WATER RESOURCES research center

Publication No. 60

EVALUATION OF ELECTROMAGNETIC TERRAIN CONDUCTIVITY MEASUREMENTS FOR DETECTION AND MAPPING OF SALT WATER INTERFACES IN COASTAL AQUIFERS

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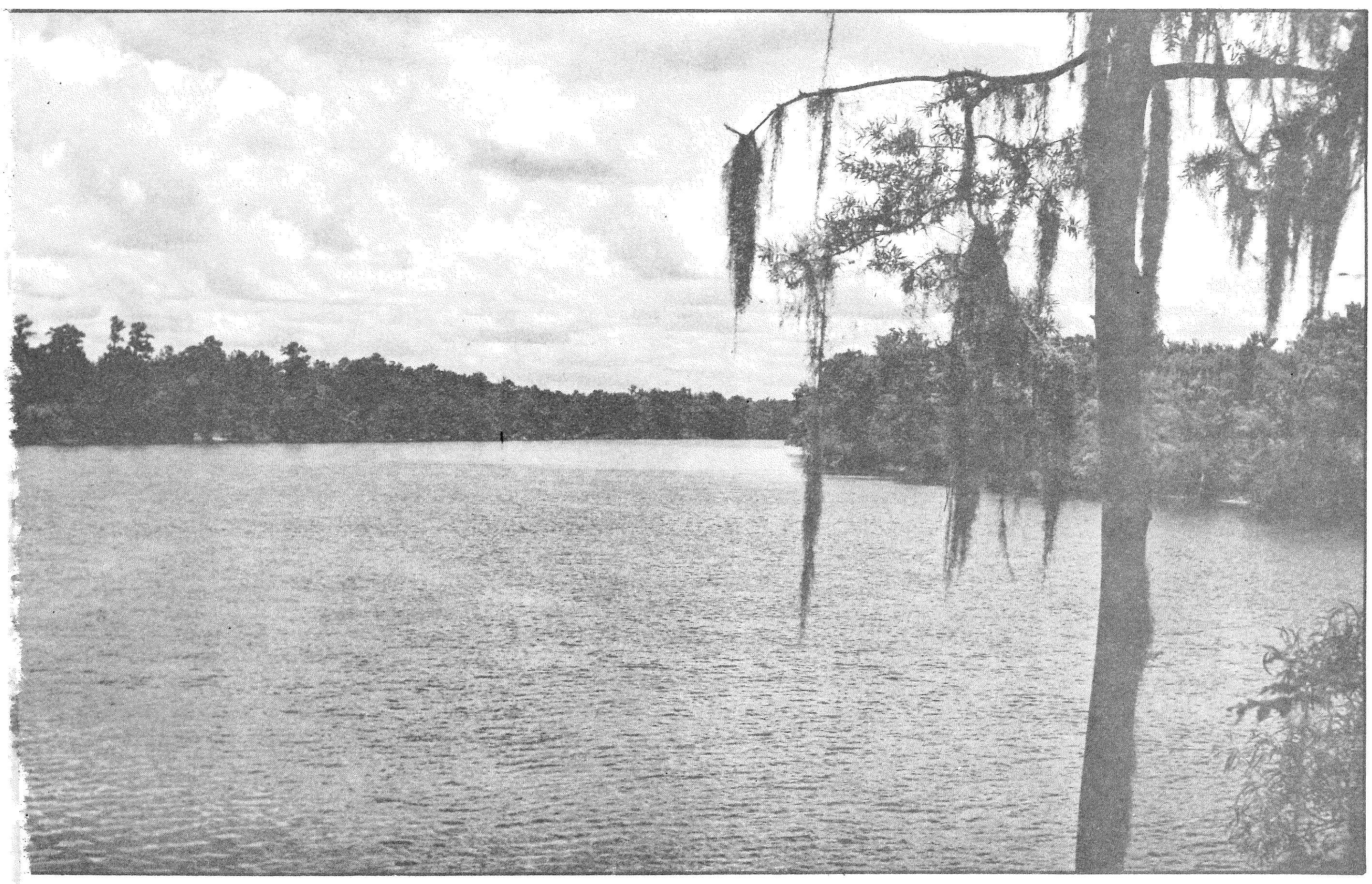

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ABSTRACT

In coastal areas salt-water intrusion represents a significant threat to water quality in coastal aquifer systems, and the position of the salt-water/fresh-water interface represents the seaward and lower boundary of the potable water zone. Previously chloride concentrations have been measured in monitor wells and wells of opportunity in order to locate and monitor the interface position. Such studies are costly and usually include relatively few data points. DC resistivity surveys can also be used to locate and monitor the interface, however interpretation of DC data requires some specialized training. The electromagnetic method evaluated in this study proved to be rapid, very inexpensive, and it yields useful qualitative data with little or not interpretation. Data can be obtained and interpreted by personnel with little or no special training.

The study compared chloride monitor well, DC resistivity, and EM conductivity surveys in Citrus and Collier Counties, Florida. The EM method gives results which agree well with both the DC and monitor well results. Both the DC and EM data provide more detailed information on the interface configuration monitor well results. Both the DC and EM data provide more detailed information on the interface configuration because of the greater data density of the geophysical surveys. The EM surveys are very rapid; 5-15 stations can be occupied per hour. The rate depends on the distance between stations and the number of measurements at each station. Comparison with the DC data suggests that the EM instrument used (Geonics EM 34-3) can consistently provide information to a depth of 30 meters, and at most stations, to a depth of 60 meters. At the limits of depth of investigation interference from power lines, lightning, and other EM field sources becomes a problem.

Interferences sources are usually quite localized, and can be avoided.

Quantitative interpretation of the EM results was only possible where the geoelectric section can be represented by a simple two-layer solution. In Collier County such conditions were met when the interface was within a few meters of the surface. Because the depth of penetration of the EM method is fixed and independent of terrain conductivity, conductivity measurements for different depths of investigation can be used to qualitatively determine the variation of conductivity with depth. Such qualitative interpretation is simple and direct and can be made from the field measurements with no intermediate interpretation steps required.

The EM conductivity method is very useful for rapid, inexpensive ground water surveys where the objective is to locate zones of conductive pore fluids at depths of less than 30-40 meters. Although interpretation is indirect and qualitative, neither data acquisition of interpretation require special training. This characteristic of the EM method makes it very suitable for use by agencies where highly trained technical personnel are not available.

ACKNOWLEDGEMENTS

This project was supported in part by the Florida Water Resources Research Center, Office of Water Resources Technology, U. S. Department of the Interior. Michael C. Layton, David S. Smith, Michael Bradley, and Chris Mraz, all students at the University of South Florida, cooperated in various portions of the field work. Dr. James P. Heaney, Director, Florida Water Resources Research Center, edited the final report. Mr. Abe Kreitman and Dr. Leslie Wedderburn, South Florida Water Management District, provided some of the background data for Collier County. The Division of Sponsored Research, University of South Florida contributed part of the cost of the research equipment. Mrs. Iris Rose and Mrs. Mary Haney prepared the manuscript. The assistance of these individuals and organizations in completing this project is greatly appreciated.

INTRODUCTION

Statement of the Problem

Increasing population pressures in coastal zones, both in Florida and in other parts of the country, are placing severe stresses on coastal ground water systems. These systems are highly susceptible to contamination by sea water intruding landward in response to overpumping of aquifer systems or coastline alterations such as dredge and fill operations. Water resource managers have an urgent need to be able to locate the present position of the interface and to monitor its movement at regular intervals.

Present methods used to locate the salt-water interface include surface DC resistivity surveys and water sampling of coastal wells for chloride content. The former method suffers from interpretation problems, and the latter is both expensive and yields low data densities. This project investigated a very promising remote sensing method, electromagnetic terrain conductivity surveys. This technique is very rapid and terrain conductivity is read directly from the instrument. No data inversion is required to obtain the conductivity values.

Objectives

The principal objective of the project is to investigate the utility of the electromagnetic method for locating and mapping salt-water interfaces in coastal aquifers. This includes a detailed comparison of the EM results with DC resistivity surveys and data from monitor wells, determination of proper field procedures and special problems, and a cost effectiveness comparison with other available methods.

THEORY

Electrical Properties of Earth Materials

The physical property measured by the electromagnetic method used in this study is conductivity (the inverse of resistivity). The definition of resistivity and conductivity is illustrated in Figure 1. It is apparent that conductivity or resistivity is an inherent property of a particular material, and is independent of geometry, as opposed to conductance and resistance. The units of resistivity are ohm-meters in SI units, and conductivity is measured in mhos/meter. The instrument used (Geonics EM-34-3) measures conductivity directly in millimhos/meter.

The conductivities of most minerals are very low, and most can be considered to be insulators. Some metallic minerals and silicate clay minerals do have significant conductivities because of metallic electronic conduction in the former and an electrically unbalanced crystal structure in the latter. Most silicate and carbonate minerals have resistivities of 10^3-10^9 ohm-meters. However, saturated earth materials exhibit bulk conductivities orders of magnitude higher than the minerals they are composed of (Table 1).

Bulk conductivities of geologic units are much higher than of the minerals they are composed of because most electrical current flow is through moist or saturated pore spaces in the soil or rock, and not through the mineral grains themselves. As a result, the two factors which most strongly influence conductivity values in earth materials are effective porosity and pore fluid conductivity. Effective porosity is defined as the interconnected pore volume divided by the total volume.

There are three porosity related phenomena which influence bulk conductivity. One is tortuousity, or the deviation of average current flow paths from a straight line due to flow around mineral grains. Higher tortuousity

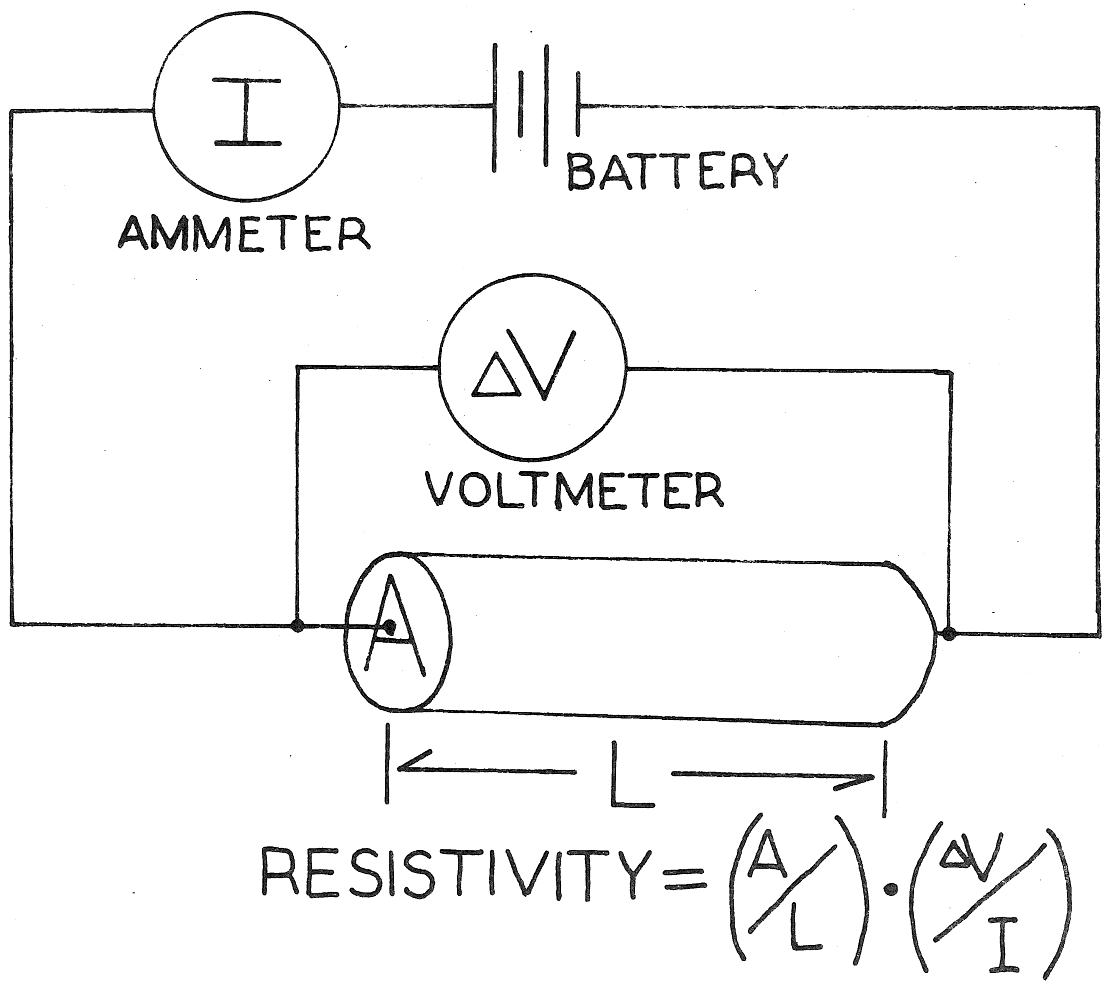

Figure 1. Definition of resistivity and conductivity.

TABLE 1

Resistivities of common rocks and minerals

material	resistivity (ohm-m) range	resistivity (ohm-m) average
argentite (Ag_2S)	$2 \times 10^{-3} - 10^{-4}$	1.7×10^{-3}
chalcolite (Cu_2S)	$3 \times 10^{-5} - 0.6$	10^{-4}
pyrite (FeS_2)	$2.9 \times 10^{-5} - 1.5$	3×10^{-1}
bauxite ($Al_2O_3 \cdot nH_2O$)	$2 \times 10^{2} - 6 \times 10^{3}$	10^{3}
quartz (SiO_2)	$10^{10} - 10^{14}$	10^{12}
rock salt (NaCl)		10^{13}
calcite ($CaCO_3$)		10^{12}
silicate clays	1 - 100	
alluvium and sands	10 - 800	
saturated limestone	50 - 600	
saturated sandstone	30 - 1000	
shales	20 - 2000	

(Telford and others, 1976)

means lower conductivity. The most important porosity related effects are surface conduction and pore fluid conduction. As water is a polar molecule, it forms an electrically bonded layer on the surfaces of mineral grains, particularly silicate clay minerals. This electronic double layer is more conductive than the mineral itself. Pore fluid conduction is direct ionic conduction by the pore fluid. As both pore surface area and total cross-sectional area increase with increasing porosity, porous fine-grained materials exhibit higher conductivities than less porous units.

Pore fluid conductivity obviously influences bulk conductivity as flow through pore spaces is one of the two dominant current paths. Figure 2 illustrates the relationship between bulk resistivity and pore fluid resistivity. At low fluid resistivities there is an approximately 1:1 relationship between pore fluid resistivity and bulk resistivity. As pore fluid resistivity increases, the 1:1 relationship no longer applies, and bulk resistivity increases rapidly. From this graph it can be inferred that when fluid resistivity is high, the value of bulk resistivity will be most strongly influenced by porosity, and when pore fluid resistivity is low, bulk resistivity will be dominated by the pore fluid resistivity.

Application of Surface Electrical Methods to Ground Water Surveys

Direct current (DC) resistivity surveys of ground water systems date back to at least the 1930's. Swartz (1937, 1939) used DC soundings to delineate fresh water lenses in salt water bodies on the Hawaiian Islands. Other investigations of saline or brackish ground water systems using DC methods were conducted by Zohdy and others (1969), Flathe (1970), Zohdy and others (1974), Gorhan (1976), Worthington, 1977, and Reed and others, (1981). Numerous studies have been conducted to locate contaminated waters, such as landfill leachates, mine drainage, and sewage effluent (Cartwright and McComas, 1968; Warner, 1969; Hackbarth, 1971; Merkel, 1973; Fink and

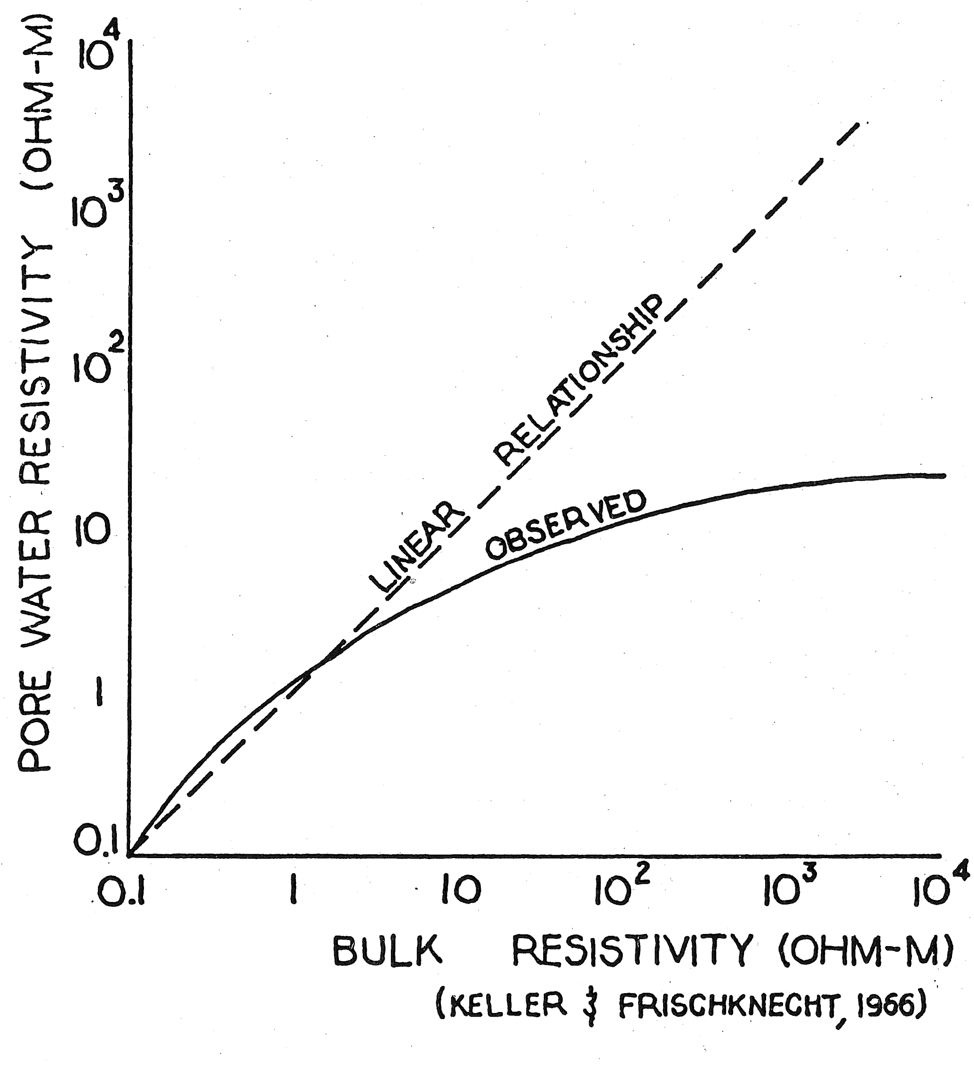

Figure 2. Relationship between pore fluid resistivity and bulk resistivity.

