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ELECTRICAL RESISTIVITY SURVEY OF FRESHWATER LENS IN WELL FIELD NORTH OF COCKBURN TOWN, SAN SALVADOR, BAHAMAS

Gayla D. Gross and A. W. Gerhard Kunze
Department of Geology
University of Akron
Akron, Ohio 44325

ABSTRACT

The distribution of fresh groundwater lenses in the well field north of Cockburn Town, San Salvador, was investigated using surface electrical resistivity measurements utilizing the Schlumberger electrode array in conjunction with static water level and salinity/conductivity measurements from twenty-two test and production water wells. Seventeen of the tested wells contained fresh water, the remaining four were brackish (with salinity over 1,500 ppm). Tidal and other fluctuations of 0.3 to 0.6 m were observed in several of the wells.

The data from fifteen vertical electrical sounding (VES) stations were inverted digitally using two different computer programs: the interactive modelling program RESIX by Interpex (1988) and the USGS inversion program ("INVERSE") by Zohdy (1974). Both programs indicate that fresh ground water is present throughout the study area except at two stations north of the airstrip, where brackish conditions are known to prevail. Average freshwater lens thicknesses indicated are on the order of 6 m, with the maximum thickness exceeding 10 m. Comparison of computed model resistivities with measured well water resistivities indicates aquifer porosities ranging from 13% to 56% and averaging approximately 22%. An attempt to compare modelled water table elevations with actual water table elevations was unsuccessful because the static water level measurements in wells were seriously degraded by tidal and other effects. Models analyzed in the traditional method yielded comparable results when the measured station elevations were used, however, this method misidentified some brackish ground water as fresh. Therefore, we conclude that the VES method provides a valuable qualitative, but not quantitative, exploration tool.

INTRODUCTION

Limited fresh groundwater supplies exist on many oceanic islands, and the small Bahamian island of San Salvador is no exception. Recently, exploratory drilling for a new fresh groundwater supply was initiated by the Bahamian government in order to expand the Cockburn Town water supply system. Sixteen test wells were completed in the vicinity of the Cockburn Town well field to identify potential sources of fresh ground water.

An electrical resistivity sounding survey was conducted in the well field area. The purpose of the investigation was two-fold: (1) to determine the extent and thickness of the fresh groundwater lens; (2) to improve and evaluate the accuracy of the resultant resistivity models by incorporating measured hydrogeologic parameters such as the static water level, and groundwater salinity and resistivity.

Ghyben-Herzberg Lens

On oceanic islands, fresh ground water ideally occurs as a Ghyben-Herzberg lens such that fresh ground water overlies saline ground water according to the relationship:

$$z = h_F \frac{d_F}{d_S - d_F} \qquad (1)$$

where $\underline{z}$ is the depth to the fresh-saline water interface below sea level, $\underline{h}_F$ is the elevation of the water table above sea level, and $\underline{d}_S$ and $\underline{d}_F$ are the densities of saline and fresh water, respectively.

The Ghyben-Herzberg relation requires that the two waters remain immiscible and static (Kohout, 1959). However, the interface between saline and fresh ground water is usually not a sharp static boundary, but a dynamic brackish transitional zone created by the dispersion of salt ions into the freshwater environment due to the reciprocative tidal motion of the salt water front (Cooper, 1959).

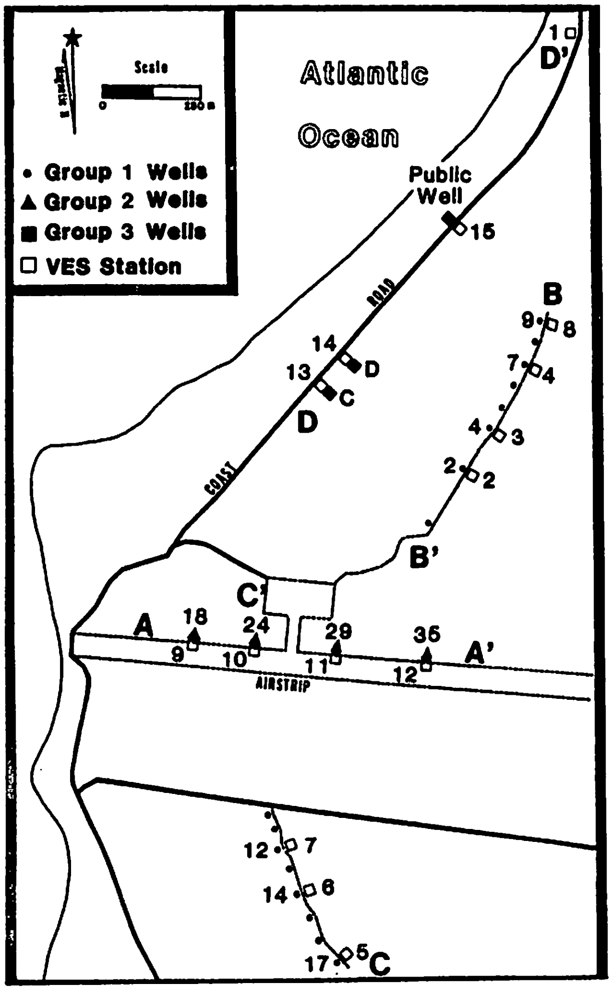

Fig. 1. Water well and VES station location map Letts indicate selected corss-sections.

