PROCEEDINGS OF THE 10TH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

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Front Cover: The reef crest indicator species, *Acropora palmata*, on Gaulin's Reef, San Salvador Island. Gaulin's Reef is a classic bank-barrier reef that has shown remarkable resilience following two significant disturbances: El Niño-induced warming of the sea surface in 1998 and Hurricane Floyd in September, 1999 (see Peckol et al., this volume). Photo by Janet Lauroesch.

Back Cover: The oolite shoals of Joulter's Cay, north of Andros Island, Bahamas, site of the pre-meeting field trip. Photo by Ben Greenstein.

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A RESISTIVITY STUDY OF THE FRESHWATER LENS PROFILE ACROSS NORTH ANDROS ISLAND, BAHAMAS

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ABSTRACT

Fresh ground water lenses in the Bahamas may be mapped using electrical resistivity surveys because of the large resistivity contrast between fresh water and salt water saturated carbonate rock. On northern Andros Island, Bahamas, numerous studies have been completed in an effort to understand the thickness and continuity of the freshwater lens from Conch Sound through Red Bays and onto the western tidal flat. These studies used electrical resistivity to determine the depth profile of the freshwater lens and the impact of well fields on this lens. The surveys utilized a variety of resistivity meters with the Schlumberger electrode configuration. The resistivity surveys were analyzed using two modeling programs, RESIX^{PLUS} and ATO. These programs allow the investigator to model the data as a 3- or 4-layer model to best represent the geology. The thickness of the freshwater lens across North Andros varies from 3 to 20 m. The thickness of the freshwater lens in the well fields ranges from 6 to 18 m, with an average of 13 m. The resistivity of the freshwater lens decreases across the island from the east to the west, indicating a more saline ground water influence. The lens across the island is continuous and may have a moderate sensitivity to subtle changes in topography. Field tests and numerical modeling show that electrical resistivity surveys performed parallel to a trench well and at least 2 m away, produce accurate measurements of the freshwater lens thickness.

INTRODUCTION

For the past eight years, students and faculty at Wright State University have been investigating the geology, hydrology, geochemistry and geophysical nature of the freshwater lens on North Andros Island. These studies have generated a clearer picture of lens development and continuity across the island. This paper presents the geophysical data gathered and gives a profile of the "health" of the North Andros aquifer. Several electrical resistivity surveys in the northern portion of Andros Island were completed between 1992 and 1999 by Cowles (1993), Wolfe (1994), Hodl (1997), Jacob (1997), and Reinker-Wilt (1998). These authors have shown that this geophysical method works well for the study area.

In the Bahamas, the majority of the fresh water resources occur as fresh ground water lenses that float on top of the denser salt water (Cant and Weech, 1986). Andros Island, the largest island on the Bahamian Platform, receives approximately 120 cm of

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rainfall per year allowing the island to develop a thick freshwater lens (Cant and Weech, 1986; Bukowski, 1999). Andros Island is sparsely populated, and the aquifer supplies the needs of the inhabitants and is used as a freshwater resource for the more populated New Providence Island and its capital city, Nassau. Pumping of Andros water for shipment to New Providence Island by the Bahamian Water and Sewerage Corporation began in 1977 and continues today. The production of large quantities of water for export raises concern for the long-term sustainability of the resource.

Data from pumping centers maintained by the Bahamian Water and Sewerage Corporation indicate that annual yields may be exceeding design capacity (Lloyd, 1991). By comparing previous data prepared by the Bahamian Water and Sewerage Corporation in 1970 with the data that were collected during this project it should be possible to record the changes in the thickness of the freshwater lens caused by the pumping of the trench wells.

ANDROS ISLAND GEOLOGY

Andros Island lies 40 km west of the island of New Providence, where Nassau, the capital city, is located (Figure 1). Andros Island is on the windward (eastern) edge of the north-central region of the Great Bahama Bank which is bounded by the Tongue of the Ocean on the east and on the west by the Florida Straits (Shinn et al., 1969; Shinn et al., 1989). It is separated from the Little Bahama Bank by Northwest Providence Channel to the north (Bathurst, 1975). Most of the island is less than 5 meters above sea level (Sealey, 1985). Along arcuate Pleistocene eolian dune ridges, that are predominantly north-south and oriented parallel to the shoreline, elevations can reach up to 30 m (Bathurst, 1975).

