Environ Geol (2007) 51:1349–1359
DOI 10.1007/s00254-006-0433-8

ORIGINAL ARTICLE

Groundwater investigation in Kuala Selangor using vertical electrical sounding (VES) surveys

Umar Hamzah · Abdul Rahim Samsudin ·
Edna Pilis Malim

Received: 4 April 2006 / Accepted: 4 July 2006 / Published online: 27 July 2006

Abstract Integrated geoelectrical and hydrochemical surveys were used to investigate and delineate different types of groundwater in the Kuala Selangor alluvial aquifer. Previous hydrogeological borehole investigation showed that this aquifer contains several types of groundwater in relation to its salinity. The high salinity of the groundwater in some areas is believed to be due to either saltwater intrusion from the nearby sea or river infiltration during high tide season. The vertical electrical sounding (VES) method was employed to study and map the subsurface variation of resistivity in the area. For each sounding measurement, a total spread length of 300 m was obtained with a vertical depth penetration of about 60 to 75 m. Chemical analysis of the groundwater samples taken from both shallow and deep boreholes was carried out for the water quality determination. A total of 45 VES stations were succesfully established along three parallel roads with a direction almost perpendicular to the coastal line. The distance between stations varies from 1 to 2 km with a maximum length of about 60 km surveyed line. Results of the vertical electrical soundings as well as the hydrochemistry of the groundwater samples show that the soil and groundwater in the study area can be grouped into fresh and brackish water zones. The subsurface resisitivity sections derived from the VES study suggest that the area is dominated by brackish soil and groundwater zones, especially in the area towards the coast. This result appears to agree well with the groundwater pumped from boreholes scattered around in the area. Water drawn from boreholes near the coast showed higher salinity compared to the water pumped from inland boreholes. Chloride values greater than 250 mg/L are considered to represent the brackish zones whilst values less than 250 mg/L represents zones of fresh soil and groundwater.

Introduction

The rapid pace of urban development and the associated increasing demand from a growing population for domestic, public and comercial water supply has triggered the Selangor state authority to decide on utilising groundwater to augment surface water as a source for public water supply. Consequently, hydrogeological investigations and groundwater potential assessments were carried out by the Mineral and Geosciences Department of Malaysia in the alluvial plain of the Selangor river basin of Malaysia in 1999 (Bachik 2000). The study area (Fig. 1) covered about 300 km^2, extending from Kuala Selangor-Batang Berjuntai to part of the Tanjong Karang areas in the Kuala Selangor district.

Geologically, the entire area is covered by unconsolidated Quaternary alluvial sediments, consisting mainly of clay and sand, overlying metasedimentary rocks of Devonian to Silurian age. Cross sections based on borehole informations along the survey lines are shown in Figs. 2, 3, 4. A total of five boreholes (BH 8 to 13) were drilled along survey line 1. Based on boreholes data, the study area is basically consisting of

---

U. Hamzah (✉) · A. R. Samsudin · E. P. Malim
School of Environment and Natural Resource Sciences,
Faculty of Science and Technology,
National University of Malaysia, 43600 Bangi,
Selangor, Malaysia
e-mail: aiman9@yahoo.com

