GEOPHYSICS, VOL. 64, NO. 2 (MARCH-APRIL 1999); P. 417–425, 8 FIGS.

Combined application of dc and TEM to sea-water intrusion mapping

Chieh-Hou Yang*, Lun-Tao Tong‡, and Ching-Feng Huang*

ABSTRACT

A geoelectric survey using a dc resistivity method and a transient electromagnetic induction (TEM) method was carried out from 1986 to 1988. It was used to help map the lateral and vertical distributions of the freshwater/salt-water interface in the Pei-kang area on the west coast of Taiwan. The dc and TEM soundings were performed at 79 localities over an area of 240 km^2 of Quaternary alluvium.

Significant changes in pore-water conductivity at some places were detected by these two methods. A low resistivity value (<1.5 ohm-m) implies salt-water contamination of groundwater. The results of spatial distribution of apparent resistivity indicate the salt-water-affected aquifers are confined to the southwest part of the study area, and the affected aquifers are confined to the top of two aquifers.

A geoelectric model with three to four layers is inferred from the joint inversion of dc and TEM data. Based on a modified Archie's law suggested by the authors, an empirical relation between pore-water resistivity of the stratum and formation resistivity can be obtained. It can be used to convert the computed resistivity of each geoelectric layer (aquifer) to the resistivity of the water contained in these layer, thus leading to the assessment of groundwater contamination.

Repeated dc resistivity measurements have been carried out at selected locations once every year from 1986 to 1988. These data were used to monitor the temporal variation and a possible spreading of the salt-water invasion.

During 1995, a dc survey was conducted in the same area to compare with the dc sounding results obtained in 1988. The final results provide an evaluation of the efficiency of groundwater management in the study area.

INTRODUCTION

Geoelectrical techniques have been used successfully to detect the freshwater/salt-water interface in coastal aquifers. These methods include the dc resistivity method (Patra, 1967; Yang, 1981), profiling electromagnetic (EM) method (Stewart, 1982), transient electromagnetic induction (TEM) method (Gay, 1983; Fitterman and Hoekstra, 1984; Stewart and Gay, 1986), and controlled source audiomagnetotellurics (CSAMT) method (Yang et al., 1994). All of these techniques/methods provide valuable information regarding the interface between fresh water and salt water. To improve interpretation of the sounding data, a joint inversion scheme has been developed (cf., Vozoff and Jupp, 1975; Gomez-Trevino and Edwards, 1983; Raiche et al., 1985). This scheme improves the recovery of the earth model. However, only a few papers which treat detection of salt-water-affected aquifers with joint inversion have been reported in the literature.

This paper evaluates a long-term detection of possible change in the spatial distribution of the fresh-/salt-water interface in the Pei-kang area of the central part of the Taiwan west coast by using a joint inversion scheme and long-term dc measurements. The joint inversion was carried out with dc resistivity and TEM data to infer the conductivity distribution of aquifers. Previously, the study area was selected because of the need to use groundwater to irrigate rice and sugar cane fields. During the last thirty years, however, rapid economic growth and the growing demand for water for domestic, irrigation, and industrial uses has affected the groundwater quality in the survey area. The development of freshwater supplies has been particularly heavy from the alluvial aquifers underlying the Pei-kang area. Agriculture and freshwater fisheries (fish farms) are both major groundwater users in this area. Continual withdrawal has resulted in problems such as regional decline of groundwater levels, land subsidence, poor drainage,

---

Presented at the 60th Annual Meeting, Society of Exploration Geophysicists. Manuscript received by the Editor October 7, 1996; revised manuscript received September 2, 1998.
*National Central University, Institute of Applied Geology, Chungli 32054, Taiwan. E-mail: yang@app.geo.ncu.edu.tw.
‡ERL/Industrial Technology Research Institute, Bldg. 28, 195-6 Sec., Chung Hsing Road, Chutung Hsinchu 310, Taiwan.

and saltwater intrusion problems. Demand for fresh water has outpaced supply and water shortages occur, particularly during drought years. Thousands of wells were drilled to supply groundwater to meet the demand for fresh water. The maximum depth of these wells is in the range of 90 to 150 m. Overpumping of the groundwater has made the water table lower than sea level. As time progresses, some areas have seen salt concentration in the soils so great that agricultural use has been abandoned.

The conventional methods using chemical analysis of water sample measurements to assess these salt-affected areas are very time consuming, labor intensive, and expensive. In addition, most of the private wells were not available for those measurements. For this reason, a field experiment has been conducted in the Pei-kang area to demonstrate the advantage of using joint dc and TEM surveys to study the polluting plumes of two salt-water-contaminated aquifers. Results show that the methods have successfully delineated the contamination of an aquifer and allow assessment of the rate and direction of the spread of salt-water contamination. In addition, to determine the salt-water intrusion boundaries, we suggest a modified Archie's law to evaluate the pore-water conductivity of an aquifer by including the information of water wells. Thus, a more precise picture of groundwater contamination in each aquifer can be obtained by joint inversion of the dc and TEM data. The final joint inversion resistivity model is converted to spatial distribution of pore-water conductivity by using a modification of Archie's law. Also included in this paper is a study using temporal dc resistivity measurements to map the spatial variation of salt-water-contaminated aquifers.

GEOLOGY

The Pei-kang area, displayed in Figure 1, encompasses about 240 km^2 in west-central Taiwan. The study area lies between the town of Shui-son (to the east) and the Taiwan Strait (to the west). It is also bounded by two Rivers: the Chiu-hu-wei River to the north and Po-tzu River to the south. The topography in the study area is quite flat; the elevation ranges from 1 to 6 m above sea level. The maximum high-tide level is about 2 m.

