Time Domain Electromagnetic Soundings for Mapping Sea-Water Intrusion in Monterey County, California

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ABSTRACT

In November 1986, a surface geophysical survey was performed in Monterey County, California using Time Domain Electromagnetic (TDEM) soundings. Prior to this time, the Monterey County Flood Control and Water Conservation District had relied largely on water quality samples from monitoring wells to determine the extent of sea-water intrusion in the Salinas Valley. This monitoring program had found that of the three aquifers in the study area, two aquifers, the "180-ft" and the "400-ft," had been intruded. The third aquifer, the "900-ft" aquifer, had not shown signs of sea-water intrusion. The District decided to use surface geophysics to obtain information about water quality between monitoring wells and to contour the position of the 500-ppm isochlor in both of the upper aquifers.

Because the conductivity of water increases with chloride concentration, electrical methods are well-suited for mapping chloride concentration in ground water. The TDEM sounding method was selected as the surface electrical measurement technique. It had proven successful for mapping interfaces between fresh water and salt water on surveys in Cape Cod, Massachusetts, in several areas in Florida, and in southern California. A total of 100 soundings were measured in the project area, requiring three weeks of field work. The soundings were located by using the information available from monitoring wells. Lines of soundings were run approximately perpendicular to the anticipated position of the 500-ppm isochlor to better define the location of the isochlor.

Several soundings were measured adjacent to wells to aid in correlating the geophysical interpretations to known water quality data. By correlating the surface geophysics to water quality data from monitoring wells, the position of the 500-ppm isochlor could be mapped in both the "180-ft" and "400-ft" aquifer.

The positions of the contours of the 500-ppm isochlor derived from monitoring wells and from 100 TDEM soundings show excellent agreement. There is more local detail in the isochlor contours derived from geophysical interpretations than in the contours derived from monitoring wells, mainly because of the higher TDEM station density.

1.0. INTRODUCTION

Sea-water intrusion in the Salinas Valley coastal aquifers was first recognized in the mid-1930s. Since then, it has spread into the ground-water aquifers beneath thousands of acres of prime agricultural land. The economic threat to agriculture and municipalities in the intrusion area has become increasingly pronounced as solutions to combat this menace are studied.

Recently, an agreement was reached between members of the agricultural community, a local municipal water district, and the United States Army at Fort Ord. This agreement involves the implementation of a solution which will ultimately bring a halt to sea-water intrusion. The conceptual solution is to supply the affected area with an alternative water supply and to eliminate pumping within a defined project area. However, the definition of the project area boundaries poses a number of logistical, economical, and political questions. Hence, the need arose to rapidly determine the extent of sea-water intrusion.

In November 1986 a surface geophysical survey was conducted to map the extent of chloride contamination in two heavily utilized confined aquifers. The objectives of the survey were to delineate the position of the 500-parts-per-million (ppm) chloride contour (isochlor) in both the upper "180-ft" and lower "400-ft" water-bearing formations. The study area extended from Moss Landing on the north to Marina and Fort Ord on the south and inland approximately five miles (Figure 1).

Many water wells in the vicinity of the study area are monitored on a regular basis for general mineral chemistry by the District. While the landward extent of sea-water intrusion has been generally well-defined, stratigraphic and salinity

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information needed to be interpolated between widely spaced monitoring wells. Confirmation of the District's 500-ppm isochlors was therefore deemed necessary.

Because the conductivity of water increases with increasing salinity, electrical methods are well-suited for mapping changes in the salinity of ground water. There are several surface techniques that can be employed to determine electrical resistivity stratification with depth, such as direct current resistivity (Van Nostrand and Cook, 1966), frequency domain electromagnetic profiling (Stewart, 1982), controlled source audiomagnetotellurics (CSAMT) (Zonge *et al.*, 1980), and TDEM (Kaufman and Keller, 1983). The TDEM center loop sounding method was selected because of, (1) its better vertical and lateral resolution; (2) its lower sensitivity to geologic noise; and (3) its prior success in mapping salt-water intrusion (e.g., Fitterman and Stewart, 1986). A total of 100 TDEM soundings were measured in the project area, which required three weeks of field work to complete.

2.0. BACKGROUND INFORMATION

2.1. General Geology of the Area

The Salinas Valley is a large intermontane valley, extending approximately 120 miles southward from Monterey Bay (Figure 1). The Salinas River meanders through the valley and is bounded on the west by the Sierra De Salinas and on the northeast and southeast by the Diablo Range.

In the project area, at the northern end of the Salinas Valley, three major confining zones separate the alluvial fill into four predominant aquifers: the perched, the "180-ft," the "400-ft," and the "900-ft" (deep) aquifers (Boyle Eng. Corp., 1986). A schematic cross section is shown in Figure 2 to illustrate the various zones.

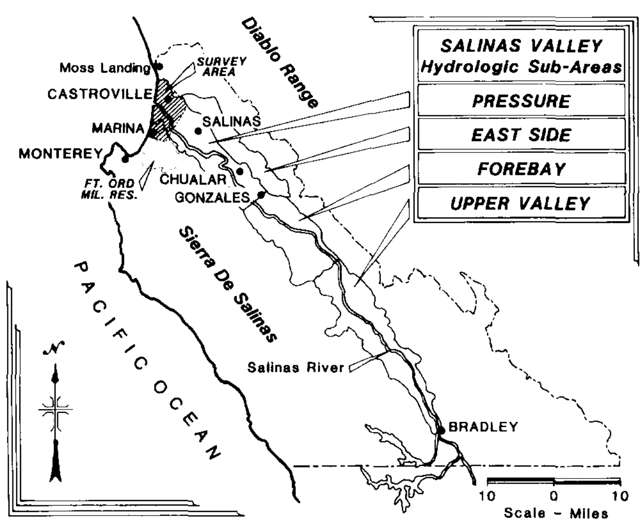

Fig. 1. Location map of survey area.

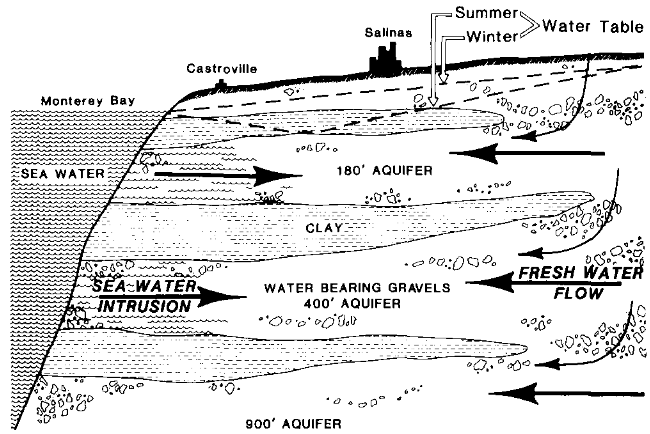

Fig. 2. Schematic hydrogeologic cross section of aquifers and aquitards in survey area.