The lithology of Andros Island consists solely of carbonate rocks. The Lucayan Formation (Late Pliocene-Pleistocene limestone) is the main aquifer in the Bahamas (Beach and Ginsburg, 1980; Cant and Weech, 1986). On North Andros Island the Lucayan has an average thickness of 43 meters and is a dull yellow to buff, non-skeletal limestone (Beach and Ginsburg, 1980). A paleosol occurs at the surface of North Andros below which the rocks are dominated by Pleistocene oolitic, peloidal and bioclastic grainstones and packstones (Carney and Boardman, 1991; Boardman et al., 1995). Using Joulters Cays as a modern analog, Carney and Boardman (1991) interpreted the Lucayan limestone of Andros as a Pleistocene ooid shoal complex with associated reefs, lagoons, eolian dune deposits, stabilized sand flats, and island deposits.

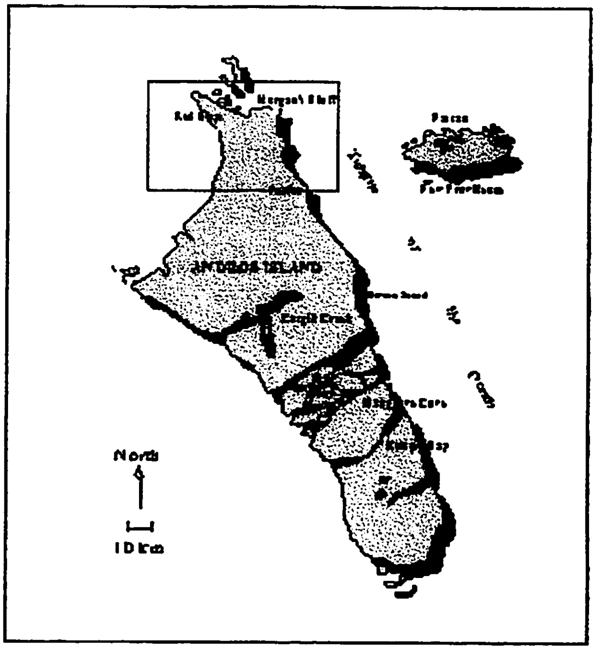


Figure 1. Map of Andros Island with the study area outlined

Discontinuity surfaces interpreted as horizons of subaerial exposure are common throughout the formation. In the subsurface of North Andros, paleosols are found at depths of 2 to 4 m, 7 m, and 12 m (Boardman and Carney, 1997).

ANDROS ISLAND HYDROLOGY

Andros Island is in a semi-humid climatic zone receiving an average of 120 cm of rainfall annually with precipitation occurring seasonally (Cant and Weech, 1986; Tarbox, 1987; Vacher and Wallis, 1992). The fresh ground water occurs as an extensive lens, which is recharged by rainfall and is bounded at the base and laterally by saltwater. The freshwater lens is present because discharge of fresh water to the sea does not exceed recharge from precipitation (Bukowski, 1999). Theoretically the thickest part of the lens should be in the center of the island (Little et al., 1973; Lloyd, 1991). The Ghyben-Herzberg theory states that the thickness of the freshwater lens is directly proportional to the elevation of the water table above sea level (Fetter, 1994). On Andros the depth of the freshwater below sea level is approximately 10 times the head above sea level, rather than the 40 times of the typical Ghyben-Herzberg theoretical lens (Bukowski, 1999). The depth to the water table in the study area is 1 to 2 m below the ground surface, this is approximately 1 m above present sea level (Cowles, 1993; Wolfe, 1994; Jacob, 1997). The flow of water is from the thickest portion of the lens, which is toward the center of the island, outward toward the shore (Bukowski, 1999).

There are three main well fields, each consisting of a large number of trench wells, producing millions of gallons of fresh water every day for shipment to Nassau (Cowles, 1993; Bukowski, 1999). The Water and Sewerage Corporation produced a preliminary isopach map of the fresh water lens on North Andros based on boreholes and limited resistivity data gathered in 1973. An updated isopach map of the fresh water lens was also generated incorporating more resistivity data gathered during 1988 and 1989 (Figure 2). The 1973 map shows two distinctive thick areas approximately in the same areas as the three well fields. By 1989 the lens had apparently thinned and consisted of one centrally located area.