Aulenbach, 1974; Stollar and Roux, 1975; Kelly, 1976; Klefstad and others, 1976; and U.S. Environmental Protection Agency, 1978).

In all of these studies the target detected by the DC resistivity method was high-conductivity pore fluids. These fluids were sea water, mineralized, arid-zone ground waters, landfill leachates, etc., which had significantly higher conductivities than surrounding or nearby fluids. The location and geometry of the high conductivity waters could be determined because of the strong bulk conductivity contrasts between contaminated and uncontaminated areas.

Four previous studies (Biewinga, 1977; Koefed and Biewinga, 1976; Patra, 1970; Ryu, Morrison, and Ward, 1972) have evaluated the application of electromagnetic (EM) methods to ground water and engineering applications. These studies demonstrate that EM methods have several advantages as compared to DC methods, and have sufficient resolution to be useful in ground water surveys. Ryu and others, (1972) suggested the use of ground-based EM techniques for saline water investigations, but to date this application of EM methods has not been well evaluated. The results of this study can be extended to other ground water problems where the target is highly conductive pore fluids, as the source of the geophysical signature would be the same.

EM Conductivity Measurement

Electromagnetic conductivity measurements are made using an EM field generated by a carefully controlled alternating current in a transmitter coil. Changes in the primary field (phase, amplitude, orientation) with time and distance can be related to the electrical properties of the earth in the vicinity of the transmitter and receiver. The receiver is a passive coil which measures either the amplitude, orientation, and/or phase-shift of the secondary field created by the interaction of the primary (transmitted) field and the earth.

Electromagnetic soundings may be made by varying either the frequency of the AC current (frequency-domain) or by measuring the remnant EM field at discrete intervals after the transmitter is abruptly shut-off (transient or time domain). Decreasing the frequency or increasing the time after transmitter shut-off that a measurement is made both increase the effective depth of penetration. The instrument used in this study is a frequency-domain meter.

In Figure 3 the transmitter coil, T_x, is carrying an alternating current at an audio frequency. The receiver coil, R_x, is a short distance away (distance s, the intercoil spacing). The earth beneath the two coils will be considered uniform. The time-varying magnetic field, H_p, generated by the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field, H_s, which is sensed by the receiver coil together with the primary field, H_p (McNeill, 1980).

For the general case, the secondary field is a complex function of intercoil spacing (s), operating frequency (f), and the ground conductivity, σ. However, if certain conditions of frequency, intercoil spacing, and maximum ground conductivity expected are met, the function reduces to: (McNeill, 1980)

$$\frac{H_s}{H_p} = \frac{i\omega\mu s^2\sigma}{4} \qquad (1)$$

H_s = secondary magnetic field,
H_p = primary magnetic field,
ω = 2 f,
μ = permeability of free space,
σ = ground conductivity,
s = intercoil spacing, and
i = $\sqrt{-1}$

Equation (1) states that if the assumptions are met, the ratio of the amplitudes of the secondary and primary fields is directly proportional to ground conductivity. By measuring the ratio of the field strengths the apparent

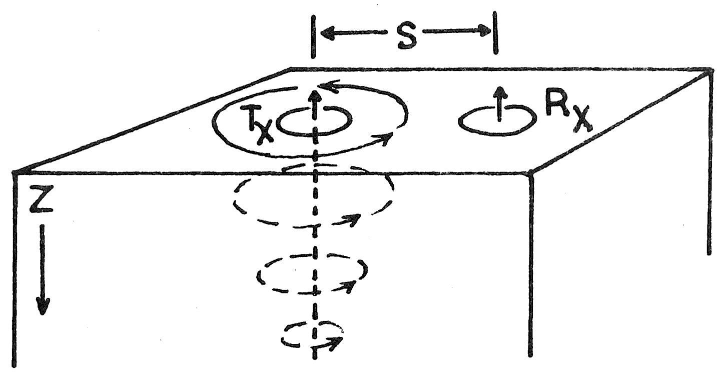

Figure 3. Induced current flow in a homogeneous half-space.

ground conductivity is given by (McNeill, 1980):

$$\sigma_a = \frac{4}{\omega\mu s^2}\left(\frac{H_s}{H_p}\right) \tag{2}$$

The instrument used in this project operates at three set frequencies and coil spacings of 10, 20, and 40 meters. The effective depth of exploration is a function of intercoil spacing. For vertical dipoles (coils horizontal) the effective depth is 1.5s, or 15, 30, and 60 meters. For horizontal dipoles (coils vertical) the effective depth of exploration is 0.75s, or 7.5, 15, and 30 meters. As currents are introduced into the ground by induction, no ground-contacting electrodes are necessary, in contrast to DC resistivity surveys. Also readings may be taken continuously along a survey line, almost as fast as one can walk.

The instrument used is a Geonics EM 34-3. The transmitter coil is about 1m in diameter and weighs 6 kg. The receiver coil is about the same size and weighs 3 kg. Each coil has an associated console weighing about 3 kg. Power is supplied by flashlight batteries. The entire instrument, including connecting cables, weighs about 40 kg in its field case and is easily portable.

DATA ACQUISITION AND REDUCTION

Field Sites

Two field sites were chosen for the evaluation of the EM method, Citrus County and Collier County, Florida (Figure 4). In both areas high-conductivity pore waters are present at shallow depths in contact with pore waters of low conductivity. Also both areas have been investigated in previous studies using DC resistivity methods, geochemical surveys of well waters, and in Collier County, geophysical borehole electric logs. It is these supporting geologic, geochemical, and geophysical data which were used to evaluate the

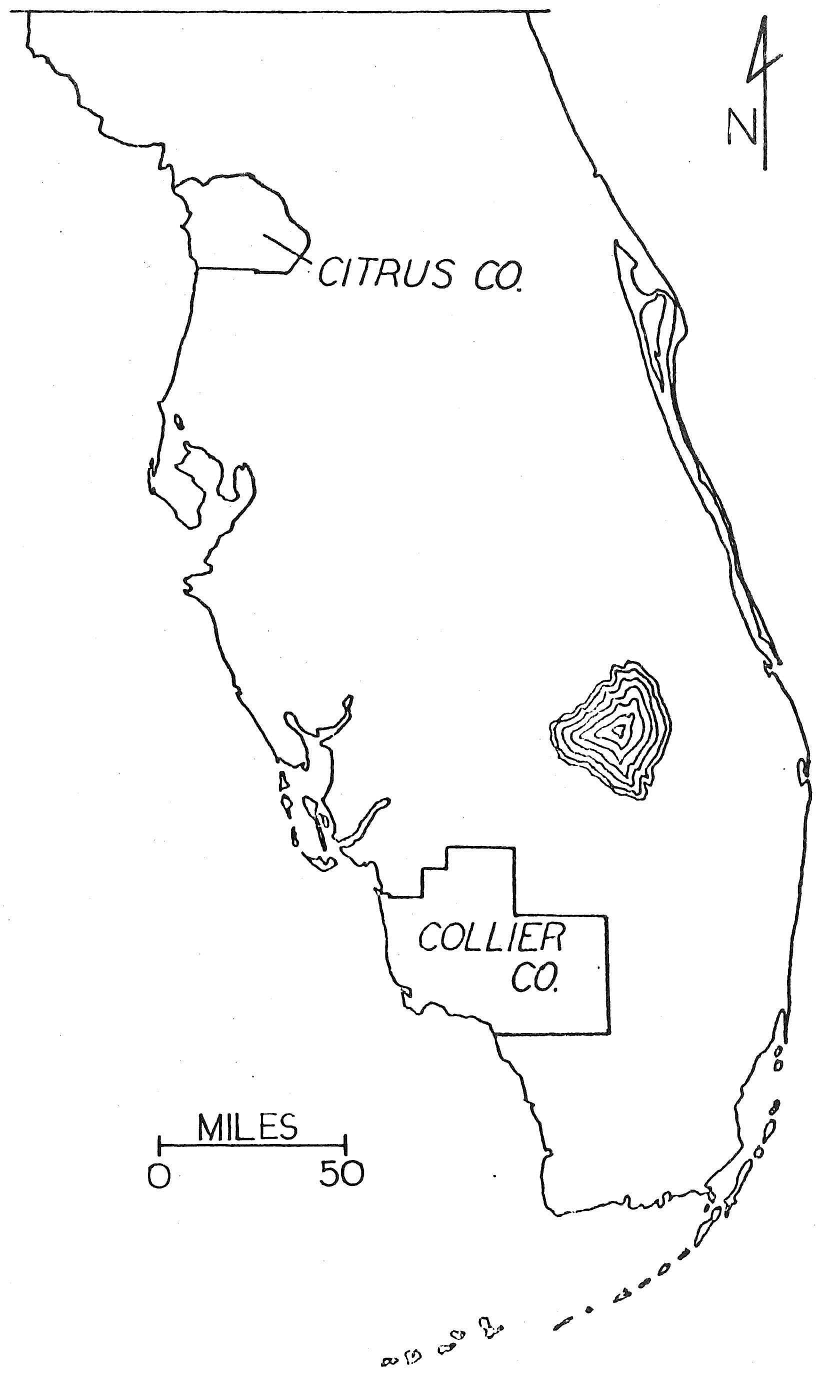

Figure 4. Location of Citrus and Collier Counties, Florida.

results of the EM surveys.

Citrus County is located on the west central Gulf coast of Florida. The area studied extends from Homossassa north to Crystal River (Figure 5). Extensive salt marshes up to several miles wide border the coast and are bounded on the landward side by oak-pine and fresh water swamp hardwood woodlands. Carbonate bedrock of the Floridan Aquifer is at or near the surface throughout the area. Extensive solution of the limestone has occurred, creating many karst features. Large springs discharge at Homossassa Springs, at several points along the Hall's River, and at Crystal Springs. Many smaller springs occur in the lower coastal area. Inland of the spring discharge zone there are almost no perennial streams, as drainage is internal. Spring discharges are fresh to brackish, with springs along the Hall's River discharging waters with chloride concentrations as high as 2,200 mg/ℓ.

The Floridan Aquifer consists of Eocene limestones and dolostones of the Lake City limestone, Avon Park Limstone, and the Ocala Group (oldest to youngest). The Ocala Group is the oldest unit to be exposed at the surface. The bedrock units are overlain by a thin veneer of sand which thickens to the east, particularly east of US 19.

Fretwell and Stewart (1981) have completed a DC resistivity study of coastal Citrus County. The results of this study are summarized in Figure 5. Figure 5 also illustrates the position of the 250 mg/ℓ isochlor at a depth of 32.5m as determined by Mills and Ryder (1977) from samples from the chloride monitor wells indicated on Figure 5.

Collier County is located in southwest Florida on the Gulf of Mexico (Figure 4). The region is one of extremely low relief, the highest elevations within the study area are less than 3m. Vegetation consists of cypress strands, pine-palmetto flatwoods, and sawgrass prairies. The coast is bordered by extensive salt marshes and mangrove swamps. Ground-water gradients are very low, less than 2×10^{-4} m/m, and the water table is at or near the sur-

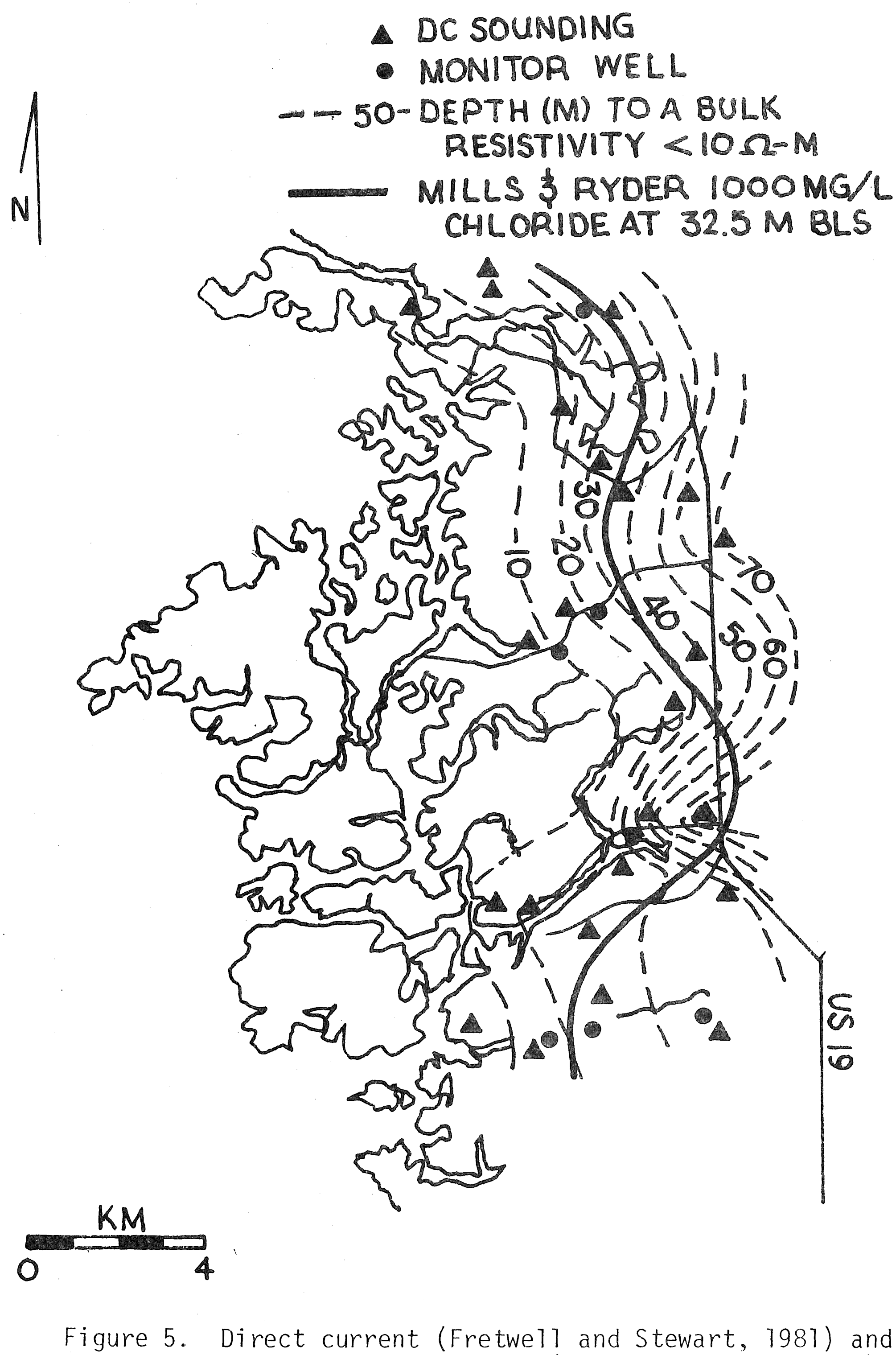

Figure 5. Direct current (Fretwell and Stewart, 1981) and monitor well studies (Mills and Ryder, 1977), Citrus County, Florida.

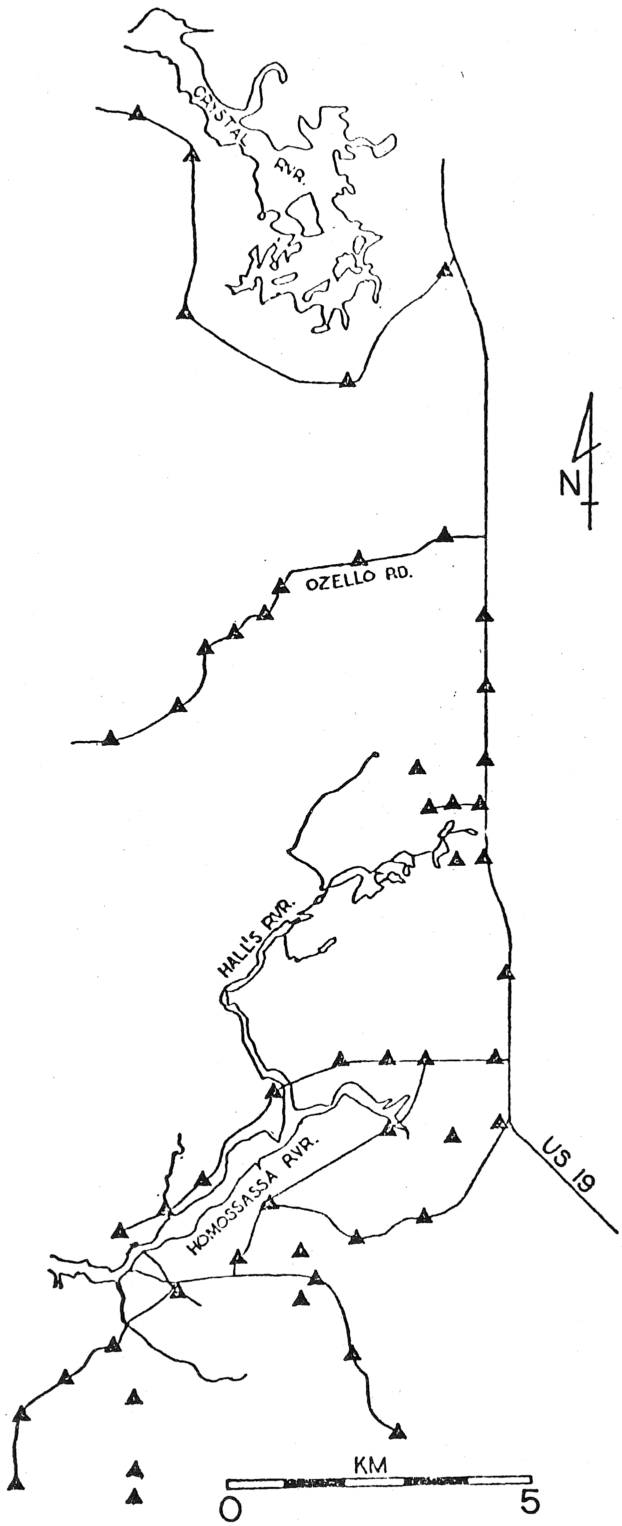

Figure 5a. Location of Em sounding sites, Citrus County, Florida.

face throughout the project site. The shallow aquifer consists of four principal units; a fine,quartz,surface sand 0-3m below land surface (BLS); hard, well-lithified limestone, 0-6m BLS; soft, micritic, shelly, sandy limestones to 20-25m BLS; soft, limey sandstones from about 20-25m BLS to 50-60m BLS (Jakob, 1980). The bottom of the shallow aquifer system is a carbonate mud. The harder limestones of the upper 20m of the section have extensive solution cavities and high permeabilities, but low porosities.