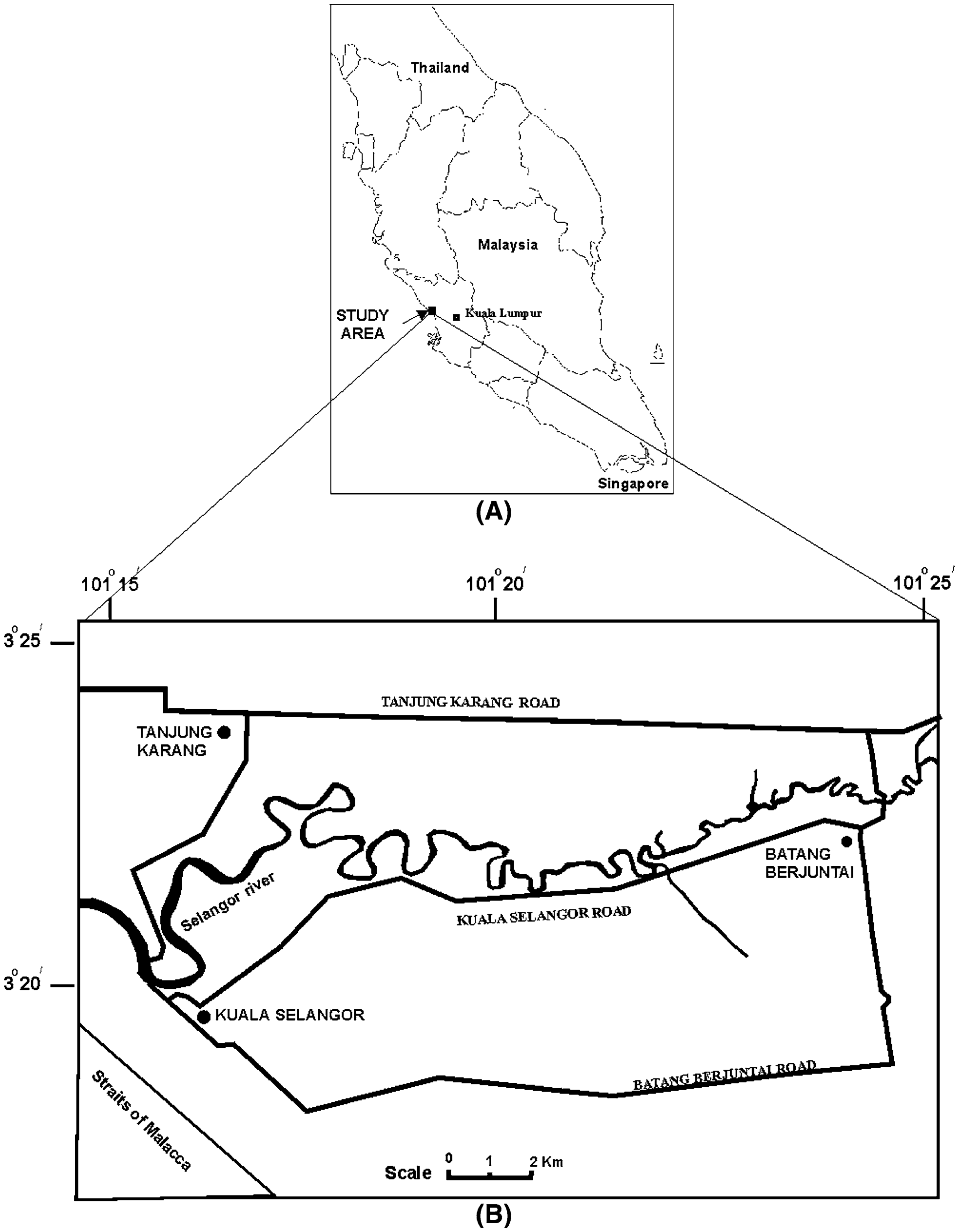


Fig. 1 Location of the study area

interbedded sand and clay layers overlying the metasediment bedrock. Clay and peat with thickness ranging from 10 to 20 m represents the top layer in boreholes 8, 9 and 13. Underlying the clay layer is sand and gravel layer with thickness ranging from 20 to 50 m. In boreholes 10 and 11, the top layer is represented by sand and gravel and those layers are deposited on the metasediment bedrock. The sand and gravel layer of boreholes 8, 9 and 13 is also deposited on the metasediment. In general, the alluvial layers are found thicker towards the coast. Boreholes data indicate that the depth of sand and gravel layer varies from about 30 m in BH 11 to approximately 70 m in BH 13. Thin clay layers were also found interbedded in the sand and gravel as indicated in BH 13. Fig. 3, shows the geological cross section drawn, based on boreholes data of BH 1, 5 and 7 which are located along survey line 2. Except for BH 5, BH 1 and 7 show similar lithological pattern consisting of clay and peat layer overlying the sand and gravel as in line 1. In the case of BH 5, the clay layer is found overlying the metasediment bedrock. Fig. 4 shows the geological cross section of line 3 drawn based on BH 2, 3 and 4. In general, the thickness of clay, sand and gravel layers are thicker towards the coast with thicknest ranging from about 15 to 38 m.

