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AN ELECTROMAGNETIC GEOPHYSICAL SURVEY OF THE FRESHWATER LENS OF ISLA DE MONA, PUERTO RICO

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An electromagnetic reconnaissance of the freshwater lens of Isla de Mona, Puerto Rico was conducted with both terrain conductivity (TC) and transient electromagnetic (TEM) surface geophysical techniques. These geophysical surveys were limited to the southern and western parts of the island because of problems with access and cultural metallic objects such as reinforced concrete roadways on the eastern part of the island. The geophysical data were supplemented with the location of a freshwater spring found by scuba divers at a depth of about 20 m below sea level along the northern coast of the island. The geophysical data suggest that the freshwater lens has a maximum thickness of 20 m in the southern half of the island. The freshwater lens is not thickest at the center of the island but nearer the southwestern edge in Quaternary deposits and the eastern edge of the island in the Tertiary carbonates. This finding indicates that the ground-water flow paths on Isla de Mona are not radially symmetrical from the center of the island to the ocean. The asymmetry of the freshwater lens indicates that the differences in hydraulic conductivity are a major factor in determining the shape of the freshwater lens. The porosity of the aquifer, as determined by the geophysical data is about 33%.

Isla de Mona is an uninhabited 55-km² island located between Puerto Rico and Hispaniola. The island consists of a nearly circular carbonate plateau that has been uplifted and is bounded by vertical cliffs that range from 40 to 80 m msl. A narrow 3 km² coastal plain abuts the plateau to the southwest (Fig. 1). Most of the island is composed of carbonate rocks, with little insoluble residue, of marine origin that were first considered to be Miocene (Kaye 1959; Briggs & Seiders 1972). The coastal plain attains an elevation of 10 m msl and is composed of Pleistocene to Holocene reef and beach deposits (Briggs & Seiders 1972; Taggart 1992).

The density difference between ocean water and freshwater is such that 41 volumes of freshwater have the same mass as 40 volumes of ocean water. The Ghyben-Herzberg principle, which assumes hydrostatic conditions (Vacher 1988), states that for each unit of elevation the water table is above sea level there will be 40 units of freshwater below sea level. The overall thickness of the freshwater lens is the sum of the part below sea level and the part above, but as 98% of the freshwater is below sea level, the contribution above sea level is frequently ignored.

The shape of the saline-freshwater interface is a sensitive measure of aquifer characteristics integrated over large areas (Vacher 1988). In the absence of pumping, the shape of the saline-freshwater interface is determined by the distribution of the ratio of recharge to hydraulic conductivity (Vacher 1988). If recharge is uniform and hydraulic conductivity is isotropic and homogeneous then the shape of the freshwater body floating on the saline water will be that of a lens, thin near the coast and thickening inland. Because of its shape, the freshwater

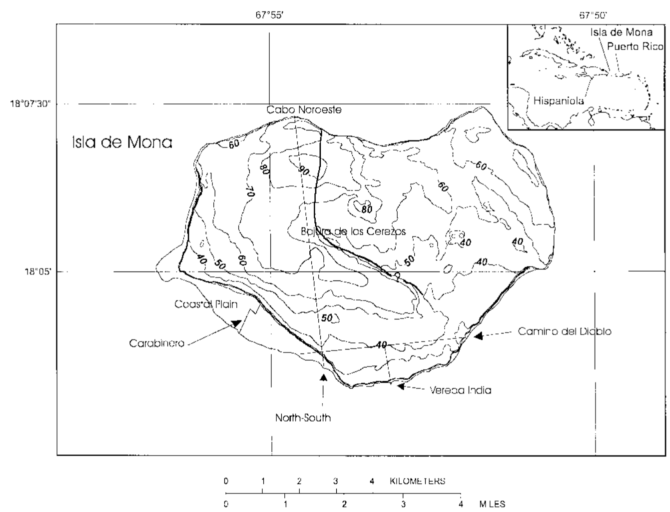

Figure 1. Location and topographic map of Isla de Mona, Puerto Rico. Elevations are in meters above sea level. The principal physiographic areas of the island are the coastal plain and the plateau, which includes the Bajura de los Cerezos and Cabo Noroeste. The four transects are Carabinero, Vereda India, Camino del Diablo, and North-South. The 10-, 20-, and 30- m contours are obscured at this scale because of their proximity to one another. The geologic fault mapped by Briggs and Seiders (1972) is shown as a heavy line.

part of an island aquifer is frequently referred to as a "lens." If recharge and hydraulic conductivity are heterogeneous, then the lens will be thicker where the recharge is greater or where the hydraulic conductivity is lower.

