Characterization of shallow groundwater in Eocene sediments of Panama Canal Watershed using electrical techniques

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Abstract - *This work is focused on the detection of seepages caused by the affluent located in a small area of the Panama Canal Basin during the dry season, and to define the subsurface stratigraphy (Eocene sediments) that characterize this area through a geophysical survey. Two electrical resistivity tomography were developed to identify the extent of infiltration and the nature of the clay layers vertically and laterally, these results were corroborated by a drilling operation in the vicinity of electrical tests and based on this information, established a model for a two-dimensional geoelectric profile in order to compare (i) the pseudo-sections of synthetic and measured apparent electrical resistivity, and (ii) the electrical resistivity tomography as a result of the inversions of such pseudo-sections. The results of electrical resistivity tomography obtained in the two profiles revealed the existence of (i) a surface layer moderately resistant (18-85 ohm.m) with a thickness not exceeding 1,8 m, (ii) an area of high electrical conductivity (3,8 to 10,7 ohm.m) with a thickness not exceeding 9.5 m and (iii) a resistant substratum with electrical resistivity values calculated in excess of 30,1 ohm.m and a range depth ranging from 2 to 11,5 m. The drilling operation in the vicinity of the geophysical tests revealed the presence of clay with varying moisture content and density, and thicknesses that corroborate the results of the geophysical evidence. The two-dimensional geoelectrical model of Profile 1 was established according to the results of electrical resistivity tomography as well as the profile and information of the drilling operation. Based on the results of this study, we conclude that the infiltration generated by the affluent in this part of the Isthmus of Panama are very important, even in periods when precipitation levels are.*

Keywords - *Apparent resistivity,electrical resistivity tomography,forward problem, Gamboa zone, inverse data, Panama Canal watershed, synthetic data.*

Resumen - *El objetivo de este trabajo se focalizó en la detección de las infiltraciones causadas por los afluentes ubicados en una pequeña zona de la Cuenca del Canal de Panamá durante la época seca, y de definir la estratigrafía del subsuelo (sedimentos eocénicos) que caracteriza a dicha zona a través de la prospección geofísica. Se desarrollaron dos tomografías de resistividad eléctrica para identificar la extensión de las infiltraciones y la naturaleza de las capas arcillosas tanto en profundidad como lateralmente; estos resultados fueron corroborados por una perforación realizada en las cercanías de las pruebas eléctricas y en base a toda esta información, se estableció un modelo geoeléctrico bidimensional para uno de los perfiles con el objetivo de comparar (i) las pseudo-secciones de resistividad aparente sintética y medida, y (ii) las tomografías de resistividad eléctricas como resultados de las inversiones de dichas pseudo-secciones. Los resultados de las tomografías de resistividad eléctrica obtenidos en los dos perfiles* *revelaron la existencia de (i) una capa superficial moderadamente resistente (18-85 ohm.m) con un espesor que no sobrepasa los 1,8 m, (ii) una zona de alta conductividad eléctrica (3,8-10,7 ohm.m) con un espesor que no supera los 9,5 m y (iii) un substrato resistente con valores de resistividad eléctrica calculados que superan los 30,1 ohm.m y un rango de profundidad que se extiende desde 2 hasta 11,5 m. La perforación realizada en las cercanías de las pruebas geofísicas revelaron la presencia de arcilla con variaciones en contenido de humedad y densidad, y con espesores que corroboran los resultados de las pruebas geofísicas. El modelo geoeléctrico bidimensional del Perfil 1 se estableció de acuerdo a los resultados de la tomografía de resistividad eléctrica de dicho perfil y a la información de la perforación realizada. Basado en los resultados del presente estudio, se concluye que las infiltraciones generadas por los afluentes en esta parte del Istmo de Panamá son muy importantes, aun en períodos en donde los niveles de precipitación son bajos.*

Palabras claves - *Cuenca del Canal de Panamá, datos sintéticos, inversión de datos, problema directo, resistividad aparente, tomografía de resistividad eléctrica, zona de Gamboa.*

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1. INTRODUCTION

The Canal of Panama is located in the Central American isthmus, corresponding to a clearly tropical region that is governed during the whole year by the dry and rainy stations (Figure 1). This canal is a route of interoceanic navigation between the Caribbean sea and the Pacific Ocean and it crosses the isthmus of Panama in his narrowest point. From its opening on August 15, 1914, the Canal of Panama has had a notable effect on the marine communication by having shortened time and distances necessary to transport people and materials; thus economic dynamism. The canal provided the cheapest route for transport between two oceans. This fact has influenced in a decisive way the patterns of world commerce, impelling the economic growth of the developed countries and enabling expansion of many remote regions of the world.