Fig. 2 Geology of line 1 based on boreholes data

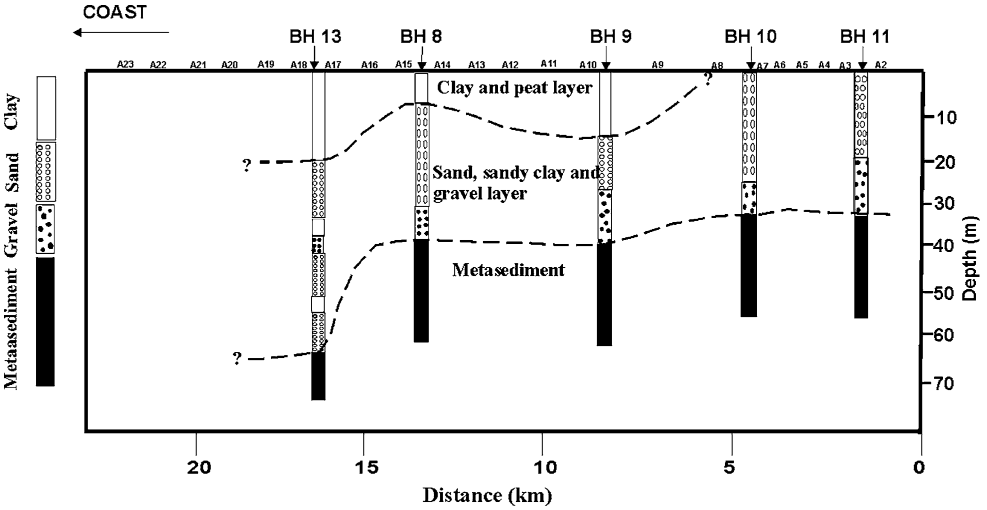


Fig. 3 Geology of line 2 based on boreholes data

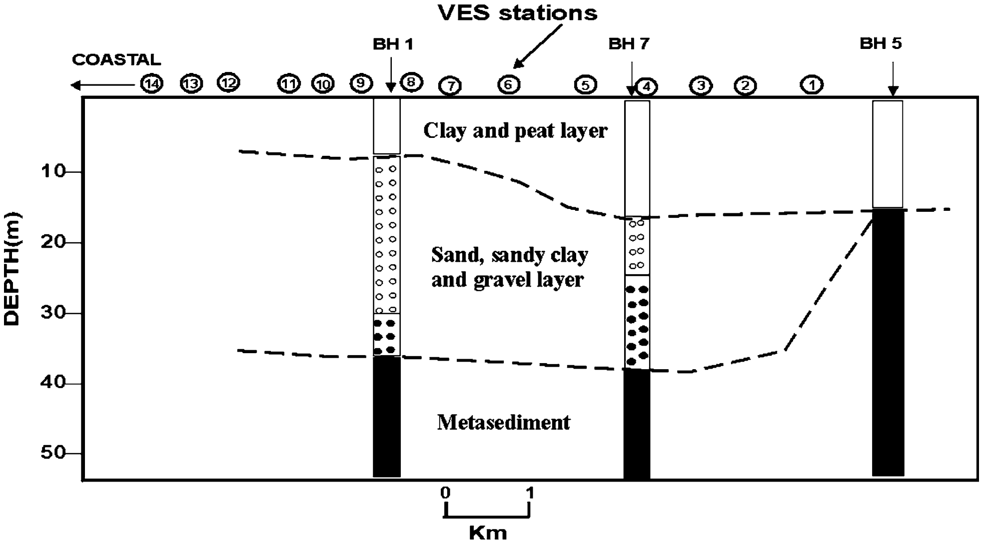
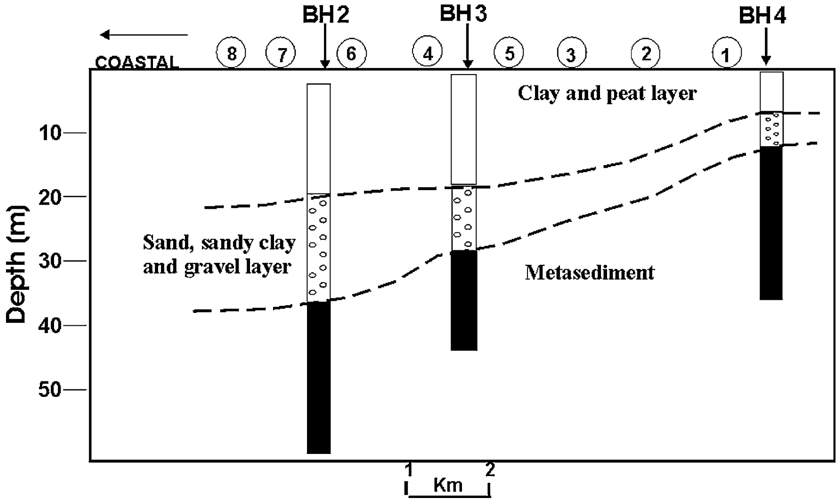


Fig. 4 Geology of line 3 based on boreholes data



The types of surveys carried out by the Mineral and Geosciences Department included rotary drilling for exploration boreholes and testing of water quality through hydrochemical analysis of the extracted groundwater. Pumping tests at two exploratory boreholes showed that the water extracted from the aquifer was about 3,200 m^3/day. Except for the high iron and ammonia content which can be reduced, the other water quality parameters are within the Ministry of Health Standards for drinking water (Bachik 2000). The aquifer thickness varies from 20 to 30 m and is made up of sand and gravels mixed with clay lenses. This confined aquifer overlies the sedimentary bedrock and is overlain by a yellowish brown hard clay layer of about 15 m thickness. Out of 16 boreholes drilled in the study area, 13 boreholes were located in the confined aquifer which were overlain by clay and peat top materials, and only three boreholes (BH10, BH11 and BH12) were drilled in the unconfined aquifer. Depth of the water table in these boreholes during the drilling varies from 0.05 to 2.35 m.

Results of the hydrochemical analysis showed that the groundwater in the study area can be classified into fresh and brackish waters and varies with the location of the drilling sites. Maps based on this analysis showed that the brackish water zone is parallel to the coast and extends inland for about 2–4 km (Bachik 2000). This high groundwater salinity is believed to have originated from either seawater intrusion or infiltration from the nearby Selangor River during high tide.

A geophysical technique, commonly used for mapping the shallow subsurface for environmental and hydrogeological studies, is the electrical resistivity technique (Frohlich and Urish 2002). This survey is routinely employed in groundwater exploration to locate zones of relatively high conductivity corresponding to saturated strata at depths down to 200 m (Lashkaripour 2003). This kind of survey may also provide indications of groundwater quality. The method provides adequate depth penetration and quantitative results to solve more problems of groundwater in the alluvium, karstic and another hard formation aquifer. Some uses of this inexpensive and useful method in groundwater exploration are, determination of depth, thickness and boundary of aquifer (Zohdy 1989; Young et al. 1998), determination of interface of saline and fresh water (Choudury et al. 2001), porosity of aquifer (Jackson et al. 1978) and contamination of groundwater (Kelly 1976; Kaya 2001).