Information about the distribution of recharge and hydraulic conductivity in the aquifer can be inferred from studying either the water table or the saline-freshwater interface. According to the Ghyben-Herzberg principle, the two surfaces should mirror each other but with features magnified 40 times in the saline-freshwater interface. Regions of high hydraulic conductivity will have low gradients of hydraulic head. If this region is connected to the ocean, then the heads will be above sea level but lower than in other areas with lower hydraulic conductivity. Consequently, in the region of high hydraulic conductivity the saline-freshwater interface is relatively high.

Rocks saturated with saline water are more electrically conductive than rocks saturated with freshwater. Electromagnetic methods are sensitive to conductors so the saline-freshwater interface makes a good geophysical target. Limestone saturated with freshwater or air is resistive, so that the water table is a poor target for electromagnetic methods (Kauahikaua 1987).

By measuring the electrical conductivity of the earth as a function of depth, electromagnetic geophysics can map the relative thickness of the freshwater lens. The transition from freshwater to saline water in the aquifer is a zone of rapidly rising bulk electrical conductivity. Inversion of electromagnetic geophysical data usually locates this transition zone as a sharp interface without providing any information about its thickness (Kauahikaua 1987). An example of a study where TC data were used to map the thickness of the freshwater lens on a carbonate island and compared to the lens thickness as mapped from well data can be found in Wightman *et al*. (1990).

Current ground-water development on Isla de Mona consists of five hand-dug wells, one of which is occasionally pumped to provide water for showers and sanitary purposes. The deepest of the five hand-dug wells is 3 m deep with the water table at about 2.2 m below land surface. The electrical conductivity of the water in the five wells ranges from 240 to 1500 mS/m (1 mS/m = 10 µS/cm). Cave divers have measured groundwater conductivities in subaqueous caves along the southeastern coast of the island ranging from 900 to 4000 mS/m (Richards *et al.* 1995).

Jordan (1973) calculated a water budget for Isla de Mona. Average rainfall is 810 mm/a and he estimates evapotranspiration to be 710 mm, which leaves an average of 100 mm/a available for runoff and to recharge the aquifer. By assuming a ground-water gradient similar to that of northern Puerto Rico, Jordan arrived at a hypothetical maximum thickness of the freshwater lens of 76 m. His map of the hypothetical freshwater lens assumes that hydraulic conductivity is isotropic and homogenous and, thus, the contours are concentric versions of the coastline.

A heavy rainfall event was observed in May 1992 when 230 mm of rain fell in 72 hours. Ponding occurred on large sections of the coastal plain and water was observed cascading off the cliff face. Some of the water cascading off the cliff face would flow directly into the ocean while some could enter the aquifer on the coastal plain. A similar flood occurred in 1994 (Felix López, U.S. Fish and Wildlife Service, written communication 1997).

This study of the hydrogeology of Isla de Mona was conducted by the U.S. Geological Survey in cooperation with the Puerto Rico Department of Natural and Environmental Resources. As part of this study, electromagnetic surface geophysical data were collected to gain a better understanding of the shape of the freshwater lens on the island. Inferences about ground-water flow paths are then made based on the shape of the freshwater lens as defined by surface geophysics. The shape of the saline-freshwater interface under the coastal plain was described by Richards *et al*. (1995). The TEM data on the north-south transect of the plateau were published by Martínez *et al*. (1995). This report includes the TC data from the plateau as well as more data from divers. The effect of these additions is to give a much broader picture of the shape of the saline-freshwater lens under the plateau than was previously available.