The recent alluvium, including clayey loam and sandy loam layers, are spread widely throughout the area. Based on the lithologic logs of gas wells in the study area, the thickness of the alluvial aquifer system is >600 m. The irregular combination of a series of sand and clay layers within the alluvium reflects the alternation between Cho-shui River facies and the coastal facies. These alluvial deposits are the major water-bearing units in the Pei-kang area. The major groundwater recharge area is located in the eastern hills. Overpumping of the groundwater has made the water table lower than sea level. Based on the outcrop and the hydrologic information obtained from the wells shallower than 150 m in depth, the main aquifers are considered to be in the depth range of 60 to 130 m. The average thickness of these aquifers is about 30 m.

RESULTS FROM dc RESISTIVITY SOUNDINGS

From 1986–1988, vertical electric soundings (VES) using the linear four-electrode Schlumberger array were carried out at 79 locations in the study area. Equipment used in the survey included TSQ-3 and IPR-10A resistivity meters, manufactured by Scintrex, Canada. The average maximum current electrode spacing was about 600 m. Survey lines crossed each other at several locations. Results confirmed the homogeneity of electric properties of the layers in the horizontal direction in the survey area.

Figure 1 shows the spatial distribution of the sounding locations and the characteristic of the VES curves for each location. Lower apparent resistivity (<10 ohm-m), shown by black, appears in the south bank of the Niu-tiau-wan River and along the banks of the Pei-kang and Po-tzu Rivers. Figure 2a is the map of apparent resistivity values for four different Schumberger half-electrode spacings (AB/2), namely, 1, 8, 40, and 80 m, respectively. It covers the area between the Chiu-hu-wei and Pei-kang Rivers. The spatial distribution of low-resistivity zones shown on the map indicates the observed contaminated area increases as the spacing, AB/2, increases from 8 m to 40 m and then decreases as depth (i.e., AB/2) increases to 80 m. It also shows that the contaminated area trends southeastward as depth increases.

RESULTS FROM TEM SOUNDINGS

TEM soundings were collected with a 50 × 50-m coincident loop geometry. The Sirotem II, manufactured by GEOEX, Australia, was used to collect the field data. Data were processed by the technique developed by Yang and Tong (1988) based on the Jupp–Vozoff inversion scheme (Vozoff and Jupp, 1975). Figure 2b shows the contours of apparent resistivity for four values of delay time: 2.055, 5.779, 13.227, and 28.123 ms respectively. The size of the contaminated zones increases with delay time. At delay times of 13.227 ms and 28.123 ms, the contaminated area decreases. Comparison of Figures 2a and 2b shows the similarity between TEM and dc results. Referring to the lithologic sections obtained in the wells and the final 1-D inversion models for both TEM and dc sounding data, the contaminated aquifers appear to be confined to the depth around 40 to 80 m, encompassing the top of the two main aquifers in the study area.

JOINT INVERSION RESULTS

Joint dc and TEM inversion can be used to visualize the conceptual model for hydrologic studies where stand-alone results from the two sounding methods indicate that both methods are capable of detecting the fresh-/salt-water interface. Joint inversion of these data sets provides for better depth estimates of the aquifers. Examination of the profiles obtained by the joint inversion of data obtained from the dc and TEM methods reveals a conceptual model consisting of three main aquifers, designated from top to bottom as A, B, and C. The zones with resistivity values 1.5 ohm-m were interpreted as the salt-water intrusion zones. The unconfined A aquifer has a thickness of 7 to 10 m and consists of loose sand and sandy loam. The A aquifer underlies a clay-free topsoil and generally does not extend to a depth of 20 m. Thus, the A aquifer is easily contaminated by the overflow of sea water or fertilizer residue directly from above. This fact is reflected from the low-resistivity zones shown in the southwestern part of the study area (Figure 1). The base of the B aquifer is at the depth from 60 to 80 m and is marked by alternation of sand and clay with low-resistivity from 1.5 to 40 ohm-m. The resistivity zones <1.5 ohm-m are confined in the region between the Niu-tiau-wan and Po-tzu