At present, the Canal of is challenged to guarantee the supply of sufficient water to satisfy the demands of consumption in the urban centers located in the neighborhood of the Canal and for the navigation and functioning of the canal, and whose behavior expresses increasing needs by both. To this challenge is added the importance conserving the resources and the sustainable development of the regions of the Panama Canal watershed.

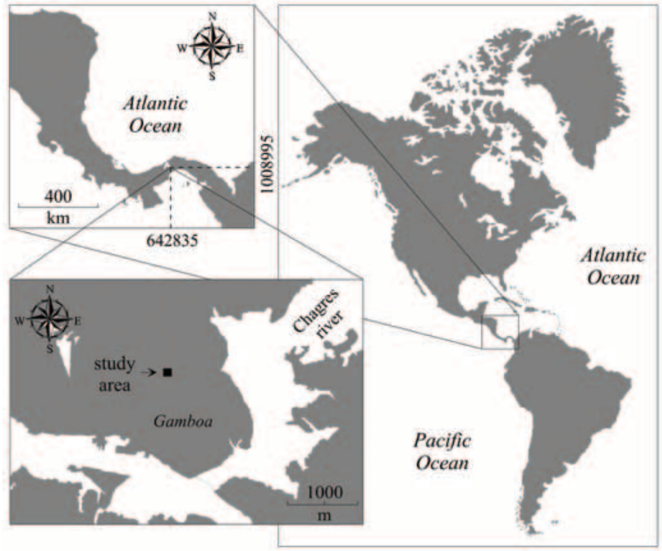

Figure 1. Gamboa area geographic location-Panama Canal watershed.

Inside the metropolitan area, the hydrographic basin of the river Chagres is directly tied to the hydraulic stability of the Canal. Preservation of the basin of the river Chagres is the basis of the program of conservation of natural resources in the Metropolitan zone. The geophysical study that next appears focused in one of the most important zones of the above mentioned basin: the area of Gamboa, which is located in the Southeast sector of the Gatún Lake and in the mouth of the river Chagres (see Figure 1). The target of the study centered on determining the zones of infiltration that experience the sedimentary soils of a small area of the sector of Gamboa due to an affluent, by means of the use of the electrical resistivity tomography during the dry season.

A total of two electrical profiles of 47 m long were developed in the field of interest; Figure 2 presents the distribution of these profiles, the system of affluent in Gamboa that feeds the lake Gatún and the perforation (boring) drilled to few meters of the profiles.

This electrical technique is one of the geophysical methods most used in studies of groundwaters and thanks to the development of computational technologies for the rapid acquisition of the field information and inversion geoelectrical algorithms, this method has been considered as the most effective for the exploration of the subsoil in high resolution [1].

In addition to the geophysical explorations and to the results obtained in the perforation (boring) to 10,5 m deep below ground surface developed in the Southwestern sector between both profiles, a 2D electrical model was developed for Profile 1 using a software algorithm based on finite difference approximation [2].

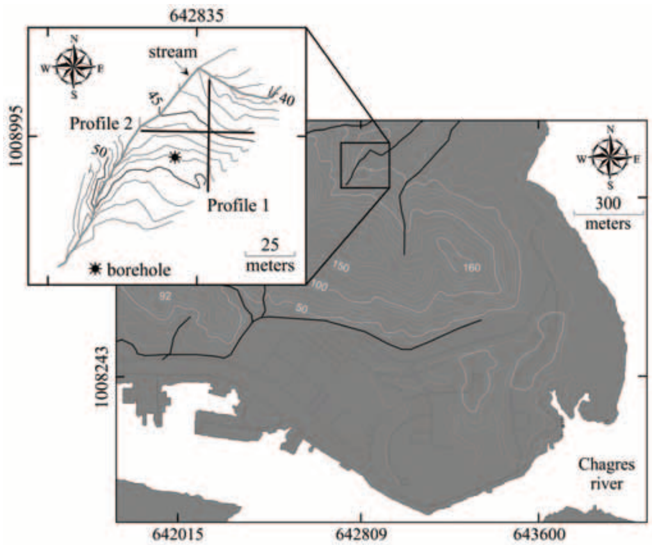

Figure 2. Detailed map of site and electrical profiles distribution and perforation in Gamboa area, Panama Canal Watershed.

The goal of electric modeling consisted of generating a set of virtual values of apparent resistivity according to the values of resistivity measured in the above mentioned profile. Also the results of the electrical resistivity tomographies obtained from the resolution of the inverse problem for both sets of information of apparent resistivity were compared.