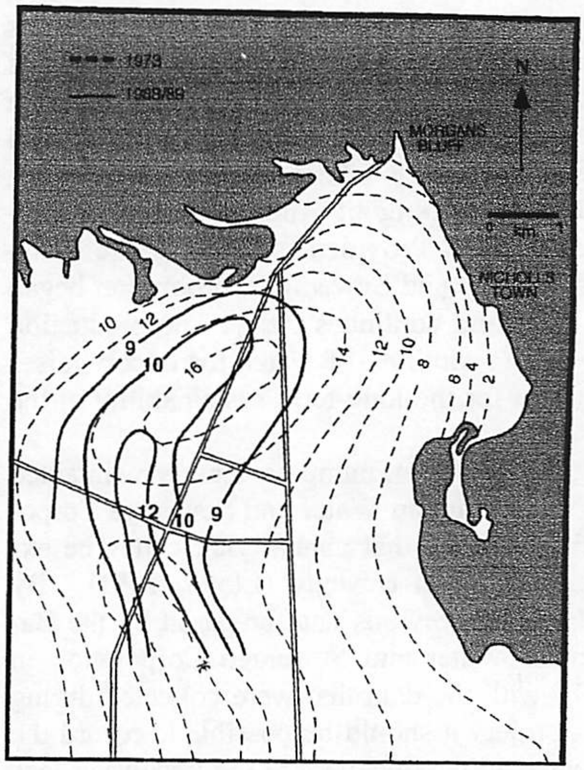


Figure 2. Isopach map of the freshwater lens on northern Andros Island in 1973 and 1988/89.

The well fields on North Andros are 305 m long inter-connected trenches approximately 1 m wide and 2 m deep. The trenches consist of four radial arms connected to a central cruciform that is connected to other cruciforms by culverts (Figure 3). The water flows to a central pump by gravity through these trenches; the pump then removes the water to a reservoir and holding tanks at Morgan's Bluff.

PREVIOUS WORK

Resistivity methods involve passing an electrical current between points on the earth's surface and, at two other points, measuring the electrical potential difference produced by that current flow through the earth. From this, an

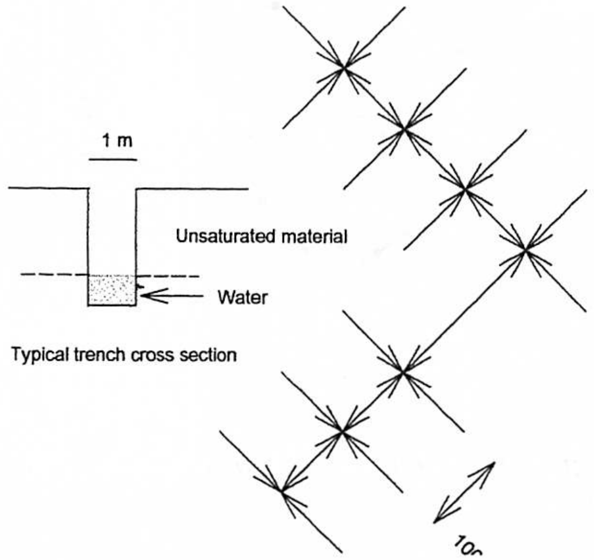
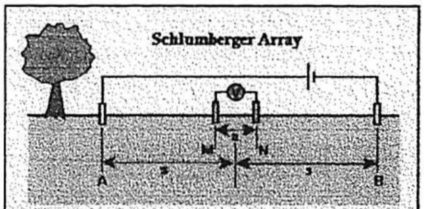


Figure 3. Schematic representation of a trench well field with an insert showing the trench cross section.

apparent resistivity value can be calculated (Burger, 1992). As the distance between the current electrodes is increased, the depth that the current penetrates into the subsurface is increased. A sequence of measurements with expanding electrode spacing around a common center point is called a vertical electric sounding (VES). The resistivity of the earth materials is very dependent on the pore fluid. Saltwater saturated rock has a significantly lower resistivity than freshwater saturated rock. Measuring the apparent resistivity as a function of electrode spacing allows calculation of the depth to the interface between fresh and salt water.