METHODS

Both of the electromagnetic geophysical techniques used in this study use induction to measure the electrical conductivity of the earth as a function of depth. The TC technique is a frequency-domain system where the secondary magnetic field is measured by the receiver coil continuously as it is being induced by the transmitter coil. The TC equipment used in this study was the EM34-3 produced by Geonics Limited*. This instrument transmits at frequencies of 400, 1600, and 6400 Hz; the frequencies are coupled with coil spacings of 40, 20, and 10 m, respectively. At each coil spacing, a measurement is taken with the coils in vertical and horizontal orientations. This produces six data points with various depths of penetration. The dipole of the electromagnetic field produced by the coil is at right angles to that coil. A more complete description of the theory of the equipment can be found in McNeill (1980).

The TEM technique is a time-domain method in which a current in a transmitter loop is abruptly shut off and the collapse of the electromagnetic field around the transmitter loop induces a transient current in the ground. The TEM equipment used in this study was the EM47, produced by Geonics Limited. The receiver coil measures the time decay of this transient current. The induced current disperses outward with time and, thus, the information from later times is from deeper depths (Fitterman & Stewart 1986). In this study two transmitter loop sizes were used. On the coastal plain where the elevation of the land surface is less than 10 m, a 5 m by 5 m, 8-turn transmitter loop that has 200 m² of effective area was used. On the plateau where the elevation of the land surface ranges from 30 to 90 m msl, a 100 m by 100 m transmitter loop

*The use of brand names is for identification only and is not an endorsement by the U.S. Geological Survey.

was used. The larger loop takes considerably more time to set up but allows for greater penetration depths.

Each TEM data set consists of 20 readings of apparent conductivity at different times after current shut off and at each of two transmitter repetition frequencies: 285 and 30 Hz. By decreasing the transmitter repetition frequency, readings are taken at later times after the current is shut off, thus allowing the definition of a different section of the time-decay curve. The data from the two transmitter repetition frequencies overlap so the apparent conductivity is known at a total of only 30 different times. The TEM data collected in the field are the voltages in the receiver coil versus time that then are converted at the time of measurement to apparent resistivity (which is the reciprocal of apparent conductivity - the conductivity that the equipment would read if the earth were a homogenous half space). Each data set was repeated six times. The TEM data are examined to see if the curve of apparent resistivity versus time is smooth and that the six readings produced repeatable results. The theory behind this technique is described by Fitterman and Stewart (1986).

The TC and TEM techniques result in 6 and 30 apparent conductivities at each site, respectively. The greater data density gives the TEM better vertical resolution. The TC method, however, is much faster. TC readings can be collected in 5 to 8 minutes while the TEM requires about 45 minutes for the smaller loop.

The computer programs used to interpret the TC and TEM data were the EMIX34 and the TEMIX47, respectively, by Interpex Limited. The programs are similar in function and use the changes in apparent conductivity with depth to find a layered earth solution (Interpex 1988ab). The interpreter enters an initial geoelectric model. Through an iterative process, the program varies the thickness and electrical conductivity of each layer, but not the number of layers, until it finds a final geoelectric model that statistically best fits the data. Estimating the number of layers in the initial model and their values requires the use of geologic or hydrologic data. An example of using TC data and the EMIX34 program to measure the elevation of the saline-freshwater interface on a small oceanic island can be found in Anthony (1992). In this study, two-layer models were used to interpret the electromagnetic geophysical data. The upper layer represents the unsaturated zone and the freshwater-saturated zone whereas the lower layer represents the saline water-saturated zone. The thickness of the first layer represents the depth of the saline-freshwater interface below the land surface. The geoelectric modeling of electromagnetic geophysical data does not always result in unique solutions. The problem of non-unique solutions becomes more significant when the number of layers is increased.

No geophysical data were collected on the northern half of the island because it is inaccessible. The only evidence of the thickness of the freshwater lens on the northern half of the island is from reports by scuba divers. Freshwater discharges from submarine springs were encountered by divers while conducting research on the Hawksbill turtle (*Eretmochelys imbricata*) that inhabits the waters around Isla de Mona. The index of refraction of water is a function of its salinity. The mixing of waters of different salinities produces a blurry area that can be visually identified by divers.

RESULTS

In May and September 1993, a total of 147 TC data sets were collected at 126 sites on the island; 123 on the coastal plain and 24 on the plateau. In July 1994, 21 TEM data sets were collected; 16 on the coastal plain and 5 on the plateau (Fig. 3) (Richards *et al.* 1995; Martínez *et al.* 1995). On the coastal plain most data, both TC and TEM, were collected on unpaved roads and the grass landing strip. On the plateau the TC data were collected along an unpaved road, the Camino del Diablo, and a trail, the Vereda India. The TEM data were collected along the trail to the Bajura de los Cerezos.