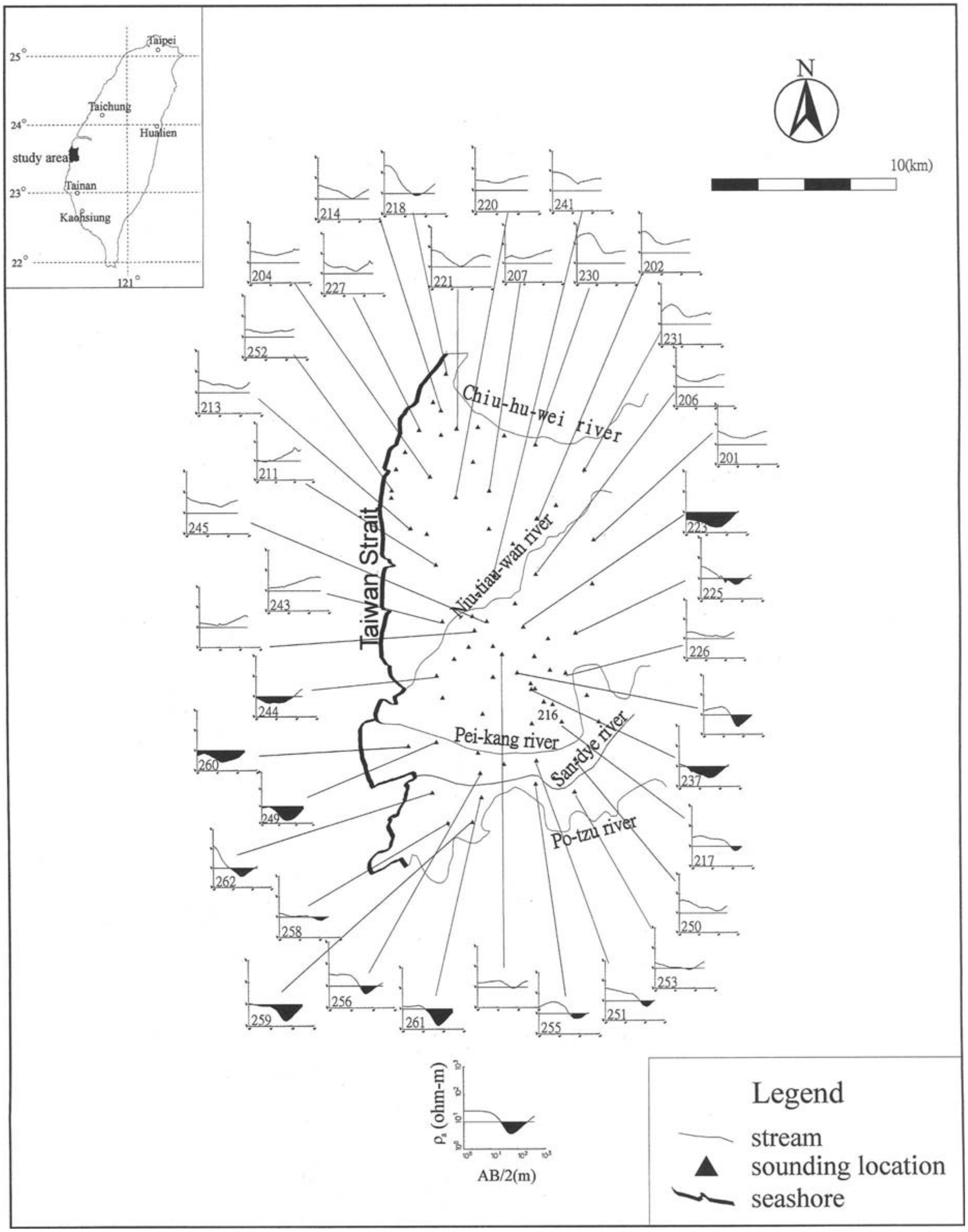


FIG. 1. Location map of dc sounding sites and the corresponding VES curves. The numbers near the origin of the coordinates of VES curves are the number of sounding locations.

Rivers, trending southwest–northeast. This is considered to be salt-water contamination. Since the presence of clay at the top of the B aquifer may significantly impede downward movement of salt water from the contaminant A aquifer, the salt water contained in the B aquifer may be contributed by local over-pumping of groundwater, which was contaminated by landward salt-water intrusion from the Pei-kang River. In addition, this area was a marine environment 6000 years ago; some residual connate salt water contained in the aquifer may contribute to the low resistivity of the B aquifer. The less-contaminated or unpolluted C aquifer can be recognized at depths >60 m. This is the main water supply zone for the pumping wells in the survey area. The surface water system diagram obtained from well data (Figure 3) illustrates this result and shows the lateral variation of A, B, and C aquifers.

EVALUATION OF THE CONDUCTIVITY OF THE AQUIFERS

Using a modified form of Archie's law (1942), we assume the resistivity of the aquifer (ρ) has a linear relationship with the resistivity of the water (ρ_w) contained in those layers, such that

$$\rho = F\rho_w, \qquad (1)$$

where F is the formation factor of the aquifer or layers. The values of water resistivity were measured in wells. The resistivity of each aquifer was obtained from the resistivity section based on the joint inversion from the results at or near those wells. Results are shown in Figure 4. A value of 2.2 for F can be determined from this figure. It can be seen that statistical uncertainty arising from the use of our empirical equation can be a serious problem in quantitative pore-water resistivity evaluation. However, the points that have a variable formation factor (off the dashed line shown in Figure 4) are concentrated to the top of the alluvium fan or along the coast. If we neglect these anomalous data (ST. 201 and ST. 213), the estimated relationship between the aquifer resistivity and pore-water resistivity closely follows a line of constant formation factor. Therefore, using an average value of the formation factor over the area of dc and TEM surveys to infer the pore-water resistivity is reasonable.

Pore-water resistivity for the aquifer in each location is extracted from the dc data using equation (1). The map of pore-water conductivity for each aquifer is shown in Figure 5. The distribution of the pore-water conductivity of the A aquifer shown in Figure 5a is generally high, which may relate to both the soil type and the remnant fertilizer. Localized high-level contamination (high conductivity) appearing in the southwestern part, especially at the outlet of the Pei-kang River, can be delineated. This serious salt-water contaminated area may be caused by the remnant infiltrating of flooding sea water from the ground surface during large typhoons that arrive periodically between May and October. Figure 5b gives the spatial variation of pore-water conductivity of the B aquifer. It is obvious that the range of the salt-water-contaminated zone is greater than the A aquifer and is confined to the region between the Niu-tiau-wan River and the Po-tzu River, trending