2. GEOLOGICAL AND CLIMATE DESCRIPTION

Four tectonic plates influence the complex geology of the Isthmus of Panama, and that in accordance with [3] and [4] the same have been recounted to the block of Panama. The isthmus is a part of a volcanic arch which genesis goes back to the period of the early Miocene (~ 17 Ma).

The tectonic distortions and flaws molded the terrestrial forms up to the current moment. The rocky bed includes volcanic, intrusive rocks and extrusive, pyroclastics and sedimentary [5]. The Panama Canal basin is characterized by a sequence of thicknesses of sediments and volcanic rocks of the Eocene to the Pleistocene [6]. The study site rests on the Gatuncillo Formation, characterized by the presence of siltstone, quartz, algal and foraminiferal limestone [7]. Figure 3 presents a geologic widespread map of the study zone.

In accordance with [8] the convergence of the intertropical zone is narrowly related to the rainy stations regimen in the tropical forests and this is

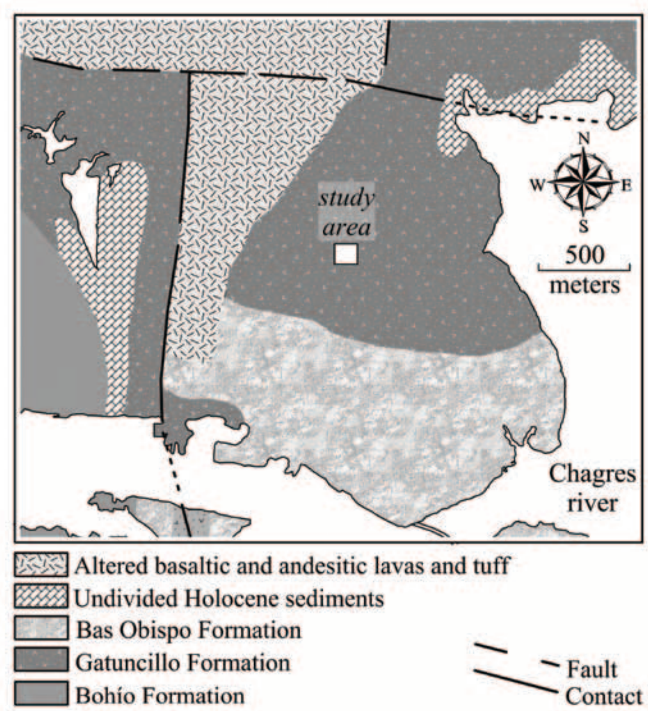

Figure 3. Geological map of Gamboa, its surroundings and study area [7].

the case of the period of rains that rule in Gamboa and in fact in the whole Panama.

In the isthmus, the rainy season in general persists from May until December and the dry from the end of December up to the end of April.

In 2009, the dry season had changes of 4,9°C with precipitations not greater than 22 mm. During the geophysical measurements, there registered void levels of precipitation and a status of temperatures of the air between 26,3 and 27,0°C greater than the average temperatures registered during the whole dry season.

3. METHODOLOGY, RESULTS OF THE FIELD APPLICATIONS AND DISCUSSION

Water is obviously an essential element for human life and geophysical tools used to determine the quality and quantity of groundwater have been used worldwide [9]. Electrical prospection was chosen as the method to measure groundwater properties for this study based on its sensitivity to water in the terrestrial stratum. This method measures the apparent electrical resistivity which corresponds to a volumetric integration of subsurface electrical resistivity; this parameter, which is expressed in ohm.m, measures the soil volume capacity for electric charge movement.

Figure 4 presents a graph on the changes of temperature of the air and precipitations for the above mentioned period of the year 2009.

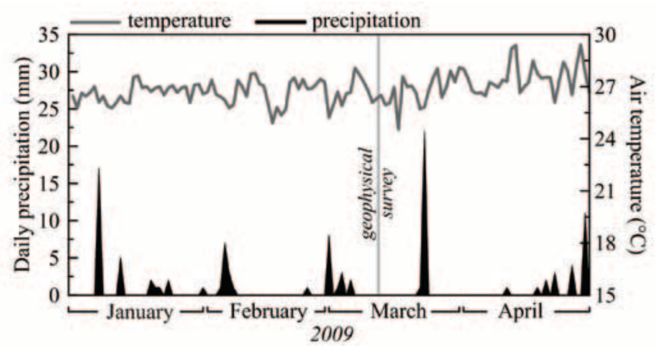

Figure 4. Daily precipitation and air temperature recorded data in Gamboa meteorological station. Information given by ACP (Panama Canal Authority) Water Division – Hydric Resources Section.

