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Non-Invasive Time-Lapse Imaging of Rainfall Infiltration Levels in the Sedimentary Soils of Central Panama

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Abstract

The economic and commercial worldwide impact of the Panama Canal makes this route one of the most important international maritime routes. The quality of water in communities located near the vicinity of the Canal makes conservation and understanding of water resources a priority. In order to identify the stratigraphy and to understand the infiltration processes caused by the rains in the area of Gamboa between the transition (dry to rainy season) and rainy seasons, a time-lapse electrical resistivity tomography analysis was performed. The results showed two horizons constituted mainly by clay material. The first one composed of clay and accumulation of rocks in some areas and the second, the same clay material with certain level of moisture. About the time-lapse results, the negative percent change of resistivity (between 0 and -46.5%) obtained are associated with the rainfall that reached 19 mm during the last days of the second survey; this fact demonstrates the remarkable contribution of the rains to the groundwater that feed the Panama Canal. Moreover, the positive percent change of resistivity (between 0 and 50%) are linked to artefacts which can be common linked to inversion scheme, electrode array or electrode removal and relocation process.

Keywords

time lapse analysis, electrical resistivity tomography (ERT), inversion artifacts, Gamboa area, Panama Canal

1. Introduction

In order to characterize subsoil and to understand the nature of water infiltrations in tropical zones, a set of important parameters such as the geometric structure and hydrological properties of aquifers have been defined. Research has shown that conventional soil/water sampling, in-situ testing, and laboratory measurements alone cannot meet these objectives and can therefore lead to dispersed information. In the last decade, geophysical methods have emerged that can be complemented with previous hydrogeological data. These geophysical methods are non-invasive, inexpensive and can be developed with large space-time sampling. The application of these techniques to hydrogeological problems is an issue that has been compiled by some authors, for example: Kirsch (2006), Vereecken et al. (2006), Rubin and Hubbard (2006), Robinson et al. (2008) and Yeh et al. (2008). Of all existing geophysical techniques, electric prospecting is the one that has been extensively used in groundwater studies because of the sensitivity of electrical charges to the liquids contained in the subsoil. The works of Barker and Moore (1998), Chambers et al. (2008), Miller et al. (2008), Descloîtres et al. (2008) and Brunet et al. (2010) correspond to studies of groundwater monitoring at various seasons of the year through the application of ERT in conjunction with a time-lapse analysis. The aim of this work is to apply the techniques of geophysical prospecting, more specifically the geoelectrical techniques in an important control zone, which is part of the Panama Canal watershed, to understand the levels of infiltration of rainfall in its soils and learn of the effects that inversion artefacts have on the final interpretation of the results obtained in these type of studies.

2. Site Features

The site of interest is located in the Gamboa area, specifically in the eastern sector of the Panama Canal, a few kilometers from the entrance of the Chagres River. The area is located within Soberanía Park, an area protected by the National Environment Authority, and where a great variety of animal species, vegetation and fresh water sources exist. Figure 1 shows the geographical location of the site of interest and distribution of the profile. Tropical forests such as those that are characteristic of the Gamboa area can be described though various factors that relates to the formation of soils such as: climate, organisms, topography, geological elements and weather. Rain and the temperature help control the leaching and weathering of soil minerals, and as a result have a very important role in determining the chemical properties of the soil.

Seasonal precipitation in Panama differs in intensity and amount of leaching is relative to seasonal climates. Some research suggests that the increasing duration of the dry season corresponds to increased fluctuations in soil microbial populations and nutrient release. According to a report by the Smithsonian Institute, most of the mature forests are located within the Chagres National Park. The Gamboa area is drained by a series of small streams that generally persist throughout the year because of high precipitation. Two streams drain the south side of a hill near the site and three streams drain the northern sector; however, field research has shown that the stream located further east does not flow continuously.