Subterranean solution cavities enhance transition zone development by quickly transmitting ocean water directly into the aquifer, where it intermixes with and reduces the vertical extent of the freshwater lens (Cant and Weech, 1986). The thickness of the transition zone is proportional to the amount of mixing of the two waters; in general, thickness should decrease inland as the tidal wave is attenuated.

In addition, several other factors affect the thickness of the fresh groundwater lens on San Salvador. Cant and Weech (1986) report that the southeastern Bahamian islands receive less than 900 mm precipitation per year. According to Sealey (1985), San Salvador averages 1,000 to 1,250 mm in precipitation annually. As a result of these low rates, net groundwater loss due to evapotranspiration is significant and disconnected thin, fresh, or brackish groundwater lenses are common in the southeastern Bahamas and on San Salvador.

The subsurface of San Salvador is inhomogeneous and contains paleosols or micritic layers that act as aquitards. Such aquitards commonly occur at the bottom of freshwater lenses and protect them from saltwater encroachment (Persons, 1975; Little and others, 1977). In such situations, the water table is semi-perched and does not obey the Ghyben-Herzberg relationship.

PROCEDURES

Most of the field work was conducted between December 30, 1988, and January 5, 1989. Levelling surveys using a surveyor's transit and stadia rod were conducted in July 1989 and June 1990, providing elevations for benchmark VAD 6.7 and twenty-two of the wells (the public well and station 1 were not surveyed).

The resistivity field equipment consisted of a University of Akron custom-built power unit with built-in ammeter, a Soiltest R-65 voltmeter, copper current and porous pot potential electrodes, and peripherals. The survey utilized the Schlumberger electrode configuration in an expanding array with current electrode half-spacing intervals (L) ranging from 0.7 m to 142 m at 6 points per logarithmic decade. The resulting vertical electrical sounding data from 15 VES stations located beside selected test wells and public-water supply wells (Fig. 1) were inverted digitally using two different computer programs: the interactive personal computer program RESIX (Interpex, 1988), and a USGS program by Zohdy (1974), here dubbed "Inverse".

The well monitoring equipment consisted of a YSI Model 33 salinity-conductivity-temperature (S-C-T) meter and probe, a custom-built electric tape measurer, and a custom-built well water-level fluctuation recorder. Twenty-two wells were measured for salinity, conductivity, temperature, and water level (WL). A total of seven wells were monitored for WL fluctuations. The wells were divided into three groupings

(Fig. 1). Group 1, wells 1 through 17, consists of sixteen recently-completed uncased, 10 cm diameter test wells (well 3 was dry and abandoned). Group 2 consists of four partially cased, 20 cm diameter production wells that are part of the current water supply system (wells 18, 24, 29, and 35). Group 3 consists of three large dug wells that are not currently being used as water supplies (wells C, D, and the public well).

In the evaluation process, the models generated by each program were compared to their corresponding water well information. Ideally, each model should have four distinct resistivity layers indicative of the vadose, freshwater-saturated, transition, and the saltwater-saturated zones. Surficial material (such as sand or asphalt), paleosols, micritic layers, and karst horizons may contribute additional resistivity layers.

For shale-free rock formations, the measured resistivity is due almost entirely to conductive interstitial pore water (Schlumberger, 1987). Hence, the formation resistivity (R_O) in the phreatic zone is related to the pore water resistivity (R_W):

$$R_O = F \bullet R_W \qquad (2)$$

where F is the formation resistivity factor for a particular geologic material. For well-cemented carbonates, F is related to porosity (p) according to the basic Archie formula:

$$F = 1/p^2 \qquad (3)$$

This relationship was found to be approximately true for San Salvador carbonates with porosities between 20 and 32% (Weir and Kunze, 1988).

For modelling and interpretation purposes, the following R_W values and specific salinity ranges were used: fresh water was taken as having less than 1,500 ppm salinity (the World Health Organization drinking water standard); brackish water as 1,500 to 33,000 ppm salinity, and salt water as having salinity greater than 33,000 ppm. The corresponding minimum R_W values at the mean aquifer temperature of 26.6° C are 3.62 Ω-m for fresh ground water, and 0.19 Ω-m for brackish ground water in the transition zone. R_W for saline ground water is 0.19 Ω-m or less.

Each resistivity layer model of every station (except stations 1 and 12) was evaluated in terms of water resistivity R_W measured in the station's adjacent water well. The model resistivity of the freshwater-saturated zone (R_O) tapped by the well and the well water resistivity R_W (inverse of conductivity measured in the well) were used to calculate porosity and F of the saturated zone using equations (2) and (3).