Particular geological factors that affect the electrical resistivity value include granularity, water mineralization, water amount and clay amount [10]. These properties are influenced by thermodynamic parameters such as pressure and temperature and by the environmental chemistry in which the electrical charges are moving ([11] and [12]).

Electrical prospection is characterized by the injection of an electrical current at a given intensity through two electrodes (A and B) and recording the electrical potential difference by means of another pair of electrodes (M and N) taken a few centimeters beneath the top of the soil. This recording is representative of a determined soil volume and depends on the geometry and position of the electrode array used. In our case we used a Wenner-α configuration in which the electrodes A, M, N and B are collinear and the separations between adjacent electrodes are the equal. To obtain an electrical tomography, it is necessary that the four electrodes are aligned with AM = MN = NB = a, as shown in Figure 5.

Once the first measurement was collected, the four electrodes were moved to the next position and the second measurement was collected. This procedure was repeated along the entire profile. The first data group corresponds to the top depth level of first depth level denoted by n = 1. In order

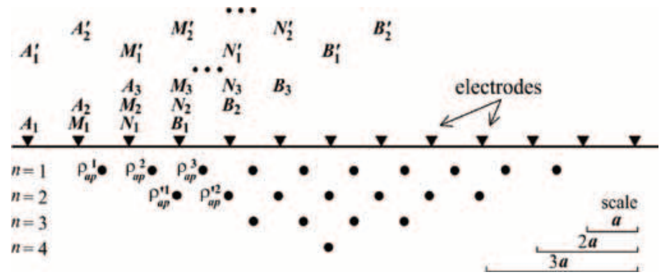

Figure 5. Wenner-α electrode configuration schematic representation used in the current study with 4 depth (*n*) levels as an example.

to get the second level (n = 2), the above operation is repeated, but with AM = MN = NB = 2a. It is important to point out that the Wenner-α array selection has several advantages over other array types; these advantages include (i) an intermediate range of depth, (ii) an intermediate resolution and (iii) a moderated sensitivity to geological noise [13]. In addition, as [14] points out, the final output of this array is a smooth signal. The electrical resistivity tomography method allows for the recording of a large amount of data through different possible combinations of the four electrodes. Such recordings are gathered by a pseudo-section of apparent resistivity where the vertical axis corresponds to a pseudo-depth. By convention, the recordings are located at a depth that is the function of the electrode separation and the configuration (see Figure 5).

A prototype of electrical source of 400 V output was developed with a switch that interconnects all the electrodes that were used for the acquisition of the information of electrical apparent resistivity. A separation of 1 m was established between 48 electrodes in both profiles with a number of depth levels equal to 15. The information of apparent resistivity measured along these profiles was transferred to a computer, processed and interpreted using a 2D inversion algorithm which subdivides the subsoil into a number of rectangular cells for which positions and sizes have been established [15]. Later, the resistivity of each cell is calculated in order to produce a pseudo-section of apparent resistivity (resolution of the forward problem).

The above mentioned pseudo-section is then compared with the information measured on the surface and its difference can be represented in terms of an RMS error. For this latter the program EarthImager 2D of AGI Advanced was used, which determines automatically a two-dimensional model of real resistivity of the subsoil from the information that constitutes the pseudo-section of apparent resistivity measurements. The calculation of the values of resistivity is carried out thanks to the forward modeling based on the works of [16] and the application of are gularized least-squares optimization method as inversion method in electrical exploration. In this work there appears the results obtained with the application of a special constraint to this method of inversion known as robust inversion.

The selection of this method is due to the existence of rock accumulations, roots and the strong existing interface between the groundwaters and the surrounding material; [17] allude to the selection of the method of smoothed based on the nature of the study area. The equations obtained from Taylor's expansion of the first order that relates the model parameters and the model response, and the misfit corresponding to the difference between the model response and the field information, define the solution of Gauss-Newton. The implementation of the robust method to this solution consists of the formulation of iteratively reweighted least-squares method [18], and whose mathematical structure has the following form:

$$\left(\mathbf{J}_i^T \mathbf{R}_a \mathbf{J}_i + \alpha_i \mathbf{W}^T \mathbf{R}_b \mathbf{W}\right)\Delta \mathbf{m}_i = \\ = \mathbf{J}_i^T \mathbf{R}_a \mathbf{g}_i - \alpha_i \mathbf{W}^T \mathbf{R}_b \mathbf{W} \mathbf{m}_{i-1}. \qquad (1)$$