Extensive investigations have been made of ground-water conditions in southwest Collier County (Figure 6). Jakob (1980) completed a water quality and hydrogeologic study using test wells and some geophysical logging. Stewart and Lizanec (1981) have completed a DC resistivity survey of much of western Collier County, including the study area. Over 100 vertical electrical soundings completed with DC resistivity equipment are available for comparisons with the EM data.

Field Procedures

Site selection is considerably easier with EM equipment than with DC survey lines which require a straight, open stretch five times as long as the desired exploration depth. Also as DC electrodes are connected by wires, driveways and cross-streets have to be avoided to prevent damage to wires by cars. The EM equipment required a maximum distance of 40 meters, and at many sites only the 10 and 20m intercoil spacings were used. Because of the greater flexibility of site selection and the speed with which readings can be taken, data points can (and should) be located closer together than DC soundings, providing greater data densities for the same or less field time.

If all three intercoil spacings are to be used the 40m reference cable, connecting the receiver and transmitter coils, is used. Most of the time required for a reading at a site is consumed in laying out and taking up the

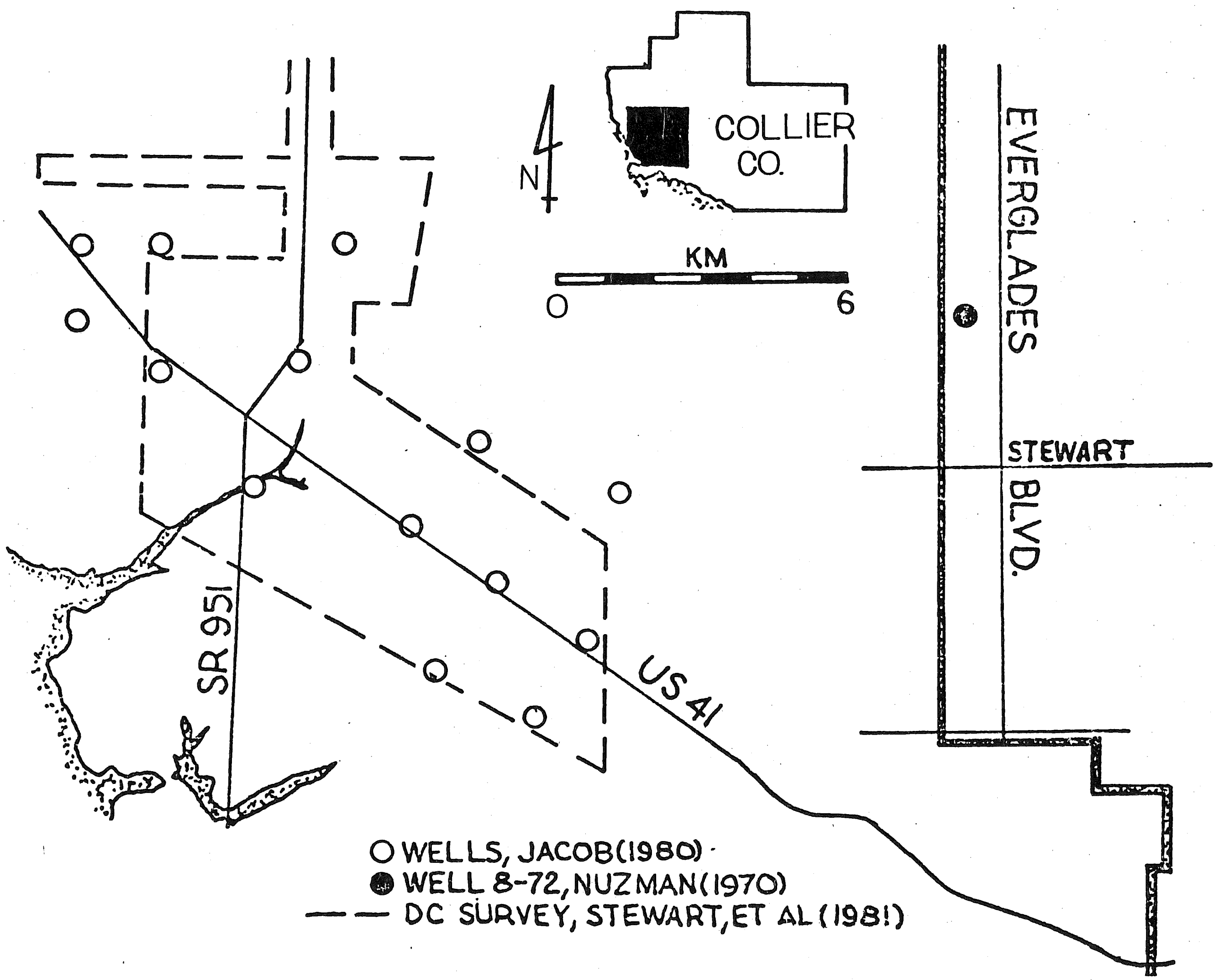

Figure 6. Direct current (Stewart and others, 1981) and monitor well studies (Jakob, 1980; Nuzman, 1970), Collier County, Florida.

connecting cable, so if the 40m intercoil spacing is not used, using the shorter connecting cables greatly shortens the time required for each reading. For all coil spacings the intercoil distance can be determined by a meter on the receiver console, eliminating the need for a measuring tape.

To take a reading at a site the intercoil spacing is determined approximately by pacing off the distance or by marks placed on the reference cable, and exactly from a meter on the instrument. Readings are then taken with the coils upright (horizontal dipoles) and lying on the ground (vertical dipoles). Care should be taken to maintain proper coil alignment. At some sites, and particularly for the 40m intercoil spacing, interference will prevent a reading from being taken. The most common sources of interference encountered in this study were powerlines and transformers, radio towers, lightning, and large, unshielded electric motors. Often moving a few hundred feet or to the other side of the road cures the problem. Power lines do not always cause interference. At many sites readings were taken successfully under or near power lines. However, finding suitable sites in developed areas can be difficult, and several sites may have to be occupied before a reading can be taken. As the 40m intercoil spacing is most sensitive to interference, eliminating this spacing can eliminate much of the problem.

Data Interpretation

The values of terrain conductivity can be plotted directly on a map and contoured. Normally one map is prepared for each intercoil spacing. As the depth of penetration is determined by the transmitter frequency and the intercoil spacing, the maps of conductivity for each coil spacing represent different depths of investigation. The differences between values at different intercoil spacings can be used to obtain some idea of the variation of conductivity with depth. Deeper conductivity anomalies will affect the values at longer intercoil spacings, but leave the values obtained at shorter spacings unchanged. The reverse is true for shallow conductivity anomalies.

This qualitative method of interpretation is similar to the DC resistivity profiling method, where apparent resistivities are determined along a profile using a constant electrode spacing. However, in the DC method the depth of investigation is only approximately known and varies with both the electrode spacing and the bulk resistivity. The advantage of the EM method for this type of profiling is that the depth of investigation, and hence the approximate depths of the anomalies are known. Also since no electrodes are implanted in the ground, small, near-surface changes in electrical properties do not strongly influence EM conductivity values, as is the case with DC measurements, particularly when using the Wenner electrode array.

To aid in this direct, qualitative interpretation, it is helpful to draft the conductivity contour maps on mylar or translucent paper so that the maps for various intercoil spacings can be more easily compared, and anomalous areas outlined. A similar procedure may be used with profile data, where terrain conductivity is measured along a line.

It should be noted that the effect of conductivity changes at depth on the measured amplitude of the secondary field (H_S) is a non-linear function of depth. Figure 7 illustrates the relative response of the EM 34-3 to conductivity changes vs. depth. The two curves represent the response for vertical coils (horizontal dipoles, $\emptyset_H$) and horizontal coils (vertical dipoles, $\emptyset_V$). For vertical coils ($\emptyset_H$) the response is greatest for materials at the surface, and decreases rapidly with depth. The response to conductivity changes at the surface is twice as large as the response to changes at a depth of 0.3s, and ten times as large as the response at 1.0s. Below a depth of 1.0s only very large conductivity changes would affect the observed conductivity values.

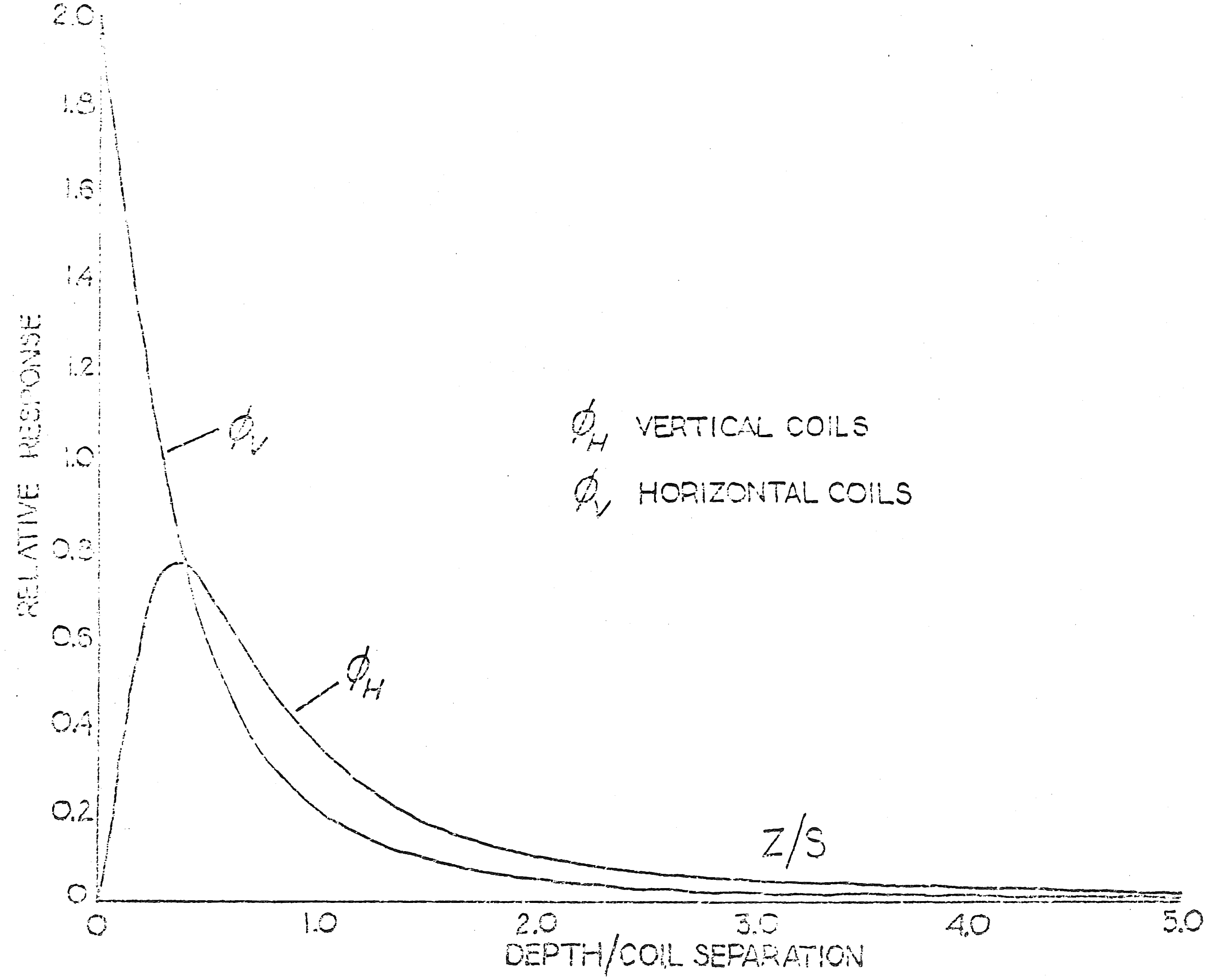

Figure 7. Relative response vs. depth of EM 34-3 terrain conductivity meter (McNeill, 1980).

For horizontal coils (ϕ_V) the relative response at the surface is zero, and increases sharply to a maximum at a depth of 0.4s, then drops off sharply again with depth. It is interesting to note that there is only about a 25% variation in response to materials between 0.2s and 0.65s. This suggests that the horizontal coil configuration at an intercoil spacing of 10m, for example, will be most responsive to conductivity changes between depths of 2 to 6.5m, and less responsive to shallower or deeper changes. This characteristic of the horizontal coil (vertical dipole) configuration is very useful where very shallow conductivity variations might otherwise mask deeper variations. Also comparison of horizontal and vertical coil measurements taken at the same intercoil spacing can yield qualitative estimates of the change in conductivity with depth.

Figure 8 is a plot of cumulative response versus the ratio of depth, z, to intercoil spacing, s. It can be seen that for vertical coils (R_H) about 70% of the response is due to materials at a depth less than 0.75s. For horizontal coils (R_V) about 70% of the response is due to materials at a depth less than 1.5s. This is the basis for the rule of thumb that the vertical coil configuration sounds to a depth equal to 0.75s, and the horizontal coil configuration to a depth of 1.5s. It should be noted however, that about 30% of the response is due to materials below these depths. Both Figures 7 and 8 are independent of terrain conductivity.

Using three intercoil spacings enough data can be obtained to resolve the apparent conductivities into a simple two-layer solution. Two methods for completing such a solution and the necessary curves are described in McNeill (1980b). Such solutions could be used to find the depth to a strong conductivity contrast such as a salt-water interface, impermeable bedrock, or a clay layer. These solutions should be applied only where the electrical section can reasonably be represented by two layers. In complex cases these solutions may yield answers which are significantly in error. The functions

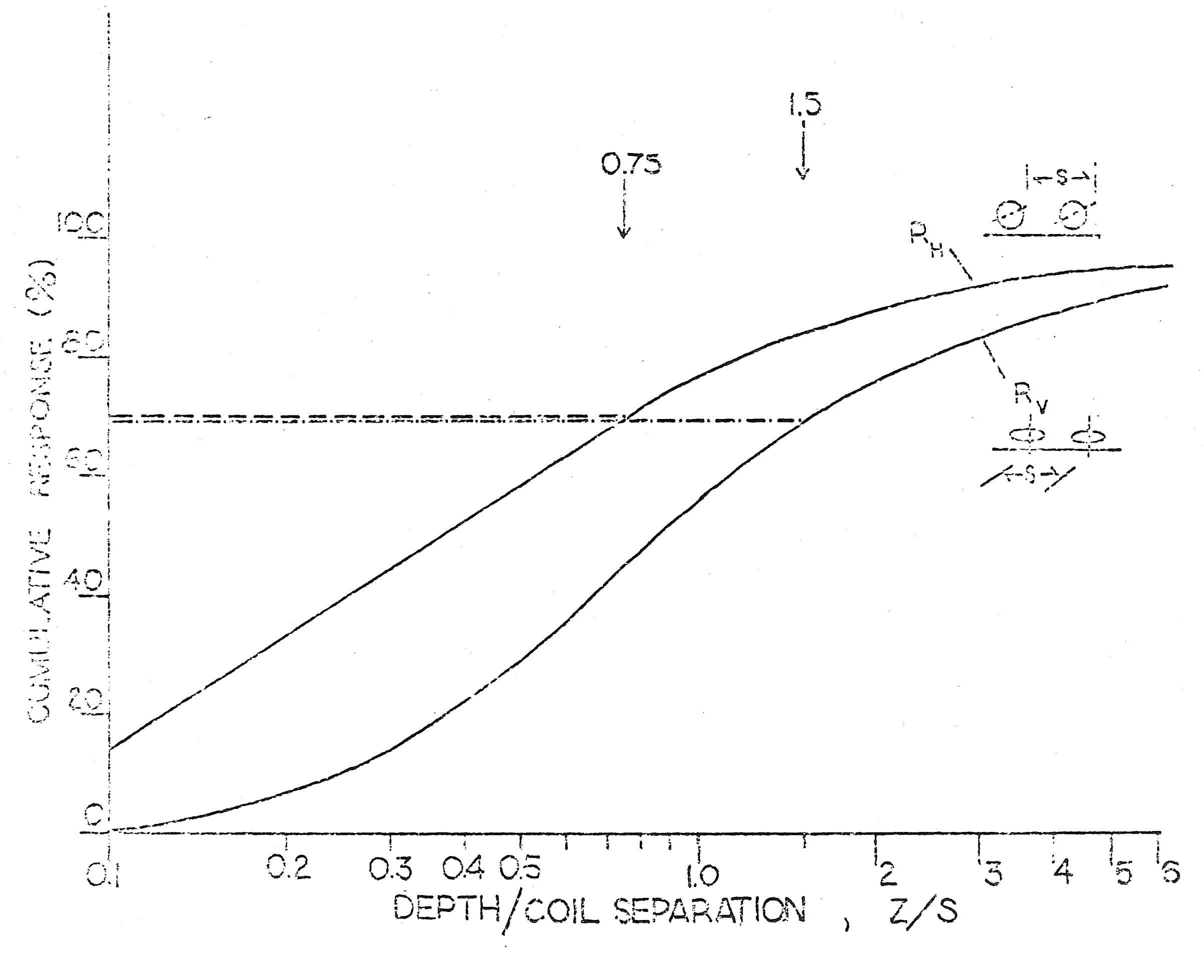

Figure 8. Cumulative response vs. depth of EM-3 terrain conductivity meter (McNeill, 1980).

$R_H(z/s)$ and $R_V(z/s)$ can also be used to calculate the predicted effect of a horizontally stratified earth of known or assumed conductivities (McNeill, 1980b). Calculated conductivities of proposed models can be compared with observed conductivities as an aid in interpretation. Using this method unreasonable interpretations can quickly be eliminated.