Using this value of F, the thickness of the freshwater-saturated zone was determined by solving for R_O at a minimum R_W of 3.62 Ω-m. The depth where the model values fall below this minimum R_O marks the base of the fresh groundwater lens. Similarly, the base of the transition zone was found by comparing model values to the R_O corresponding to R_W of 0.19 Ω-m.

Finally, the elevation (h_F) of the top of the lens was calculated through the Ghyben-Herzberg relationship using the model depth of the bottom of the fresh groundwater lens, and densities for fresh water and normal sea water (at 26.6° C) of 0.998 g/cc and 1.023 g/cc respectively. These calculations assume porosity to remain constant over the entire thickness of the resistivity column.

Traditional Method of Analysis

For comparison, the data were also analyzed by the traditional method used by Kunze and others (1989) to see if, in the absence of well control, VES models can be relied upon as a tool in groundwater exploration. The traditional method of data interpretation relies exclusively on the VES results and the expected 18-fold resistivity contrast at the freshwater-saltwater interface. Assuming 25% porosity, and maximum salinities of 1,500 ppm (fresh water) and 35,000 ppm (brackish water), the minimum values of R_O are 55 Ω-m (fresh water-saturated) and 3 Ω-m (brackish water-saturated). The freshwater lens thickness was calculated through the Ghyben-Herzberg relationship from the depth of the interface, using measured station elevations and the same water densities as indicated above.

RESULTS

Groundwater Measurements

Because the wells are shallow, their salinity/conductivity profiles showed little or no change with increasing depth (Table 1). In fact, the lowest conductivity reading was almost

Table 1. Water well data, including measured water table and well elevations.

Well	Average Resist.[1] (Ω-m)	Average GW Temp. °C	Average GW Salinity (ppm)	Well Elev. (m)	GW Elev. (m)	GW Density g/cc, 26.6°C
1	15.7	26.0	475	3.51	-0.02	0.9973
2	10.8	25.6	600	5.32	0.17	0.9974
4	2.41	26.3	2,450	4.63	-0.01	0.9987
5	3.29	26.1	1,830	2.54	-0.17	0.9983
6	3.55	26.9	1,640	2.32	0.04	0.9982
7	7.37	26.5	900	2.13	-0.22	0.9977
8	4.69	26.8	1,140	1.93	-0.01	0.9978
9	3.62	26.6	1,760	2.27	0.00	0.9983
10	5.81	27.6	1,000	3.82	-0.02	0.9977
11	6.22	27.0	1,000	2.54	-0.10	0.9977
12	5.65	26.8	1,100	3.29	0.01	0.9978
13	5.96	26.7	1,100	2.99	-0.02	0.9978
14	5.50	26.8	1,130	3.18	0.07	0.9978
15	7.09	26.3	900	3.43	-0.10	0.9977
16	6.22	26.7	900	3.18	-0.13	0.9977
17	5.92	27.7	1,000	3.76	-0.28	0.9977
18	9.12	29.0	700	1.17	-0.34	0.9975
24	19.0	28.9	375	1.18	-0.20	0.9972
29		not measured		1.47	not measured	
35	22.6	28.0	325	2.04	0.00	0.9972
C	19.6	24.2	400	2.16	-0.05	0.9973
D	16.7	24.2	300	2.23	-0.12	0.9972
P.W.	23.4	24.3	150	2.20[2]	-0.15	0.9970
Sta. 1				2.20[2]		
VAD 6.7		___		2.12		

26.6 = Mean Aquifer Temp.

[1] Reciprocal of average of borehole conductivity measurements (without the deepest reading).

[2] These elevations were estimated from the topographic map of San Salvador.

always less than any of the overlying readings due to non-conductive suspended solids concentrated near the bottom of the wells that were disturbed by the probe. Well water salinities (as measured by the YSI-33 meter) ranged from 150 to 2,450 ppm. The highest salinities were measured in wells 4, 5, 6, and 9, which were all brackish. Salinities in wells 10 through 17 averaged around 1,000 ppm. The lowest salinities (150 to 700 ppm) were measured in the wells of groups two and three.

The measured water table elevations were mostly negative with respect to mean sea level: values ranged from +17 to -34 cm. These negative values may be due to tidal oscillations and represent low tidal phases. To investigate this possibility, water-level fluctuations were continuously recorded for 19 to 20 hours in wells 17, 18, and 9 (July 1989), and for 25 to 41 hours in wells 1, 10, 27, and 34 (December 1989 and January 1990). The results of this investigation are reported elsewhere in this volume (Kunze and others, 1991) and show pronounced semidiurnal tidal oscillations with tidal ranges on the order of 50 cm in wells 1, 9, 10, and 18. Irregular water level fluctuations of similar amplitudes, but apparently unrelated to the tides, were recorded in wells 27 and 34. No significant water level changes occurred in well 17. Because no consistent spatial pattern in well tide amplitudes and lag times emerged, because none of the tidal observations fit established hydrologic models, and because the accuracy of some of the water level recordings is suspect, no meaningful tidal corrections could be made to the previously measured well water elevations.