The pumped aquifers are mainly the "180-ft" and the "400-ft." The perched and the deep aquifers are experiencing limited extractions at this time. The costs involved in drilling into the deep zone prohibit a large number of wells from being developed (Leedshill-Herkenhoff, Inc., 1985). The perched water above the "180-ft" aquifer is heavily influenced by land-use practices, which include farming, industry, and urbanization. This has resulted in poor quality water.

Recharge of these aquifers occurs primarily in the Forebay area, an unconfined ground-water zone located 20 to 40 miles inland from the coast (Figure 1). There is limited vertical recharge in the "400-ft" aquifer due to the semipervious clays which separate the aquifers. The "180-ft" aquifer receives minor amounts of recharge from areas between Chualar and the coast.

During the dry months, low or nonexistent flows in the Salinas River are augmented by scheduled releases of water from two reservoirs in southern Monterey County. These reservoirs, Nacimiento and San Antonio, have a combined storage capacity of 700,000 acre-feet. The reservoirs function as a means of both flood control and water conservation.

2.2. The "180-ft" Aquifer

The "180-ft" aquifer in the project area ranges in thickness from about 53 m (175 ft) to 76 m (250 ft), consisting of interbedded gravel, sand, silt, and clay. The upper clay layer, known as the Salinas aquiclude, confines this aquifer in most of the project area. This clay layer is continuous between Salinas and Castroville, and breaks up between Chualar and Gonzales (Boyle Eng. Corp., 1986).

Water quality in this aquifer is affected both by leakage of salts from heavy fertilization from the overlying perched aquifer, and by sea-water intrusion. In the nonintruded area, dissolved solids are dominantly calcium-sulfate and calcium-sodium-bicarbonate-sulfate. In the intruded area the main dissolved solids are calcium-chloride and sodium-chloride. The relatively high percentage of calcium ions indicate that several other sources of contamination in addition to sea water are present (USGS, 1984).

The "180-ft" aquifer has been the most heavily utilized source of water in this area. Demands placed on this aquifer have lowered the piezometric level, which in turn has allowed a reversal of the normal seaward ground-water gradient (Leedshill-Herkenhoff, Inc. 1985). The result is extensive sea-water intrusion.

Sea water is known to contaminate the "180-ft" aquifer inland as far as five miles. The area overlying this intrusion encompasses some 15,000 acres. In recent years, sea-water contamination has increased at a rate of 450 acres annually. A breakdown of this rate over time is shown in Figure 3 (Leedshill-Herkenhoff, Inc., 1985).

As the "180-ft" aquifer became increasingly contaminated, wells were abandoned and the search for fresh water moved deeper into the lower "400-ft" aquifer.

2.3. The "400-ft" Aquifer

The thickness of the "400-ft" aquifer ranges from 61 m (200 ft) to 76 m (250 ft). This water-bearing formation consists primarily of sands, gravels, and clay lenses. A semiconfining clay layer of discontinuous sands and clays separates the "400-ft" aquifer from the "180-ft" zone from the coast to Gonzales (Boyle Eng. Corp., 1986).

In the nonintruded area, water in the "400-ft" aquifer is generally less mineralized than that of the upper aquifer. Predominant dissolved solids consist of calcium-bicarbonate or sodium-calcium-bicarbonate ions. The difference in water quality between "180-ft" and "400-ft" aquifers in the project area indicates a poor hydraulic connection. The water in the lower zone intruded with sea water has dominantly sodium-chloride ions but with a percentage of calcium ions greater than found for sea water (USGS, 1984).

The increasing heavy utilization of this lower aquifer by agriculture and municipal interests has resulted in sea-water intrusion beneath approximately 6,300 acres. In recent years sea water has been spreading into the "400-ft" aquifer at the rate of 275 acres per year as shown in Figure 4 (Leedshill-Herkenhoff, Inc., 1985).

Average Rates of Sea-water Intrusion

180' AQUIFER	Period	Acres Intruded	Acres/Years
North of Salinas River	Pre-1944	1,287	---
	1944-75	7,023	227
	1975-83	1,988	248
South of Salinas River	Pre-1944	571	---
	1966-75	2,385	238
	1975-83	1,599	200

RE: SALINAS VALLEY SEA-WATER INTRUSION STUDY; JAN., 1985, LEEDSHILL-HERKENHOFF INC.

TOTAL 14,853

Fig. 3. Rates of sea-water intrusion in "180-ft" aquifer.

Average Rates of Sea-water Intrusion

400' AQUIFER	Period	Acres Intruded	Acres/Years
North of Salinas River	Pre-1959	20	---
	1959-75	2,057	129
	1975-83	976	122
South of Salinas River	Pre-1966	777	---
	1966-75	1,223	122
	1975-83	1,225	153

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TOTAL 6,278

Fig. 4. Rates of sea-water intrusion in "400-ft" aquifer.

2.4. The "900-ft" Aquifer

The thickness of the deep zone varies from 183 m (600 ft) to 366 m (1200 ft) (Leedshill-Herkenhoff, Inc., 1985). Currently, a limited number of wells pump the aquifer. Costs involved in drilling into this formation are slowing the utilization of this water. To date, sea-water contamination in this deep zone is not evident.

Water quality in the deep aquifer is characterized as "soft" water. Sodium and chloride ions dominate and small concentrations of calcium-magnesium ions are observed. The use of this deep water poses some problems for farming practices (Thorup, 1976). Because of the high concentrations of sodium-chloride (although generally within Class II irrigation standards) and low amounts of calcium and magnesium, gypsum must be added to soils to maintain permeability.

As costs of alternative water supplies to the intruded area increase, the pumping of water from the deep aquifer becomes economically attractive. The potential for sea-water intrusion increases as a greater number of water wells are drilled into this formation.

2.5. Previous District Work

Since 1952, the Monterey County Flood Control District has been actively monitoring water quality and levels in the "180-ft" and "400-ft" aquifers. A network of monitoring wells was set up to provide information on the depth to water in the valley aquifers. The level of water in wells is normally used to determine areas of overdraft and the location of pumping troughs. This information has been vital in determining the direction of ground-water flow throughout the Salinas Valley, particularly as it relates to sea-water intrusion.

Presently, the District is maintaining approximately 100 wells to monitor changes in water levels and quality in and around the intruded zones. Monitoring for changes in water quality includes the annual determination of electrical conductivity and chloride concentration. Once every five years the District performs a complete mineral analysis on each well. If a water sample is thought to be contaminated with sea water, as evidenced by an elevated chloride or electrical conductivity value, a chloride/carbonate + bicarbonate ratio is used for recognition of sea water in ground water (Todd, 1980).