In this equation $\mathbf{J}$ is the Jacobian matrix of partial derivatives, $\mathbf{R}_a$ and $\mathbf{R}_b$ are the weighting matrices introduced in such a way that the different elements of the data misfit and of the model roughness vectors are approximately equal weights in the inversion process [15]. $\mathbf{W}$ corresponds to a roughness filter, $\mathbf{g}$ is a vector that contains the differences between the logarithms of the measured and calculated apparent resistivity values, and $\Delta \mathbf{m}_i$ is the change in the model parameters of the for i-th iteration, which is given by:

$$\Delta \mathbf{m}_i = \mathbf{m}_i - \mathbf{m}_{i-1} \qquad (2)$$

with $\mathbf{m}_{i-1}$ is the model parameters vector for the previous iteration. corresponds to a damping factor related to the model roughness. This inversion method considers an exponential distribution of the data errors [19]. This method possesses the advantage of reproducing models with strong limits that separate zones of relatively constant electrical resistivity [15] y [20]. Other works allude to the versatility of this method at similar cases, for example to see [21], [15] y [22].

Profiles 1 and 2 are the electrical resistivity tomographies under depth of investigation greater than 10 m (to see Figure 6 a and b). Figure 6 (a) depicts three horizons and a strong anomaly in the initial part of Profile α_i 1he above mentioned anomaly is represented across a dark tonality which range of calculated electrical resistivity extends from 85 up to 239,0 ohm.m, the same one possesses an extension of approximately 8,5 m and a thickness that does not exceed 5 m. This anomaly is associated with an accumulation of rocks and roots of trees. The first horizon corresponds to a moderated superficial layer of resistivity (18-85 ohm.m) extending 45 m along the above mentioned profile; the thickness of this horizon does not exceed 1,8 m. This superficial horizon is associated with a clayish material with a low moisture content, resulting from the absence of rains and the evapotranspiration during the dry season.

In the same profile, below the first horizon there is the second one represented by an anomaly of light gray tonality that spreads from the 12 m up to 47 m along the profile; the calculated electrical resistivity range that characterizes this horizon ranges between 3,8 and 10,7 ohm.m. The thickness of this horizon is lower than 11 m and the same one finds associated with a clayish material with a moisture content of generated by an source that surrounds the site. The third and last horizon detected in this survey has a range of values of calculated electrical resistivity that ranges from 10,7 up to 85 ohm.m which is associated with a clay material of greater thickness compared to the detected ones before; the depth of this horizon spreads from 3,5 up to 11,5 m.

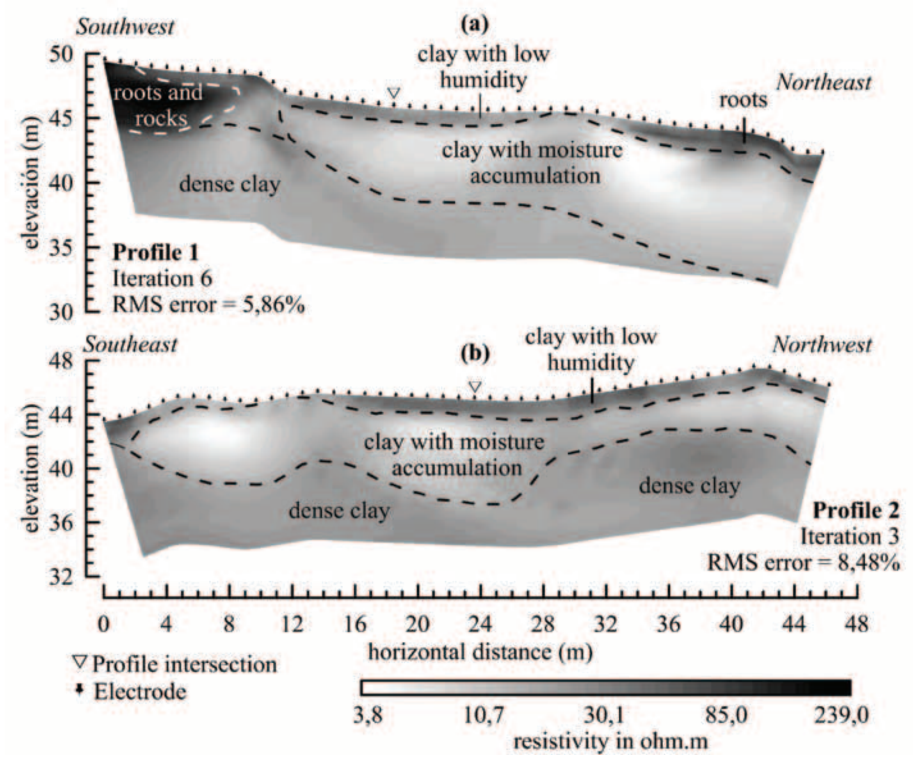

Figure 6. Electrical resistivity tomography for profiles (a) 1 and (b) 2.