Cowles (1993) completed 13 resistivity soundings along a 2.1-km profile along Charlie's Blue Hole Road. This east-west road intersects Queen's Highway and is located on the eastern side of North Andros Island. The soundings were completed using a Schlumberger electrode configuration (Figure 4) and a Johnson IC-69 resistivity meter. His modeling with the computer program RESIX^{PLUS} produced 3 and 4 layer models. As a three layer model the subsurface consists of an unsaturated zone, freshwater lens, and saltwater. The four-layer model takes into account a brackish mixing zone between the freshwater and saltwater zones. His 3 layer models indicated the freshwater lens varied in thickness from 9.2 m to 14 m. A thinning of the lens occurs in the area of Charlie's Blue Hole. His 4 layer models indicated the freshwater lens varied in thickness from 7.5 m to 11.2 m. The mixing zone varied from 8.6 m to 13.8 m thick.



$$\rho_a = \frac{\pi(s^2 - a^2/4)}{a}\frac{\Delta V}{i}$$

Figure 4. Resistivity schematic and apparent resistivity formula.

Extending Cowles' 1993 research, Wolfe (1994) conducted three series of resistivity soundings along perpendicular transects to Charlie's Blue Hole Road using the Schlumberger electrode configuration and a Terrameter SAS-300C resistivity meter. Wolfe used two modeling programs, RESIX-^{PLUS} and ATO. His 3 layer models produced a freshwater lens thicknes ranging from 2 m to 19 m. His 4 layer models produced a freshwater lens thickness ranging from 1 m to 13.4 m, with a mixing zone thickness of between 1 m and 11 m.

Hodl (1997) conducted a resistivity survey that included 8 stations along Red Bays Road in the northwestern portion of Andros Island. She utilized the Schlumberger electrode configuration and collected the data with a Sting R1 resistivity meter. She processed the data using the RESIX^{PLUS} computer software, and her best-fit models indicated a fresh water lens that ranged from 9 m to 30 m thick. The mixing zone ranged from 4 m to 9.7 m thick.

Jacob (1997) performed three azimuthal resistivity surveys, as well as obtaining VES data from four locations on North Andros. The three azimuthal survey sites were located on Charlie's Blue Hole Road, Main Lumber Road, and on the east side of Queen's Highway south of Red Bays Road junction. She collected the data with a Sting R1 resistivity meter employing the Schlumberger electrode configuration for the VES surveys and the Wenner electrode array (Burger, 1992) for the azimuthal resistivity surveys. Azimuthal resistivity surveys investigate the horizontal anisotropy in resistivity in order to determine the fracture orientation in the subsurface, or other preferred ground water flow paths. The azimuthal surveys were performed by rotating the electrode array about a fixed point at increments of 15°. Figure 5 is a rose diagram for a typical survey. The Paradox of Anisotropy (Keller and Frischneckt, 1966) tells that the orientation of the major axis of the apparent resistivity ellipse is the fracture orientation. Jacob (1997) showed that a fracture system oriented approximately N60E dominates the subsurface in the Charlie's Blue Hole area. The results for soundings made at the anisotropy test sites are included in our final interpretation.

Reinker-Wilt (1998) took 14 resistivity soundings located approximately 2 km north of Red Bays Road and included some of Hodl's (1997) stations. She utilized the Schlumberger electrode configuration and collected data with a Johnson IC-69 resistivity

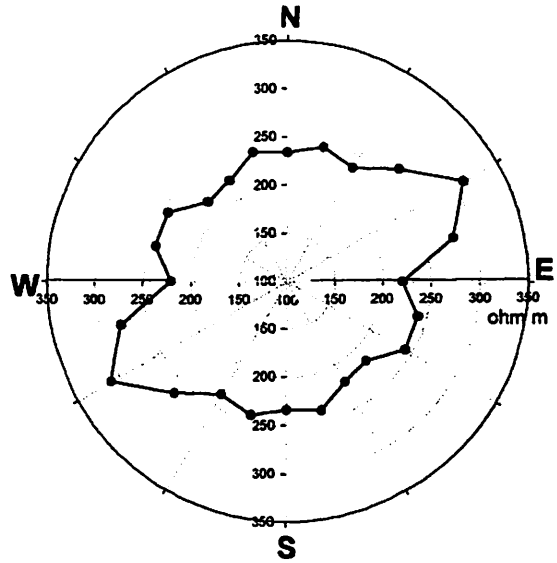


Figure 5. Polar plot of apparent resistivity azimuth

meter. The data were processed using the RESIX^{PLUS} computer software, and generated a 3-layer model of a fresh water lens that was between 3.4 m to 18.8 m thick. The 4 layer models indicated a fresh water lens thickness that ranges from 3.4 m to 17 m. The mixing zone thickness ranged from 1 m to 7 m. dependence for a 10 m Wenner array.

