# Time-lapse electrical resistivity tomography for assessment of seasonal moisture variations in a tropical regolith

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#### Abstract:

Monitoring and quantifying hydrological flows in the vadose zone is complicated to analyze due to the effects of rainfall in the tropics, the dynamic interactions among rains, the vegetation layer, moisture in the soil, and the entire regolith. Quantifying subsurface hydrological flows at specific scales and high resolution presents further difficulties. To overcome these issues, resistivity methods can play an important role. This paper examines the results of gravimetric moisture content monitoring in the Panamanian tropics through time-lapse electrical resistivity tomography analysis. Changes in the electrical properties of soil were quantified through six tomographic tests performed between February 2012 and March 2013 along with a profile. Significant changes in resistivity were identified between February (dry season) and May, and August and October (rainy season), with negative percentages (-60%)indicating the effects of rain infiltration at the surface and positive percentages (60%) linked to moisture absorption in the soil, electrode relocation for each test or inversion processes. Additional laboratory analyses of soil samples were carried out to obtain gravimetric moisture content tomograms. The changes of this parameter in the subsurface horizons, and the percentage differences in the calculated resistivity values, are helpful for determining the impact of rain on the soils.

KEYWORDS Time-lapse electrical resistivity tomography; resistivity method; 2D inversion; gravimetric moisture content; groundwater; shallow infiltration

#### **INTRODUCTION**

Electrical resistivity tomography (ERT) techniques have become important in hydrological and hydrogeological studies, especially for monitoring fluid dynamics within the most superficial layers of the planet, due to the high sensitivity of the data obtained via the application of various inversion schemes. This type of analysis has been used for monitoring over long time periods, to examine the influence of climate and vegetation on root-zone moisture (Jayawickreme et al., 2008), the evolution of leachates and tracers (Kemna et al., 2002; Dahlin et al., 2006, 2014), landslide processes (Chambers et al., 2009), earth embankments (Chambers et al., 2008), local seasonal changes (Descloitres et al., 2008), in situ remediations (Tildy et al., 2017), and to characterize watersheds (Miller et al., 2008). Over short time periods, leachate dynamics in landfills and sewage treatment areas (Guérin et al., 2004; Grellier et al., 2005, 2008; Lillo et al., 2009), tracers (Cassiani et al., 2006; Oldenborger et al., 2007), and unsaturated zones (Deiana et al., 2007) have been examined.

In the Panamanian tropics, analyses of variations in soil electrical properties by time-lapse ERT and rainfall simulators have improved understanding of the nature of infiltration by irrigation (Ogden *et al.*, 2010, 2014; Kempema *et al.*, 2015; Litt *et al.*, 2019), and seasonal variation therein (Mojica *et al.*, 2013; Ho *et al.*, 2017). Moisture content images generated by ERT, and empirical study of petrophysical properties, could facilitate hydrological studies in tropical areas of Latin America (e.g. watersheds), by providing valuable information on preferential flows in the subsoil.

Panama has an extensive hydrographic network and an average annual rainfall of 2924 mm/year, with both rainy (April to November) and dry (December to March) seasons. The Panama Canal watershed is one of the most prominent in the country; it supplies water to one of the most important maritime routes worldwide and the growing populations of Panama City and Colón (Garcimartín *et al.*, 2020). In addition, the Panama Canal Authority has initiated a program to protect the hydrographic watershed

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through protective vegetation layers. Therefore, a tool for assessing seasonal variation of soil moisture to a depth of 10 m in tropical regolith is critical because rooting depth in tropical regoliths under forests can be deep and little information is available in the literature on forest rooting depths in the tropics.

This study was performed to monitor changes in the gravimetric moisture content of inceptisol soils in the northeastern sector of Panama City using a time-lapse ERT method. Figure S1 shows the location of the study area. For hydrogeophysical monitoring, six electrical resistivity tomographies were performed along a 47-m-long profile between February 2012 and March 2013.