RESULTS AND DISCUSSION

Citrus County

As described earlier, coastal Citrus County is underlain by an unconfined to poorly confined, karstic, limestone aquifer. Much of the groundwater discharge along the coast is from major springs. Two previous surveys (Fretwell and Stewart, 1981; Mills and Ryder, 1977) are available for comparison with the EM data (Figure 5). The target in this area was a sharp conductivity contrast between salt- and fresh-water saturated zones of the aquifer. Close spacing of data points was possible where roads allowed access, but much of the coastal area is undeveloped, limiting access in some areas.

Initially, 10, 20, and 40m intercoil spacings were used at each sounding site. However, it quickly became apparent that the 10m spacing did not penetrate deeply enough to sense the interface except very close to the coast. Interference from transmission lines and other cultural features frequently made accurate readings at the 40m intercoil spacing difficult or impossible. As a result the survey was completed using only the 20m spacing, in both the horizontal and vertical coil configurations. This proved to be a very efficient and effective survey method.

Figure 9 is a contour map of resistivity in ohm-meters for the 20m vertical coil configuration. Figure 10 is a similar map for the 20m horizontal coil configuration. Note that the contour intervals are not equal, but increase

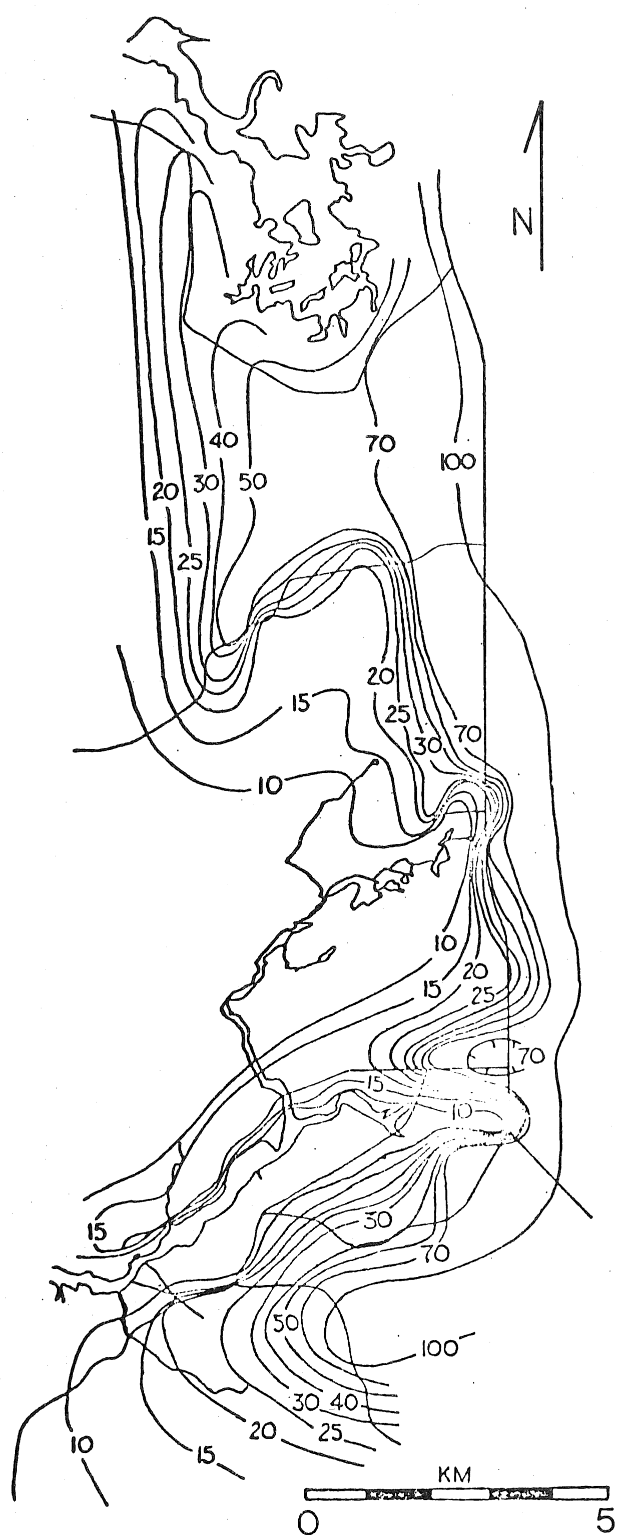

Figure 9. Contour map of terrain resistivity, 20m intercoil spacing with vertical coils (horizontal dipoles), Citrus County, Florida. Resistivity in ohm-m.

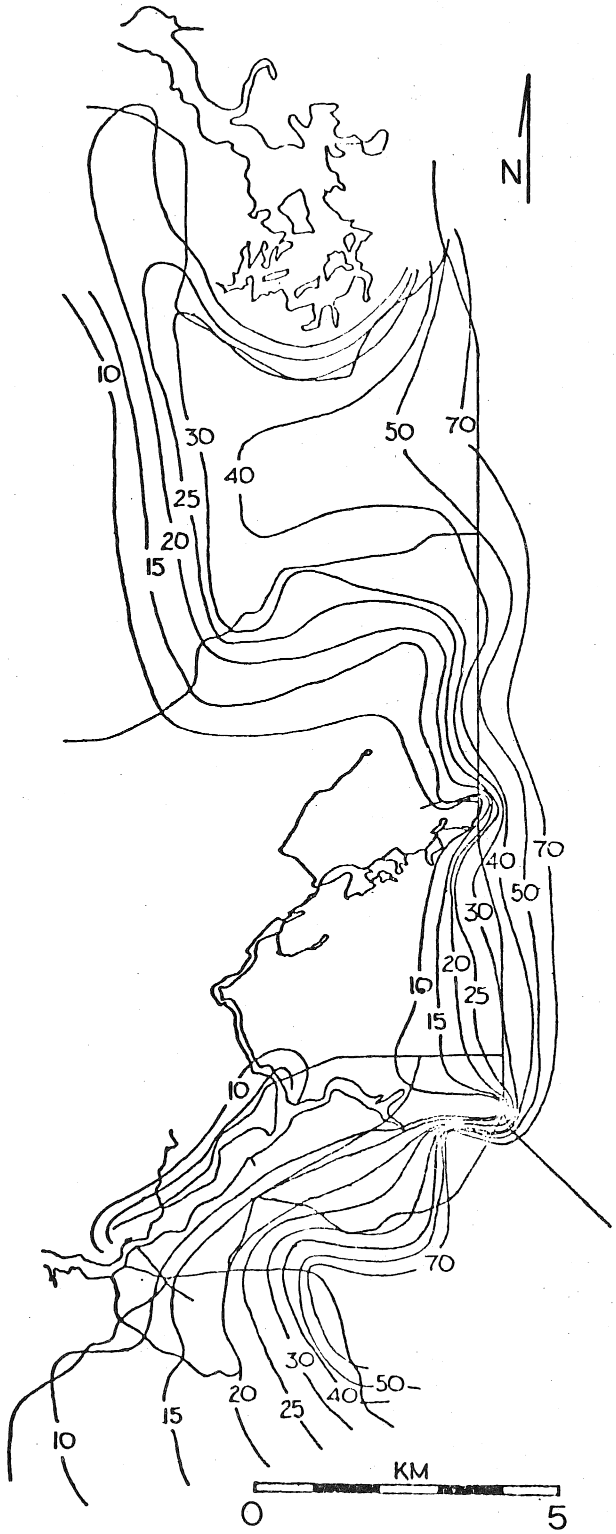

Figure 10. Contour map of terrain resistivity, 20m intercoil spacing with horizontal coils (vertical dipoles), Citrus County, Florida. Resistivity in ohm-m.

with increasing resistivity. Locations of data points used in constructing both maps are given in Figure 5.

Comparing Figures 9 and 10 reveals features common to both. The most striking are the pronounced landward reentrants of the contours around Homossassa Springs, Hall's Spring, and Crystal River springs. Apparently these major ground water discharge points create a very steep salt-water/ fresh-water interface in their vicinity. As they are ground water potential sinks, and depth to the interface is determined by potentials, it would be expected that the interface would be close to the surface seaward of the springs. The EM data clearly outline the interface configuration. A narrow high resistivity zone extends seaward along the north side of the Homossassa River on both figures but is more pronounced at the shallower depths indicated by the 20 meter vertical coil configuration map (Figure 9). In the center of the area a shallow reentrant is evident along Ozello Road. This reentrant extends farther inland on the 20m vertical coil configuration map (Figure 10), suggesting a shallow landward extension of the interface underlain by fresher waters. This relationship between the 20 meter vertical and horizontal configuration contours is reversed in most of the area, with resistivities decreasing with depth, indicating a landward slope to the interface. In general the slope of the interface is more gradual between the major springs, indicating a less concentrated discharge zone.

Where data points coincide, the EM maps (Figures 9 and 10) are very similar to the depth to the salt-water interface mapped by Fretwell and Stewart (1981) using DC resistivity soundings (Figure 5). For example the interface configuration near Homossassa Springs is very similar on all three maps, including the seaward interface extension on the north side of Homossassa Springs. However, the DC data do not define the shallow re entrant along Ozello Road where Figure 5 shows only a few DC soundings. The EM data, because of the greater density, more closely define the shape of the interface. The 20-30 ohm-meter contours on the 20 meter horizontal coil configuration map (Figure 10) closely parallel the 20 meter depth contour on Figure 5.

Figure 5 also illustrates the position of the 250 mg/ℓ isochlor at a depth of 32.5 meters as defined by Mills and Ryder (1977). The DC and EM contour maps agree in general with the 250 mg/ℓ isochlor line (Figures 5, 9, 10). However, there is a major discrepancy between the geophysical data and the Mills and Ryder study just north of Homossassa Springs, where the geophysical data suggest a seaward extension north of the springs. Mills and Ryder (1977) show a gentle landward reentrant around the springs. Part of the discrepancy may be due to the number of data points used in each study. Within the study area the Mills and Ryder isochlor position is based on 6 wells, Fretwell and Stewart's DC sounding map is based on 17 points, and the EM maps, 50 data points. The zone between 30 and 50 ohm-meters on Figure 10 (20m, horizontal coils) agrees most closely with the position of the 250 mg/ℓ isochlor at a depth of 32.5m.

Collier County

Collier County is a region of low relief, and as a result of the low ground-water gradients and potentials, brackish and saline waters are found at shallow depths in the surficial aquifer. As described by Stewart and others, (1981), these brackish or saline waters have two sources. One is landward intrusion by sea water in coastal areas, and the other is upward leakance of mineralized waters from lower aquifer systems. This project investigated the use of the EM survey method at a coastal site and two inland sites in order to determine the utility of the EM method for detecting both types of occurrence of high conductivity ground waters (Figure 6).

The first Collier County site investigated was the Belle Meade area, southeast of Naples (Belle Meade 7.5' quadrangle). The objective here was to determine the configuration of the salt-water/fresh-water interface at the seaward margin of the aquifer. Two previous studies (Stewart and others, 1981; Jakob, 1980) provide extensive DC resistivity, geologic, and geochemical information for comparison with the EM data (Figure 6). Both of these studies were concerned with defining the salt-water interface.

EM data were collected at 52 sites (Figure 11). Belle Meade is undergoing rapid development, and as a result access for soundings was good. Less interference was encountered in this area as compared to Citrus County. Forty meter intercoil spacing readings could be completed at 34 of the 52 sites, and 10 and 20 meter readings were completed at 51 of the 52 sites. The soundings are concentrated around Henderson Creek, as it was expected that this tidal estuary would have a significant effect on the shape of the interface.

Figure 12 is a contour map of EM terrain resistivity measured with the 10 meter intercoil spacing and vertical coils (horizontal dipoles). In general resistivity decreases toward the coast, and the interface or transition zone is roughly parallel to US 41. Henderson Creek is obviously both a discharge zone for the shallow ground water system and a source of brackish waters, as the resistivity contours bend sharply landward around the creek. SR 951 also influences the 10m map, creating a pronounced seaward extension. This extension may be due in large part to the elevated road grade creating both higher near-surface resistivities and perhaps higher ground-water gradients (deeper interface). However, part of this seaward extension is not associated with the road grade and probably represents natural conditions. The resistivity gradients are steepest between resistivities of 20-40 ohm-meters, suggesting that this is the zone where the interface slope is also the steepest. Approximately 1.6 miles southeast of the 41/951 junction the

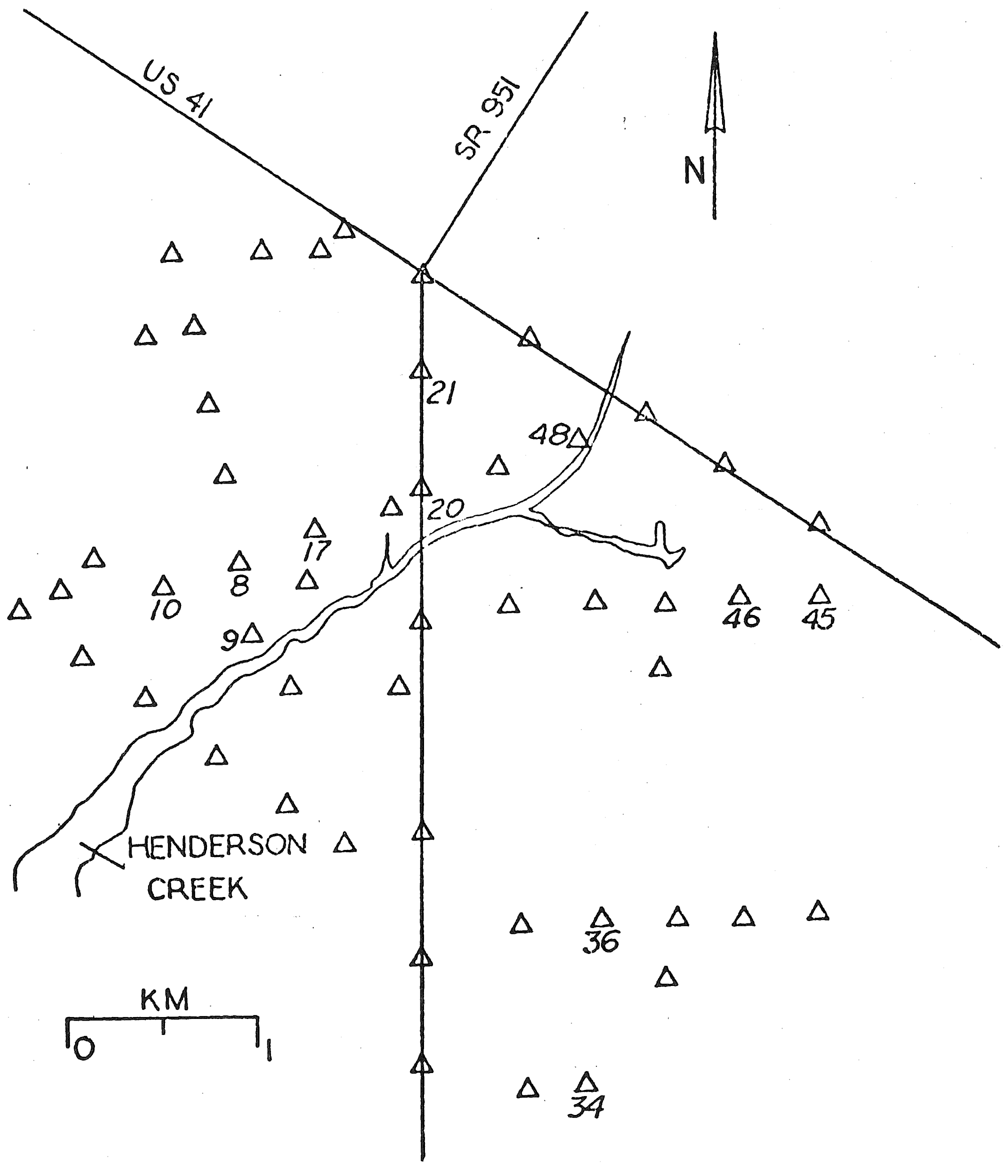

Figure 11. Electromagnetic sounding sites, Belle Meade Study, Collier County, Florida.

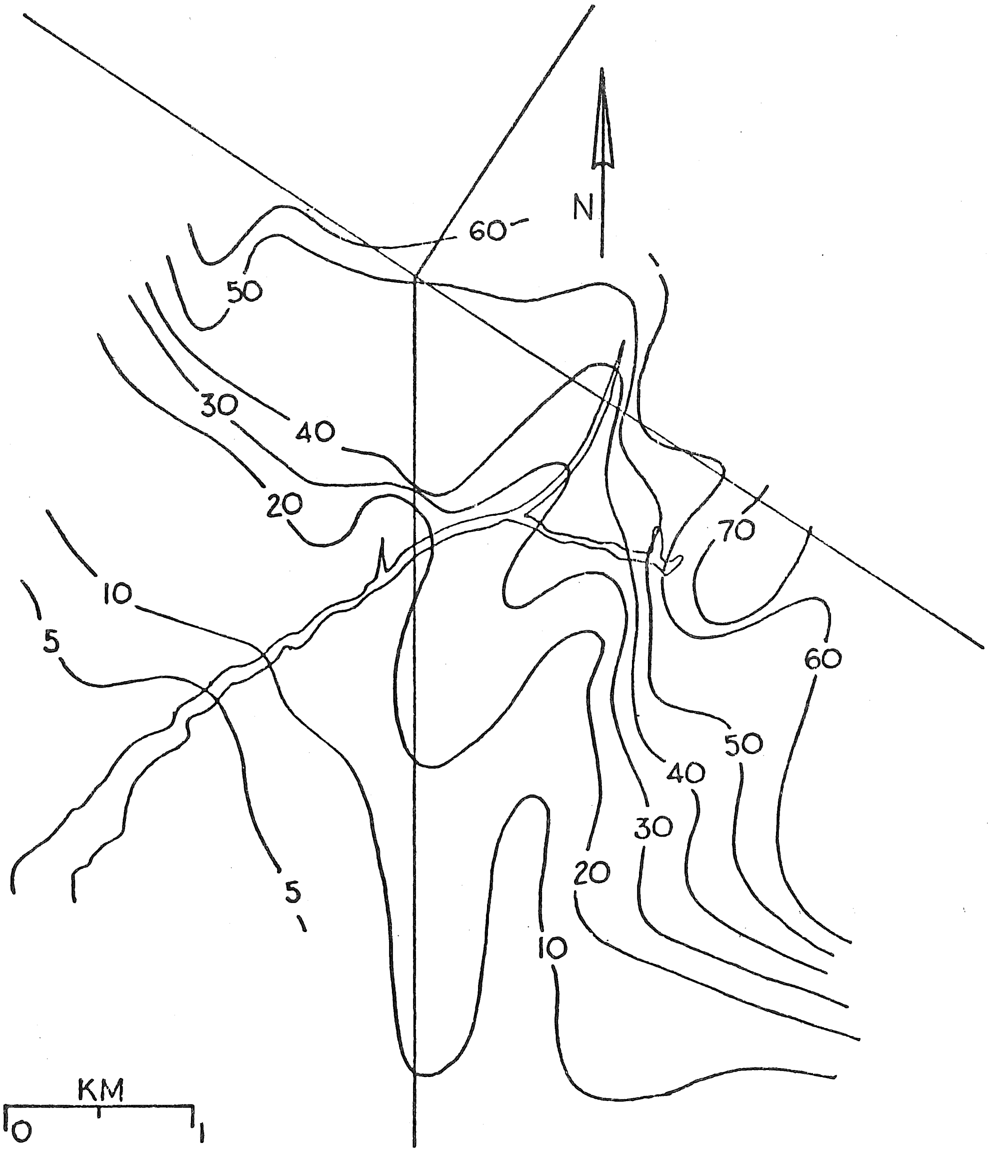

Figure 12. Contour map of terrain resistivity, 10m intercoil spacing with vertical coils (horizontal dipoles), Belle Meade, Florida. Resistivity in ohm-m.

contours indicate a reentrant, which together with the re entrant associated with Henderson Creek, flanks a seaward extension. This is an area of slightly higher elevation associated with a hard, shallow, limestone caprock. The higher resistivities are probably a result of both the low porosity of the caprock and higher resistivity pore fluids.