In 1999 thirty-one resistivity soundings were completed by one of the authors (A. Adams) using the Schlumberger electrode configuration and a Sting R1 resistivity meter. Seventeen resistivity soundings were completed within the Bahamian Water and Sewerage Corporation's well fields. Eleven resistivity soundings provided additional information regarding a potentially anomalous area north of Red Bays road that was encountered by Reinker-Wilt in her 1998 investigation. Three resistivity soundings aided in defining the depth and extent of the freshwater lens into the western tidal flats. The data were processed using the RESIX^{PLUS} computer software, and generated a 3 layer model of a fresh water lens that ranged from 10 to 19 m thick in the well fields, and from 3 to 21 m for the rest of the study area (Red Bays and the western tidal flat). A summary may of surveys between 1992-1999 is presented below.

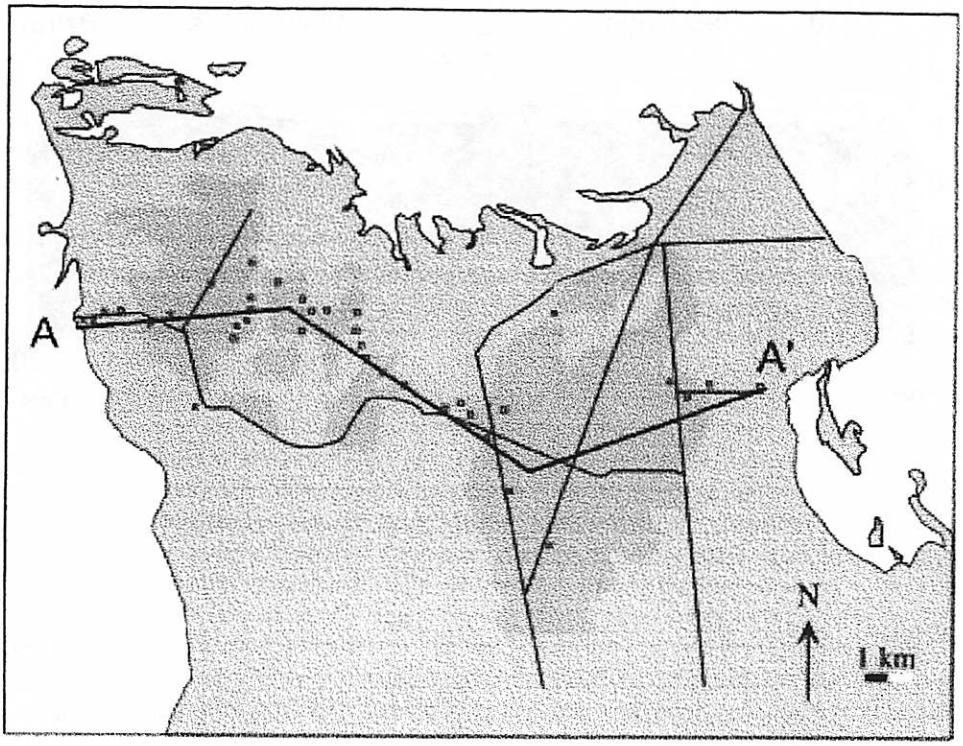


Figure 6. North Andros Island with Profile A-A'. Squares indicate resistivity soundings

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One of the critical areas for determining the depth to the saltwater interface is in the well fields. Access in the well fields is limited to strips along the trenches. Since the trenches cut 2 meters into the rock, the assumption of We used a 2.5D finite-element modeling program (Zhou, 1998; Wolfe, 1999) to calculate the effect of the trench. We also performed field measurements collecting sounding curves parallel to a trench at distances ranging from 0.5 to 2 mhorizontal layering that is used in resistivity interpretation is violated near the trenches. Two approaches were used to determine the effect on calculated depths of a nearby trench.

RESULTS

Fresh ground water occurs everywhere in the study area. A compilation of the resistivity data from 1992 to 1999 was used to generate the cross-island cross section shown in Figure 7. The modeled depth from the surface to the top of the freshwater lens has a mean of 2.5 m. The depth to the top of the saltwater zone ranges from 6.6 m to 24 m with a mean of 14.5 m. The thickness of the freshwater lens ranges from 3.8 m to 21 m with a mean of 12.1 m. Resistivity in the fresh water lens ranged from 9.6 Ωm to 1530 Ωm with high spikes to 2300 Ωm and 2700 Ωm (Figure 8).