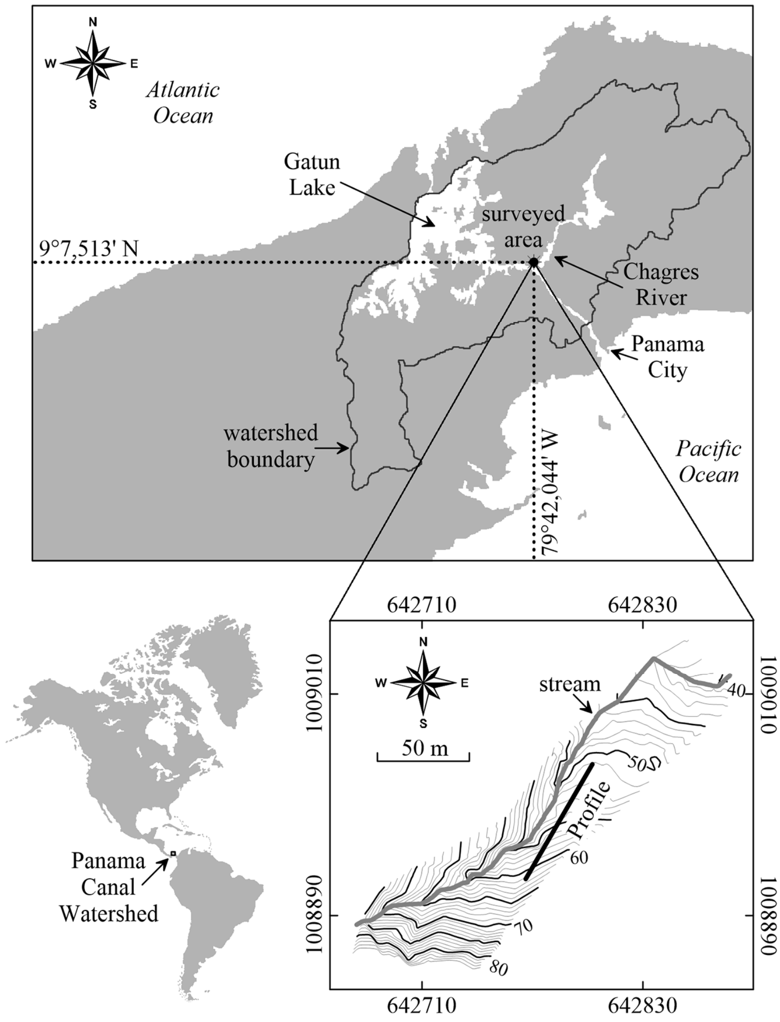

Figure 1. Test Site Location and ERT Line, Panama Canal Watershed

3. Geological Context of the Gamboa Area

According to Coates and Obando (1996) and Coates (1999), the Panama Canal rests on the Panama Canal watershed which corresponds to a geological basin that extends over the tectonic limit of two blocks that are part of Panama subplate. According with Stewart et al. (1980) and Escalante (1990) this basin has a thick sequence of sediments and volcanic rocks (>2900 m) with an age ranging from the Cretaceous to the Holocene periods. According to the generalized geological map of Figure 2, the site of interest lies in the Eocenic Formation of Gatuncillo, this being the sedimentary unit of greater depth compared with another geological formation around it.

Woodring (1957) and Escalante (1990) indicate that this geological formation rests discontinuously on a volcanic basement that is characteristic of the Pre-Tertiary period. The Gatuncillo Formation has geological features such as shale, sandstone, limestone and foraminifera.