Figure 13 is the contour map for the 20m vertical coil resistivity measurements. The general pattern is very similar to the 10m map, except that the contours have moved inland, indicating the landward descent of the interface. Figure 14 is the contour map for the 40m vertical coil readings. This map is based on 34 points as compared with 51 for Figures 12 and 13. The general contour patterns are similar to the 10 and 20 meter maps. Resistivities are lower, and the resistivity gradients are more gentle. The landward reentrant of the interface along Henderson Creek is clearly defined, as is the general NW-SE strike of the interface.

Figure 15 is the depth to a chloride ion concentration of 250 mg/ℓ in 56 wells sampled by Jakob (1980). Of these wells 7 are South Florida Water Management District monitor wells and 49 are domestic wells. Stratified water samples could be obtained from the District wells, but the private wells give average chloride values. The shape of Jakob's map is strikingly similar to the 40 meter EM resistivity map (Figure 14). The only difference is that the EM data is somewhat more detailed near Henderson Creek. Comparison of contour values suggests that the 30 ohm-meter contour of Figure 14 closely parallels the 8 meter contour of Figure 15, suggesting that when resistivities obtained at the 40 meter spacing are less than 30 ohm-meters, high chloride content waters are within 8-10m of the surface.

Figure 16 is a contour map of the depth to resistivities equal to or

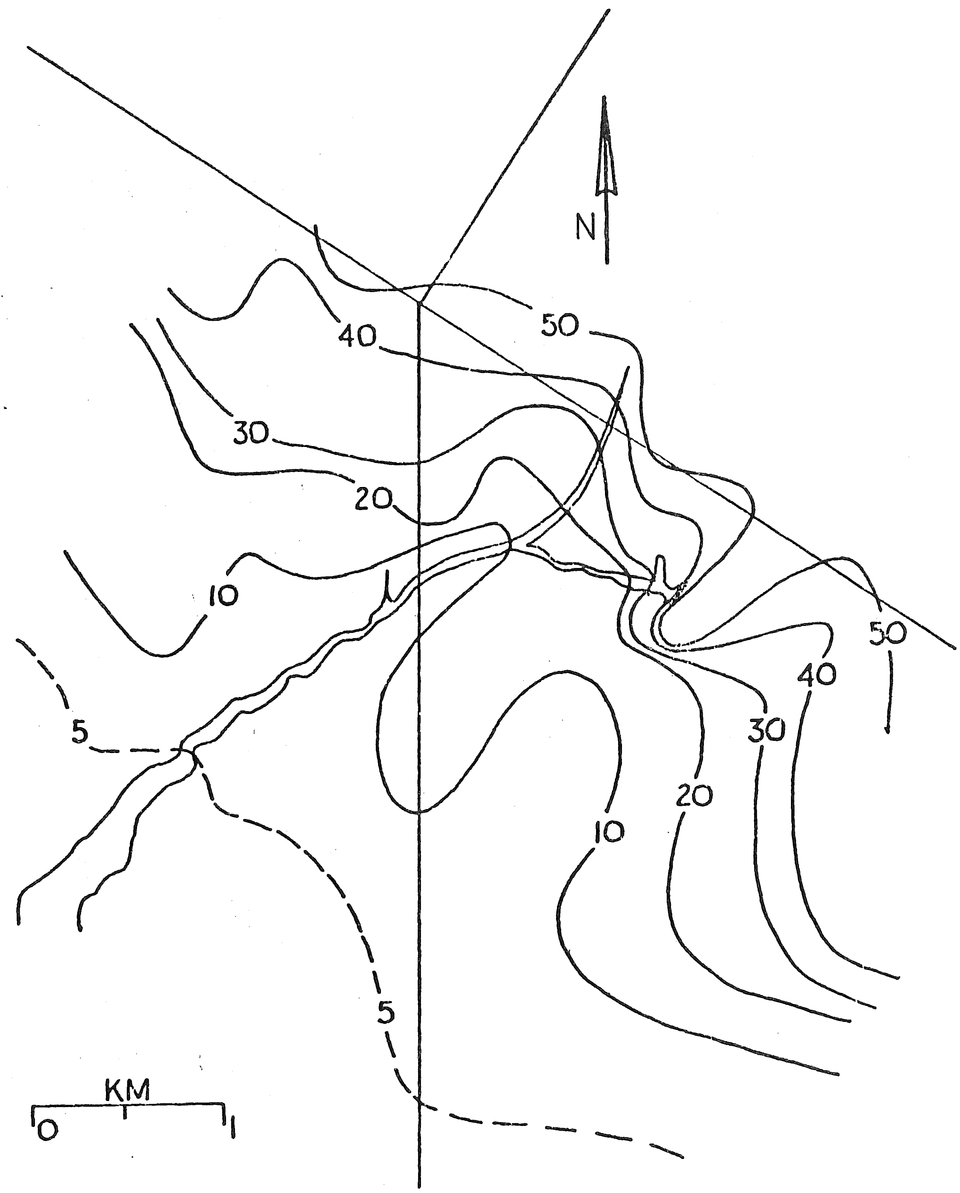

Figure 13. Contour map of terrain resistivity, 20m intercoil spacing with vertical coils (horizontal dipoles), Belle Meade, Florida. Resistivity in ohm-m.

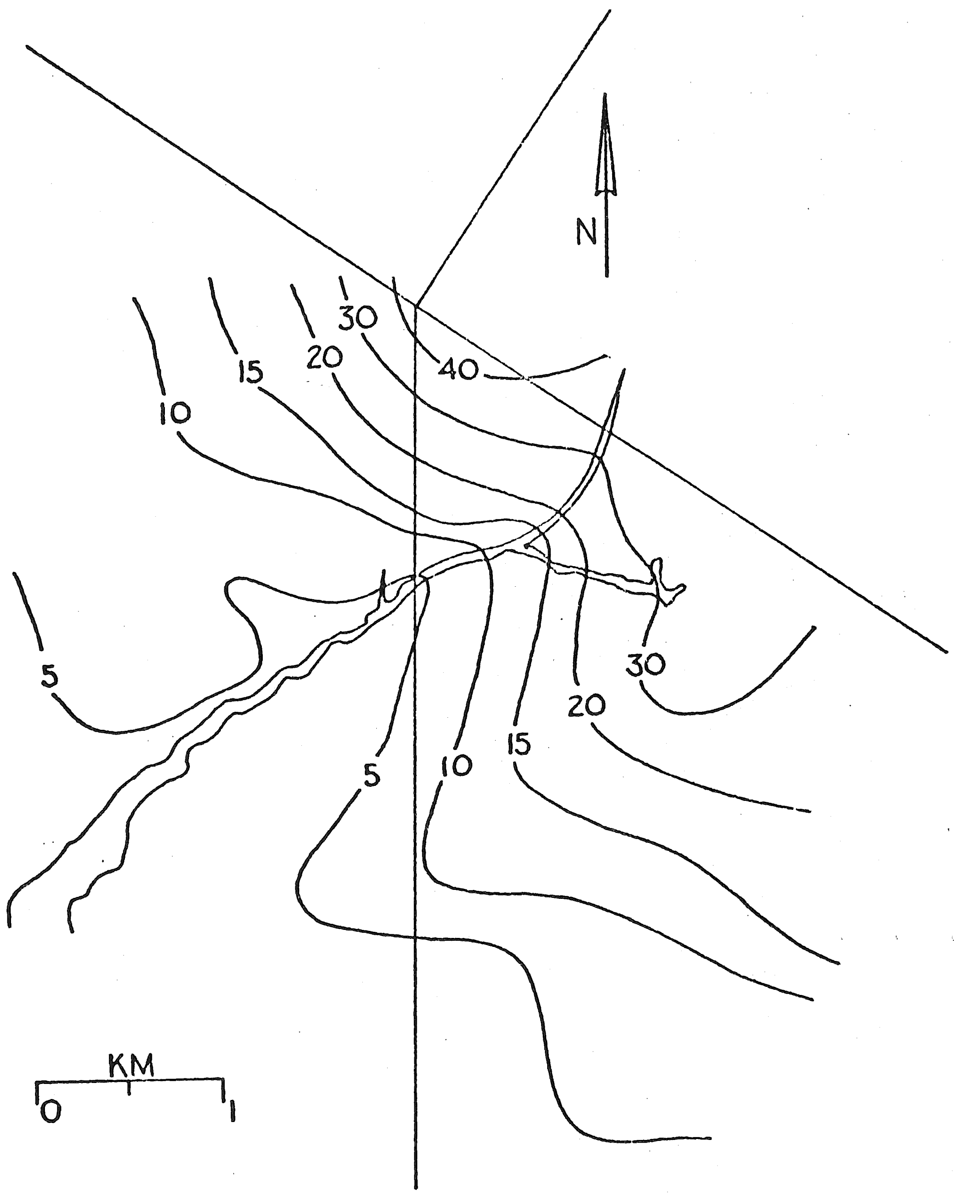

Figure 14. Contour map of terrain resistivity, 40m intercoil spacing with vertical coils (horizontal dipoles), Belle Meade, Florida. Resistivity in ohm-m.

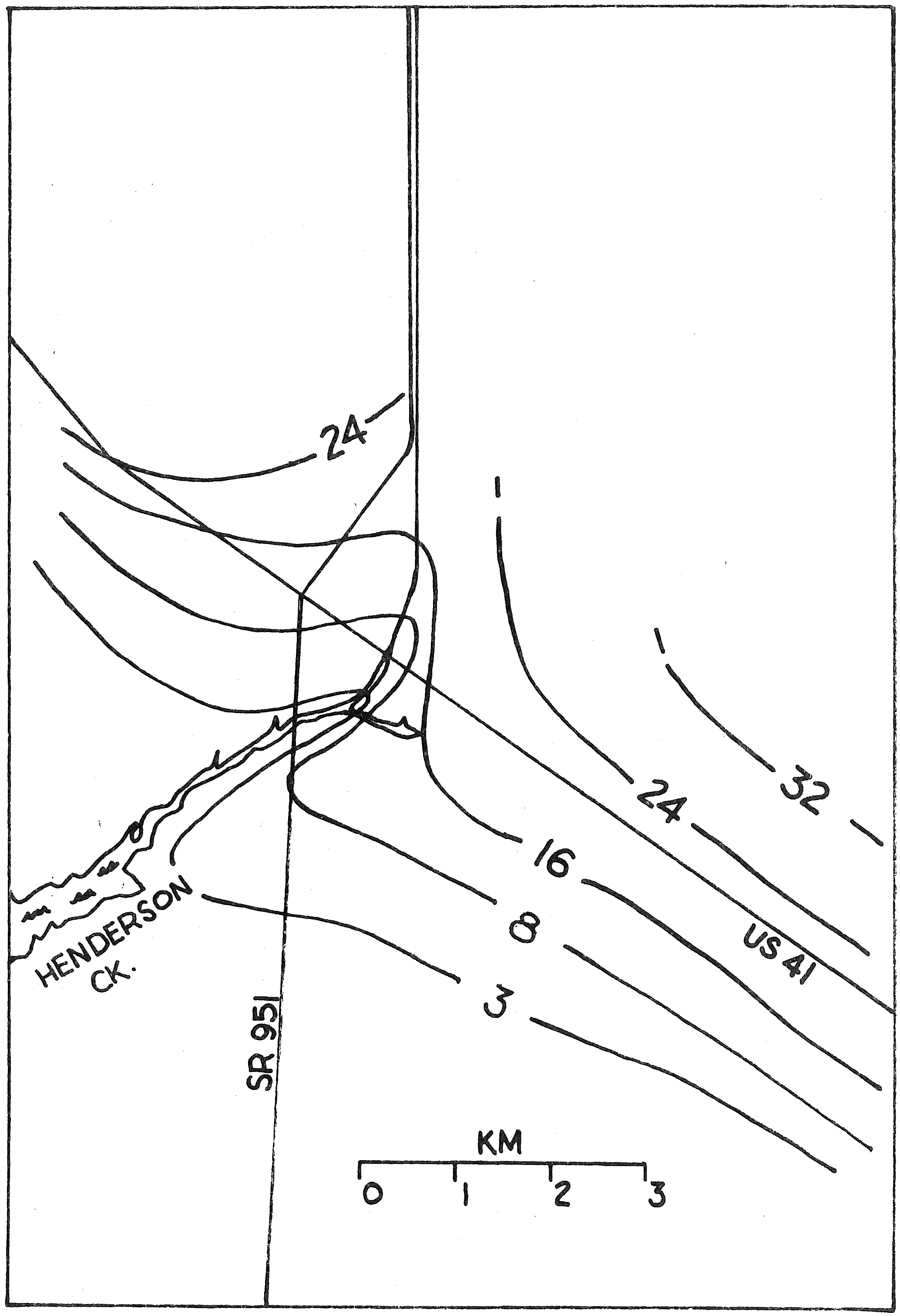

Figure 15. Depth to 250 mg/ℓ isochlor (Jakob, 1980), Belle Meade, Florida.

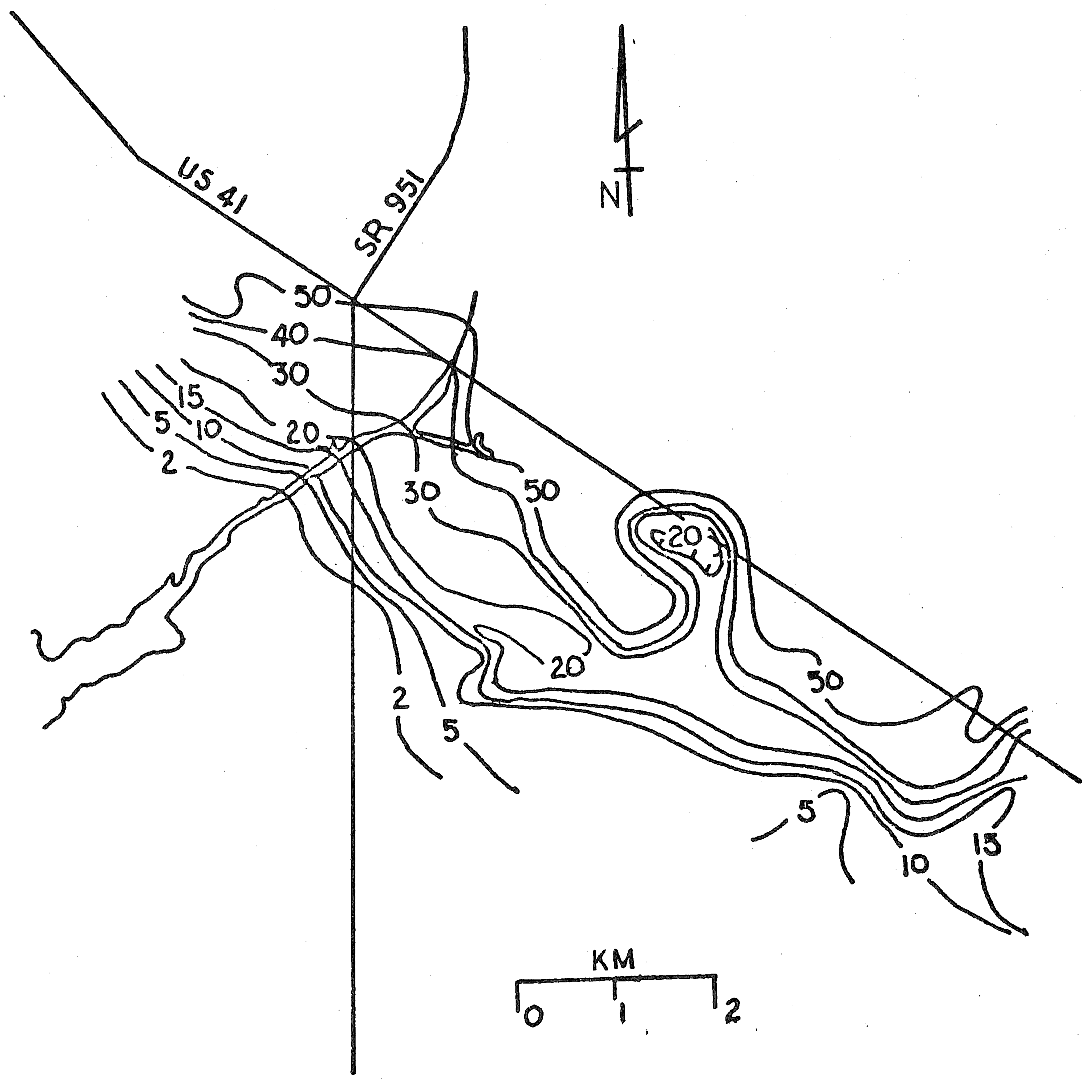

Figure 16. Contour map of the depth to a bulk resistivity of 10 ohm-meters or less, as determined by DC resistivity soundings (Stewart and others, 1981), Belle Meade, Florida. Depth in meters.

less than 10 ohm-m, based on data obtained from DC resistivity soundings (Stewart and others, 1981). This map is based on 94 vertical electrical soundings. Comparison with Jakob's map (Figure 15) and the three EM maps (Figures 12, 13, 14) shows that the general NW-SE trend of the interface is defined by all three methods (EM, DC, and wells). The well data of Jakob is most similar to the EM data, particularly the 40m readings. The DC data do not show as great an influence of Henderson Creek as the EM and well data. The DC data contours in the vicinity of Henderson Creek are more subdued and deviate less from the general NW-SE strike than the EM data. This may be partly the result of a greater EM data density along the creek as compared with the DC data. It should be noted that DC bulk resistivities of less than 10 ohm-meters have been correlated with chloride-ion concentrations in excess of 400 mg/ℓ in southwest Collier County (Stewart and others, 1981), while Jakob's data represent the 250 mg/ℓ isochlor.