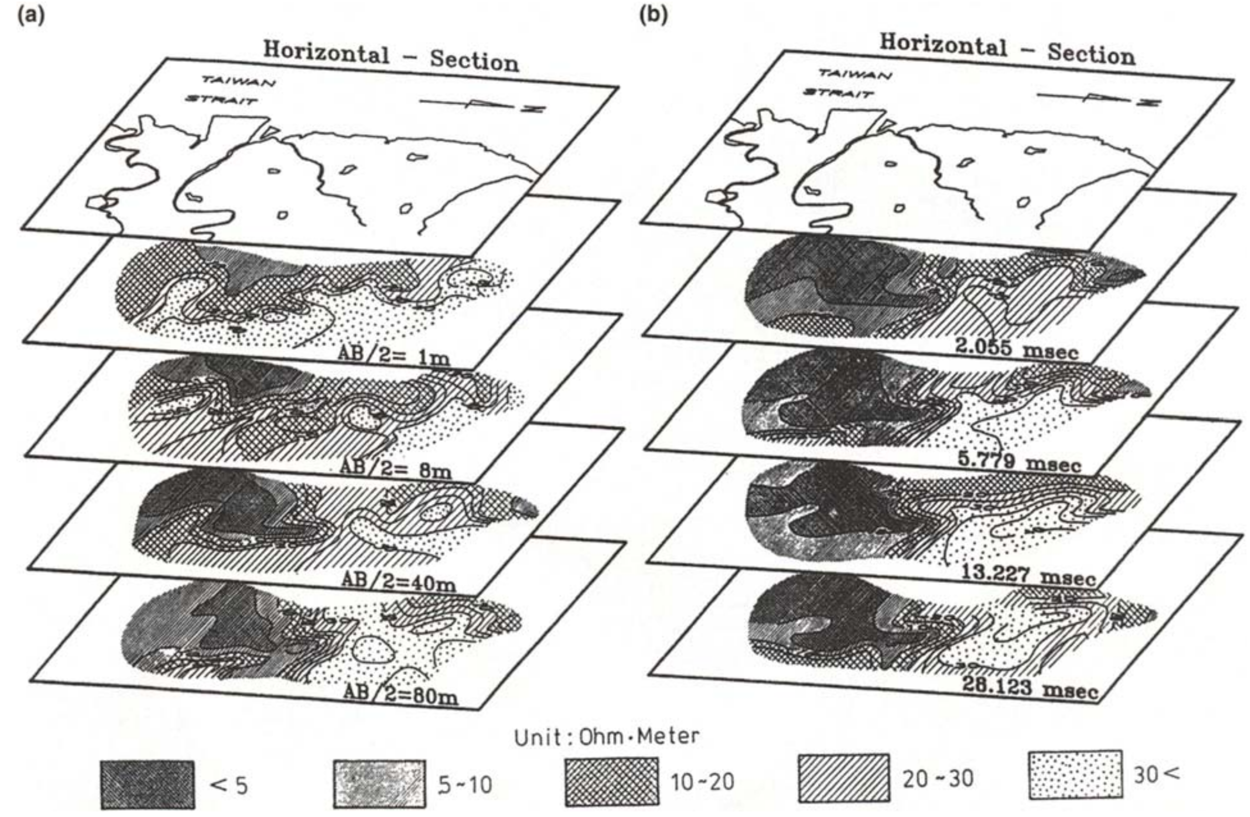


FIG. 2. Map of the apparent resistivity for (a) different Schlumberger half-electrode spacing and (b) different delay time for transient electromagnetic sounding.

southwest–northeast. The clayey overburden of the B aquifer impedes the downward movement of the contaminants from the A aquifer; thus, the A aquifer has not significantly affected the B aquifer. Similarly, the resistivity of the B aquifer has little effect on the resistivity of the C aquifer (Figure 5c) because the study area had several episodes of previous marine transgression and regression. Since the Pei-kang River and its neighboring area were in a marine environment 6000 years ago, there may be some residual connate salt water contained in the B aquifer. However, long-term monitoring of some locations in areas of subsurface contamination, together with the trend of downward (decreasing apparent resistivity) and right (increasing AB/2) migration of VES sounding curves, indicates salinity of the B aquifer has increased for increasing depth from 1986 to 1988, mainly along the bank of the Pei-kang River. Therefore, in addition to the above-mentioned effect of residual of connate salt water, it can be interpreted that sea-water intrusion has occurred locally in this zone. Overpumping the fresh water has led to a lateral intrusion of the sea water to the B aquifer from the bank of the Pei-kang River. The C aquifer is not likely affected by the brine intrusion, however (see Figure 5c).

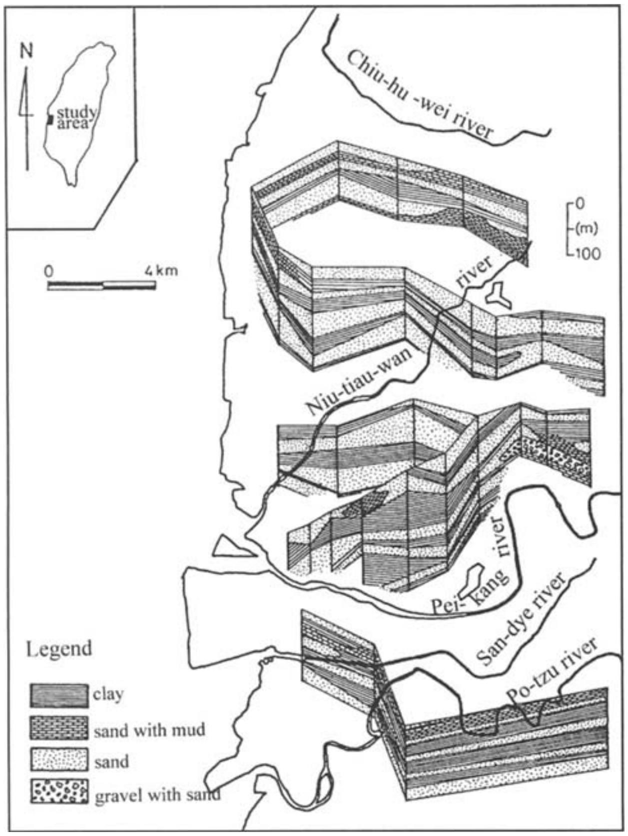


FIG. 3. Fence diagram of study area (after Liu, 1986).