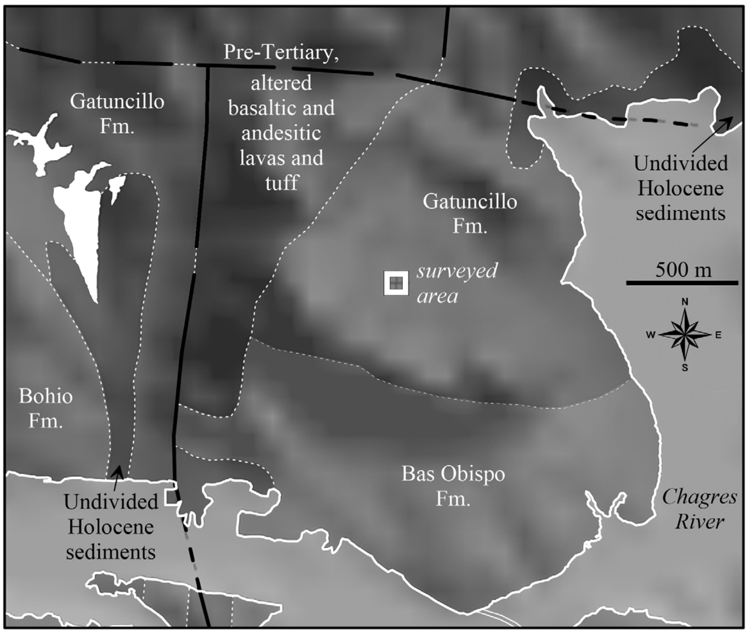

Figure 2. Test Site Location and ERT Line, Panama Canal Watershed

4. Materials and Methods

Monitoring of moisture levels in the subsoil made through the electric prospection entails the development of a set of ERTs along the same profile at different times. The generation of an ERT involves several important aspects such as: (*i*) the process of acquiring the data in the field, (*ii*) solving the direct problem or direct modeling, and (*iii*) solving the inverse problem to obtain an image dimension similar to a vertical plane with the actual distribution of the electrical properties of the subsoil in terms of the actual depth.

4.1 Process of Acquisition of the Data

The electrical method is based on the measurement of the apparent electrical resistivity of the subsoil; it is obtained by injecting a certain intensity of electrical current into the ground through two electrodes (A and B) connected to a source. The voltage generated at the surface can be measured through another two electrodes (M and N); with these data and the geometry of the 4 electrodes distributed in the surface it is possible to obtain the value of the electrical resistivity apparent of subsoil in **Ω**.m. Telford et al. (1990) and Parasnis (1997) provide a detailed explanation of the principles.

The generation of an ERT demands the measurement of a significant number of apparent electrical resistivity data; for this, a set of electrodes are inserted in the ground's surface at the same distance between them and are connected to a switch through a system of cables and this, to a source that in this case corresponded to an AC device with 400 V as output. In this study, a total of 39 stainless steel electrodes were distributed along the profile outlined in Figure 1, separated by a distance of 2 m between them.

Figure 3 shows and example of the measurement process of apparent electrical resistivity values for 5 levels of depth or pseudo-depths along a profile with 16 electrodes; the first apparent electrical resistivity value is obtained by injecting the electric current through the first and fourth electrodes (A_1 and B_1 of Figure 3), and recording the voltage across the second and third electrodes (M_1 and N_1 of Figure 3), this simple array is known as Wenner-α configuration.

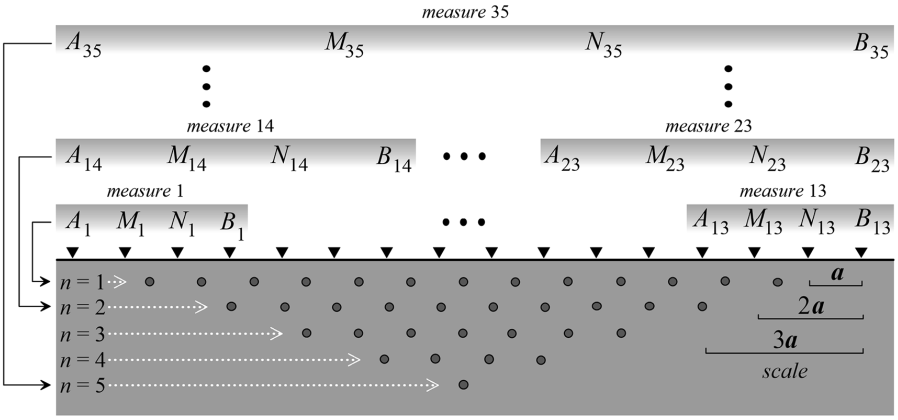

Figure 3. Sequence of Measurement of Apparent Electrical Resistivity Values Along a Profile. Each Point Measure Position is Attributed to a Pseudo-Depth Proportional to the Separation of the Electrodes (See Dark Circles under the Profile); the Inverted Triangles Represent the Electrodes