Most constituent minerals of sedimentary rocks are electrically resistant and the passage of electricity thus takes place mainly by ionic conduction in the pore waters. The resistivity of the rock is thus mainly controlled by the fraction of water present and will decrease as the salinity of the water increases, as demonstrated by Archie (1942). Consequently, in an homogeneous aquifer, it is possible to distinguish fresh from brackish groundwater based on the resistivity measurement. For rocks or materials composed of non-conducting matrix minerals and saturated with water, an empirical relationship known as Archie's Law is used in analysis of electrical properties (Keller and Frischknecht 1977). Archie's Law states that;

$$\rho_{\mathrm{ROCK}} = \rho_{\mathrm{FLUID}} \mathrm{A}\, \Phi^{-\mathrm{m}}$$

where ρ_{ROCK} is the resistivity of clean rock or clay-free rock, ρ_{FLUID} is the resistivity of fluid in the pores of the rock, Φ is the porosity (ratio of void volume/total volume) and A and m are constants that depend on the geometry of the pores. For many rocks, $A = 1$ and $m = 2$ (Nigmatullin et al. 1992). From the above equation, resistivity value will most likely depends on the resistivity of fluid in the pores for clay-free rocks and the electrical resistivity of a fluid depends on the amount of ionic material in solution and on the temperature of the fluid. Therefore fresh water can be distinguished from the brackish water based on the measured resistivity values. Archie's Law is not valid for rocks containing a significant percentage of clay because clay minerals have the property of sorbing certain anions and cations and retaining these in an exchangeable state (Keller and Frsichknecht 1977). In clay-water mixtures, the exchange ions may separate from the clay mineral in a process like ionization and move into the solution to increase the concentration of ions already in the solution and consequently will lower the pore-water resistivity.

Studies on salinity of groundwater by electrical resistivity methods have been reported by many authors. Samsudin et al. (1997) described the results of vertical electrical sounding (VES) surveys in their salinity study of coastal groundwater aquifers in north Kelantan and considered resistivity value of about 45 Ωm as the boundary between fresh and brackish water-saturated layer. A similar study by Surip (1994) in the eastern coast of Peninsular Malaysia showed that the saline alluvial layer has a resistivity lower than 2 Ωm, fresh water-saturated alluvial layer resistivity is between 75 and 300 Ωm with values in between 2 and 75 Ωm representing brackish water-saturated alluvial facies. Rafek and Samsudin (1989) undertook a resistivity survey in areas dominated by marine clay and showed that the saline clay material has resistivity values less than 1.0 Ωm. Bugg and Lloyd (1976) and

Urish and Frohlich (1990) in coastal groundwater explorations showed that the boundary of fresh and brackish water-saturated layer is about 48 Ωm corresponding to 500 mg/L chloride content.

The aim of this study was to investigate the distribution of soil and groundwater salinity in the Kuala Selangor coastal area based on surface geophysical electrical surveys. With this target in mind, vertical electrical sounding surveys were carried out at 45 stations along three parallel roads perpendicular to the coast. These results were then compared with the findings from the hydrochemical analysis.

Methodology

The electrical resistivity survey involved vertical electrical sounding (VES) is based on measuring the potentials between one pair of electrodes while transmitting a direct current between another pair of electrodes. Depth of current penetration is proportional to the spacing between the electrodes in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground (Koefoed 1979). VES survey was carried out in the study area with an ABEM SAS 300 C Terrameter for measuring the earth resistance, four one-metre length of 1.5 cm diameter cylindrical steel stakes as electrodes, and wire to connect the electrodes to the Terrameter. The wire is coiled around reels for ease in winding and unwinding as electrode spreads are increased. The length of wire on reels connecting the resistivity meter to the current electrodes is 200 m while the length of wire for connecting the potential electrodes is 20 m. The ABEM SAS 300 C equipment is light and powerful for deep current penetration. The resistivity survey was completed with 45 sounding stations in three survey lines. The location of VES stations and the survey lines are presented in Fig. 5. The electrical sounding in this study was conducted by using the Schlumberger array (Koefoed 1979). This array is a popular method, which is rather time consuming. The Schlumberger soundings were carried out with current electrode spacing (AB) ranging from 2 to 300 m (AB/2 = 1 m to 150 m). The distance used for potential electrode spacing (MN) ranged from 0.3 m to 10 m (MN/2 = 0.15 m to 5 m). The field data acquisition was generally carried out by moving two or four of the electrodes used, between each measurement.

RESIX (Interpex Ltd 1990) which is an interactive, graphically oriented, forward and inverse modeling program was used for interpreting sounding data in