The finite-element modeling and data collected in the area of the well fields show that the effect of the Andros trench wells decreases rapidly with distance from the trench (Figure 9). A sounding parallel to the trench well is practical when offsets of the electrode line are greater than one meter (Figure 10). A shallow layer of water in the trench wells can be ignored. Thus, model results from data meeting this criterion were included in the cross section.

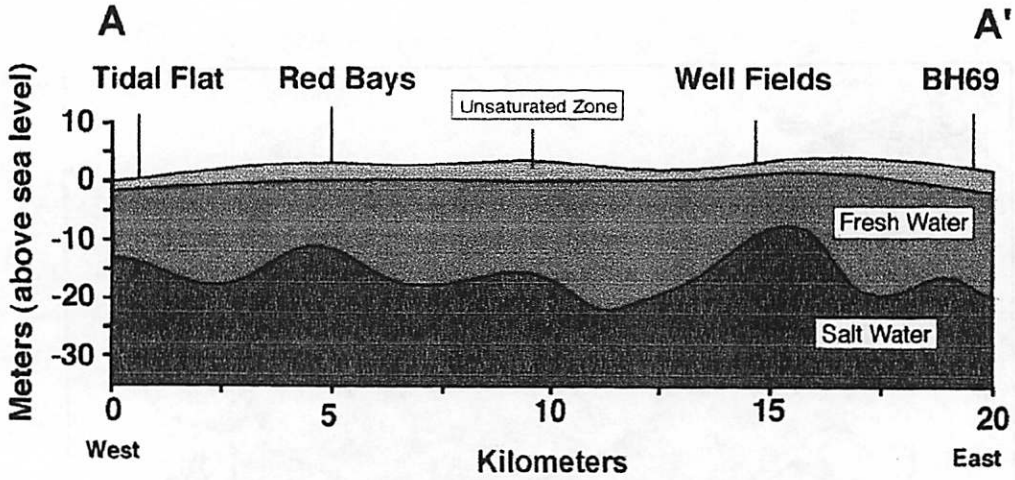

Figure 7. Island water profile A-A' from resistivity

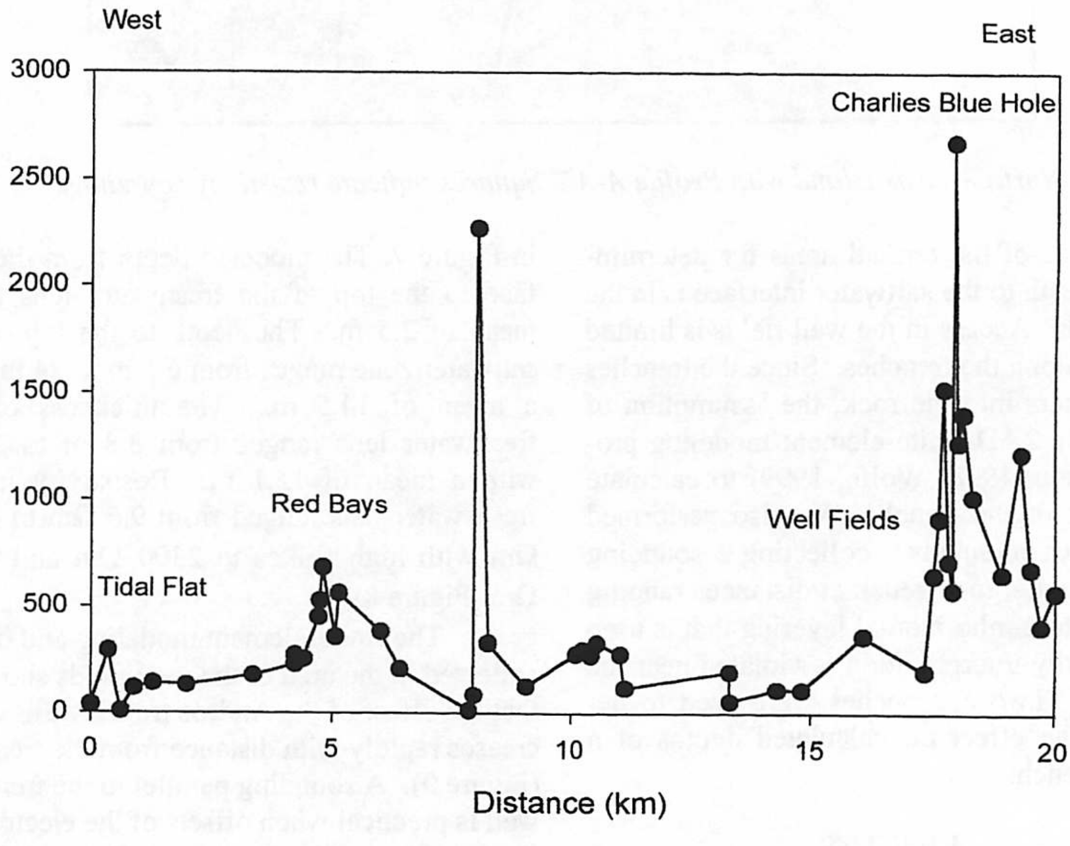

Figure 8. Resistivity of the fresh water lens.

The cross section shows three areas of thinning: within the Bahamian Water and Sewerage Corporation's well fields; at Red Bays, near a well field that is utilized by the town; and at Charlie's Blue Hole, a karst solution feature. The cross section also shows that the lens is continuous across the island, even in areas of low topography. It also shows that the freshwater lens thins towards the west coast.

North Andros Island has a well-developed freshwater lens, which is exploited by a series of trench wells. Because of the possibility that fresh water in the aquifer is currently being depleted it is necessary to monitor the rate of saltwater incursion in order to prevent saltwater contamination of the freshwater aquifer.

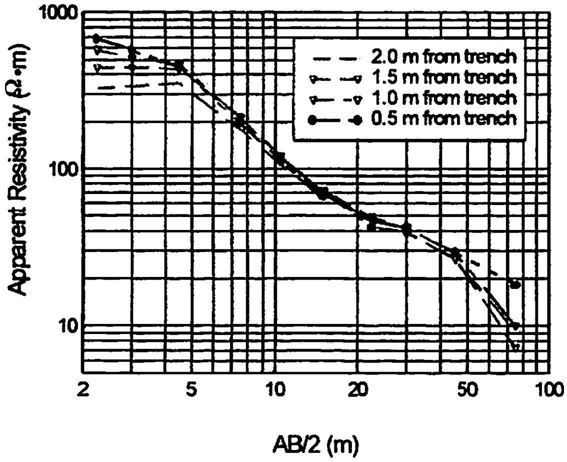

Figure 9. Schlumberger sounding curves from finite-element modeling for a 15 m deep saltwater interface with a range of electrode offsets from the trench.