Monitoring wells that reach chloride concentrations of 500 ppm are considered to be significantly intruded with sea water. These wells then become data points for plotting the 500-ppm isochlor. Relying on present and historical data, contours are then drawn based on the chloride values in the contaminated wells. Although 100 monitoring wells may appear to represent an adequate data density, many of these monitoring wells are behind the interface and no longer yield information on the position of the 500-ppm isochlor. Geophysical stations can be positioned ahead of the interface, and their locations can be altered from year to year.

3.0. TDEM SURVEY

The resistivity of water-bearing rocks is a function of water content, water salinity, and the manner in which the water is distributed throughout the rock. Water content in turn is determined by porosity and degree of saturation. The relation between formation resistivity, R_o, resistivity of pore water, R_w, and porosity, ϕ, is expressed by Archie's Law (Archie, 1942) given by:

$$R_o = a\, R_w\, \phi^{-m}$$

where a and m are empirical constants.

The resistivity of pore water is determined by concentration of dissolved solids, type of solids, and to a minor extent by temperature. A measurement of pore-water resistivity cannot resolve the type of dissolved solids. It is, however, common to relate electrical resistivity to an equivalent chloride concentration (e.g., Kwader, 1986). This relation can be used as an indicator of total dissolved solids for sea water, but it is not valid when a significant part of the dissolved solids are of other origin.

There is a large library of information about values of the empirical constants a and m for sedimentary rocks (Keller, 1977). For unconsolidated sands and gravel, there is considerably less available information. Some of the information about the empirical constants in unconsolidated sand and gravel aquifers is summarized by Kwader (1986). Also, some detailed regional investigations relate formation resistivities to total dissolved solids (e.g., Guo, 1986).

Deviation from Archie's Law behavior may occur at low concentration of dissolved solids. The reason for this is that surface conductance caused by the exchangeable ions of soil and rock complexes may become a major fraction of total ions (e.g., Kwader, 1986).

3.1. Principles of TDEM

In all electrical and electromagnetic techniques for measuring the electrical resistivity of the ground, the electrical resistivity is derived by determining resistance to flow of electrical current. An important difference between various techniques is the manner of driving current flow. In TDEM, currents are induced by a time-varying magnetic field of a transmitter (Kaufman and Keller, 1983). The transmitter configuration used was a square loop of insulated wire laid on the ground surface (Figure 5). A multi-turn air coil receiver (about 1-m diameter) is placed in the center of the loop. The sizes of the transmitter loops employed were varied depending on the required exploration depth (see Section 3.2).

The current waveform driven through the transmitter loops is shown in Figure 6. The waveform consists of equal periods of time-on and time-off. The base frequencies (Figure 6a) of the Geonics EM-37 employed in these investigations

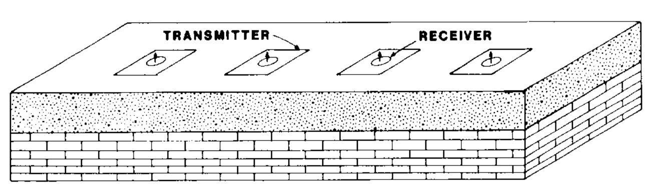

Fig. 5. Transmitter-receiver arrays used in center loop TDEM soundings.

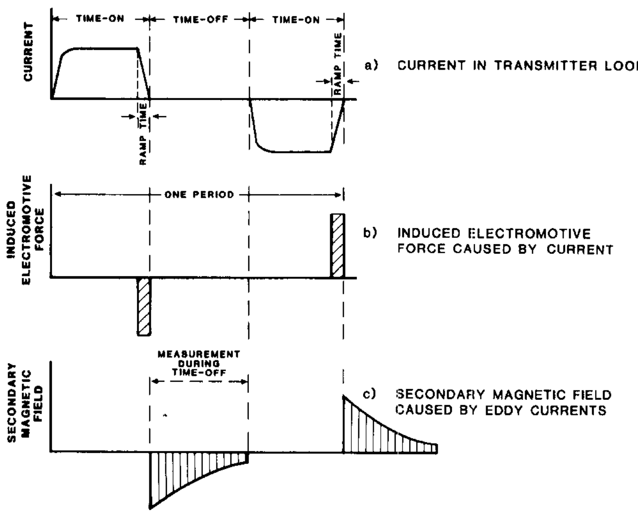

Fig. 6. Current waveform used in Geonics EM-37 employed for survey.

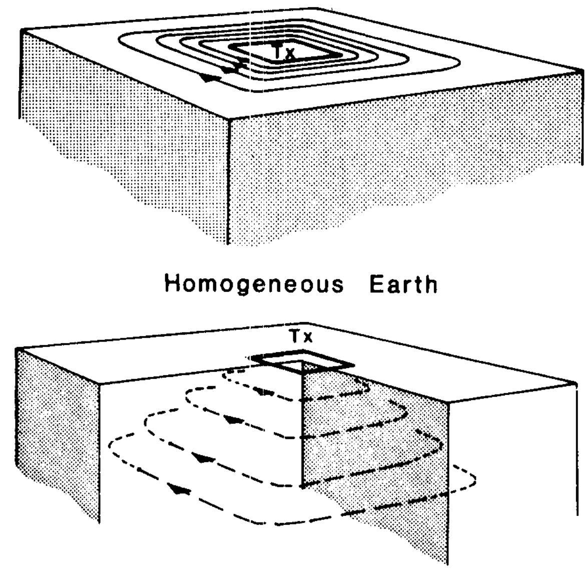

Fig. 7. Schematic illustration of eddy current flow induced in subsurface by transmitter loop at two times after transmitter current turnoff.

are 30 hz, 3 hz, and 0.3 hz. These frequencies result in on/off intervals of 8.33, 83.3, and 833 msec, respectively.

The current driven through the transmitter loop creates a primary magnetic field. During the rapid current turnoff, this primary magnetic field is time-variant and in accordance with Faraday's Law, there will be an electromagnetic induction during this time (Figure 6b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground resistivity (Kaufman and Keller, 1983).

In horizontally layered ground, the eddy currents are horizontally closed rings concentric about the center of the transmitter loop. A schematic illustration of these currents is shown in Figure 7. Immediately after turnoff, the currents are concentrated near the surface (Figure 7a). With increasing time, currents are induced at greater depth (Figure 7b). Another useful presentation of current behavior as a function of time are the "smoke rings" (Nabighian, 1979) illustrated in Figure 8. The "smoke rings" are contours of current density, and Figure 8 shows these contours at different times after turnoff. The locations of current maxima can be seen to migrate to greater depth with increasing time, and away from under the center of the transmitter loop.