Using the 10, 20, and 40 meter readings for either coil orientation, two-layer solutions may be obtained from EM conductivity data (McNeill, 1980). Using the graphical method described by McNeill, an attempt was made to obtain two-layer solutions for the 34 sites where values for all three coil spacings are available. Such two-layer solutions assume the simplest possible case of a uniform, fresh water saturated zone overlying a uniform, salt-water saturated zone. Because of the non-uniform geologic and hydrogeologic conditions in the Belle Meade area, at only 11 of the 34 possible sites could a two-layer solution be obtained. These solutions are listed in Table 2. Most of the two-layer solutions are from values obtained at sites close to Henderson Creek or coastal marshes. In these areas the salt-water interface is close to the surface, and the two-layer assumption is reasonable. When the interface is deeper, the section becomes electrically too complex for a

Table 2

Belle Meade two-layer solutions

station	ρ_1	ρ_2	h	comment
8	29	2	7.8	Near Henderson Creek
9	34	4.2	4.8	" " "
10	28.5	3.0	6.4	" " "
17	106	3	23	" " "
20	7.8	4	8	" " "
21	385	28.5	2.8	
34	18	2.8	4.5	Coastal marsh
36	3	1.7	22.5	" "
45	15	9	4.7	
46	71	16	3.4	
48	57	10	17	Upper end Henderson Creek

p_1 = resistivity of first layer in ohm-m

p_2 = resistivity of second layer in ohm-m

h = thickness of first layer in m

two-layer model to be fitted to the data. The interpretation procedure is uncomplicated, and such two-layer solutions may be useful where geologically and hydrogeologically justified.

Two conductivity profiles were obtained along SR 864 and the southern end of SR 951 (Fig. 17). The objective was to evaluate the sensitivity of the EM method for locating shallow, high-conductivity pore fluids in the shallow aquifer system. DC resistivity profiles and well sample conductivities delineate several zones of poor-quality water within 30m of the surface (Stewart and others, 1981). Figure 18 is a resistivity cross-section along SE 864 constructed from DC resistivity soundings, and Figure 19 is a similar section for that part of SR 951 between SR 864 and US 41. Figures 20 and 21 are the corresponding EM profiles.

Comparison of the EM resistivity values with the bulk resistivity values obtained from DC methods helps to illustrate the EM response to subsurface conductivity changes and serves as an example of EM interpretation. At station 3 on the 864 EM profile (Fig. 20), the low values of resistivity are due to the 10m resistivity zone between 3 and 23m on the DC profile. The response is the strongest for the 10m horizontal and 20m vertical and horizontal soundings. The 10m vertical response is influenced by the higher resistivities at 1-2m. At station 4 the influence of higher resistivities between 3-13m at the surface affects all of the EM soundings, but most strongly the 10m horizontal and 20m vertical, which both have effective depths of 15m. Between stations 4 and 6 low resistivities are present at the surface and both of the 10m EM soundings respond sharply. The 30 ohm-m contour (Fig. 18) descends between stations 6 and 9 and EM resistivities rise But a zone of lower resistivity from 5-12m at station 7 causes a low for both 20m EM soundings. The stronger response

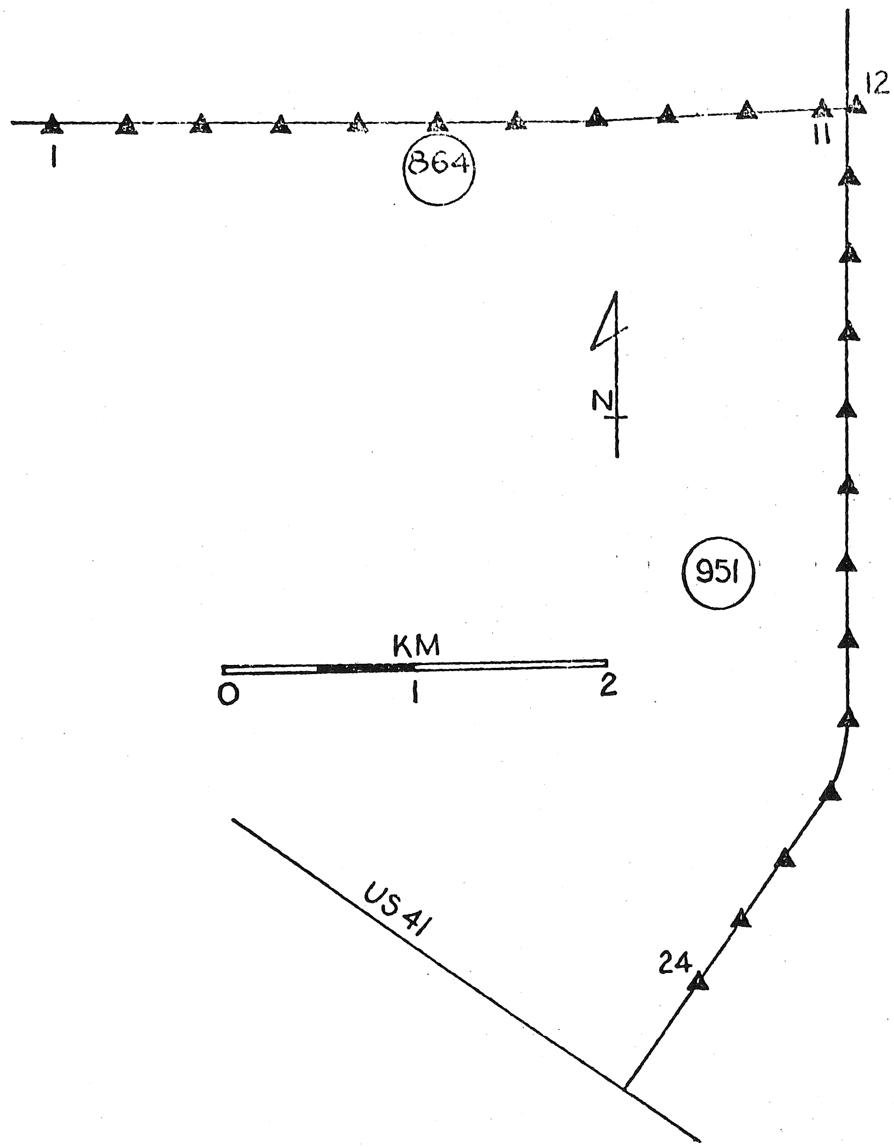

Figure 17. Electromagnetic sounding stations along SR 864 and SR 951, Collier County, Florida.

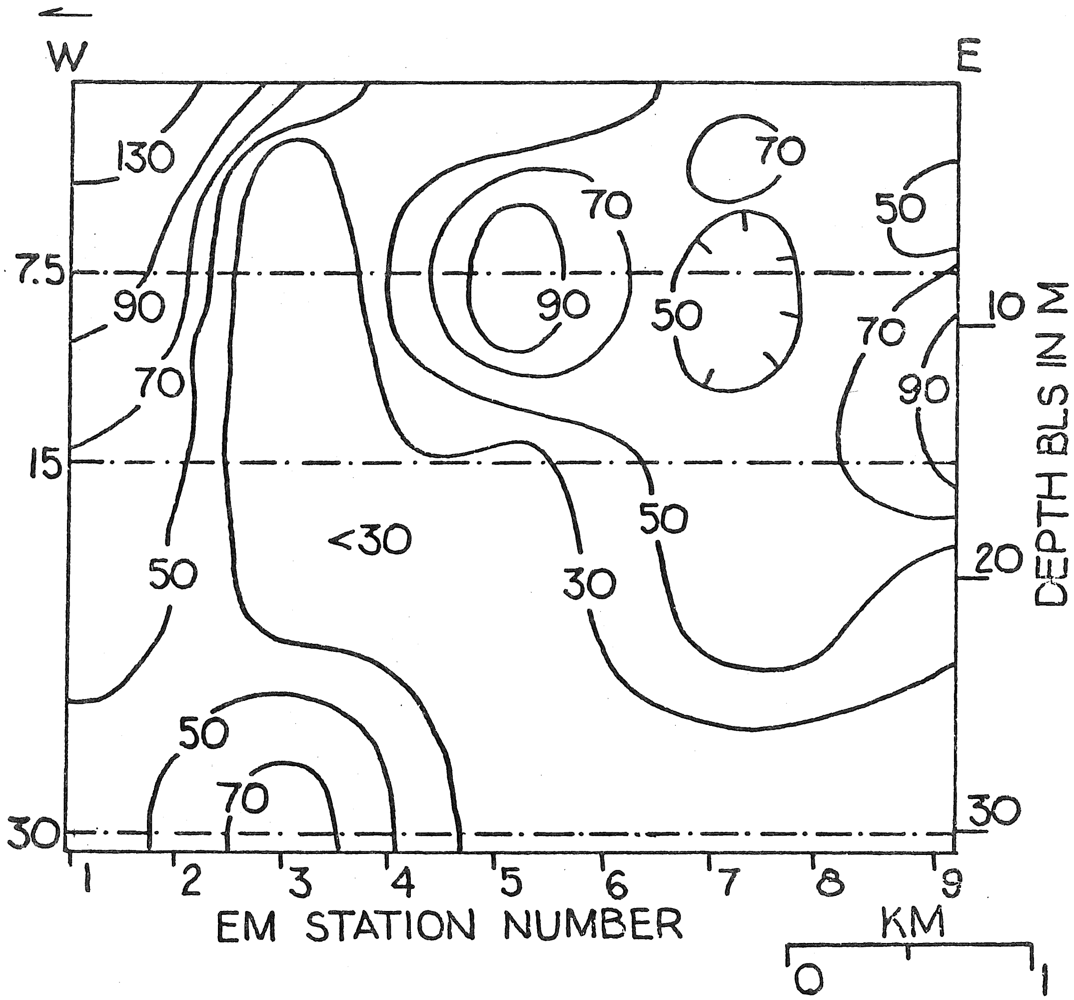

Figure 18. Resistivity cross-section along SR 864, as determined by DC resistivity soundings (Stewart and others, 1981), Collier County, Florida. Contours in ohm-m.

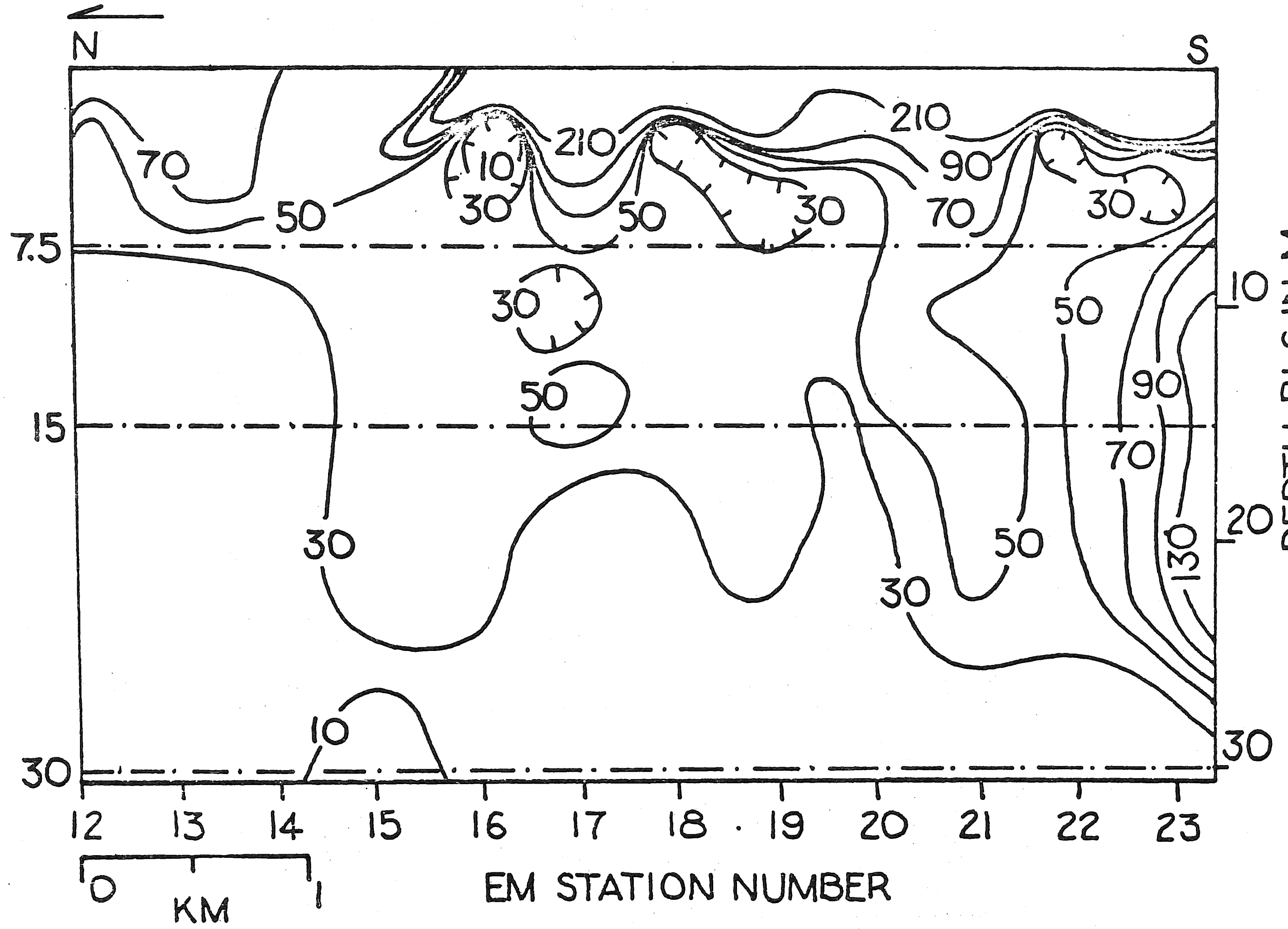

Figure 19. Resistivity cross-section along SR 951, as determined by DC resistivity soundings (Stewart and others, 1981), Collier County, Florida. Contours in ohm-m.

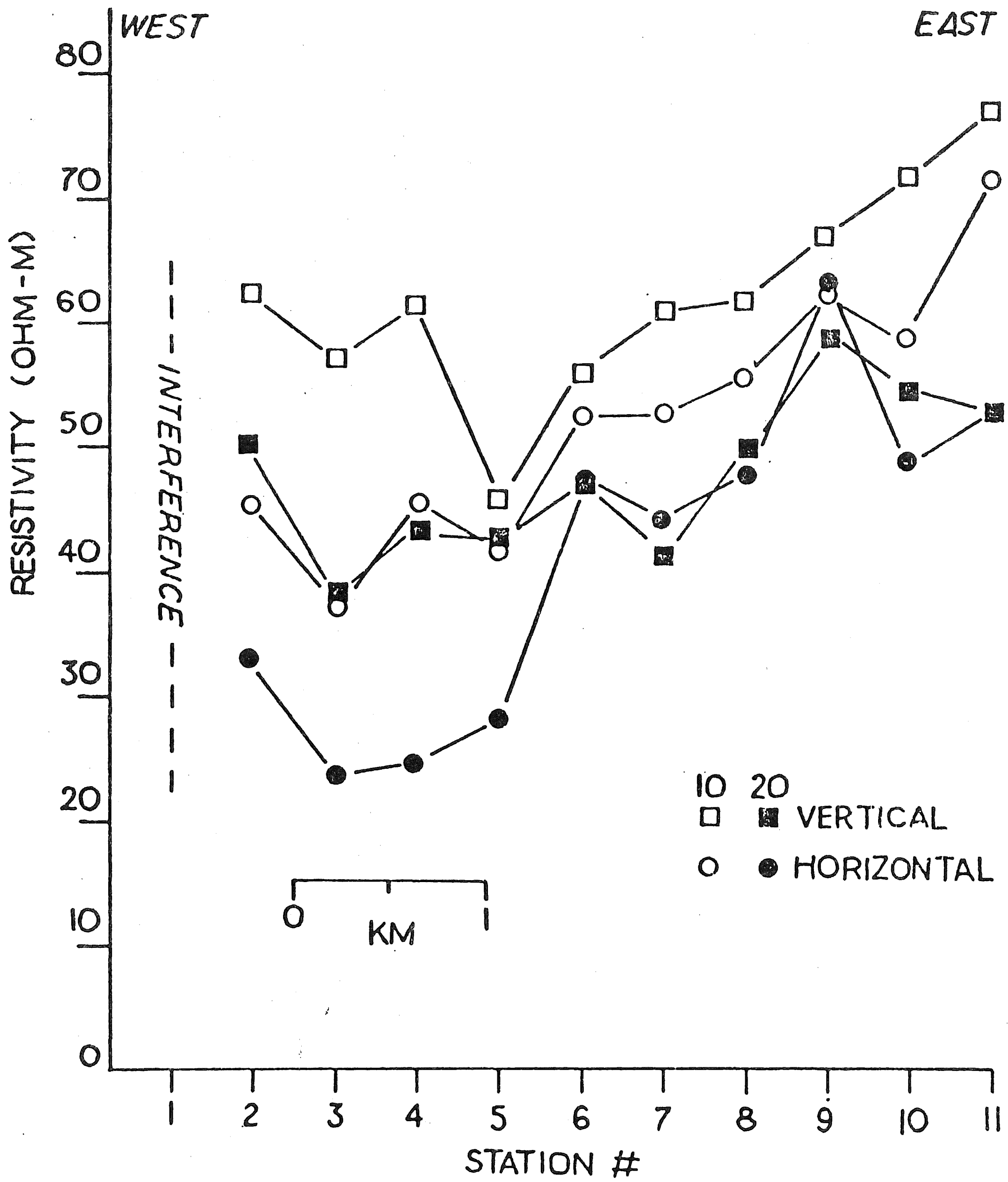

Figure 20. Electromagnetic resistivity values for stations along SR 864, Collier County, Florida.