A sounding parallel to the trench well is practical when offsets of the electrode line are greater than one meter. Trench wells of the depth seen on Andros do not violate the utility of the horizontal layer assumption of the data as distance from the trench approaches 2 m.

Three-layer modeling indicates a continuous freshwater lens that varies in thickness from 3.8 m to 21 m within the study area. In the well fields the freshwater lens thickness ranges from 6 to 12 m indicating a lens that is slightly thinner than the Bahamian Water and Sewerage Corporations isopach maps indicate. The three-layer model incorporates the mixing zone into the lens thickness and therefore may be a slight overestimate of the freshwater lens thickness, on the order of 1 to 3 meters. The average trend of the thickness of the aquifer decreases across Andros by 1.25 m from east to west.

The freshwater lens is thinned in the well fields due to pumping, as well as in the Charlie's Blue Hole area due to evaporation. In 1973, the freshwater lens was between 15 and 10 m thick. In 1988/89, the freshwater lens was between 12 and 9 m thick. In 1999 the freshwater lens was between 12 and 6 m. thick.

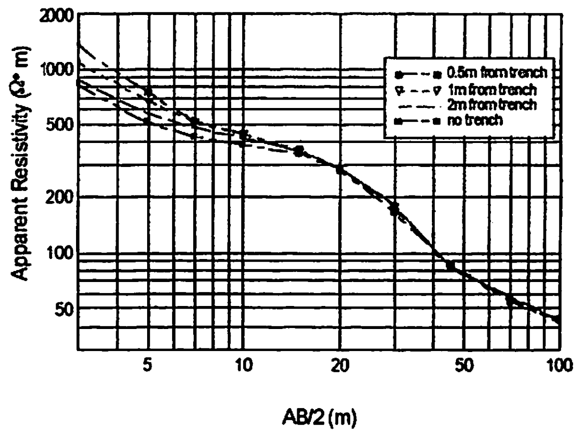

Figure 10. Measured Schlumberger sounding curves for a range of electrode offsets from the trench.

Apparently, pumping is causing a thinning of the lens but only at a rate of a few meters per decade.

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