The receiver measures the electromotive forces (emf's) due the secondary magnetic field caused by the ground eddy currents (Figure 6c). At early time when the currents are mainly concentrated near the surface, the emf's measured will mainly reflect the electrical resistivity of near-surface layers. With increasing time, as currents are induced at greater depth, the emf's measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration depth is mainly a function of time of measurement after turnoff.

The emf's measured at the surface of the ground due to the secondary magnetic fields of the ground eddy currents vary with time and distance from the center of the transmitter loop. Figure 9 shows a typical measured behavior of emf's at a

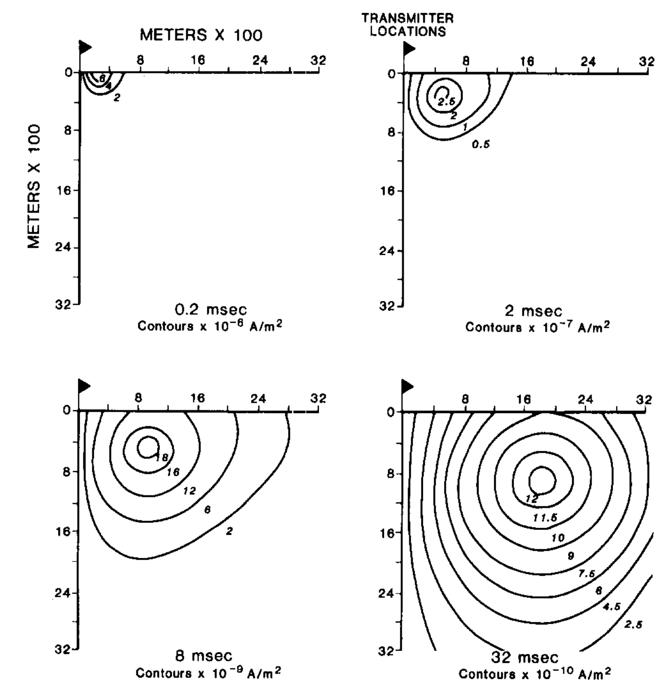

Fig. 8. Computed behavior of eddy current intensity contours at different times (after Nabighian, 1979).

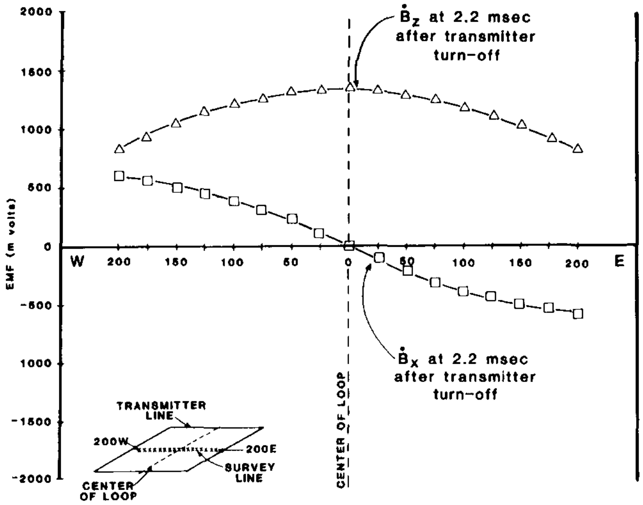

Fig. 9. Measured behavior of electromotive force due to vertical (B_z) and horizontal (B_x) magnetic field on a profile through center of 400 m by 400 m transmitter loop.

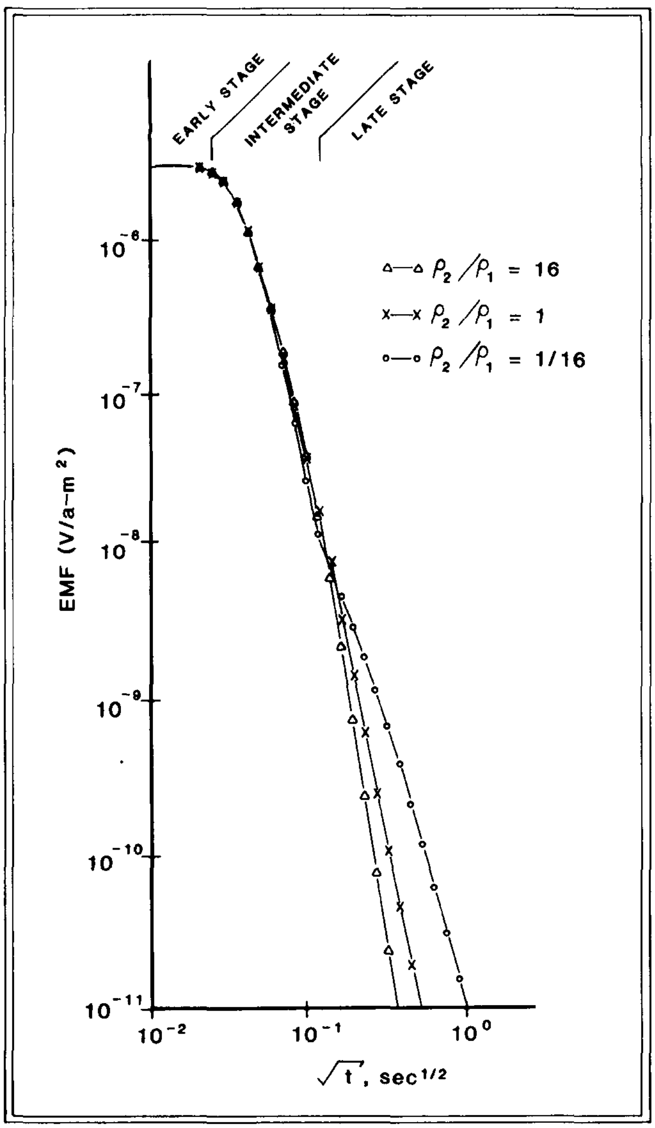

Fig. 10. Computed behavior of emf's due to vertical magnetic field (B_z) in center of 100 m by 100 m loops for three geoelectric sections.

certain time (2.2 milliseconds) after turnoff. The behavior of the emf due to the vertical magnetic field (B_z) is relatively flat about the center, so that measurements of the emf due to B_z are relatively insensitive to errors in surveying the center of the loop, or in some deviations from a square loop. The emf due to the horizontal magnetic field is zero at the center of the transmitter loop, and rapidly changes in absolute value with distance from the center. Measurements of the emf due to B_x would require careful survey control.

In TDEM soundings the geoelectric section is derived from measurement of the emf due to B_z which is measured as a function of time during the period the transmitter is off. Figure 10 shows a computed behavior of emf's due to B_z as a function of time. The emf can be seen to decay with increasing time rapidly after an initial period. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emf due to the decay of the ground eddy currents must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60-hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds; therefore, multiple data sets can be quickly obtained.