#### GEOLOGICAL AND STRATIGRAPHIC CHAR-ACTERISTICS OF THE STUDY AREA

Stewart *et al.* (1980) described the study area as being surrounded by three geological formations, i.e. the volcanic and marine facies of the Panama Formation and the undivided Holocene sediments. The Oligocene volcanic facies of the Panama Formation, containing altered andesitic rocks and tuffs, lie toward the study area's eastern part (Figure 1(a)). Rocks in this formation experienced alteration and transport due to paleogeographic watercourses.

The marine facies of the Panama Formation (see Figure 1(a)) correspond to a sedimentary formation of the Oligocene-Tertiary period. This formation, where the study

site is located, is characterized by shallow marine deposits, including sandstones, calcareous rocks, and shales. The presence of foraminifera and algae in large quantities suggests the warming of the waters at that time. The most recent formation is the undivided Holocene sediments to the south, composed of alluvial sediments deposited by rivers and streams from 2.5 Ma to the present time. These sediments show strong variability due to the diversity of geological formations crossed by water currents.

To obtain stratigraphic information and monitor water level fluctuations in the study site, a well was drilled at 18 m (as shown in Figure 1(b)). Figure 1(c) shows the stratigraphy obtained in the well, where the first 0.50 m (corresponding to the surface layer) contains a fill of weathered rock and clay. From 0.50 to 3 m, there is a layer of weathered sedimentary rocks of low to moderate hardness. These first two layers have relatively low rock quality designation (RQD) values of 10% and 20%, respectively. Fractured sedimentary rocks of moderate hardness were found at depths of 3–6.95 m; in this horizon, the RQD values ranged between 20% and 91%. Finally, unaltered sedimentary rock was detected from 6.95 to 10 m. This rock is harder and has higher RQD values of 85–98%.

#### **PERIODS OF SURVEY**

In Panama, heavy rains generally occur from October to early December. During the development of our electrical



Figure 1. (a) Generalized geological map of the study site and surrounding area (Stewart *et al.*, 1980). (b) Site map of the 47-m-long electrical profile in the northwest–southeast direction. (c) Schematic of the borehole located 18 m from the end of the profile and (d) Precipitation and air temperature data obtained between January 1, 2012, and April 19, 2013 from a meteorological station located near the study site. The vertical dotted lines indicate the dates of the electrical resistivity tomographies



Figure 2. Variations in the water table in the borehole between August 2011 and April 2013

resistivity tests, the maximum and minimum rainfall amounts were 0 and 21.08 mm/day, respectively, while the air temperature varied between 19.29°C and 32.70°C. These data were provided by a meteorological station located approximately 240 m from the study site (UTP-Tocumen Station).

Figure 1(d) shows rainfall and air temperature data from January 1, 2012, to April 19, 2013, and the dates of the six tomographic surveys performed. Instrument problems occurred during this period, so there are no meteorological data for the last two tests. To compensate for the missing data, meteorological data were retrieved from a station located 2 km from the site, operated by the Empresa de Transmisión Eléctrica S.A. (ETESA, https://www.hidromet. com.pa/es/). See Text S1 of supplements for further details.

For monitoring of the groundwater dynamics associated with seasonal variation at the study site, a Solinst Levelogger pressure transducer was installed in the control well at the maximum depth of the borehole (10 m). This borehole is 28 m above sea level and has a PVC screen with a diameter of 67 mm. The sensor was configured to take readings every 15 minutes. Data were obtained from August 23, 2011, through April 16, 2013, with an interruption between June 11 and August 1, 2012, due to instrument problems (Figure 2). As shown in Figure 2, the maximum water table depth recorded during the geophysical tests corresponded to those during the dry seasons of 2012 and 2013, with values of 1.567, 1.203, and 1.783 m recorded for Tests 1, 5, and 6, respectively. On the other hand, the minimum water table depths were recorded during the periods in which Tests 2-4 were carried out, corresponding to the rainy season.