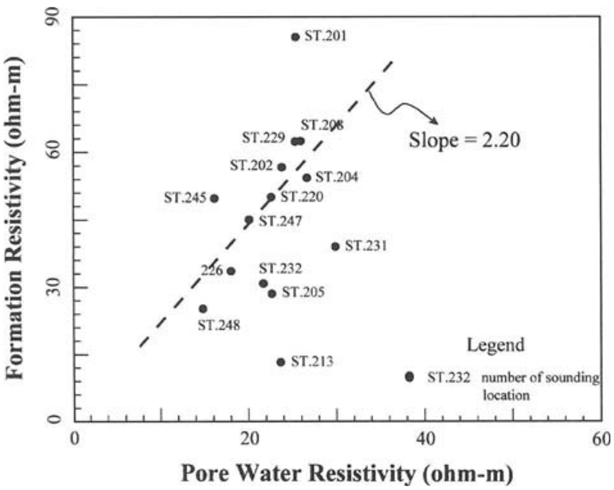


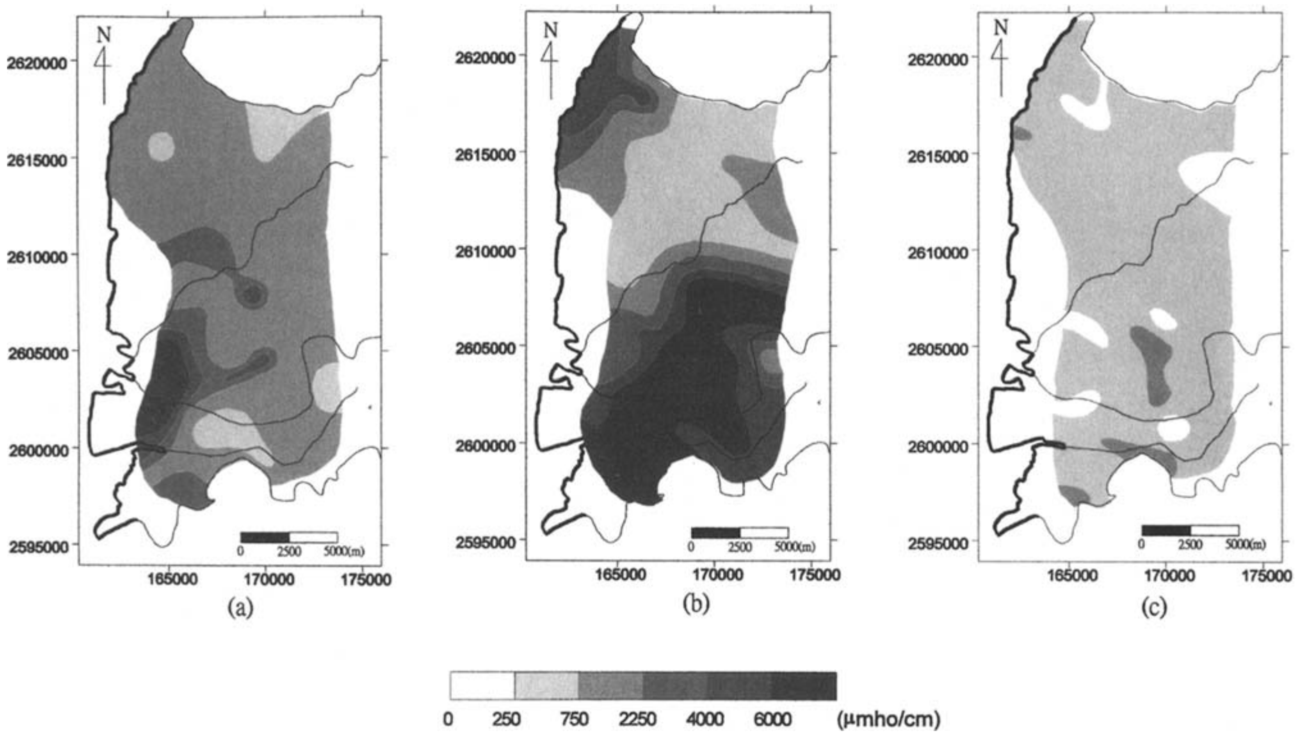
FIG. 4. Plot of formation resistivity versus pore-water resistivity.

SPREAD OF SEA-WATER INTRUSION OVER TIME

To study the temporal variation of local salt-water contamination, dc soundings were carried out once every year from 1986 to 1988 and also in 1995 at selected locations where the B aquifer was contaminated. Figure 6 shows some of the final dc sounding results collected at stations 216 and 217 (Figure 1). In both figures, increasing AB/2 of the sounding curve indicates increase of the polluted depth. The decrease of the values of apparent resistivity may reflect the increase of salinity in the aquifer. It is obvious that an increase of salt-water pollution occurred landward from 1986 to 1988, particularly in the B aquifer. It was due to local pumping groundwater rates that substantially exceeded the local safe yield. Following those years, the government realized the problem and made some attempts at management of the usage of groundwater. However, Figure 6 also shows that the apparent resistivitys in the 1995 sounding curves are increasing compared to decreasing AB/2 in the 1986–1988 results. This observation suggests that the limitation of pumping operations resulted in an approximate safe yield of groundwater in the study area; it prevented subsequent sea-water pollution of the B aquifer.