Other factors may play a role in reducing water-level elevations on islands. Sealevel, and with it groundwater levels, may be temporarily lowered by meteorological or anomalous oceanographic conditions. Some water table drawdown may be caused by pumping of nearby production wells. Finally, the possibility of systematic measurement errors cannot be dismissed completely. Unfortunately, none of these factors can be assessed quantitatively for this survey.

VES Results

Table 2. Porosities and elevations (Datum: mean sea level) of the water table, and the bases of the freshwater (FW) lens and transition zone (TZ) as modelled by "Inverse" ("I") and Resix (R).

Station	Adj. Well	% Porosity "I"	% Porosity R	Base of FW Lens (m) "I"	Base of FW Lens (m) R	Base of TZ (m) "I"	Base of TZ (m) R	Groundwater Elev. (m) "I"	Groundwater Elev. (m) R
1	-	48	56	-11.3	-5.91	*	*	0.30	0.15
2	2	20	28	-3.27	-11.2	-27.4	*	0.08	0.30
3	4	15	14	(Brackish)		-15.0	-12.0	0.36	0.29
4	7	19	24	-15.9	-14.0	-31.3	-66.7	0.40	0.36
5	17	25	23	-13.0	-4.25	-83.1	-47.3	0.33	0.11
6	14	15	18	-0.27	-4.70	-42.9	*	0.01	0.12
7	12	14	14	-5.93	-7.75	-21.1	*	0.15	0.20
8	9	13	15	(Brackish)		-21.3	-12.3	0.53	0.31
9	18	31	32	-8.25	-5.17	*	*	0.21	0.13
10	24	20	21	-8.08	-2.93	*	*	0.21	0.08
11	29	20	20	-2.05	-0.89	*	-75.3	0.05	0.02
12	35	17	17	-13.1	-5.71	-25.4	-27.7	0.34	0.15
13	C	25	44	-0.85	-2.35	*	*	0.02	0.06
14	D	13	30	-1.94	-4.40	-9.28	*	0.05	0.11
15	p.w.	43	39	-3.68	-2.07	*	*	0.10	0.05

* Indefinite thickness

Figures 2 and 3 show the VES curves and the resultant models of each station, respectively. Table 2 lists the elevations of the water table and the bases of the freshwater lens and transition zone at each station as modelled by programs "Inverse" and Resix. Both programs yielded realistic models that indicate fresh ground water present everywhere except at stations 3 and 8. Overall, the data correlate well between stations and show a thin and flat fresh-water lens. The Resix and "Inverse" lens models are comparable, thicknesses ranged from 0.3 to 16.2 m ("Inverse") and 0.9 to 14.3 m (Resix). The difference between the Resix and "Inverse" models permits an estimate of the uncertainty in the VES modelling method. The average freshwater lens thickness (from both the Resix and "Inverse" values listed in Table 2) is 6.3 m, and the mean difference between the two models is 3.7 m. Accordingly, the standard error in the modelled freshwater lens thicknesses is estimated to be on the order of ±30%.

A brackish transition zone was indicated at every station. The base of the transition zone was discerned at ten of the stations by one or both programs: its thickness ranged from 7.3 to 70 m ("Inverse") and 22 to 74 m (Resix). The other stations show a transition zone of indefinite thickness.