Table 1 shows the average interpreted conductivities of the two-layer geoelectric models that resulted from the inversion of the initial geoelectric models. First layer conductivities decreased dramatically between the coastal plain and the plateau.

Table 1. Average results of geoelectric models.

	Coastal Plain		Plateau	
	Averaged Interpreted Conductivity			
	TC method in mS/m	TEM method in mS/m	TC method in mS/m	TEM method in mS/m
Layer 1	24	33	1.8	2.4
Layer 2	540	480	430	610

At TC sites where measurements were repeated on different days the average difference of the interpreted thickness of the first layer was 24%. At the single TEM site where the measurement was repeated, the difference in the first layer thickness was 20%. All of the repeat measurements were done on the coastal plain.

The four cross sections in figure 2 show the elevation of the land surface and the interpreted position of the saline-freshwater interface. Note that for clarity, the vertical scales are different above and below sea level. In addition to the geophysical data, the north-south cross section includes data from turtle investigators. Between 1994 and 1996, they report that while diving they repeatedly found colder, fresher water entering the ocean at a number of sites with depths up to 20 m below the water surface. The deepest spring is at the base of a large boulder at Cabo Noroeste. No samples were taken and the exact salinity of this water is unknown (Robert Van Dam, written communication 1997).

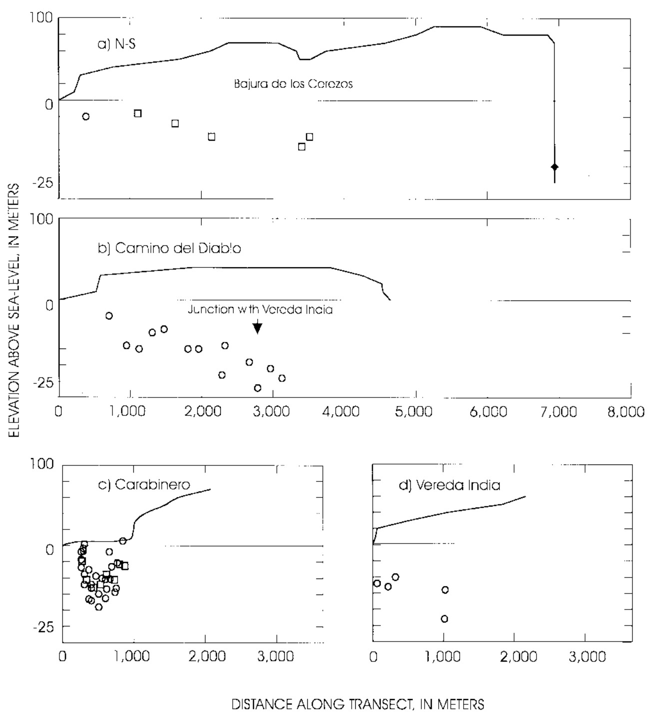

Figure 2. Elevation of the land surface and the interpreted elevation of the saline-freshwater interface at Isla de Mona, Puerto Rico along the transects indicated in figure 1. The four transects are A) North-South, B) Camino del Diablo, C) Carabinero, and D) Vereda India. Circles are terrain conductivity data, squares are transient electromagnetic data and the diamond is diving data. To show the saline-freshwater interface more clearly, the vertical scales are different above and below sea level. Vertical exaggeration of the land surface is 11:1. Vertical exaggeration of the saline-freshwater interface is 44:1.

The Carabinero transect includes both TC and TEM data. The interpreted elevation of the saline-freshwater interface is similar with both methods. The data on the Carabinero transect was collected over 14 months and there is no evidence that the thickness of the freshwater lens changed over this time.

The TC method has less vertical resolution than the TEM method so it is not surprising that the TC data appear noisier than the TEM data. On the plateau, the TC data on the Camino del Diablo are noisier than the TEM data on the north-south line. The speed of operation of the TC makes it practical to reduce noise problems by collecting more data.