Maximum effective exploration depth is a function of transmitter loop size and geoelectric section, and the latest time signal can be recovered from noise. If, for a particular loop size, noise exceeds signal in the required time range of measurement, transmitter loop sizes must be enlarged to improve signal to noise. Although the relation between time of measurements and effective exploration depth depends on several factors, an approximate concept can be obtained from Figure 11 (McNeill, 1980). This figure shows the depth of occurrence of maximum eddy current intensity as a function of time for several ground resistivities. For example, at 1 msec, the depth of maximum current is at about 150 m over ground with a resistivity of 10 ohm-m, and at about 500 m over ground with a resistivity of 100 ohm-m.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. It is common to transform the emf's measured at different times into apparent resistivities. The purpose of that transformation is to obtain a visual display of how the emf measured differs from the emf that would be measured over ground uniform

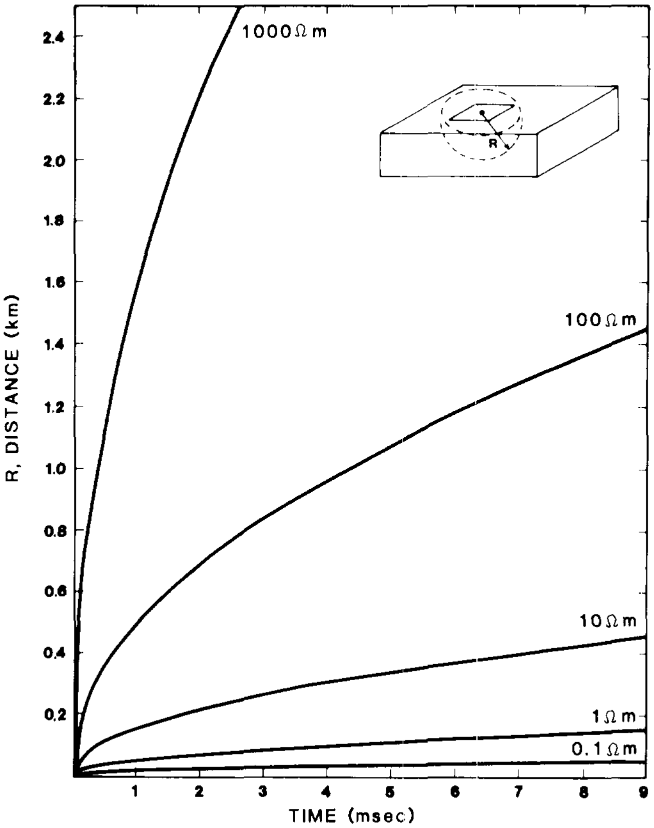

Fig. 11. Computed behavior of "rate of diffusion" of maximum current intensity for uniform ground of different resistivities (after McNeill, 1980).

in resistivity. Several definitions of apparent resistivity are used in TDEM (Kaufman and Keller, 1983). In this work some examples of "late stage" apparent resistivity curves are shown.

The objective of processing of TDEM data is to obtain a solution for the resistivity stratification of the subsurface that will produce the observed decay of emf. For mapping water quality in the aquifers in Monterey County, the gradual lateral change in resistivity justifies the use of one-dimensional interpretations. Thus, at a particular station, lateral resistivity variation, within the sphere of measurement, was neglected.

The inversion of measured TDEM data into vertical resistivity stratification (Goldman, 1988) was performed by the program ARRTI (Stoyer, 1985) in the field on a portable computer. An example of a data set derived for each sounding is given in Figures 12a and 12b. In the apparent resistivity curve on the left (Figure 12b), the measured data at each time gate is superimposed on the model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Figure 12a) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. Errors less than ±5% in most time gates, and RMS errors less than 6%, were typical for the soundings in Monterey County. Thus, for each station, thicknesses and resistivities for layers encountered within the effective exploration of the measurement are obtained.

3.2. Survey Design and Logistics

The design of geophysical surveys is preceded by collection of available geologic and drill hole information. In designing electrical surveys, it is particularly important to obtain information about the resistivity stratification. Such information may be available from electric logs run in wells. An example of such a log is shown in Figure 17. On

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.952
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39E+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.519
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.16E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

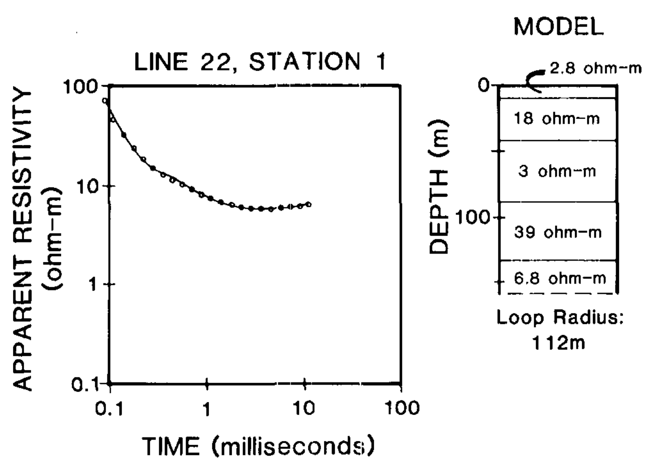

Fig. 12. Example of data obtained for each sounding; (a) inversion table, ARRTI and (b) "late stage" apparent resistivity curve with geoelectric section.

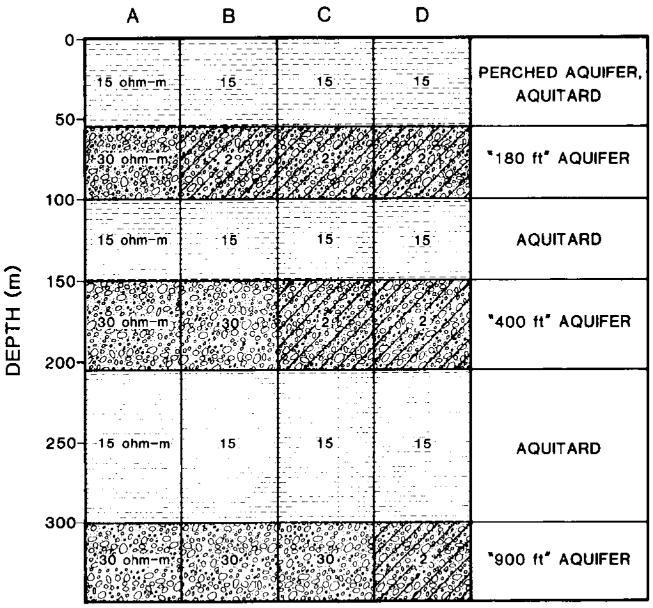

Fig. 13. Schematic geoelectric sections constructed from geologic information and resistivity logs to compute feasibility of accomplishing exploration objectives.

the basis of several such logs, the schematic geoelectric sections in Figure 13 were constructed. The detailed electrical structure observable in resistivity logs cannot be obtained from surface geophysical measurements. To construct models applicable to surface geophysics from resistivity logs, a simplified section must be made. In Figure 13 the aquitards have been assigned resistivities of 15 ohm-m, the aquifers when saturated with fresh water a resistivity of 30 ohm-m, and when intruded with salt water a resistivity of 2 ohm-m. Next, forward model curves are computed to determine the feasibility of mapping certain objectives, and the time range over which the apparent resistivity curves are diagnostic of the exploration objectives.