TEMPORAL AND SPATIAL VARIATION OF CONTAMINATED AQUIFER

In the following analysis, we use the dc sounding data obtained in 1988 and 1995 to study the temporal and spatial variation of the saltwater contaminated aquifers. As shown in Figure 7, when compared with both apparent resistivity maps obtained from 1988 and 1995, the contamination of the A aquifer is still serious in the last 7 years as noted by AB/2 data from 8 m. Following the frequent occurrence of sea-water flooding caused by typhoons, storms, and storm surges in the study area, the surface layer is sufficiently permeable to transport of sea water rapidly downward to the A aquifer, thus the A aquifer is easily contaminated. It should also be noted that the extent of contamination of the B aquifer seems to have shrunk during same period of time as evidenced by AB/2 values of 40 m. Figure 8 shows the ratio map of apparent resistivity collected in 1995 to the apparent resistivity obtained in 1988 for various AB/2. The green line shown in the figure is the estimated landward boundary of saltwater contamination zone in 1988, while the red line is that in 1995. This map does emphasize the increasing range of apparent resistivity of the B aquifer and makes this changes more easily seen. Note that the area with the ratio <1 seems to be increased from the AB/2 range from 80 to 130 m, especially along the coast. This may be a potential of salt-water contamination if we do not pay attention to managing pumping operations of the wells in this area. Since the contaminant plume of the B aquifer is little influenced by surface sea-water flooding, one possible explanation for the increasing extent of the high apparent resistivity of the B aquifer is attributed to a decreasing of salt-water intrusion from the bank of the Pei-kang River, i.e., the groundwater annual withdrawal has been controlled currently by the local government. The increase of freshwater head will prevent further salt-water intrusions from affecting the B aquifer. It can be recognized that the rate of salt-water intrusion and subsurface subsidence is slowing.



(a) (b) (c)

FIG. 5. Distribution of the water conductivity of aquifers (a) A, (b) B, and (c) C.

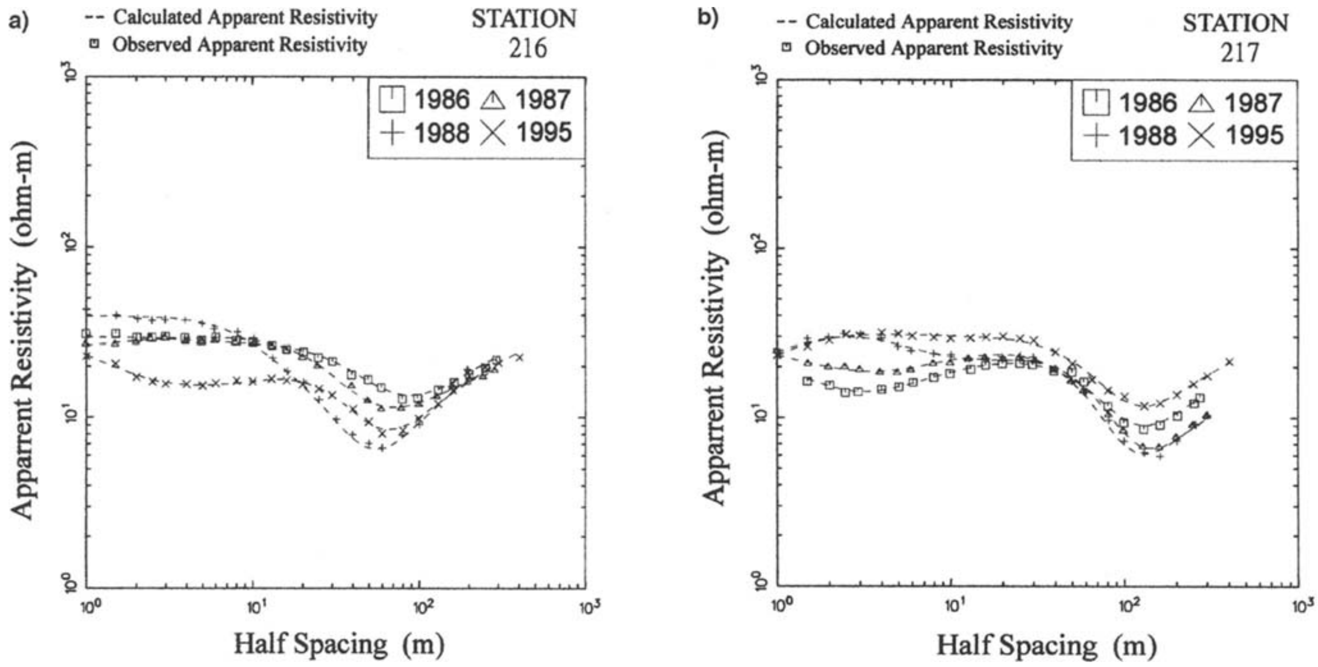


FIG. 6. VES measured once every year from 1986 to 1988 and also 1995 at sounding locations (a) 216 and (b) 217.

CONCLUSIONS

From the previous discussion, the dc and TEM methods were proved to be one of the fastest and most comprehensive methods of detecting and mapping salt-water-affected aquifers. Several points can be concluded.

First, both the dc and TEM methods are capable of delineating the interface between fresh water and salt water in the Quaternary alluvium of west-central Taiwan. Combining a sampling of dc and TEM information at different depths by different data sets may give a better subsurface picture than either method used alone. However, if we are concerned only with B aquifer contamination, either method can be used alone to delineate the sea-water intrusion.

Second, the salt-water-affected aquifer is most obvious at the depth of 20 to 60 m. The polluted zones are along the coast and banks of the Pei-kang and the Po-tzu Rivers. The minimum depth where the potable water can be found is 60 m.

Third, since the pore-water resistivity tied to the dc sounding in situ, the modified Archie's law suggested by this study provides a method to predict the conductivity of the pore water of aquifers from dc measurement in undrilled areas where no well information is available. The electrically derived map shows the spatial distribution of pore water. Changes in electrical properties of the pore water of the aquifers caused by salt-water intrusion may be used as a prospecting index for deploying monitoring wells. In addition, it may be used as a tool to classify the groundwater quality.