#### **METHODOLOGY**

## *Petrophysical analysis: gravimetric moisture content* – *electrical resistivity*

To relate the gravimetric moisture content with the calculated electrical resistivity of the subsoil, a total of 15 soil samples were taken from the study area, but only 7 were analyzed due to the conditions in which they were extracted. With the aim to obtain a relationship between the electrical resistivity of the soil samples and their moisture content, we have used semi-empirical models such as that of Archie (1942). Several studies have reported this methodology, including Jayawickreme *et al.* (2008), Wilkinson *et al.* (2011) and Carey *et al.* (2017). For more details, see Text S2 of supplements.

#### Measurement of apparent electrical resistivity data

Electrical resistivity tomography focuses on obtaining the lateral and depth distributions of the actual electrical resistivity values of the subsurface. This technique provides a subsurface resistivity profile via inversion of the set of apparent electrical resistivity values measured in the field. The generation of these data requires circulation of a certain intensity of electric current in the subsurface, using a regulated electric current source connected to a pair of metal electrodes inserted into the ground. This current circulation generates a voltage in the surrounding area, which is measured by another pair of electrodes; knowing the geometry of both pairs of electrodes allows the apparent electrical resistivity of the subsoil to be determined. This physical parameter is related to other soil properties, such as saturation, porosity, weathering, composition, temperature, and pressure.

Measurement of a single set of apparent electrical resistivity data along a profile required the use of 48 stainless steel electrodes connected to a multi-cable system and a Syscal R1 resistivity meter (Iris Instruments). For more details about geometric and acquisition setting, see Text S3 of supplements.

#### Time-lapse inversion method

Variations in the electrical properties of the subsurface due to seasonal changes (presence and absence of rainfall) can be monitored by measuring several sets of apparent electrical resistivity data obtained in the same profile but at different times (six data sets/tests in this study). More details about the inversion parameters are shown in Text S4 of supplements.

To perform 2D ERT of the subsurface for each dataset, the first dataset was defined as a reference (Test 1, corresponding to February 16, 2012). Inversion of these data was performed using a robust constraint that assumes an exponential distribution of field data errors and minimizes the L1-norm of the data (Advanced Geosciences Inc., 2007). Although the site data had a degree of noise, according to Dahlin and Zhou (2004) the use of robust inversion can provide satisfactory results. The rest of the data sets were inverted using a time-lapse inversion scheme, resulting in a difference in electrical resistivity values expressed as the ratio between the calculated resistivity data for Tests 2–6 and the reference resistivities.

#### RESULTS

#### *Gravimetric moisture content – electrical resistivity relationship, ERT and tomographic gravimetric moisture content results*

The power relationship between gravimetric moisture content and electrical resistivity was observed for the samples collected at the site and provided an acceptable coefficient of determination ( $R^2 = 0.978$ ). Figure 3 shows the decrease in electrical resistivity values due to the increase in the gravimetric moisture content in the soil samples.

The inversion done using time-lapse tomography, yielded six geoelectric tomograms (see Figure 4(a)) with acceptable root mean square (RMS) error values (< 7.32%); the error depends on the total number of measurements and reflects the difference between the predicted and measured



Figure 3. Gravimetric moisture content versus the electrical resistivity of soil samples extracted at the study site

data. Table SI shows some of the inversion parameters obtained in each test. In these results, a decrease in the calculated resistivity values can be observed where Tests 2, 3 and 4 don't show the shallow anomaly (in red and yellow tones) of resistivity higher than 24  $\Omega$  m that is presented in Test 1 between positions 0 and 30 m along the profile. This anomaly appears in Test 5 in yellow tone with intermediate values of calculated resistivity (17–21  $\Omega$  m) and is accentuated in Test 6 with high values of calculated resistivity.