Excepting the strong anomaly detected in the initial part of Profile 1, the results depicted by Profile 2 are quite similar since the moderated superficial layer of electrical resistivity is present and its thickness ranges between 0 and 1,7 m (clay material at low level of moisture). In addition the horizon of low resistivity is represented in light gray tonality (3,8 and 10,7 ohm.m) which associates with clay material with a high moisture content and finally, the layer of dense clay which is found below the horizons already defined. The latter layer has depths that spread from 4,5 up to 9,5 m.

A three-dimensional representation of these results allows more clear visualization of the different horizons typical of the site (see Figure 7). The results obtained during the electrical prospection fitted very well to the information given by the perforation (boring) developed in the site. In this test a layer of superficial clay was detected at low level of moisture, followed by the phreatic level to approximately 4 m and finally to 8,5 m deep the clay material typical of the site presents a level of thickness much bigger than the previous horizons; the perforation finished to 10,5 m deep. The fact that the thickness of the layer superficial of clay is greater than the one detected in the tomography of electrical resistivity is due to the elevation to which the perforation was initated.

4. FORWARD MODELLING

With the goal to verify the results obtained in the electrical resistivity tomography of the Profile 1 (Figure 6a), there was proposed a two-dimensional model based on the forward problem solution. The above mentioned methodology consists of finding a mathematical equation for the voltage or potential difference (V) between any pair of points in the space in function of (i) the distribution of the electrical resistivity of the subsoil (ρ or his inverse one, the electrical conductivity σ), (ii) the intensity of electrical injected current (I) and (iii) the geometry or electrode configuration used in the study. With the calculated values of the voltage the apparent resistivity data is obtained. This expression of the electrical potentials is generated from certain theoretical topics related to the stationary fields, the principle of conservation of electrical charge and the Ohm's law, and the same one is represented by:

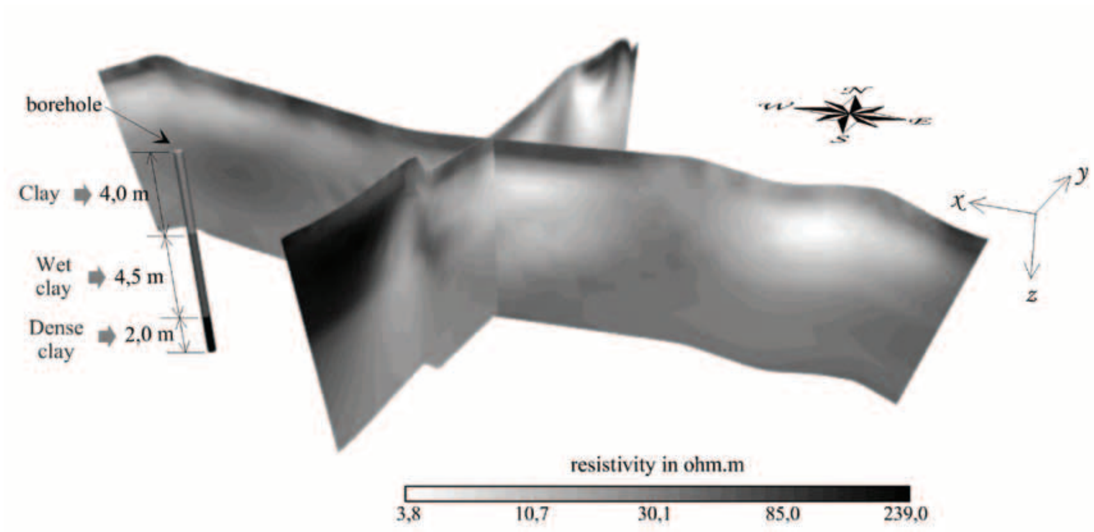

Figure 7. Tridimensional representation of electrical resistivity tomographies carried out in this study and drill results made at point showed Figure 2.

$$\nabla \bullet \left\{ \sigma(x,z) \nabla V(x,y,z) \right\} = = -\frac{\partial \varsigma}{\partial t} \delta(x - x_S)\delta(y - y_S)\delta(z - z_S). \quad (3)$$

In this expression corresponds to electrical charge density at a point in the Cartesian space and the Dirac delta function. are coordinates of the electrical current source. According to [16], this equation could be expressed at Fourier space as:

$$\nabla \bullet \left\{ \sigma(x,z) \nabla \tilde{V}(x,\lambda,z) \right\} + \lambda^2 \sigma(x,z) \cdot \cdot \tilde{V}(x,\lambda,z) = -\tilde{I} \delta(x - x_S)\delta(z - z_S). \quad (4)$$