Finally, the dc sounding data collected during different time intervals gives an indication of the temporal and spatial variation of local sea-water invasion. The spatial distribution of apparent resistivity shows the salt-water intrusion was severe before 1988. Significant improvement of the quality of the B aquifer can be recognized in 1995. The ratio of dc sounding data collected in 1995 to those in 1988 indicate the salt water affecting the A aquifer is still severe. However, the salt water affecting the B aquifer has improved in most of the area except along the coastline.

ACKNOWLEDGMENTS

This study was supported by the National Science Council grant (NSC76-0202-M008-04 and NSC85-2211-E-008-029), Republic of China. The authors thank the geoelectric group, National Central University, for their help with the field work.

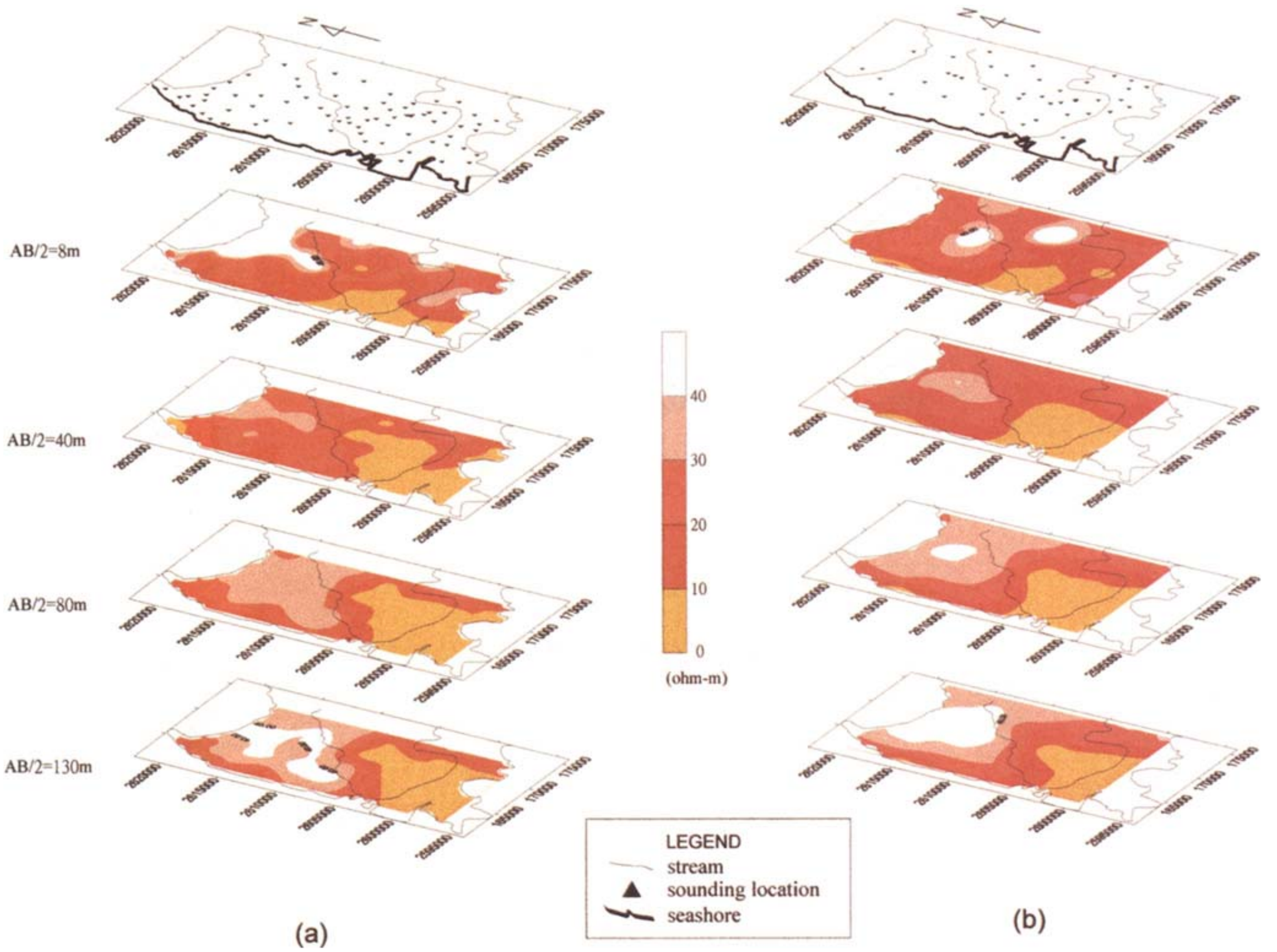


FIG. 7. Spatial variation of apparent resistivity distribution for different Schlumberger half-electrode spacings in different years: (a) 1988, (b) 1995.