Between 32.5 and 47.0 m along the profile, the shallow part of the anomaly in yellow tone of intermediate calculated resistivity values  $(17-21 \ \Omega \ m)$  in Test 1, disappears in Tests 2, 3, 4 and 5, but it increases in intensity (> 28  $\Omega \ m$ ). Test 6 presents a calculated resistivity distribution similar to Test 1. In Tests 2, 3, 4 and 5, a large part of the electrical scans is occupied by anomalies of low calculated electrical resistivity (7–14  $\Omega \ m$ ) represented in light-blue and blue tones.

The relationship obtained between the gravimetric moisture content and electrical resistivity of soil samples allowed the calculated electrical resistivity data sets to be transformed into moisture content values after the inversion process. Figure 4(b) shows the spatiotemporal evolution of the gravimetric moisture content during the study period. There were marked differences among the results of the tests performed in the dry, transition, and rainy seasons. The first and last tests were remarkably similar because they were both carried out in the dry season, albeit in different years.

In Test 1, a shallow anomaly (yellow to brown tones) with low gravimetric moisture content (< 38%) was seen, which extended laterally throughout the entire tomogram and increased in depth from north to south ( $\sim$ 0.8–5.0 m). According to the geological data obtained from the bore-



Figure 4. (a) Inverted resistivity sections, (b) gravimetric moisture content tomograms obtained from the calculated electrical resistivity, and (c) percentage changes in the calculated electrical resistivity values obtained during the study period

hole, the low gravimetric moisture contents were concentrated in the weathered sedimentary rock layer. An anomaly with a high gravimetric moisture content (> 46%) was identified below this layer (blue and light blue tones), at 0-18 m along the profile. This anomaly seemed to extend in a southerly direction, but did not extend vertically to the maximum depth. The line of demarcation of these two anomalies at the 18 m position (location of the observation well) was adjusted to the depth of the water table recorded by the piezometer; it corresponds to the presence of fractured sedimentary rock and is represented by a continuous blue line in Figure 4(b). The gravimetric moisture content decreased at depths greater than 6 m, where the value of this parameter ranged between 35% and 45% (green and yellow tones). This anomaly was associated with unaltered sedimentary rock, as determined by drilling. A similar distribution of gravimetric moisture content was observed in Test 6, where both tests were performed during the dry season.

In Test 2, a large portion of the first anomaly with low gravimetric moisture content described in Test 1 increased in intensity (< 42%) and generated a surface anomaly (light-blue and blue tones) up to a depth of approximately 2.0 m (limit of the weathered sedimentary rock). With regard to the piezometric information recorded during that day, the water table was consistent with the results of the geophysical survey. The second high moisture content anomaly described in Test 1 increased in lateral extension and depth, and was concentrated in the horizon corresponding to the fractured sedimentary rock. The deeper horizon, associated with the presence of unaltered sedimentary rock, was characterized by the same gravimetric moisture content anomaly identified in Test 1, but at lower intensity. The distribution of the gravimetric moisture content anomalies obtained from this second test was remarkably similar to those of Tests 3 and 4, including the limits of the water table obtained using the piezometer. These increases in gravimetric moisture content of the sedimentary horizons were due to the rains that occurred during these periods.

In Test 5, the shallow anomaly of high gravimetric moisture content (identified in the three previous tests) on the horizon corresponding to weathered sedimentary rock decreased laterally from 0 to 31.0 m along the profile. However, the second deeper anomaly (fractured sedimentary rock) maintained its extension. The gravimetric moisture content anomaly located at a greater depth (~6 m, represented in green and yellow tones) was similar to that revealed by previous tests. During the development of this test, the water table decreased.

#### Time-lapse ERT results

With regard to the changes in calculated electrical resistivity values over time, the first tomography in Figure 4(c) presents a shallow anomaly of negative values (-20% to -60%) in blue tones. This result showed the contribution of rain in the sector, where the negative change indicates a decrease in electrical resistivity over time (calculated from the subsoil). At depths of 1.0–3.0 m, an anomaly in lightred tone and characterized by positive changes in the calculated electrical resistivity (20–60%) is presented.