This process is repeated until the set of 4 electrodes occupy the last 4 positions along the profile (A_{13}, M_{13}, N_{13} and B_{13}). This first dataset corresponds to the first depth level ($n = 1$). The following depth levels are obtained in the same manner but for larger separations between the electrodes (2*a*, 3*a*, etc.). For the case of Gamboa, a total of 12 depth levels were obtained and an inversion scheme implemented in the Earth Imager 2D program (AGI Advanced) was used for the final interpretation.

4.2 Inversion Process of the Apparent Electrical Resistivity Data and Time-Lapse ERT Analysis

Obtaining the distribution model of subsurface resistivity through a two-dimensional image corresponds to a non-linear inverse problem; its primary objective is to generate a subsoil model capable of reproducing the measured data on the surface. In order to solve the inverse problem, we first constructed an initial resistivity model based on the distribution of the apparent electrical resistivity values; then a forward modeling is performed to calculate the synthetic electrical resistivity values. Forward modeling is focused in solving a 3D partial differential equation:

$$-\nabla \cdot \left[\sigma(x,z)\nabla V(x,y,z)\right] = I\,\delta\left(r - r_f\right)$$

Where $\sigma(x, z)$ is the electrical conductivity distribution in the (x, z) plane; I represents the intensity of the source, δ corresponds to the Dirac delta function and $r - r_f$ indicates the source location (Dey & Morrison, 1979). The sequential time-lapse ERT inversion was carried out through the approach described in EarthImager 2D (2002-2009).

In order to monitor the variations of the real electrical resistivity values of the subsoil at different times of the year, we opted to apply a time-lapse electrical resistivity tomography. This methodology consists in generating datasets of apparent electrical resistivity values at different times in which the reference or base dataset will correspond to the first set of measured data set. The time-lapse algorithm inverts the difference between these two datasets. The final result of the inversion process corresponds to a 2D image that presents the percent difference of resistivity between the two interpreted datasets; this means that in some cases it is possible to obtain positive variations that may be associated with resistivity artefacts as a result of the calculation being performed. Another possible factor could be the relocation of the electrodes (electrode mislocations) since it is impossible to leave them in the field, or it could also be the electrode array used. There has been some research showing the advantages of using asymmetric electrode arrangements (Oldenborger et al., 2005; Grellier et al., 2008; Clément et al., 2009). In this work, the first test was performed on June 25, 2009 (the transition period between the dry and rainy season), and the second test, on November 20 of the same year (end of the rainy season).

5. Result

The apparent electrical resistivity data obtained in the transition and rainy seasons are presented graphically through the pseudo-sections of Figures 4 (a) and (b), respectively.

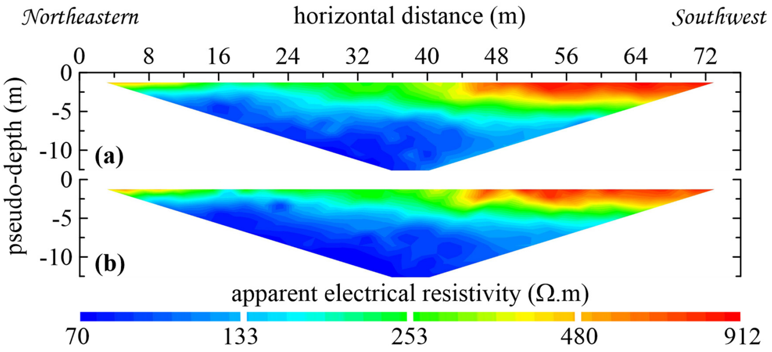

Figure 4. Apparent Electrical Resistivity Pseudo-Sections Obtained in the (a) Transition and (b) Rainy Periods

The inversion criteria defined in the previous section were applied to the two datasets of apparent electrical resistivity measured along the profile. We using the smooth and robust inversion routine of the Earth Imager 2D program (of AGI), showing this latter less artefacts.