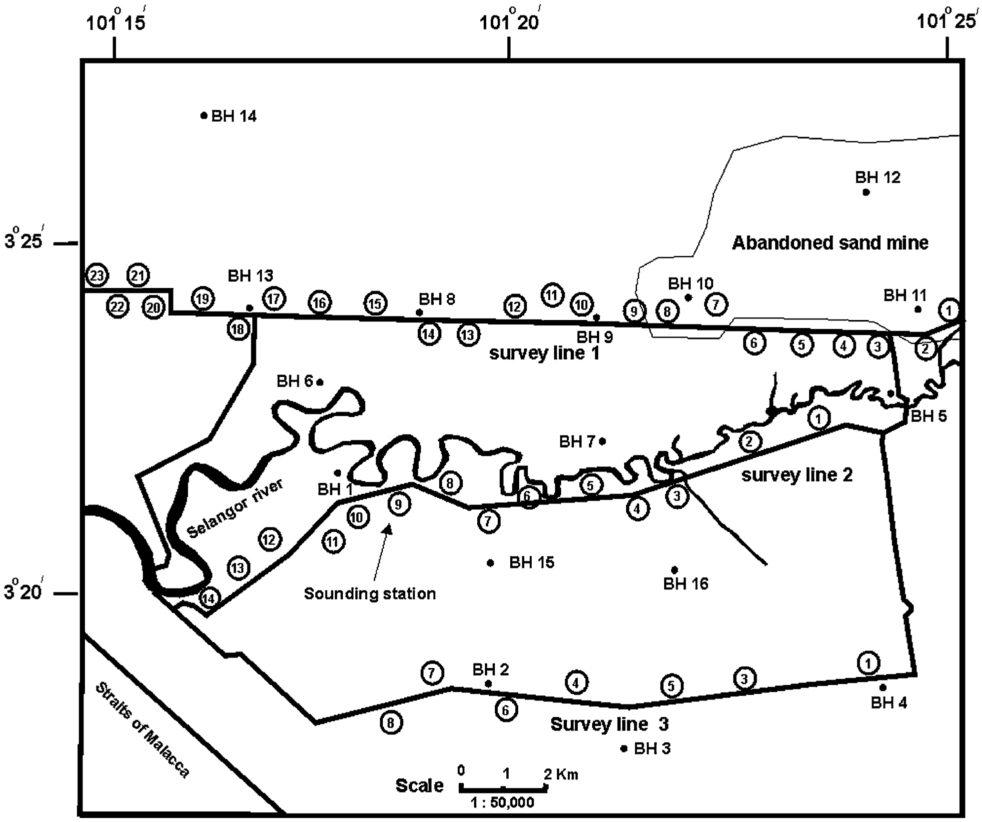


Fig. 5 Locations of VES stations and boreholes in the study area

terms of a layered (1-D) model. Sounding curves were entered as apparent resistivities versus spacing (AB/2) for Schlumberger soundings array. Estimated resistivities and thickness of layers based on borehole data were used as input parameters for a starting model in the inverse modeling. Inverse modeling produces a model that best fits the data in a least squares sense using ridge regression (Inman 1975) by iteratively adjusting the parameters of the starting model. Typical electrical sounding data and best-fit three-layer model interpretation of the study area are as shown in Fig. 6a, b.

Additional geological and hydrogeological data obtained from the Mineral and Geosciences department were used to supplement the geophysical results. The data included borehole records, pumping test records and the quality of the water, namely all major ions, pH, electrical conductivity and total dissolved solids (TDS). Sampling, preservation and water analysis were performed in accordance with the standard procedures described by APHA (1995). Prior to groundwater sampling, pH and electrical conductivity were measured in the field using HACH model conductivity-pH meter. Samples were taken for laboratory analyses of major ions. Alkalinity was determined by titration method using 0.1N HCl (Wetzel and Likens 1991). For analyses of major cations and trace elements, samples were acidified to pH < 2 with HNO_3 to prevent absorption of cations to the container surface and precipitation of dissolved ions. Samples were collected in polyethylene bottles. Cations such as Na + and K + were analyzed using Flame Photometer Spectrometer (Corning 410 model) and the rest of major ions and trace elements were analyzed in these solutions by using Atomic Absorption Spectrometer (Perkin Elmer As 91 model).

More than 90% of the dissolved solids in the ground water can be attributed to eight ions such as sodium, calcium, potassium, magnesium, sulfate, chloride, bicarbonate and carbonate. One basic measure of water quality is the TDS, which is the total amount of solids, in mg/L, that remain when a water sample is evaporated to dryness (Fetter 2001). Table 1 gives a classification scheme for water, based on the total dissolved solids. The quality of ground water varies from place to place where it can range from TDS