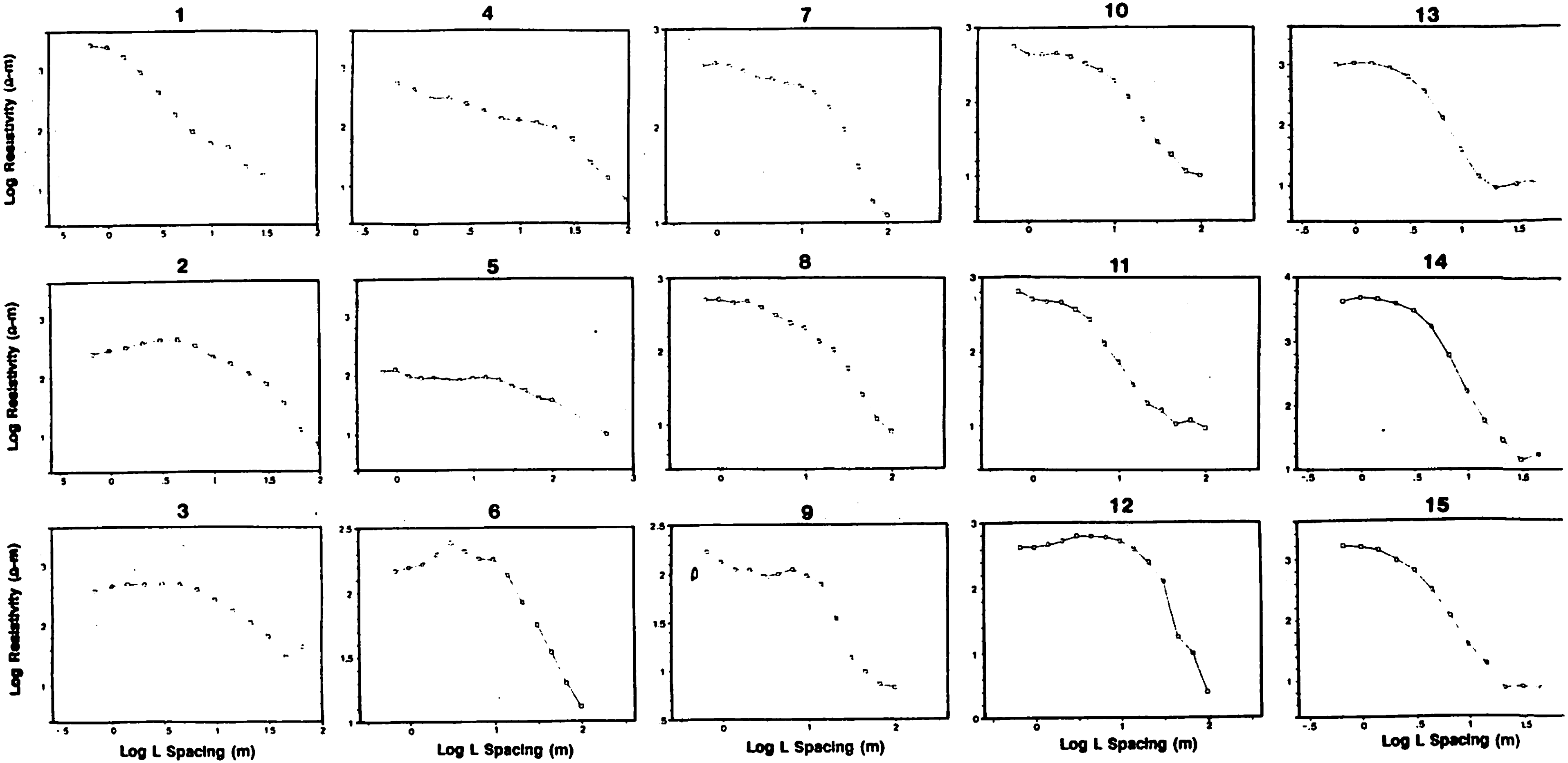

Fig. 2. Corrected VES curves for stations 1 through 15.