And after an elemental vectorial mathematical manipulation also is obtained:

$$\sigma(x,z)\nabla^2 \tilde{V}(x,\lambda,z) + \nabla^2 \left\{ \sigma(x,z) \cdot \cdot \tilde{V}(x,\lambda,z) \right\} - \tilde{V}(x,\lambda,z)\nabla^2 \sigma(x,z) - -2\lambda^2 \sigma(x,z)\tilde{V}(x,\lambda,z) = = -2\tilde{I}\delta(x - x_S)\delta(z - z_S). \quad (5)$$

Where_ $\tilde{V}$, $\tilde{I}$ and λ are voltage, electrical intensity and the transformation of in the Fourier space respectively. To solve these two equations numerical tools with suitable boundary conditions are used.

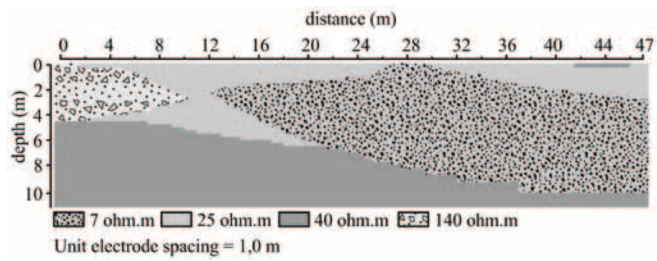

Figure 8.Theoretical resistivity model used for study of Profile 1 in Gamboa, Panama Canal watershed.

The synthetic apparent resistivity values generated from a two dimensional model were obtained by Res2Dmod [2] which is software based on finite difference numerical approximation with a modification carried out on area discretization method given by [16].

The cells model is based on both perforation (drilling) results as well as the electrical prospection carried out in the profile 1 (see Figure 8). It was defined: (i) a conductor layer of 7 ohm.m which extends from 12 to 47 m along the profile and a thickness not greater than 8,6 m.

This layer is a clay material with a notable accumulation of moisture; (ii) a resistant structure of 140 ohm.m located near the beginning of the profile and whose extension along the profile does not go beyond 11 m. The same one is related to an accumulation of rocks and roots of the site, (iii) a third horizon defined in this model that contains the previous ones but with an intermediate