The results of this process are shown as electrical resistivity tomographies corresponding to the transition (Figure 5 (a)) and rainy (Figure 5 (b)).

Two horizons were identified:

- The first surface horizon is represented in green tonality, and characterized by having a range of calculated electrical resistivity values ranging from 154 to 586 Ω.m. The thickness of this horizon ranges between 1.6 and 8.4 m for both results (Figure 5 (a) and (b)). In this layer we can identify a set of strong anomalies represented in red-yellow tonality (586-4383 Ω.m) with maximum thicknesses of 1.5 m in the two results (Figure 5).

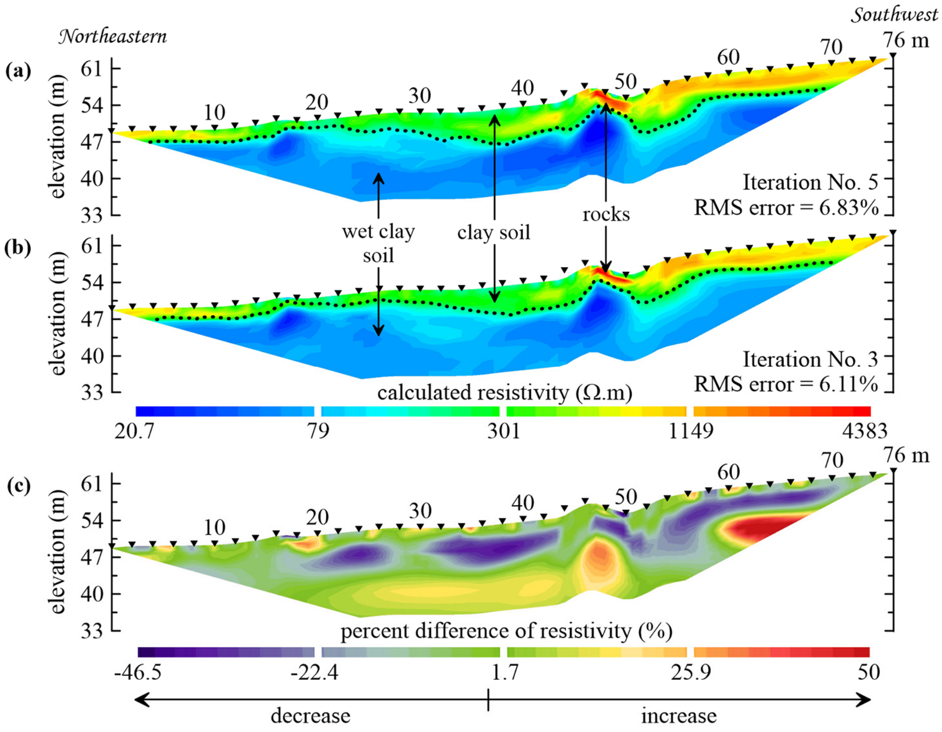

Figure 5. Time-Lapse Inversion Results for the Field Data Measured during the (a) Transition, (b) Rainy Season, and (c) the Percent Difference of Resistivity Section Obtained from This Analysis. Inverted Triangles Represent the Electrodes

- The second horizon is represented in blue tonality, with a range of values of calculated electrical resistivity that oscillates between 20.7 and 154 Ω.m.

The result of the time-lapse analysis obtained in Figure 5 shows some areas with an increase in the calculated electrical resistivity values and identified in yellow-red tonality. These zones are located both in depth and in surface, and the positive percentages of variation of resistivity obtained from this analysis oscillate between 14% and 50%.