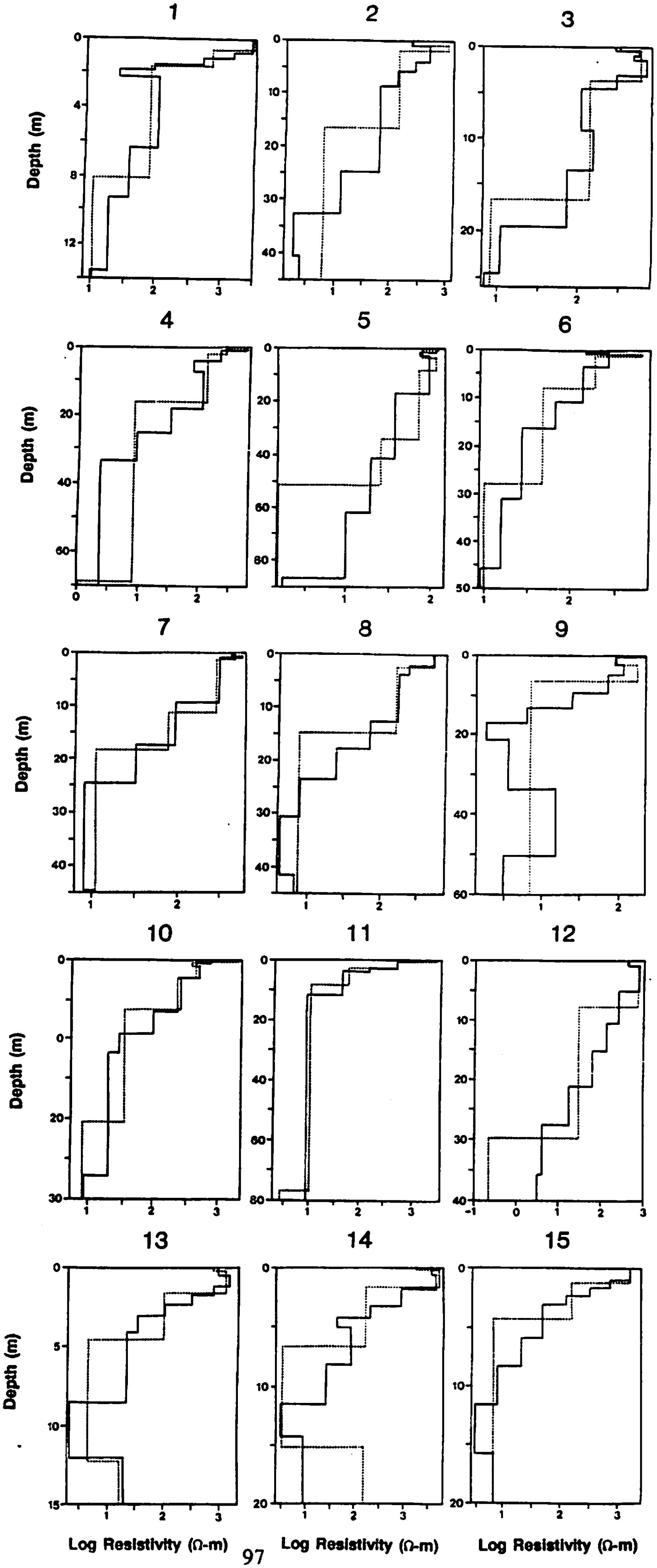

Fig. 3. Computer-generated resistivity models for stations 1 through 15. Dashed line = Resix model; Solid line = "Inverse" model.

Karstic limestones range in porosity from 5 to 50% (Freeze and Cherry, 1979). The porosity values calculated using model R_0 and well R_W were well within this range except for station 1 (Table 2). Porosity at station 1 was calculated to be 48% ("Inverse") and 56% (Resix) using R_W from the public well. Excluding station 1, porosity averaged at 24% (Resix) and 21% ("Inverse"). These values are consistent with previous porosity determinations for San Salvador carbonates (Weir and Kunze, 1988).

Anomalous layers.

No anomalous high resistivity layers were modelled that could be immediately interpreted as a subsurface paleosol layer. Only the "Inverse" model of station 9 showed a high-resistivity layer at depth that might be paleosol. This layer occurred between 33.8 and 50.5 m below the surface, the resistivity contrast was 4.3 times that of the overlying layer. Thin paleosol layers commonly are modelled as thicker, less resistive, layers by VES inversion programs (Kunze and others, 1989).

The resistivity models of stations 13 and 14 (Resix) each contained an anomalous low resistivity interval that is probably indicative of a karst zone. These intervals were at depths between 2.3 and 10.0 m below sealevel at station 13 and 4.4 to 12.8 m below sealevel at station 14. The resistivity contrasts with the overlying layers were 22 and 49 times, respectively. These intervals are interpreted as being of similar high porosity as the overlying freshwater zone, but saturated with brackish ground water and underlain by a lower-porosity layer. If this layer contained normal sea water (35,000 ppm), then the corresponding porosities are calculated as 20% (station 13) and 22% (station 14), and the underlying higher resistivity layers would have porosities of 11% (station 13) and 3% (station 14). Freshwater saturation of this low-resistivity zone is unlikely because this would require unrealistically high porosities.

"Inverse" modelled only station 13 as having an anomalous low-resistivity interval between 0.26 and -0.14 m in elevation, the resistivity contrast was 10 times that of the overlying layer. As in the Resix model, this interval occurs within the transition zone. A thin low-resistivity interval in the vadose zone was modelled by "Inverse" at station 1 at an elevation between 0.30 and -0.10 m. This may only be noise in the VES curve, or it could also be a another low-porosity zone or clay-rich zone. The resistivity contrast was 3.7 times that of the overlying layer.

Shallow, thin layers of extremely high resistivity were modelled at stations 1, 10, 11, 13, 14, and 15. The layers at stations 10 and 11 may represent the airstrip tarmac. Stations 13 and 14 are located just off of the Coast Road on the well access lane. The highly resistive layers at these stations probably reflect surficial sand prevalent in this area. Stations 1 and 15 are located adjacent to the Coast Road. The shallow high-resistivity layers at these stations most likely reflect the asphalt road pavement.

Freshwater lens thickness.

The lens configuration is presented in selected cross-sections (Figures 4 through 7). Also shown are the wells corresponding to VES stations. Of particular interest is cross-section A-A' (Fig. 4): it includes well 29, which is within a set of wells that were being pumped during the resistivity fieldwork. Both programs modelled a conspicuous upconing of brackish ground water at well 29, thus they were clearly able to detect the thinning of the fresh-water lens due to pumping of these wells.

Line B-B' (Fig. 5) includes the test wells north of the airstrip. Very little fresh ground water was detected in this area. An isolated pod of fresh ground water occurs at wells 7 and 8, and at wells 1 and 2. It is unclear how the integrity of these small lenses is maintained within the brackish conditions on either side of them. The porosity calculations indicate that the aquifer at wells 7 and 2 is slightly more porous than at wells 4 and 9. Perhaps the lower porosities surrounding wells 7 and 2 (and by inference, wells 1 and 8, which were also fresh) are indicative of a low-permeability barrier: the pods are maintained within the porous zone, while fresh water infiltration and flow elsewhere is inhibited, leading to the brackish conditions. The porosity at well 7 was calculated as 19% ("I") and 24% (R), as opposed to 9% ("I") and 13.6% (R) at well 4, and 12.5% ("I") and 15% (R) at well 9. Likewise, the porosity at well 2 is slightly greater (20% "Inverse", 28% Resix) than at neighboring well 4.