The freshwater lens is thickest under the Camino del Diablo in the southeastern section of the plateau. The last six TC readings ranged from -14 to -27 m msl with an average of -21 m msl. By comparison the two TEM data points taken in Bajura de los Cerezos, which is at the center of the island, are -11 and -14 m msl. The elevation of the submarine spring at Cabo Noroeste is -20 m msl, a lower elevation than the elevations for a majority of the geophysical data.

DISCUSSION

In Table 1, the lower electrical conductivity of the first layer is probably due to the change in the ratio between the thickness of the unsaturated and saturated zones. In the center of the coastal plain the typical depth to saline water is about 15 m, of which about 5 m is unsaturated and about 10 m is saturated with freshwater. On the plateau the typical depths are about 50 m to saline water, of which about 40 m is unsaturated and about 10 m is saturated with freshwater. These estimates of the thicknesses of the unsaturated and freshwater saturated zones assume that the Ghyben-Herzberg principle applies.

In the absence of clay, the quantitative relationship between the electrical conductivity of a formation, the electrical conductivity of the pore fluid, and the porosity of the formation is given by the following equation:

$$c_f = c_w p^m$$

where c_f is the electrical conductivity of the formation, c_w is the electrical conductivity of the pore fluid, p is the porosity, and m is a factor that in unconsolidated material is a function of particle shape. In this study, m is assumed to be equal to two. This is a modified version of Archie's Law (McNeill 1990). Table 1 lists the interpreted electrical conductivities of the second layer of the geoelectric models. The electrical conductivity of the saline water in the lagoon at the northwest end of the coastal plain was measured at 4800 mS/m. If layer 2 is assumed to be saturated with a pore fluid with an electrical conductivity of 4800 mS/m, then the interpreted porosities of the formation ranges from 30-36% with an average of 33%.

The Ghyben-Herzberg principle allows us to infer the shape of the water table from knowledge of the elevation of the saline-freshwater interface. On the southern and western parts of the island, the elevation of the water table of Isla de Mona is less than 1 m.

Assuming that there is an inverse relation between the elevations of the saline-freshwater interface and the water table when the saline-freshwater interface is at lower elevation, the water table must be at higher elevation in the same location. A minimum in the saline-freshwater elevation is a maximum in the water table, which is a ground-water divide. The geophysical data in this paper define three ground-water divides on Isla de Mona. They are the coastal plain, the northern half of the island between Bajura de los Cerezos and Cabo Noroeste, and the eastern half of the Camino del Diablo.

The divide on the coastal plain is documented on both sides with both TC and TEM data. From the center of the coastal plain, flow is radially outward with some flow paths that flow towards the plateau and then parallel to the coastline for a considerable distance before the water enters the ocean (Fig. 2c).

At the submarine spring at Cabo Noroeste, there is northward flowing water 20 m below sea level. The salinity of this water is unknown and the spring may be discharging from the transition zone. At the Bajura de los Cerezos, the elevation of the saline-freshwater interface is no more than -14 m msl, the groundwater cannot flow towards a spring at deeper depth and must flow in the other direction, probably to the south or west (Fig. 2a).

On the Camino del Diablo, we have no information about the eastern limb of the saline-freshwater interface (Fig. 2b). The data from the Camino del Diablo and Vereda India indicate flow to the south or west. It is not logical to assume that this continues to the eastern shore of the island. At some point it must have an easterly component but exactly where cannot be determined. The saline-freshwater interface is not symmetrical and the divide is much closer to the eastern than the western side of the island. There are not enough data to determine if the northern divide is continuous with the eastern divide or not.

The shape of the freshwater lens is neither symmetrical nor a smoothed version of the coastline (Fig. 3). This indicates that the distribution of the ratio of recharge to hydraulic conductivity is not homogenous. Long-term rainfall data from Isla de Mona are available from only one location and it is not known if rainfall differs significantly across the island (Jordan 1973). The plateau has only broad, shallow relief, and it is not known if the plateau generates an orographic effect.

Using groundwater models, Vacher (1988) shows that the shape of a hypothetical freshwater lens is more sensitive to realistic changes in hydraulic conductivity than to recharge. Large changes in hydraulic conductivity are more likely than large changes in recharge. In a karst environment, it is reasonable for hydraulic conductivity to vary over several orders of magnitude. The hydraulic conductivity of the carbonate rocks on Bermuda varies over four orders of magnitude (Vacher 1989). The zones of high hydraulic conductivity that are acting as drains to the aquifer could be large cave systems or they could consist of small but well connected tubes or fractures.