On the other hand, there are also areas in violet tonality which have a marked decrease in the calculated electrical resistivity values (negative percent values between -12% and -46.5%). It can be seen that said zones extend substantially along the entire profile in depth. The areas characterized in green tonality show weak variations in the values of electrical resistivity calculated.

6. Discussion

The first horizon identified in the results of Figures 5 is associated with a clay layer, typical of site geology. The strong anomalies of electrical resistivity identified in this horizon are associated with rocks and tree roots present in the site. The second horizon identified in these two results, is associated with clay material but with a certain level of moisture content. These results were corroborated by a perforation performed by the Center for Hydraulic and Hydrotechnical Research (CIHH) in the vicinity of this profile.

The time-lapse results obtained in this study have shown areas with increases in the calculated electrical resistivity values; these positive percentage values are associated to resistivity artefacts, which are linked to non-realistic information of subsoil. On the other hand, the zones that present a decrease in the values of calculated electrical resistivity are a result of the rains that occurred in the zone.

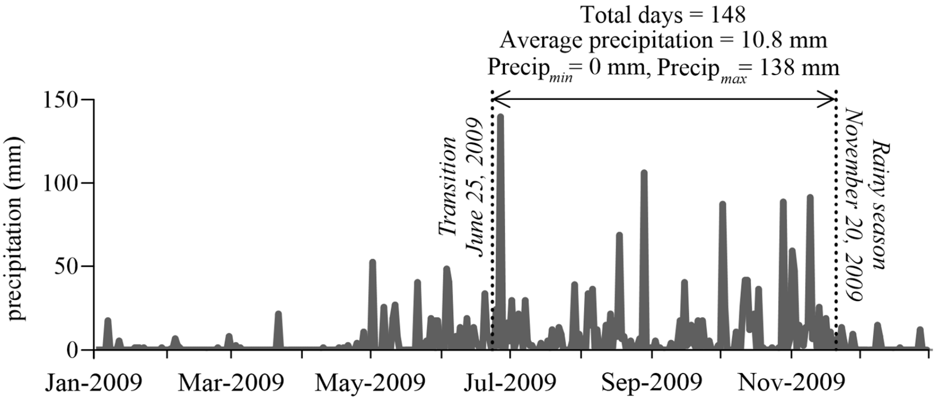

Figure 6. Graph of Monthly Precipitation Variation during 2009 in the Gamboa Area (Source: Water Resources Section, ACP)

Figure 6 shows the rainfall in the Gamboa area during 2009. According to this graph, in the period that limited the dates in which the two electrical surveys were developed, the minimum and maximum precipitation levels were 0 and 138 mm, respectively. However, the average precipitation in this period does not exceed 11 mm; the last 18 days of this period recorded an average of 19 mm, with almost constant rain except for two intermediate days where precipitation levels were 0. This is reflected in the areas that experienced a decrease in the calculated electrical resistivity values (see negative percentages of the areas in violet tonality of Figure 5).

7. Conclusions

The use of geophysical techniques in the study of groundwater corresponds to a topic that has been approached with interest by the scientific community worldwide. As part of these techniques, electrical prospecting plays a very important role because of the sensitivity of moving electrical charges to the presence of water contained in the pores of the medium under study. Hence, a time-lapse electrical resistivity tomography analysis is a useful tool for monitoring changes in the electrical properties of subsoil at different times of the year. The electrical resistivity tomographies obtained in the two important periods were able to clearly define two horizons, where the surface is formed by clay and clusters of rock and roots in some sections, followed by a layer of clay with an important content of humidity. In the area of Gamboa, the results obtained in the time-lapse analysis indicate that the rains that occur during the year in this important tropical zone, constitute the major contribution to the groundwater that feed the water system of that zone; the percentages of decrease that exceed the -45% in the soils of the area of Gamboa demonstrate this fact. On the other hand, the increases experienced in the given profile can be associated with three possible factors: the inversion scheme used in data processes, the electrode array and electrode mislocations during the development of the second survey; this fact indicates how difficult it is to eliminate this type of artefacts in a tomographic analysis.

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