Cross-section line C-C' (Fig. 6) shows test wells 10 through 17, and well 24. "Inverse" modelled the lens as very thin (0.3 m) at well 14 and Resix predicted the base of the freshwater lens as occurring within the vertical extent of

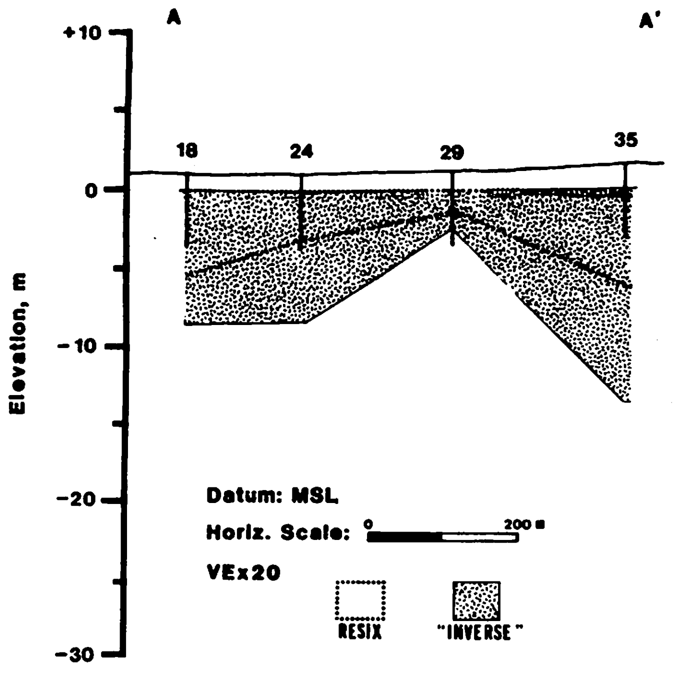

Fig. 4. Cross-section A-A'.

wells 13 through 17 and 24, however, the field salinity profiles of all these wells indicate fresh water throught the entire well depth. This contradiction between the resistivity model and the field measurements happens whenever the fundamental assumption of the VES modelling method is violated: if porosity does not remain a constant with depth, but increases instead, a false (pessimistic) interpretation of the freshwater lens thickness results. Cross-section D-D′ (Fig. 7) shows a gradual thickening of fresh ground water toward the north, hinting at a possible major freshwater lens to the north of the study area.

Traditional Method Results

Analysis of the VES models by the traditional method (based on an assumed subsurface porosity of 25%) led to results for freshwater lens thickness and water-table elevation that are in general agreement with those determined on the basis of well data. Except for a few stations, the base of the freshwater lens remained the same as in the original models. However, the brackish water conditions at stations 3 and 8 were misidentified as fresh ground water. These results illustrate that although inadequate well control and porosity assumptions lead to invalid models with regard to water quality, the lens thickness can be modelled with remarkable accuracy.

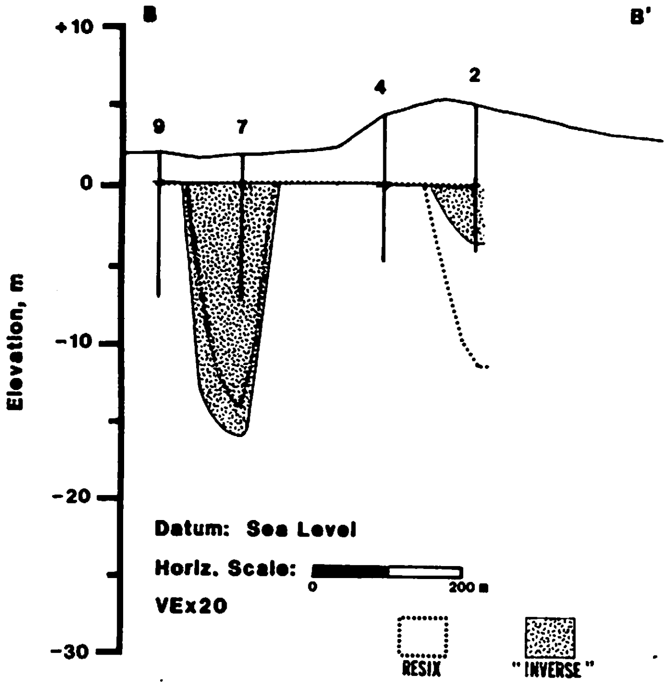

Fig. 5. Cross-section B-B'.

SUMMARY AND CONCLUSIONS

Fresh ground water occurs everywhere in the study area except at stations 3 and 8, where brackish conditions prevail. The substantial transition zone and short tidal lag times indicate good communication between the ocean and the aquifer. Some of the VES stations indicate unusually porous zones in the subsurface that may facilitate transfer of the tidal wave through the aquifer. The measured elevation of the water table was largely negative due to tidal and other unknown disturbances. This prevented the determination of the actual mean static water level in the study area and precluded the establishment of a Ghyben-Herzberg lens control model for comparison. Porosities modelled using the VES inversion programs "Inverse" and Resix were in an acceptable range, except for station 1.