As an example, the feasibility and diagnostic time range for mapping salt-water intrusion in the "400-ft" aquifer is evaluated in Figure 14. It shows two computed apparent resistivity curves; in curve B the "400-ft" aquifer is saturated with fresh water, and in curve C salt water has intruded the "400-ft" aquifer. The curves correspond to the geoelectric section of B and C in Figure 13. In both cases the upper "180-ft" aquifer is assumed to have been intruded by salt water, consistent with the knowledge that salt-water intrusion has progressed furthest inland in the "180-ft" aquifer. The curves differ over the time interval indicated on Figure 14. Thus, for a TDEM survey to be effective for mapping salt-water intrusion in the "400-ft" aquifer, signal must exceed noise over at least part of the diagnostic time range.

Simultaneously, with the computation of apparent resistivity curves, field strengths are computed, and on the basis of these computations, transmitter loop sizes are selected. It was determined that 100 m by 100 m transmitter loop sizes were optimum for mapping in the "180-ft" aquifer, and 200 m by 200 m loops for mapping in the "400-ft" aquifer. In the field, deviations from the geoelectric section modeled may shift the diagnostic time range. It is, therefore, important to process data in the field so that survey parameters (e.g., transmitter loop size, station spacing) can be altered to meet the objectives.

The TDEM transmitter loops were preliminarily located by using the District's existing maps of the position of the 500-ppm isochlors in both aquifers, and the loops were laid out on lines perpendicular to the isochlors. The spacing of the loops along a line was dictated by the available monitoring well control with loops placed on either side of the isochlor. In areas where there were several wells, and where the location of the isochlor was well known, the spacing between loops was decreased (to about 100 m apart). In areas of little control, the spacing was increased to insure that there would be loops on both sides of the isochlor. Several loops were placed next to monitoring wells to aid the correlation between geophysical interpretations and salinity of ground water determined from well samples. Subsequently, a field check was made of selected loop locations, and changes were made to accommodate practical considerations such as access, presence of metal fences, and utility lines.

The field measurements were made by a crew of two persons. This crew was accompanied by an employee from the Monterey County Water Management and Flood Control District who was mainly responsible for communication with landowners for access. One geophysicist daily processed

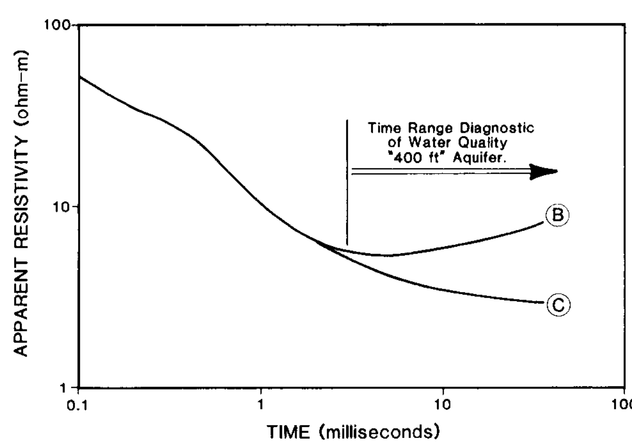

Fig. 14. Computed "late stage" apparent resistivity curves for Sections B and C in Figure 13.

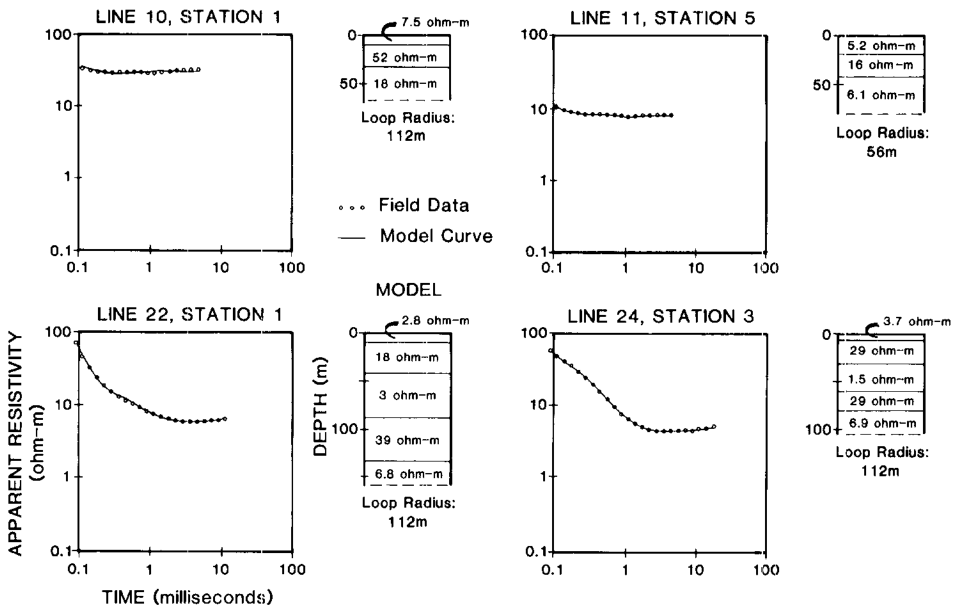

Fig. 15. Measured apparent resistivity curves and inverted geoelectric sections for four stations along Section B-B′.

the data acquired the previous day in the motel. This one-day turnaround allowed quality control and adjustment of field survey parameters to meet exploration objectives. The measurement of 100 stations with transmitter loops varying in size between 100 m by 100 m to 500 m by 500 m, required 20 days of field work.