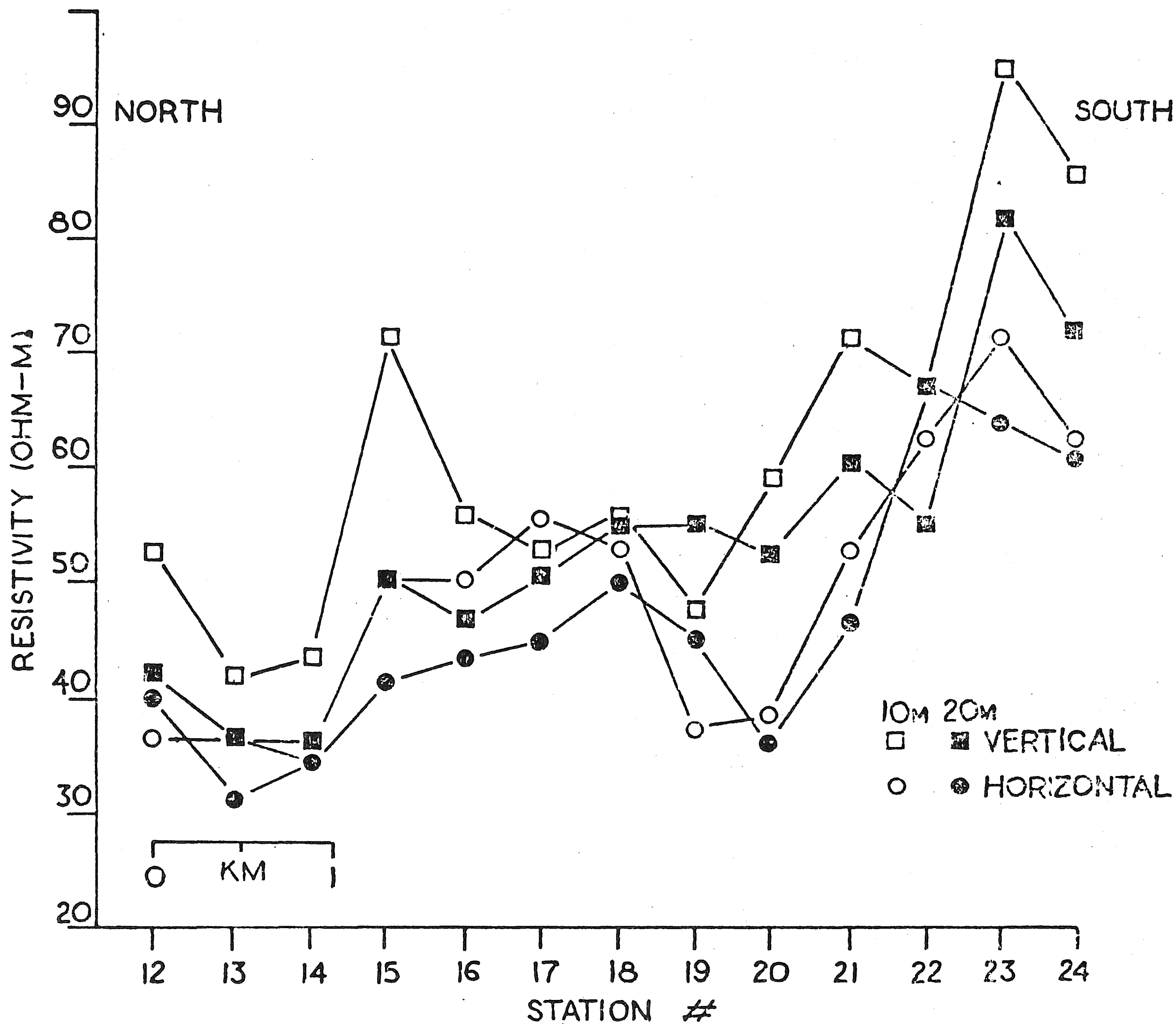

Figure 21. Electromagnetic resistivity values for stations along SR 951, Collier County, Florida.

of the 20m vertical reading as compared to the 20m horizontal value suggests that the low resistivity zone is above 15m, as shown on the DC profile.

A similar DC/EM comparison can be made for the SR 951 profiles (Figs. 19, 21). At stations 12-14 the low EM readings reflect the shallow depth of the 30 ohm-m bulk resistivity contour on Figure 19. At station 15 the edge of a very well-indurated, very resistive limestone caprock creates a high on the EM profile, with the very strong response of the 10m vertical reading suggesting a shallow source (<7.5m). An isolated low resistivity zone at stations 16-17 causes a low EM resistivity value in the shallow EM soundings. A zone of poor quality water is near the surface at station 18 and descends until station 20. All EM soundings show a corresponding resistivity low, with the responses of the deep EM soundings shifted toward the south, suggesting a low resistivity zone descending toward the south, as indicated on Figure 19. A shallow low resistivity zone at station 22 causes lower readings for both the 10 and 20m vertical EM soundings. An increase in the caprock thickness and higher resistivities at depth lead to higher EM readings at station 23. The cause of the decline in resistivities indicated by the 20m horizontal sounding is not obvious on the DC profile.

In south central Collier County, Nuzman (1970) reports a zone of high conductivity pore waters at shallow depths in test well 8-72 (Figs. 6, 22). This area was investigated with the EM terrain conductivity meter to determine the utility of using EM surveys for defining small, site-specific ground water problems. Chloride ion concentrations of shallow ground water in the southern Golden Gates area, as determined by Nuzman (1970), are highest in the vicinity of well 8-72 (Fig. 22). Two survey lines, east-west and north-south, were centered on well 8-72 (Fig. 23).

Figure 24 is a plot of the EM resistivity values for the east-west section. There is a general decrease in resistivities from station 39 to 34, with

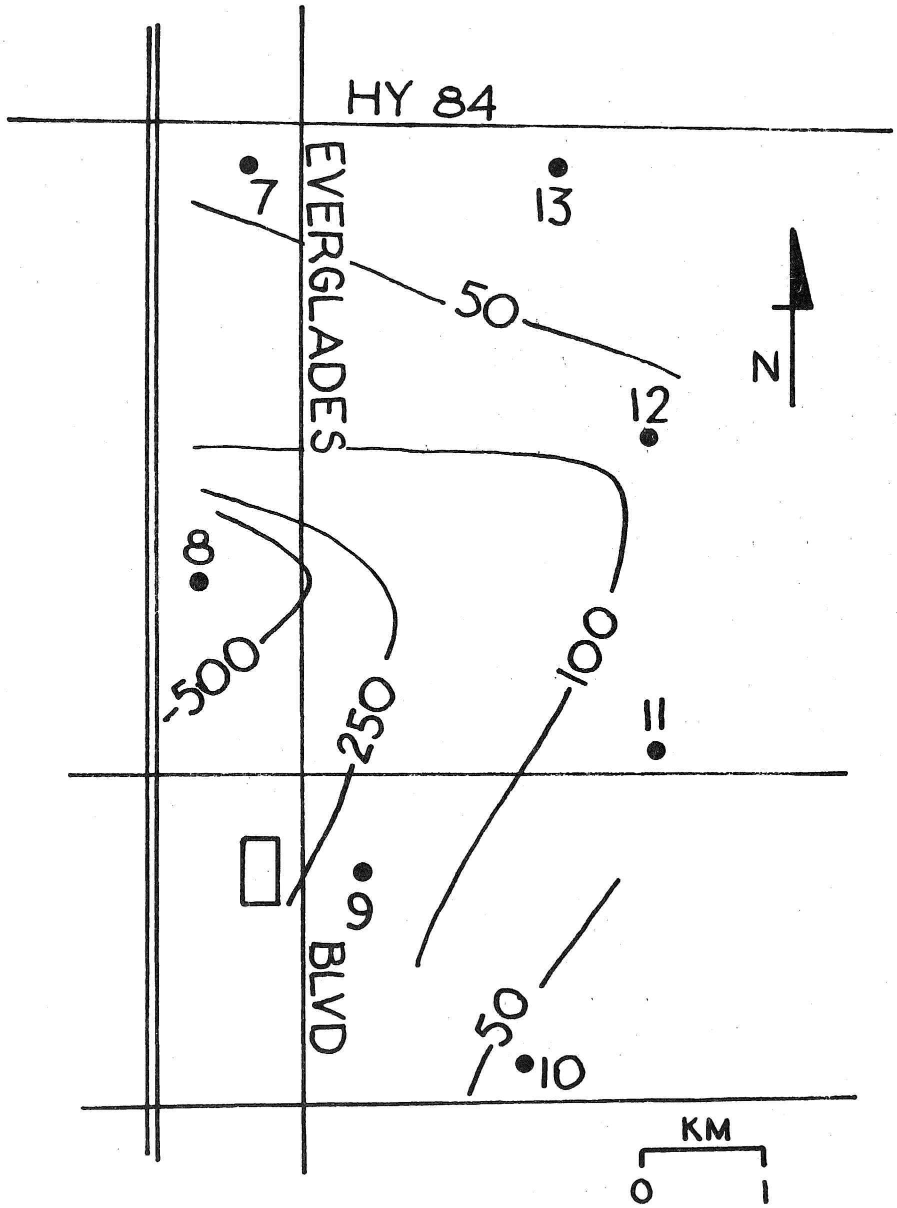

Figure 22. Contour map of chloride ion concentration of shallow ground waters (Nuzman, 1970), south central Collier County, Florida. Contours in mg/ℓ.

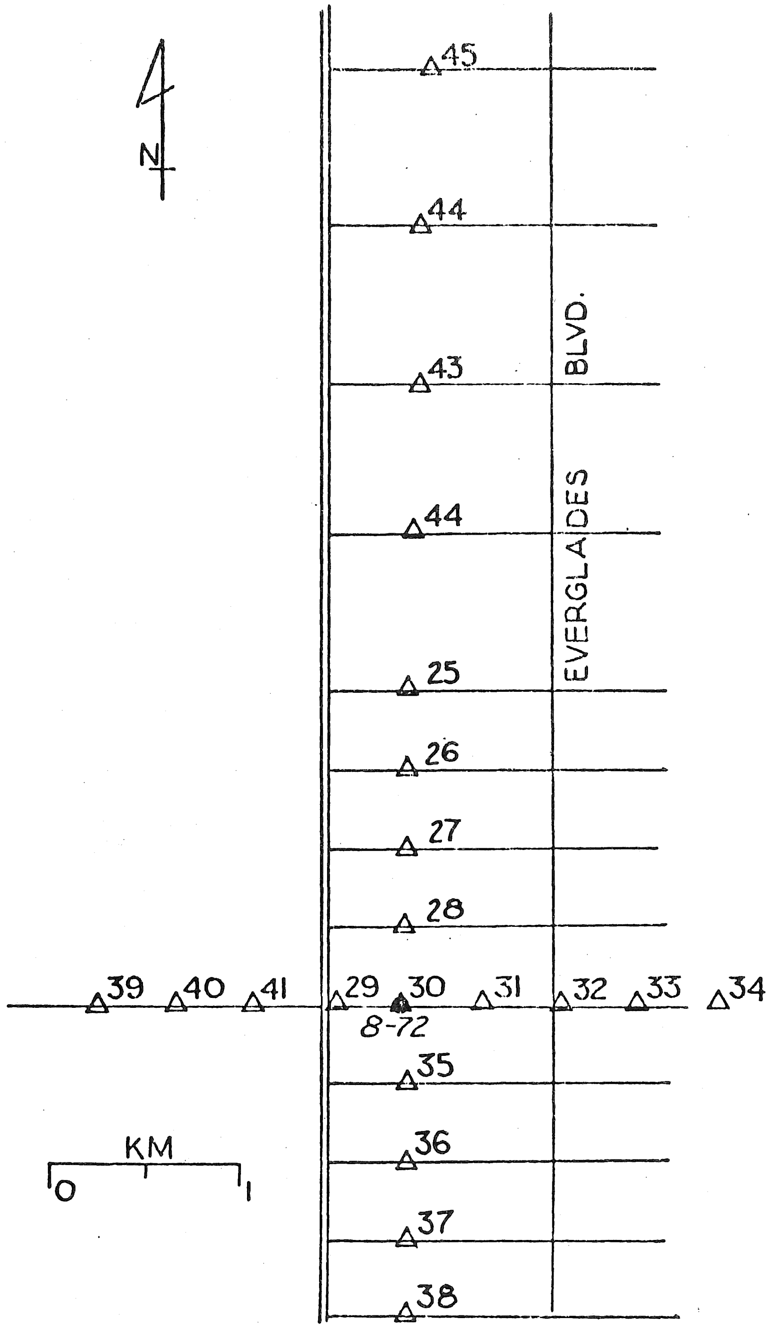

Figure 23. Location of electromagnetic sounding stations, south Golden Gate Estates, Collier County, Florida.

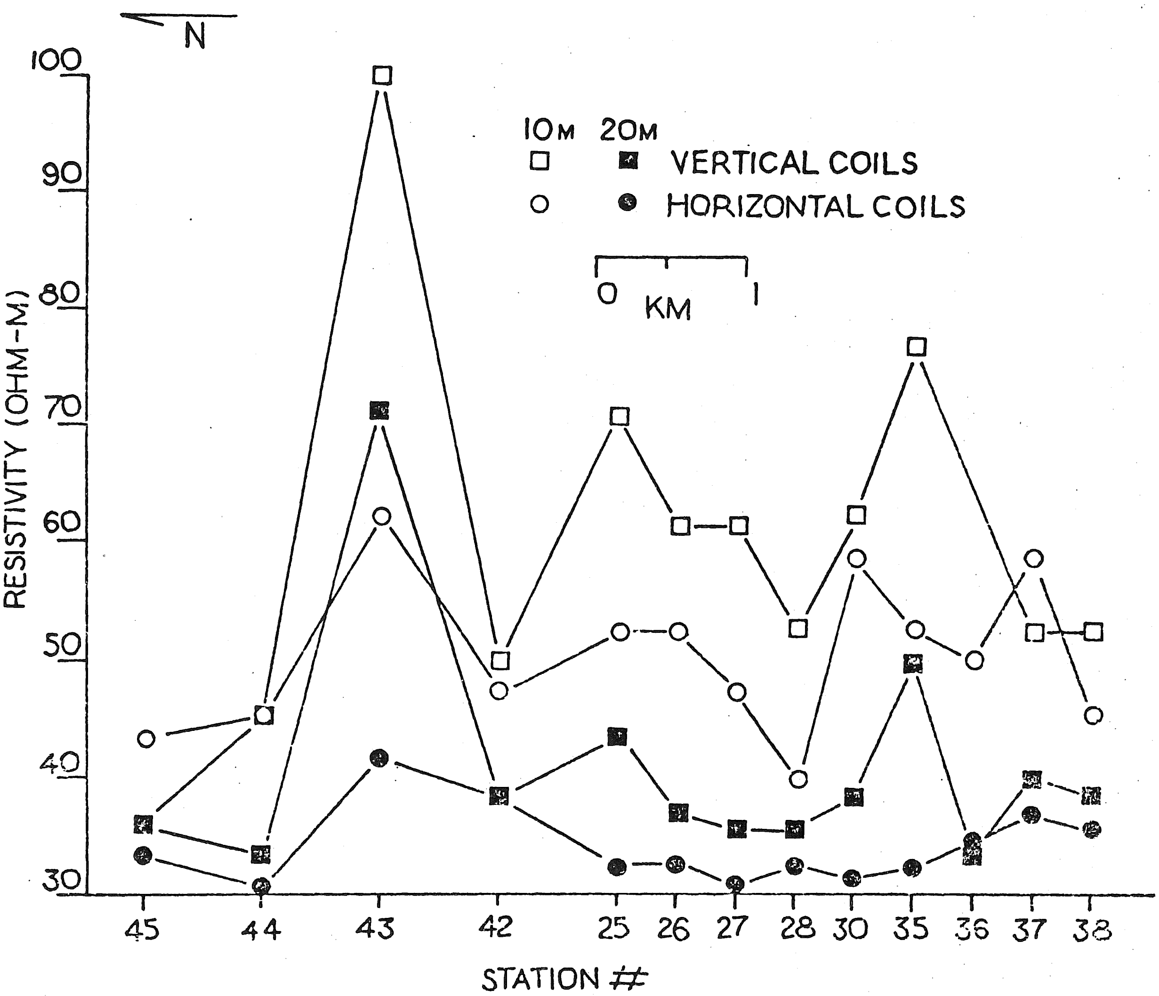

Figure 24. North to south electromagnetic resistivity profiles, south Golden Gate Estates, Collier County, Florida. Resistivity in ohm-m.

a local minimum at station 31 for the 10m vertical and horizontal readings, and the 20m vertical. The 20m horizontal coils reading shows a minimum at station 30, the location of well 8-72.

Figure 25 is a plot of the north-south profile. The EM resistivity values vary widely on this profile, and there is no discernible regional trend. The 10m coil spacing yields a sharp low for both the vertical and horizontal coil positions at station 28. The 20m vertical spacing defines a broad low resistivity zone between stations 26 and 30. The horizontal coil configuration readings indicate a somewhat broader low between stations 25-35. It is interesting to note that the low resistivity values at stations 44 and 45 correlate with an area of shallow low resistivities defined by DC soundings (Stewart and others, 1981).

Figures 26 and 27 are contour maps of the EM resistivity values in the vicinity of well 8-72 for the 10m and 20m coil spacings, respectively. Although the station locations are not ideal for accurately drawing contours, a consistent pattern emerges from the four combinations of coil spacing and configuration. A resistivity low is present in the vicinity of stations 28, 30, and 31. Along both the north-south and east-west profiles resistivities increase away from this area. The EM data are not sufficient to determine the cause of the low resistivity zone. However, the high sulfate content reported by Nuzman (1970) in well 8-72, and the limited extent of the low resistivities suggest upward movement of mineralized waters from the underlying, artesian lower Tamiami, Hawthorn, and Floridan systems. The pathway for such movement is unknown, but two possibilities are vertical solution channels in the karstic limestones, or an improperly abandoned deep well, possibly an oil and gas exploration well.