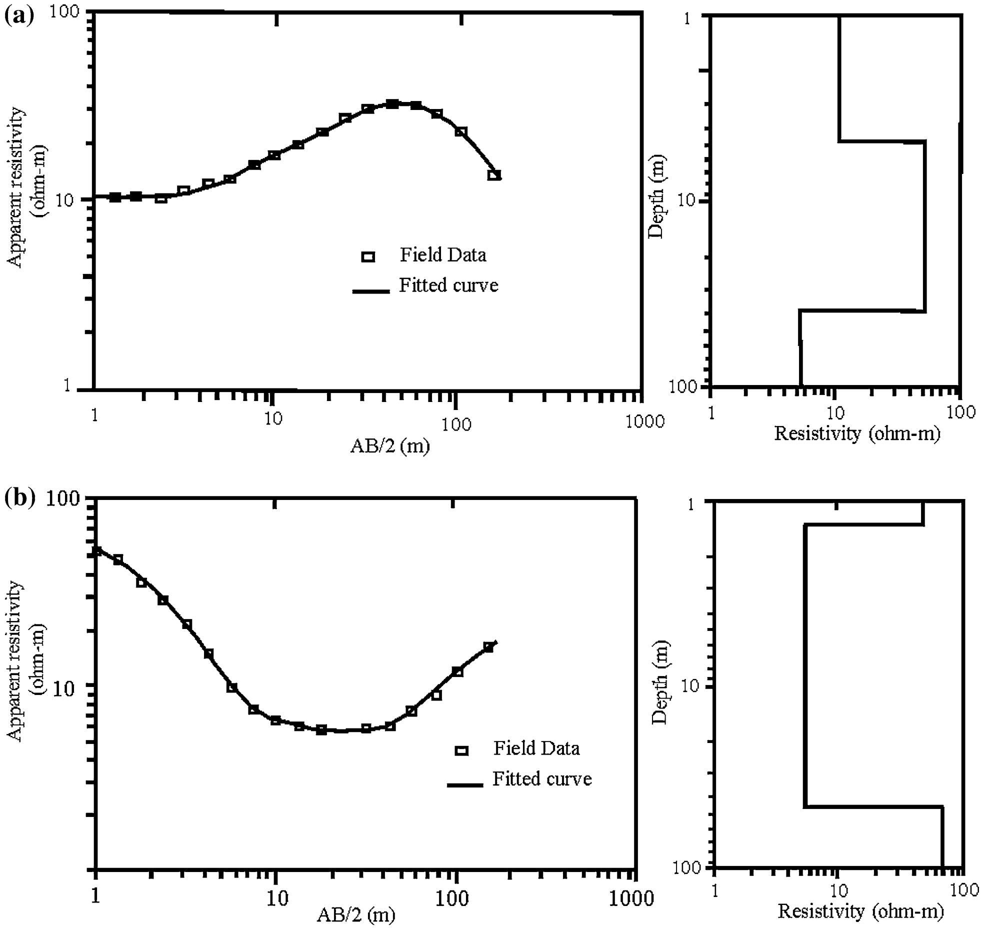


Fig. 6 Two typical VES data and best-fit three layer model interpretations

Table 1 Classification of water based on the total dissolved solids (TDS)

Class of water	TDS (mg/L)
Fresh	0–1,000
Brackish	1,000–10,000
Saline	10,000–100,000
Brine	> 100,000

contents of 100 mg/L or less for some fresh ground water to more than 100,000 mg/L for brines or seawater. Saline water has TDS content between 10,000 to 100,000 mg/L.

For reasons of analytical convenience, a practical index of salinity is electrical conductivity, expressed in units of µmhos/cm. Classification of fresh to saline waters based on electrical conductivity (Rhoades 1982) is shown in Table 2, where fresh water has a conductivity less than 700 µmhos/cm and conductivity of brine or seawater is greater than 45,000 µmhos/cm.

Field measurements of pH, temperature and specific electrical conductance were made at the time the sample of groundwater is collected. Without field pH, the concentrations of carbonate and bicarbonate cannot be determined from the alkalinity (Fetter 2001).

Results and discussion

The distribution of the exploration wells or boreholes locations in the area is shown in Fig. 5. The area is covered with Quaternary alluvial sediments in the coastal part and weathered metasediments in the eastern part. The Quaternary sediments consist of unconsolidated sand, gravel and clay, which, near the coast is partly of marine origin (Stauffer 1973). Results of groundwater quality analysis in relation to TDS and major ions content (Table 3) indicate that the groundwater quality varies considerably from saline, with total dissolved solid concentration of more than 1,000 mg/L (Samsudin et al 1997) to very fresh groundwater, containing dissolved solids of less than 100 mg/L. A closer observation of the location of the boreholes shows that the saline water with TDS values above 1,000 mg/L comes from boreholes 6 and 13 located near the coast. Chloride content from these boreholes was also found to be high with values above 1,000 mg/L. A value of TDS of above 250 mg/L is considered as the boundary between fresh and brackish groundwater facies (Sapari and Awang 1996; Samsudin et al. 1997). Surip (1994) also reported chloride content of about 6,300 mg/L for the saline groundwater sample while chloride concentration for seawater is about 19,000 mg/L. The high salinity of groundwater from these boreholes was supported by the high measured electrical conductivity (5,040 to 6,260 µmhos/cm). These conductivity values are higher than the limit (3,200 µmhos/cm) for the saline water base line as determined by Bugg and Lloyd (1976).

Fresh groundwater with TDS values of less than 250 mg/L was obtained from boreholes 9, 10, 11 and 12 that were drilled further inland. The chloride content of groundwater from these wells was also low ranging from 1 to 14 mg/L with the electrical conductivity found to be in the range of 45 to 358 µmhos/cm. Groundwater from these boreholes are classified under the sodium bicarbonate facies.

Groundwater extracted from boreholes 3, 7 and 8 showed TDS values ranging from 250 to 1,000 mg/L, with the chloride concentration ranging from 147 to 399 mg/L and electrical conductivity of between 715 to 1610 µmhos/cm (Table 3). Based on these values, the groundwater is classified as slightly brackish to fresh water. The TDS content is slightly lower than the brackish-fresh water boundary (1,000 mg/L) and the conductivity values fall within the Bugg and Lloyd (1976) limit (250–3,200 µmhos/cm) which is the upper and lower limits of brackish water conductivity.

A total of 23 VES stations with a spacing of approximately half to one km between each station were recorded along line 1 (Fig. 5). The VES profiles and the subsurface geological information based on borehole data drilled along the line are shown in Fig. 7. Interpreted resistivity values observed from these stations are from 2 to 300 Ωm. Borehole positions along the survey line are also shown in the profile. Interpretation of the soil and groundwater salinity in the study area was carried out following the Buggs and Lloyd (1976) classification where boundary between fresh and the brackish groundwater zone is 48 Ωm. Resistivity values higher than 48 Ωm is interpreted as fresh water zone while values lower than 48 Ωm represents brackish water zone. Based on these criteria, a profile delineating fresh and brackish groundwater

Table 2 Classification of water based on the electrical conductivities

Water class	Electrical conductivity (micromhos/cm)
Fresh	700
Slightly saline	700–2,000
Moderately saline	2,000–10,000
Highly saline	10,000–25,000
Very highly saline	25,000–45,000
Brine (seawater)	> 45,000