Continuing with the interpretation of the first three tomograms in Figure 4(c), there was another negative change in the calculated electrical resistivity value between 15 and 22.5 m along the profile, albeit of lower intensity relative to the superficial change described above (-20%). This could be attributed to the infiltration of rainfall into the subsoil, which in turn recharges the aquifers at the study site. The fourth tomogram in Figure 4(c) shows the same pattern of changes in the calculated electrical resistivity, but with lower intensity. This result is reasonable as it corresponds to a time-lapse analysis (between Tests 1 and 5) performed during the dry season of 2012 and some rainy days before January 2013. Finally, the fifth tomogram shows weak changes in the calculated electrical resistivity values ( $\sim0\%$ ), and is also reasonable because both tests (1 and 6) were carried out in the driest months of 2012 and 2013, according to the available meteorological information.

#### DISCUSSION

Limitations of the method used to extract the samples, and the physical characteristics of the sedimentary rocks in depth, were factors that did not allow the extraction of samples to greater depth. Nevertheless, the geotechnical analyses carried out on the soil samples obtained at a depth of 0.20 m showed low variability of porosity (0.10–0.19).

The results demonstrated the high sensitivity of the electrical properties of the sedimentary horizons to the rainy season in the Panamanian tropics. A shallow anomaly of high resistivity (Figure 4(a)) and low gravimetric moisture content (Figure 4(b)) was revealed during the dry and transition seasons (dry to rainy). However, this anomaly changed significantly when the shallow moisture increased due to rainfall. Rainfall promoted natural recharging of the aquifer almost year-round, increasing both the number and intensity of anomalies with low calculated resistivity and high gravimetric moisture content in the horizon composed of fractured sedimentary rock (Figures 4(a) and 4(b)). Deeper, calculated resistivity and moisture content anomalies varied slightly in intensity, decreasing and increasing respectively as rainfall increased in the zone of interest. In Tests 1 and 6, the boundary between the high calculated resistivity and low gravimetric moisture content anomalies (Figures 4(a) and 4(b)) and the moderate values of both parameters appeared to be associated with the water table. However, in Tests 2–5, there was a very similar anomaly distribution.

This information was corroborated by the computed changes in electrical resistivity values in the tomograms shown in Figure 4(c). Effects of rainfall in the shallow layers of the study site were observed, where weathered sedimentary rocks characterized this horizon, and negative change values were obtained (Figure 4(c)). Effects were also present at depth but with low intensity due to the aquifer recharging process. The positive changes in electrical resistivity presented in the tomograms (Figure 4(c)) represent a moisture deficit that could be associated to three possible factors: higher levels of water absorption by the roots of the trees found on the site, the inversion scheme used and relocation of electrodes during each test (Mojica *et al.*, 2013).

The first and last tests of Figure 4(c) don't show significant changes in the calculated resistivity values because both were carried out at dry seasons of different years (with similar climatic conditions).

#### CONCLUSIONS

The present study quantified changes in the gravimetric moisture content of soils in the northeast sector of Panama City during a period of 14 months with two climatic seasons (rainy and dry seasons), using the time-lapse ERT method. With this methodology, we were able to evaluate the lateral and vertical distributions of soil moisture content, quantify the contribution of the rainy season to the sedimentary soils of the Panamanian tropics, and understand the impact on aquifers in the area of interest. The changes in resistivity obtained in this study shed light on the behavior of subsurface hydrological flows and the impact of the climate on the biosphere of the Panamanian tropics. These data are important to understand soil use in this region and its impact on the hydrological cycle.

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#### **SUPPLEMENTS**

- Text S1. Description of meteorological data
- Text S2. Gravimetric moisture content versus electrical resistivity
- Text S3. Geometric and acquisition parameters setting
- Text S4. Inversion parameters
- Figure S1. Location of the study site (28 m above sea level) in the northeastern sector of Panama City. Gray lines indicate main roads
- Table SI. RMS errors and number of iterations for each test

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