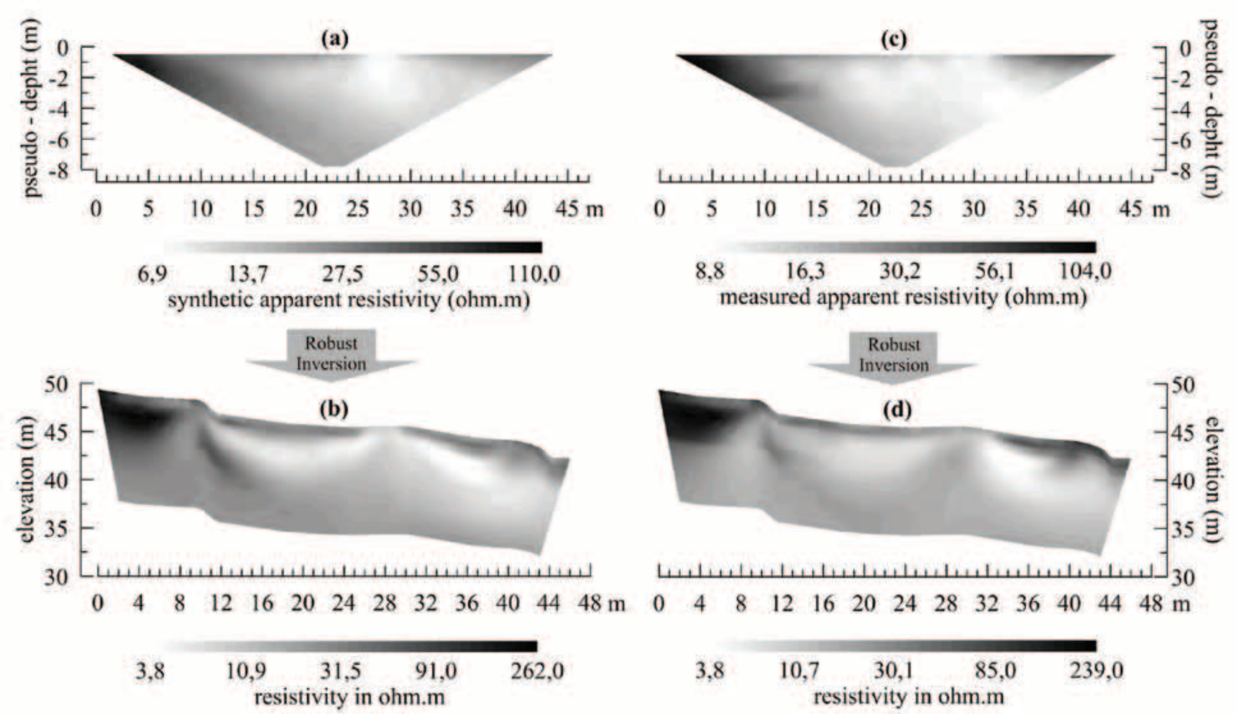

Figure 9. (a) Pseudo-section of synthetic apparent electrical resistivity values obtained from electrical model of Figure 8, (b) inversion process results obtained from Figure 9 (a); (c) pseudo-section of measured apparent electrical resistivity values and (d) result of inversion process of the pseudo-section from Figure 9 (c)-Profile 1.

value of electrical resistivity of 25 ohm.m. and (iv) a fourth horizon that represents the resistant substratum related to the same clay material (40 ohm.m). The model established in Figure 8 generated a set of apparent electrical resistivity values with an addition of 2% of gaussian noise and whose pseudo-section is presented in Figure 9 (a). The inversion of this pseudo-section of synthetic apparent data across the method of robust invesion and the implementation of the topographic data corresponding to the Profile 1, gave rise to the electrical resistivity tomographyof the Figure 9 (b).

Additional to these results, Figures 9(c) and (d) correspond to the pseudo-section of apparent measured electrical resistivity. The results obtained in this section not only show a similarity as for the distribution of the values of resistivity showed in the pseudo-sections and electrical resistivity tomographies but also in the ranges of calculated and apparent resistivity.

Figures 9 (b) and (d) indicate very similar anomalies, which demonstrate that the synthetic model of cells presented in the Figure 8 fits very well to the results obtained during the geophysical prospection. Additional to this analysis, Figure 10 presents a graph that compares the values of the apparent synthetic resistivity with those registered in Profile1 during the dry season. The distribution of the points on this graph and the straight line regression are indicative of the similarity that exists between both analyses, from what the geolectrical model proposed fits to this type of tropical zones.

5. CONCLUSIONS

The electrical prospection can play a very important role in the study of the underground waters contained in sedimentary formations in the Panama Canal watershed. The results obtained in this work reveal that the water intrusions from the area of Gamboa are significant, even in the dry season where the levels of precipitation are low and the processes of evapotranspiration are important.

Thanks to the electrical resistivity tomogrphies obtained in this study, it was possible to delimit the nature of the layers of clay where the levels of moisture in the surface are low and whose response is associated to the natural phenomena already mentioned previously, very typical of the tropical zones in this periodof the year. The interpretation of the results of the geophysical prospection is associated very well to the results of the perforation done in the outskirts of the zone of study,

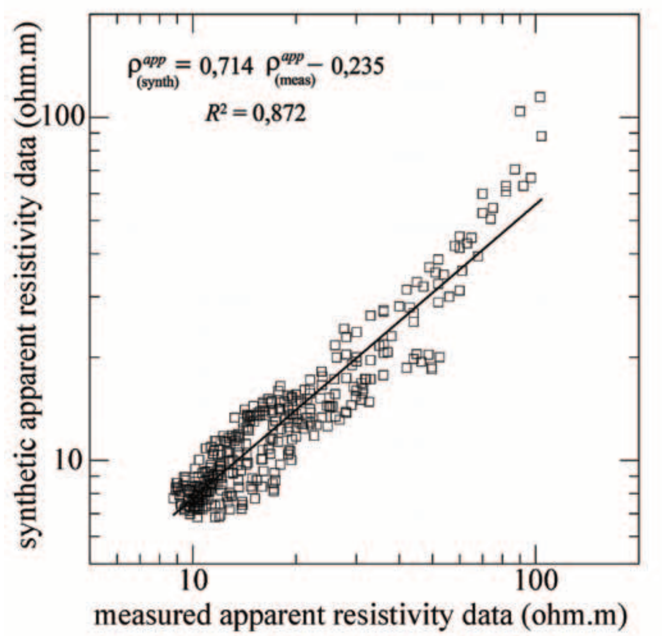

Figure 10. Comparison between the synthetic apparent resistivity data generated from the electrical model and the measured apparent resistivity along Profile 1 during dry season.

where the clay geologic formations, become present. Finally, the model of cells established in this study fits very well to the experimental obtained results, the presence of clay conductive and resistant layers constitute the most important geologic components of this site. The geophysical tests did not reveal the existence of hard bedrock to the explored depths.

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