Survey Costs

Acquisition of EM data can be very rapid. In this study soundings were

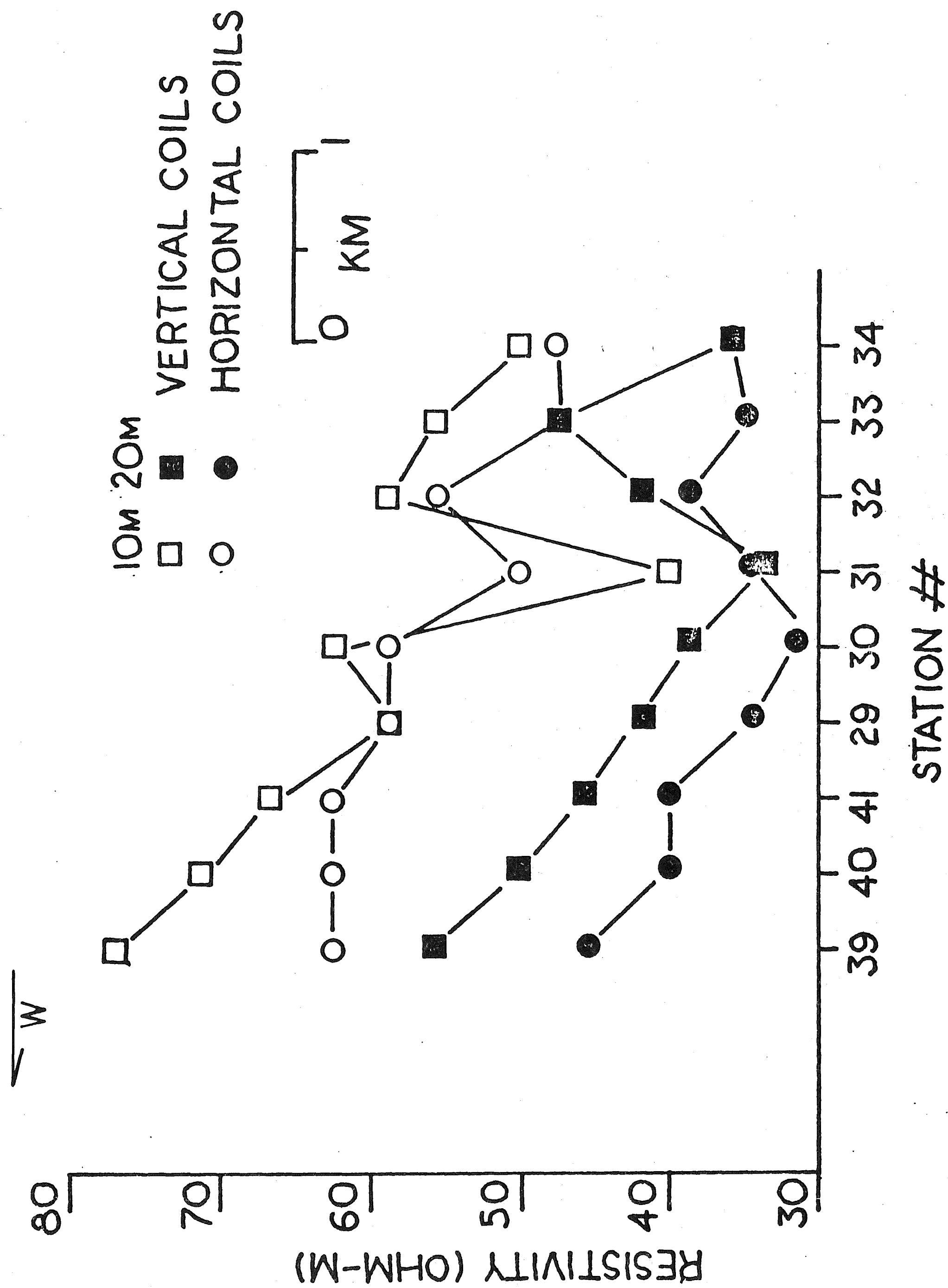

Figure 25. West to east electromagnetic resistivity profiles, south Golden Gate Estates, Collier County, Florida. Resistivity in ohm-m.

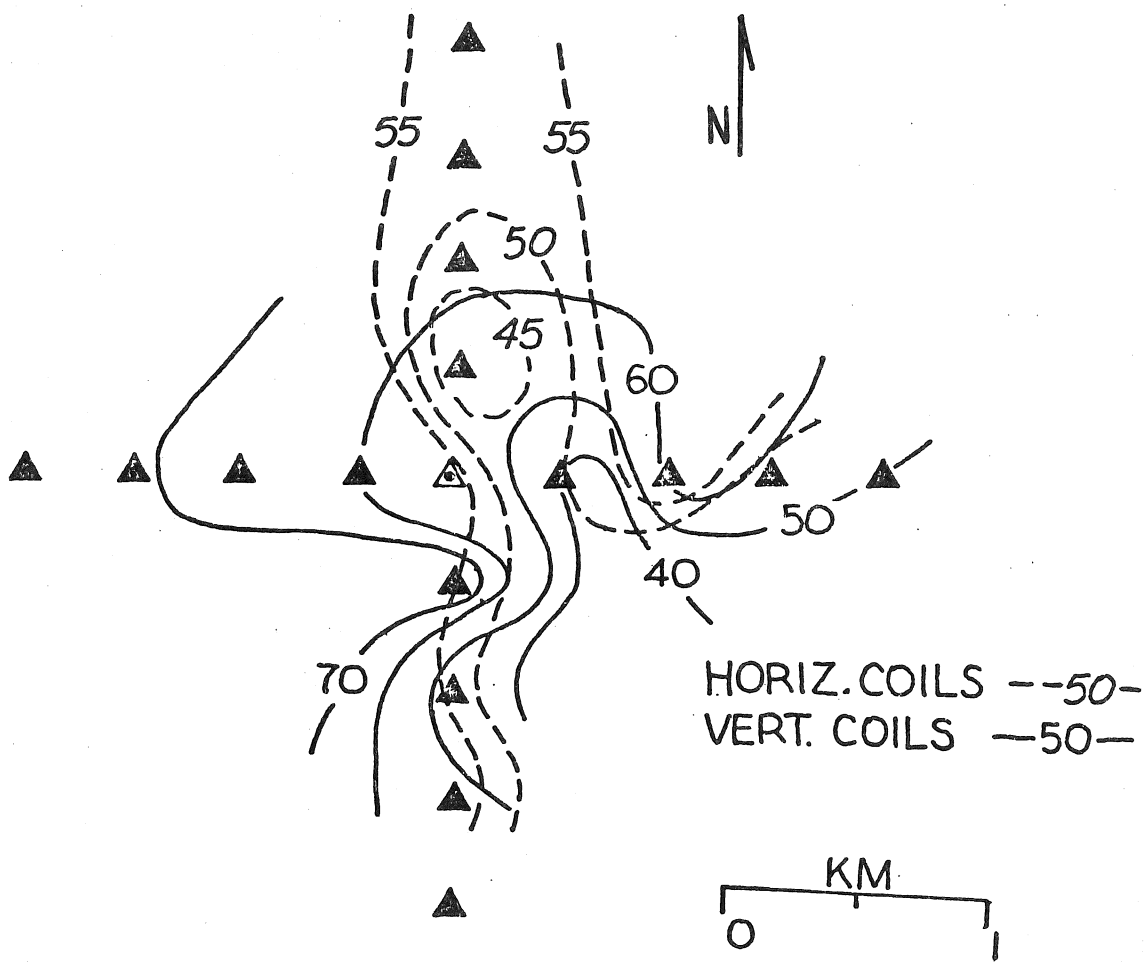

Figure 26. Contour map of electromagnetic resistivity for 10m intercoil spacing, south Golden Gate Estates, Collier County, Florida. Contours in ohm-m.

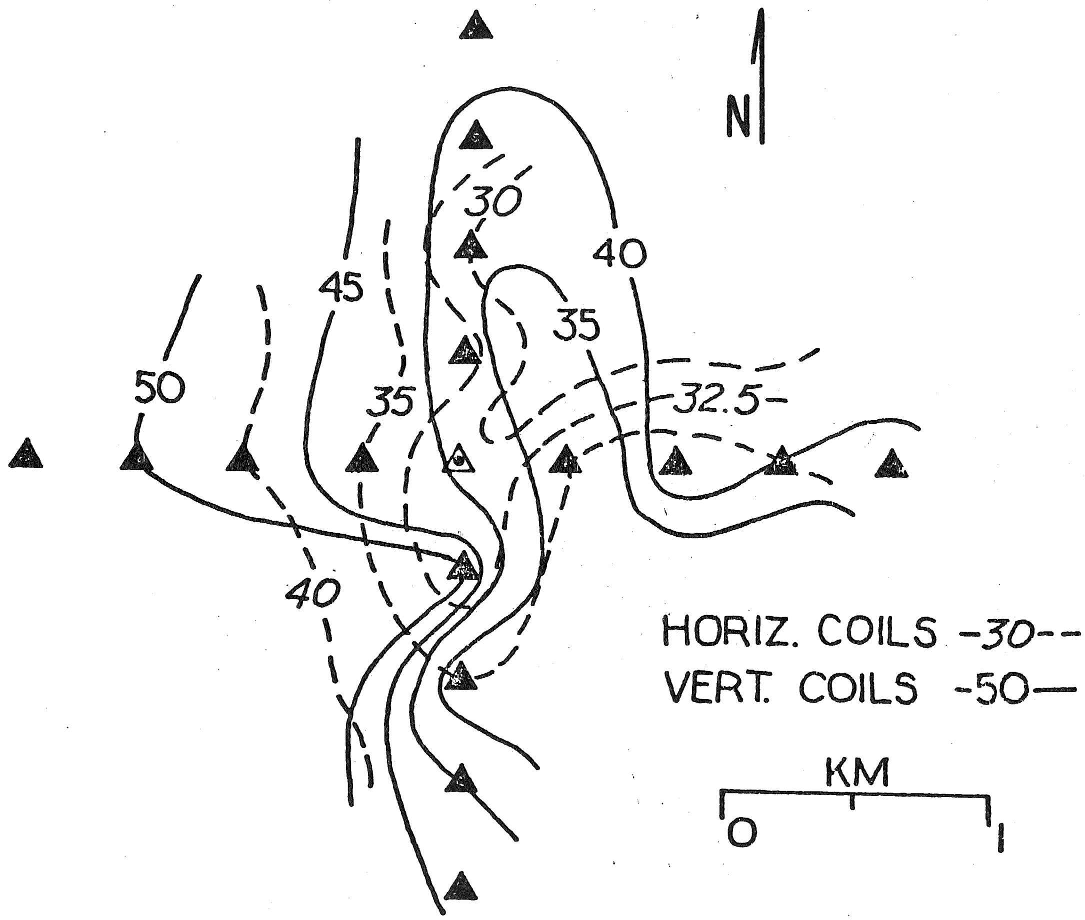

Figure 27. Contour map of electromagnetic resistivity for 20m intercoil spacing, south Golden Gate Estates, Collier County, Florida. Contours in ohm-m.

completed at a rate of 5-10 soundings per working hour. The rate depends on whether all three intercoil spacings are utilized and the distance between stations. In this study stations were a minimum of 430m apart, and driving time constituted a significant proportion of the total survey time. In studies with closely spaced stations, a rate of 20 soundings per hour is possible.

The ideal field crew is two persons. One person holds the transmitter coil and console while the other holds the receiver coil and console, determines the proper coil spacing, and records the reading. One-person surveys would be possible by using a simple wooden stand for the transmitter coil, or by using only the horizontal coil (vertical dipole) configuration. At the 10m spacing, the coils could be placed on booms mounted on a vehicle. With a two-person field party, survey rates will vary between 2.5 to 10 soundings/person-hour.

For comparison with DC and monitor well studies, costs can be estimated for the Citrus County and Belle Meade interface studies. In Citrus County, the Mills and Ryder study used 6 monitor wells with an average depth of 100 feet. Assuming an installation cost of $30/foot of properly constructed chloride monitor well, the cost is $3,000 per well, or $18,000 for all 6 wells. The DC resistivity study by Fretwell and Stewart (1981) used 28 DC soundings. A two-person field crew completed 4-5 soundings per day, for a total cost of $250/day, or about $1750 to acquire the soundings. Sounding interpretation averages 2 hours per sounding, for a cost of $50, or $1400 for 28 soundings. The basic DC survey cost then is $3150. The EM survey consists of 50 data points. The soundings were completed in one field day by a party of three. Total personnel and instrument costs were $380. As the instrument reads directly in conductivity, no additional interpretive effort is required.

The Belle Meade study of Jakob (1980) used 7 specially constructed wells, and 49 wells of opportunity. The 7 monitor wells could be constructed for $4,000 each. Stratified sampling of the 7 wells and single samples of the 49 wells of opportunity would require 5 days. Total field time would be 20 days, or $2,000. Analysis of the 56+ samples would cost $1500. Basic cost of the survey would be about $31,500. Stewart and others (1981) completed a DC resistivity survey of the same area, using 94 soundings. The data acquisition required about 20 field days for a personnel and instrument cost of $6,000. Interpretation required about 200 hours, or $5,000. Total cost was about $11,000. The 52 EM soundings required 2.5 field days using 3 people. Total personnel and instrument cost was $950. Again, as the instrument reads directly in conductivity, no involved interpretation is necessary. Converting conductivity to resistivity and entering the data on a map might require a few hours, or a total survey cost of about $1,000.

These costs are for illustration only. They do not include any additional interpretive effort, overhead, or travel costs. Everything is assumed to work correctly, i.e. all field time is productive. However, rough as these estimates may be they do illustrate the high cost of direct sampling procedures (wells). Indirect sampling procedures (geophysics) are less precise, but considerably cheaper. The most cost-efficient use of direct methods is to provide baseline data and calibration for indirect methods. Indirect methods (EM and DC surveys) suffer from ambiguities in interpretation unless geologic and water quality data are available for calibration. However, some of the uncertainties in geophysical interpretation can be overcome with calibration and a large number of data points. As indirect methods are so much less costly, much more information can be obtained for less cost. Relying on widely scattered sounding sites for EM or DC surveys severely limits the confidence in defining the target, such as the salt water interface.

Indirect methods are an excellent method for locating suitable sites for monitor wells. As direct methods are very costly, efficient placement of sampling points greatly improves the cost-efficiency of a sampling or monitoring program. For example, both the Citrus County and Belle Meade salt water interface studies reveal irregularities in the interface configuration. Knowledge of the general configuration and location of the interface would obviously improve the chances of locating monitor wells in effective sites. In this application, the EM method would be used to broadly define the interface and identify anomalous areas. Because of the rapidity and ease of interpretation of the EM survey method, areally extensive studies with many data points are not prohibitively expensive.

CONCLUSIONS

Evaluation of EM Method

Comparison of electromagnetic terrain conductivity measurements with direct current resistivity surveys and traditional monitor well surveys reveals several advantages of the EM survey method. The EM method is very rapid. Forty or fifty soundings can be completed in a field day compared to 5-10 DC soundings and the days required to drill and construct a monitor well. As the instrument reads directly in units of conductivity, no involved interpretation of the field data is required, and data can be plotted and evaluated in the field. Operation of the instrument is simple and requires no special training on the part of the operator. The instrument is very portable and does not require ground contacting electrodes or long intercoil spacings. The maximum intercoil distance required to sound to a depth of 60m is 40m. Because of the portability of the instrument and the small space required for a sounding, site selection can be very flexible.

Qualitative interpretation is relatively easy and does not require special geophysical training, but only familiarity with the instrument and its response to conductivity changes (Figs. 7, 8). As effective sounding depth is a function of intercoil spacing and coil position (horizontal or vertical) and is independent of conductivity, the variation of resistivity with depth and the approximate depth of conductivity changes can be interpreted from the variation in conductivity obtained at different intercoil spacings. Comparison with DC resistivity profiles in Collier County (Figs. 17-21) shows that reasonable estimates of the variation of conductivity with depth can be made directly from the EM field data. Simple quantitative solutions can be obtained where the geology is not complex or heterogeneous (Table 2).

The method is very good at defining the details of the salt-water interface configuration. Comparison of contours of resistivity from EM soundings with DC and monitor well data maps shows good general agreement (Figs. 5, 9, 10, 12-16). The EM method seems better suited to outlining the shape of the interface than DC or monitor well surveys because of the increased site flexibility, low cost, rapidity, and sensitivity to relatively small changes in conductivity.

The evaluation also revealed several disadvantages of the method. Although capable of sounding to depths of 30 and 60m using the 40m intercoil spacing, interference at this spacing limits site availability. Readings at this spacing are sensitive to powerlines, unshielded electric motors, and lightning. In the Belle Meade study 40m readings could only be obtained at 65% of the sounding sites. Although the instrument reads directly in units of conductivity, location of the salt water interface can only be determined approximately unless the EM data can be calibrated using more direct methods. Also as the instrument response is integrated over the effective sounding depth, small, isolated conductivity changes may be overlooked. Interpretation of the EM data is necessarily less direct than interpretation of DC soundings or well data. Only the simplest quantitative solutions are possible, and most interpretation is limited to qualitative estimates of the variation of conductivity with depth.

Recommendations

The EM terrain conductivity method is very useful for rapid, inexpensive ground water surveys where the objective is to locate zones of conductive pore fluids at depths of less than 30-40 meters. Although interpretation is indirect and qualitative, neither data acquisition or interpretation require special training. This characteristic of the EM method makes it very suitable for use by agencies where highly trained technical personnel are not available.

The Belle Meade and Citrus County studies illustrate that the EM method can successfully outline the seaward margin of the fresh water zone in shallow coastal aquifers. Because of the low cost and minimal field time for data acquisition, large areas of coastline can be surveyed and assessed quickly and inexpensively. As the geology of a coastal aquifer system remains constant with time, any changes in conductivity must be due to changes in the position of the salt water interface. Although it is difficult to precisely determine the interface depth with EM data, the instrument is very sensitive to changes in conductivity and movement of the interface will be revealed by shifts in the position of conductivity contours. Because of the low cost and ease of EM surveys, large areas could be monitored frequently to detect salt-water intrusion.

EM surveys can effectively locate sites for salt-water monitor wells. Well construction is expensive, and the comparatively minor cost of an EM survey is worth the additional information it will provide. The Belle Meade and Citrus County studies show significant landward reentrants and seaward

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