4.0. RESULTS

The first step in interpretation of TDEM measurements was to invert the apparent resistivity curves into one-dimensional resistivity stratifications. Figure 15 shows four typical apparent resistivity curves along section B-B′ (Figure 16). Typical of the apparent resistivities curves was (1) absence of random scatter in the data, and (2) inversion errors between measured data and computed data less than 5% at each time gate and less than 6% in overall RMS error. Geoelectric cross sections were constructed on lines approximately perpendicular to the 500-ppm isochlors. A geoelectric and geologic cross section along B-B′ is shown on Figure 16. The location of B-B′ is shown on Figure 21. This cross section displays the following characteristics:

1. A near-surface layer (3 m to 10 m thick) with resistivities less than 8 ohm-m. This low value of resistivity is believed to be caused by a high concentration of dissolved solids caused by heavy use of agricultural fertilizers.
2. A second layer with values of resistivities between 10 ohm-m and 60 ohm-m. This layer represents the aquitard overlying the "180-ft" aquifer.
3. A third layer representing the sands of the "180-ft" aquifer. The resistivities in this layer gradually increase inland from about 1.6 ohm-m to values greater than 10 ohm-m. This gradual increase inland relates to a gradual decrease in concentration of dissolved solids in the ground water inland.
4. A fourth layer with a resistivity between 20 ohm-m and 40 ohm-m representing the aquitard separating the "180-ft" and "400-ft" aquifer.

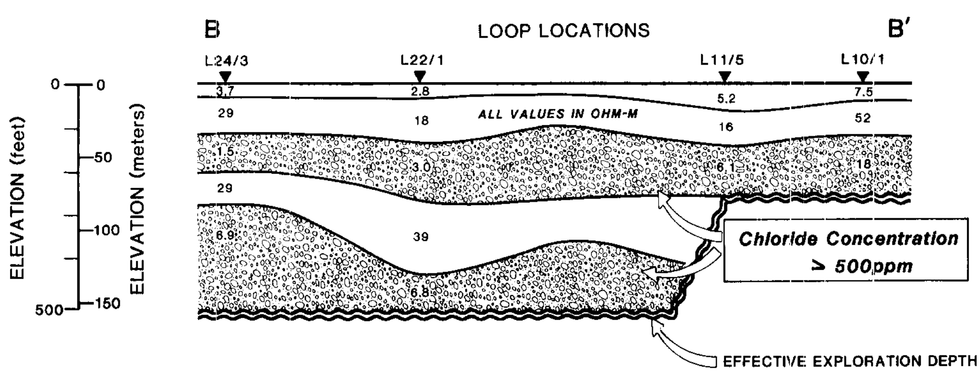

Fig. 16. Geoelectric cross section constructed from soundings along B-B′.

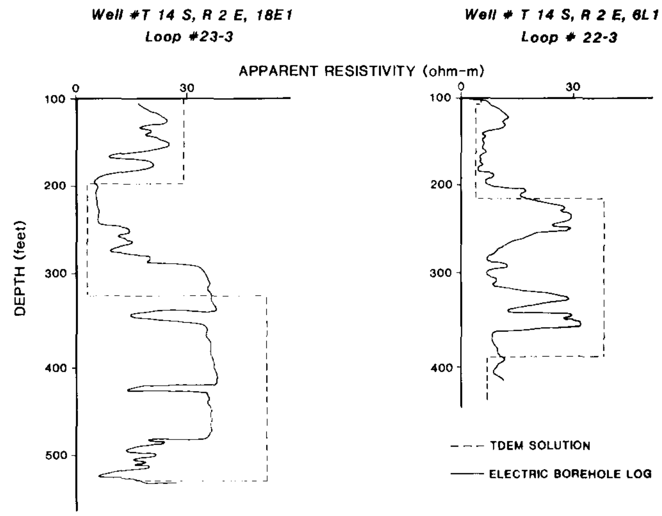

Fig. 17. Comparison of geoelectric section derived from wells and TDEM soundings.

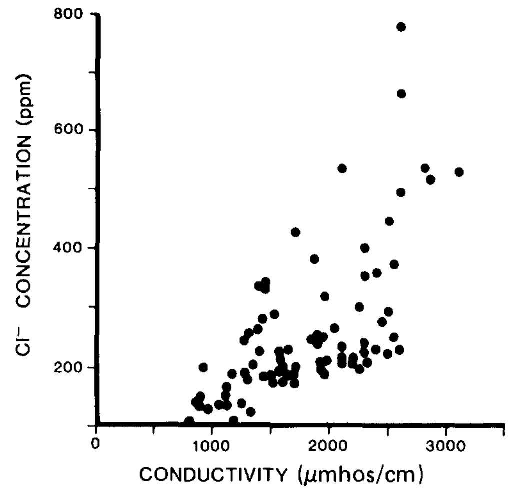

Fig. 18. Relation measured between chloride concentration and fluid conductivity on water samples from "180-ft" aquifer.

5. A fifth layer with resistivities gradually increasing inland from a low of 6.8 ohm-m. This gradual change in resistivity again is related to variation in concentration of dissolved solids in the ground water.

6. The effective exploration depth along B-B′ was about 200 m from the shoreline to station 11/5, and about 100 m from station 11/5 inland, because smaller loop sizes were employed over areas where only the "180-ft" aquifer was expected to be intruded by sea water.

The geoelectric sections derived from TDEM interpretation were compared with sections derived from resistivity logs run in wells. A major problem with that comparison was the relative low quality of resistivity logs. The comparisons of two geoelectric sections derived from TDEM soundings near wells with the resistivity logs run in those wells are shown in Figure 17. The comparison shows that:

1. There is good agreement between the TDEM-derived section and resistivity log in the sequences and depths of occurrence of layers of high and low resistivity. Agreements between depths of interfaces are within ±10% of total depth.

2. There are differences of up to 100% between absolute values of resistivities. This discrepancy is believed to be mainly due to measurement errors in the resistivity logs.

From the geoelectric section B-B′ of Figure 16, a qualitative idea of the variation in concentration of dissolved solids with distance in the "180-ft" and "400-ft" aquifer are obtained. The resistivities of the aquifers increase gradually inland. To derive from this geoelectric section more quantitative information about concentration of dissolved solids, an attempt was made to correlate formation resistivities measured with TDEM to chloride concentration. First, the relation between chloride concentration and water conductivity on samples from wells was investigated. The available data are summarized in Figures 18 and 19 for samples from the "180-ft" and "400-ft" aquifer. There is considerable scatter in the data from the "180-ft" aquifer. The main reason for this scatter is believed to be cross-contamination between the heavily fertilized near-surface layers and the "180-ft" aquifer, so that anions other than chlorides affect the relation between chloride concentration and conductivity. Little scatter is observed in the samples from the "400-ft" aquifer and 500-ppm chlorides correspond to a fluid conductivity of about 2000 μmhos/cm or a fluid resistivity of 5 ohm-m. This is in agreement with the information summarized by Kwader (1986).