The data were also analyzed without well control in the traditional method. This method yielded generally satisfactory results: the models were in essential agreement with those obtained using well control. However, the porosity assumption negates any assessment of water quality: the traditional method completely missed the brackish conditions at stations 3 and 8. Clearly, any model using VES data must be accompanied

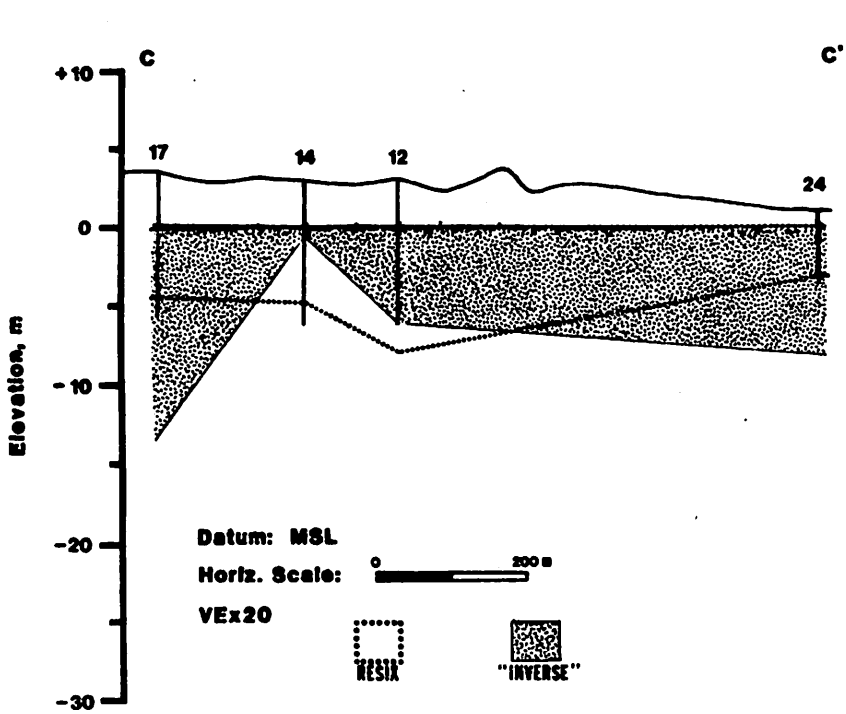

Fig. 6. Cross-section C-C'.

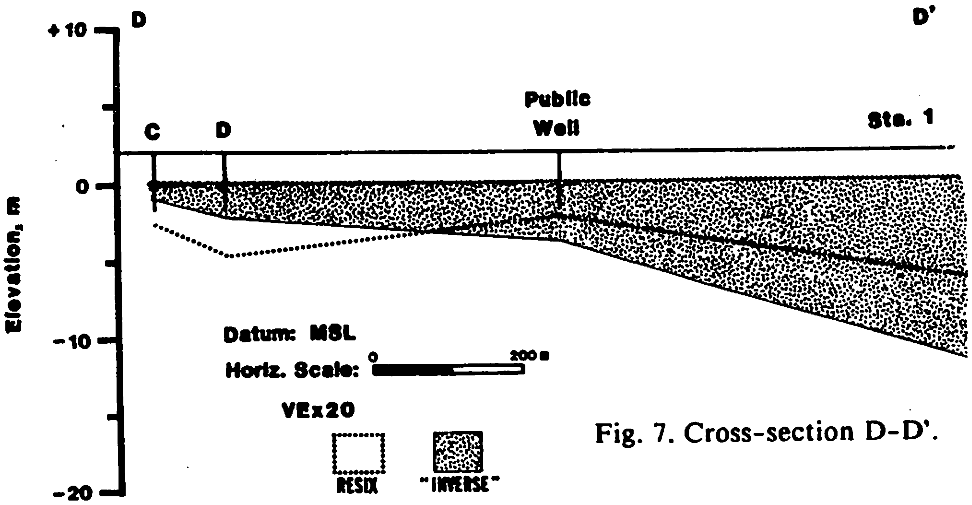

Fig. 7. Cross-section D-D'.

by adequate well control if useful inferences regarding water quality are to be made. Nevertheless, all VES surveys can be considered to be a valuable general exploration tool.

The dynamic nature of the groundwater lens on San Salvador necessitates inclusion of tidal and atmospheric fluctation data in any future hydrogeologic study. Future VES surveys should be accompanied by adequate well control, including wells that penetrate through the transition zone, and accurate measurement of station elevations. A more comprehensive VES survey of this study area would require more stations than were used in this survey, however, the dense vegetation here may render this option impossible. Finally, the two programs used here yielded comparable results. Future VES surveys can be performed utilizing either inversion program without fear of overlooking entirely different model possibilities.

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