Table 3 Concentration of elements in mg/L based on chemical analysis of boreholes water samples (Bachik 2000)

Boreholes												
Parameter (mg/L)	BH3	BH6	BH7	BH8	BH9	BH10	BH11	BH12	BH13	BH14	BH15	BH16
Mg	18	46	24	3.3	2.4	15	7.8	1.0	58	163	46	36
Ca	97	164	111	1.8	1.1	4.7	22	0.9	35	129	44	59
Na	18	46	24	3.3	2.4	15	7.8	1	58	935	1005	467
K	253	990	148	143	35	9.9	6.1	9.8	890	33	40	39
HCO2	16	24	12	6.7	8.5	7.7	2.9	1.7	27	7	634	218
Cl	203	1844	399	147	1	2	14	2	1445	2318	1446	788
Salinity	Fresh	Brack	Brack	Fresh	Fresh	Fresh	Fresh	Fresh	Brack	Brack	Brack	Brack
SO4	3	62	3	3	3	3	3	3	3	4	3	3
NO3	7.7	0.6	0.9	0.6	6.6	7.3	8	0.7	1.3	1	24.4	17.4
NH4	1.3	2.6	1.4	0.5	0.5	0.5	0.5	0.6	2.5	6.5	0.5	0.5
Fe	4.1	4.8	0.2	2.4	0.2	51	14	7.3	18	60	1.7	8.8
Mn	0.3	2.9	0.2	0.1	0.1	0.3	0.2	0.1	0.9	5	0.2	1.2
Cu	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pb	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Zn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
Al	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.2	0.3
Ni	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sr	0.08	0.40	0.66	0.02	0.10	0.09	0.09	0.01	0.30	1.28	0.34	0.39
Ba	0.1	0.1	0.9	0.1	0.1	0.1	0.1	6.8	0.1	1	0.6	0.5
pH	7.7	6.9	7.5	7.6	8.2	7.1	7.2	6.8	7.6	5.2	7.8	8
μ (umhos/cm)	1453	6260	1610	715	358	208	170	45	5040	7580	5760	3040
SiO2	56	14	17	24	17	31	33	17	14	10	12	12
TDS	840	3436	932	412	198	148	122	62	2696	3596	2924	1552
Turbidity (NTU)	561	103	7	302	13	253	110	83	121	509	15	72
Hardness	98	599	376	18	13	74	87	6	326	993	299	296

zones was established for line 1. In general, most of the upper part of the profile can be considered as brackish layer. This brackish layer (2–48 Ωm) is thicker towards the coast with a maximum depth of about 50–60 m and thinner towards the interior with a minimum thickness of about 2–3 m. The fresh groundwater zone (48–300 Ωm)

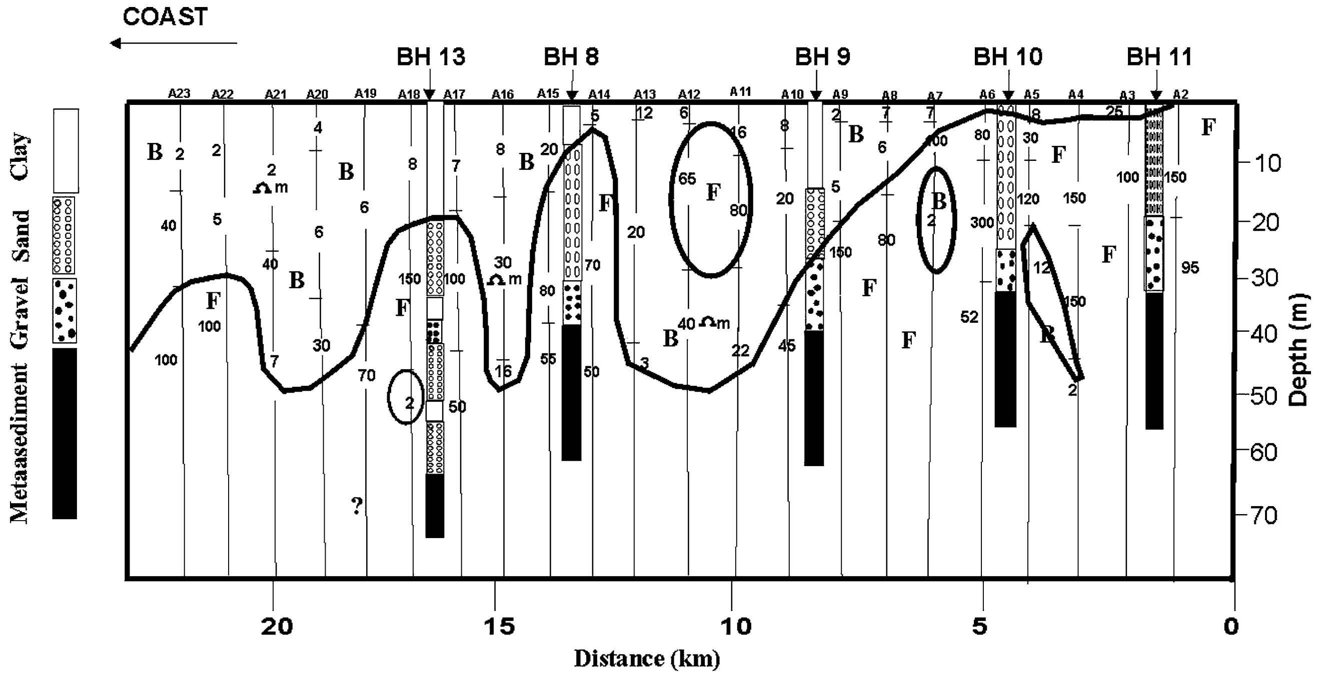


Fig. 7 Subsurface resistivity profile of line 1 (*F* = fresh, *B* = brackish)