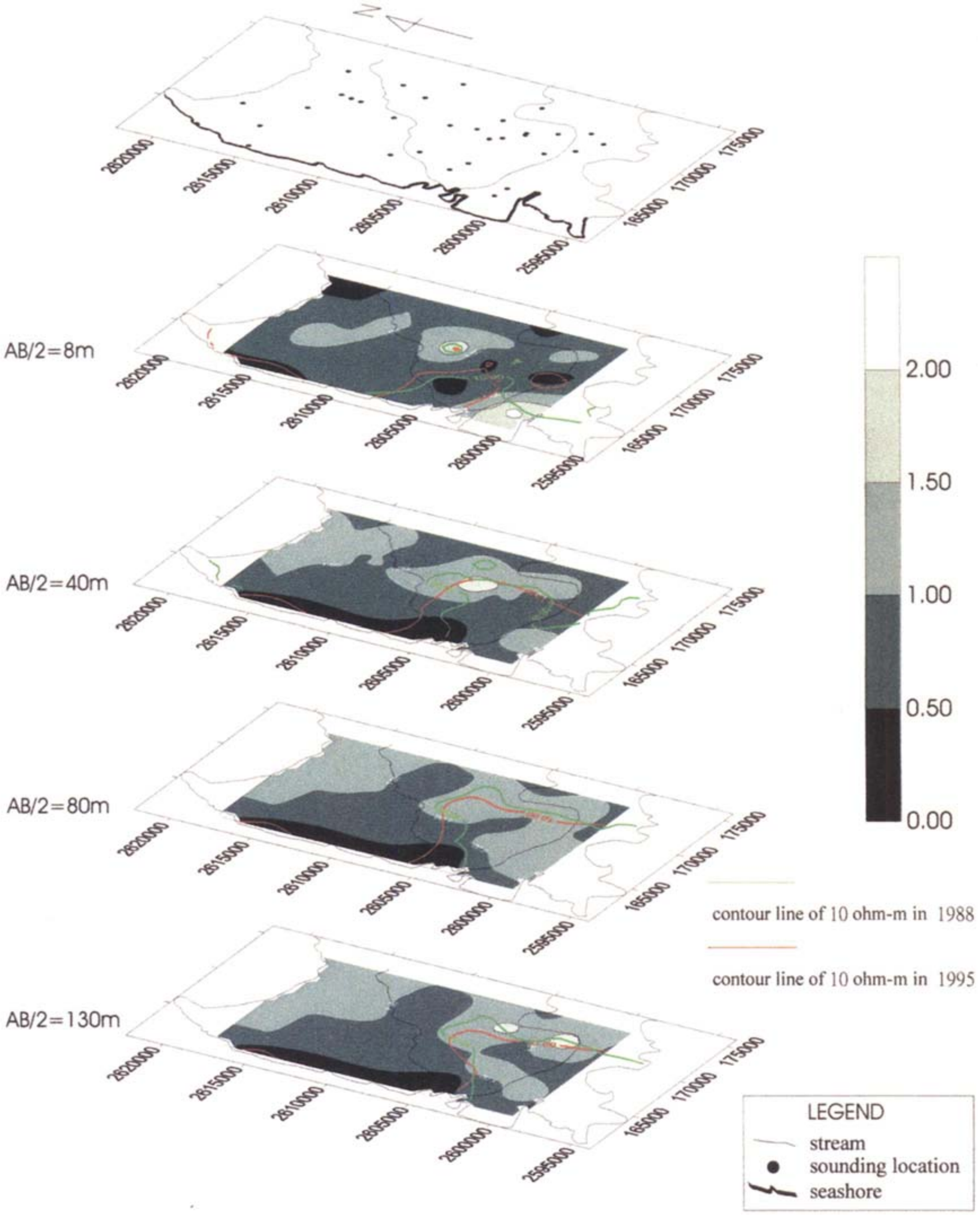


FIG. 8. Ratio map for apparent resistivity obtained in 1995 to apparent resistivity obtained in 1988 with various half-electrode spacing. The green line shown in the figure is the estimated landward boundary of the saltwater contamination zone in 1988, while the red line is that in 1995.

REFERENCES

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Am. Inst. Min. Metallurg. Petr. Eng. Tech. Paper 1422.

Fitterman, D. V., and Hoekstra, P., 1984, Mapping of saltwater intrusions with transient electromagnetic soundings: National Water Well Assn./EPA. Conference on Surface and Borehole Geophysical Methods in Groundwater Investigations, Proceedings, 429–454.

Gay, M. C., 1983, Evaluation of transient electromagnetic soundings for deep detection of salt-water interfaces: Unpublished M.Sc. thesis, Univ. of South Florida.

Gomez-Trevino, E., and Edwards, R. N., 1983, Electromagnetic soundings in the sedimentary basin of southern Ontario—A case history: Geophysics, **48**, 311–326.

Liu, C. C., 1986, A study of groundwater quality in Pei-kang area: M.Sc thesis, National Taiwan Normal Univ. (in Chinese)

Patra, H. P., 1967, A note on the possibility of saline-water invasion around the Jaldha coast, West Bengal (India): Geoexploration, **5**, 95–101.

Raiche, A. P., Jupp, D. L. B., Rutter, H., and Vozoff, K., 1985, The joint use of coincident loop transient electromagnetic and Schlumberger sounding to resolve layered structures: Geophysics, **50**, 1618–1627.

Stewart, M. T., 1982, Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers: Ground Water, **20**, 538–545.

Stewart, M., and Gay, M. C., 1986, Evaluation of transient electromagnetic soundings for deep detection of conductive fluids: Ground Water, **24**, 351–356.

Vozoff, K., and Jupp, D. L. B., 1975, Joint inversion of geophysical data: Geophys. J. Roy. Astr. Soc., **42**, 977–991.

Yang, C. H., 1981, Subsurface water exploration in the Taoyuan–Chungli area, north Taiwan: Bull. of Geophys., National Central University, **21**, 1–14.

Yang, C. H., Jeng, L. W., Lue, C. C., and Chou, C. G., 1994, Detecting sea water intrusion by geoelectric methods: Groundwater Resource and Water Quality Protection Meeting, Proceedings, 427–439. (in Chinese)

Yang, C. H., and Tong, L. T., 1988, Joint inversion of DC, TEM and MT data: 58th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 408–410.