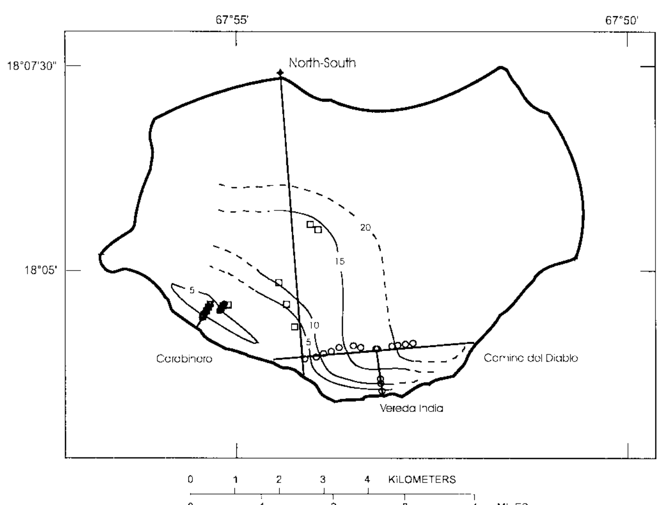

Figure 3. Elevation of the saline-freshwater interface as interpreted from geophysical and diving data, dashed where approximate, Isla de Mona, Puerto Rico. Elevations are in meters below mean sea level. Interval between contour lines is 5 m. The 5 m contour on the coastal plain is drawn based on more data than are shown here. Circles are terrain conductivity data, squares are transient electromagnetic, and the diamond is diving data.

At the contact between the plateau and the coastal plain, the direction of the ground-water flow from the plateau changes and groundwater diverts around the coastal plain. Somewhere in the area of the contact between the coastal plain and the plateau there must be an area of relatively high hydraulic conductivity that drains water from the center of the island and diverts it around the coastal plain. Three possible causes for this drainage pattern include; (1) there could be a flank margin cave along the contact; or (2) the younger rocks of the coastal plain could have lower hydraulic conductivity; or (3) there could be structural reasons that cause hydraulic conductivity to be anisotropic and higher to the northwest and southeast than to the southwest. Some evidence supports all three of these hypotheses. A small, presumably flank margin, cave was found by at the contact between the plateau and the coastal plain while the authors were collecting geophysical data. The cave did not appear to reach the water table but it was not fully explored due to a lack of time. In the Bahamas and Bermuda, the increase in hydraulic conductivity with age has been documented (Vacher 1989). The last possibility is supported by a number of structural features that run from northwest to southeast; the contact between the coastal plain and the plateau, the Bajura de los Cerezos, and numerous pits on the trail to the Bajura de los Cerezos show elongation in a northwest-southeast direction (Frank *et al*. 1998).

The flow of groundwater on the plateau is to the south and west. The dip of the rocks is also to the southwest and this may be influencing the direction of flow. The spring at Cabo Noroeste is near a mapped fault (Briggs & Seiders 1972), and there may be a zone of high hydraulic conductivity along the fault.

CONCLUSIONS

TC and TEM geophysical methods were used to map the shape of the saline-freshwater interface on Isla de Mona. Data from scuba divers provide information from a part of the aquifer that was not studied by surface geophysics. Interpretation of the surface geophysical data gives a conceptual model of the freshwater lens of Isla de Mona. By establishing probable flow paths and depths to saline water, the model developed gives insights that can guide other data-collection activities. The surface geophysical data indicate that the maximum thickness of the freshwater lens is 20 m on the eastern edge of the plateau. In the center of the island the freshwater lens is no more than 14 m thick and 10 m thick on the coastal plain. Divers found water of unknown salinity discharging into the ocean at -20 m msl on the northern half of the island where it was impossible to collect geophysical data.

The asymmetrical shape of the freshwater lens indicates that hydraulic conductivity is heterogenous. Groundwater tends to flow around the coastal plain. There probably is a contrast in hydraulic conductivity between the relatively low coastal plain and the higher conductivity under the plateau. The exact form of this contrast cannot be determined.

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