Geophysics*, 24, 383-392.

Moreira C.A., Lopes S.M., Schweig C., Seixas A.R., 2012, Geoelectrical prospection of disseminated sulfide mineral occurrences in Camaquã sedimentary basin, Rio Grande do Sul state, Brazil. *Brazilian Journal of Geophysics*, 30, 169-179.

Moon C.J., Whateley M.K.G., Evans A.M., 2006, Introduction of mineral exploration. 2°ed., Blackwell Publishing, Malden, 499 pp.

Mussett A.E., Khan M.A., 2000, Looking into the Earth: an introduction to geological geophysics. Cambridge University Press, New York, 493 pp.

Nemerow N.L., Agardy F.J., Sullivan P., Salvato J.A., 2009, Environmental Engineering: prevention and response to water, food, and air-borne disease and illness. 6°ed., John Wiley & Sons, New Jersey, 394 pp.

Nyquist J.E., Peake J.S., Roth M.J.S., 2007, Comparison of an optimized resistivity array with dipole-dipole soundings in karst terrain. *Geophysics*, 72, 139-144.

Okpoli C.C., 2013, Sensitivity and resolution capacity of Electrode configurations. I*nternational Journal of Geophysics*, 2013, 12p.

Oliva A., Chang H.K., Caetano-Chang M.R., 2005, Determinação da condutividade hidráulica da Formação Rio Claro: análise comparativa através de análise granulométrica e ensaios com permeâmetro guelph e testes de slug. *Aguas Subterrâneas*, 19, 1-17.

Oliva A., Chang H.K., 2007, Mapeamento do Lençol Freático no Município de Rio Claro (SP) Empregando a Técnica de Sondagem Elétrica Vertical. *Revista Brasileira de Geociências*, 26, 27-34.

Peirce J.J., Weiner R.F., Vesilind P.A., 1998, Environmental pollution and control. 4°ed., Butterworth-Heinemann, Woburn, 409 pp.

Sara M., 2003, Site assessment and remediation handbook. 2°ed., Lewis Publishers, Florida, 1161 pp.

Salem H.S., 2001, Modelling of lithology and hydraulic conductivity of shallow sediments from resistivity measurements using Schlumberger vertical electrical soundings. *Energy Sources*, 23, 599-618.

Samouëlian A., Cousin I., Richard G., Tabbagh A., Bruand A., 2003, Electrical Resistivity Imaging for Detecting Soil Cracking at the Centimetric Scale. *Soil Science Society of America Journal*, 67, 1319-1326.

Sequeira Gómez L., Escolero Fuentes O., 2010, The application of electrical methods in exploration for ground water resources in the River Malacatoya sub-basin, Nicaragua. *Geofísica Internacional*, 49, 27-41.

Twardowska I., Allen H.E., Häggblom M.H., 2006, Soil and water pollution: monitoring, protection and remediation. Nato Science Series, Springer, Krakom, 662 pp.

Urrutia-Fucugauchi J., Trigo-Huesca A., Téllez-García E., Pérez-Cruz L., Méndez-Rivero F. 2014. Volcano-sedimentary stratigraphy in the Valsequillo Basin, Central Mexico inferred from electrical resistivity soundings. *Geofísica Internacional*, 53, 87-94.

Zhou Q.Y., Shimada J., Sato A., 2001, Three-dimensional spatial and temporal monitoring of soil water content using electrical resistivity tomography. *Water Resources Research*, 37:273-285.