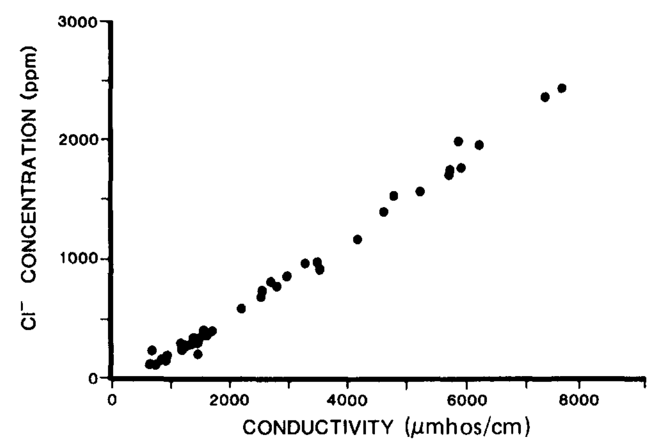

Fig. 19. Relation measured between chloride concentration and fluid conductivity on water samples from "400-ft" aquifer.

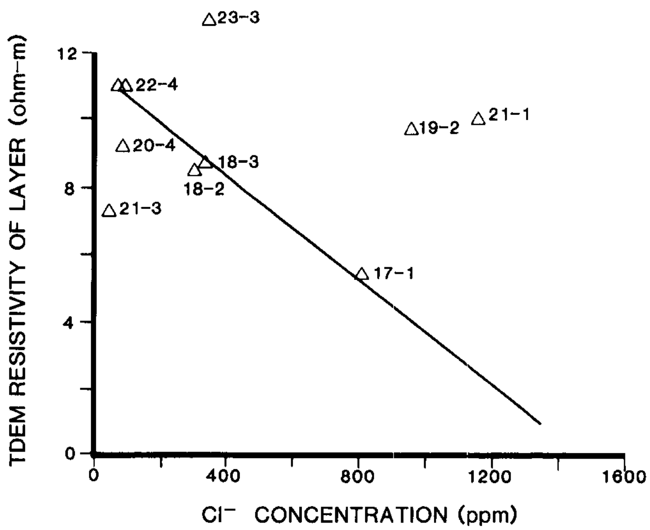

Fig. 20. Relation between chloride concentration and formation resistivity in selected wells.

In surface electrical methods, bulk resistivities rather than fluid resistivities are measured. To correlate bulk resistivities to chloride concentration, two approaches were investigated:

1. Correlation of formation resistivities from resistivity logs run in wells with measurements of chloride concentration of water samples from the same wells. This correlation was hindered by (1) the relatively limited number of wells on which electric logs were run, and (2) the quality of available logs was inconsistent. By carefully selecting logs of good quality, and representative of the regional hydrologic regime, six data points were available for the "400-ft" aquifer. These data points are shown in Figure 20. On the basis of this figure, a formation resistivity of 8 ohm-m is expected to correspond to a chloride concentration of 500 ppm.

2. Use of Archie's Law with typical values of porosity (0.35) and a value of m = 1.35, as given by Kwader (1986) for sand aquifers. Using these values for porosity and empirical constant m, a formation resistivity of 20 ohm-m would be calculated to correspond to a chloride concentration of 500 ppm. A value of 20 ohm-m would also be consistent with the data of Guo (1986) for sand aquifers in China. A value of 20 ohm-m is not realistic for the aquifer in Monterey County, since values as high as 20 ohm-m were seldom observed in the aquifers either in resistivity logs on TDEM inversions. The reasons for this are expected to be (1) the aquifers do not consist of clean sands and gravels but are interbedded with silt and clay layers, so that particularly at low values of TDS exchangeable ions are a major fraction of total ions, (2) anions other than chlorides (sulphates) are significant, particularly in the "180-ft" aquifer.

The contours of 8 ohm-m in the "180-ft" and "400-ft" aquifer are displayed on Figure 21. These contours are expected to correspond to contours of 500-ppm isochlors. When these contours derived from TDEM soundings are compared with the contours derived from monitoring wells, also shown on Figure 21, good agreement is observed. Mainly because of the higher density of available stations, more detail is seen in the contours derived from surface geophysics.

Measurements with the Geonics EM-37 with 500 m by 500 m transmitter loops over areas where the "180-ft" and "400-ft" aquifer had been intruded by sea water cannot be made to sufficient late time to provide information about water quality in the "900-ft" aquifer. Measurements with the Geonics EM-42 are planned for mapping in the "900-ft" aquifer to obtain a better signal to noise.

5.0. CONCLUSIONS

The results of the interpretation of TDEM soundings indicate that TDEM soundings are an effective way to determine the resistivity stratification with depth. Good data quality was obtained in a relatively urban environment. The formation resistivities in the "400-ft" aquifer could be measured, when the overlying "180-ft" aquifer was intruded by sea water and had low formation resistivity. Thus, TDEM soundings can effectively explore below highly conductive layers. In fact, offshore frozen ground distribution has been mapped under 30 m of sea water with TDEM soundings (Ehrenbard *et al.*, 1983).

To relate formation resistivities to concentration of dissolved solids, ground truth data are required. The most direct ground truth data would

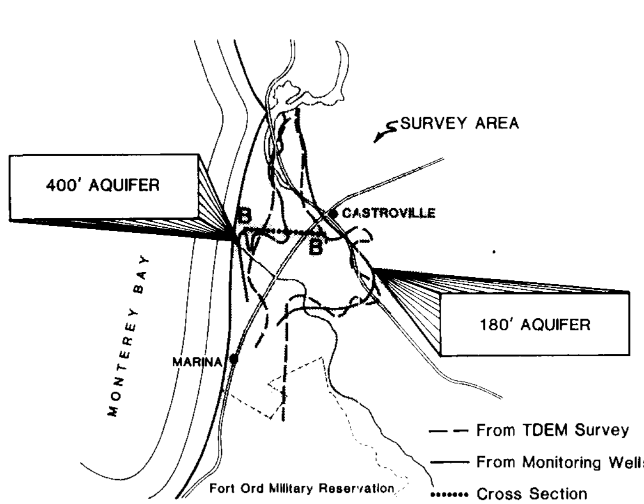

Fig. 21. Comparison of 500-ppm isochlor contours derived from monitoring wells, and from interpretation of TDEM soundings in "180-ft" and "400-ft" aquifers.

be measurement of formation resistivity from resistivity logs correlated to mineral chemistry of water samples from the same well. A good example of the effectiveness of such approach is given by Guo (1986). Few such measurements were available in the study area.

This investigation shows that TDEM soundings can play a major role in salt-water intrusion studies of coastal aquifers. Because of the relatively low cost of a TDEM sounding, a high station density can be afforded. Also, station locations can be inexpensively altered from year to year to monitor the progression or retreat of a fresh-water/salt-water interface. However, to realize the full benefits of surface geophysics, interpretation must be closely integrated with other exploration tools, such as mineral chemistry on samples from monitoring wells, and borehole logging. The time must come when surface geophysics, drilling, sampling, and logging programs are planned not in isolation, but as an integrated effort.

6.0. ACKNOWLEDGMENTS

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