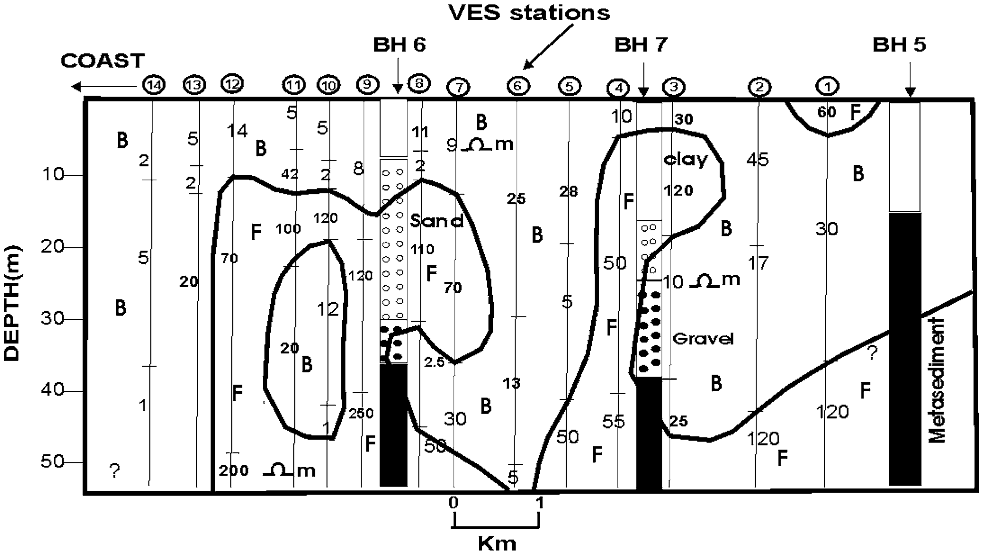
underlies the brackish zone and in some part is sandwiched between the brackish zones. Based on the geological section derived from boreholes data, the surface data of VES resistivity values have a good comparison with the surface clay layer that the boreholes data show. In this case, the low resistivity values of VES data might possibly be representing the top clay layer along profile 1. The effect of clay minerals in increasing the conductivity of groundwater distributed through the pore spaces has been described by Keller and Frischknecht (1977).

Line 2 profile is also dominated by brackish groundwater zone as shown by the resistivity values ranging from 1 to 45 Ωm. Resistivity values ranging from 50 to 250 Ωm represent the fresh groundwater zones (Fig. 8). A much simpler resistivity distribution pattern is shown in profile 3, where the brackish groundwater zone dominates the middle and upper zones whereas the fresh groundwater zone is found underlying the brackish one. The resistivity for the brackish zone ranges from 4 to 45 Ωm whereas the resistivity for the fresh groundwater zone ranges from 50 to 500 Ωm (Fig. 9).

These water facies zones showed good correlation when compared with the pumped groundwater quality determined from the hydrochemical analysis. Groundwater drawn from boreholes 8 to 11 was found to be fresh and is from the fresh groundwater zone based on VES resistivity section of line 1 (Fig. 7). Water from borehole 13 was determined as brackish and it originates from the brackish zone with resistivity of about 2 Ωm. A good correlation of water quality was also found between water quality based on chemical analysis of pumped water and from VES survey for line 2 (Fig. 8). Water drawn from boreholes 6 and 7 was classified as brackish, based on chemical analysis and this water, pumped from a gravelly aquifer, comes from a zone of very low resistivity (2.5 Ωm) near borehole 6 and 10 Ωm near borehole 7. A very good correlation between hydrochemical analysis and VES results was also shown in profile 3 (Fig. 9). Freshwater from borehole 3 was drawn from high resistivity (150–550 Ωm) area which corresponds to the fresh groundwater zone according to the VES survey.

Data from this integrated study prove that water quality from the exploration boreholes and groundwater quality from geophysical surveys varies from fresh to brackish depending on the locations. Based on the resistivity values, cross sections of line 1, 2 and 3 are dominated by brackish groundwater zones and the fresh groundwater zones are found to be as isolated patches in brackish zones as clearly shown in Figs. 7, 8. A much simpler pattern is shown in Fig. 9 where the brackish zone dominates the western part of the profile. There are several possible mechanisms that can explain the occurrence of brackish groundwater zones in the study area. Since a large part of the area is classified as brackish, the saline water might have originated from relict seawater within the aquifer system. During the Pleistocene time, the sea level stood at a much higher level than it does today (Johnston 1983) and the aquifer system was invaded with seawater. When the sea level dropped to the present position, some of this seawater may not have been completely flushed from the aquifer. Generally, this unflushed relict seawater is found in the layer of relatively low permeablitiy such as clay in the form of adsorbed sodium chloride salts. A lateral encroachment of recent seawater is an unlikely explanation for the presence of brackish groundwater zones in the area. If seawater

Fig. 8 Subsurface resistivity profile for survey line 2



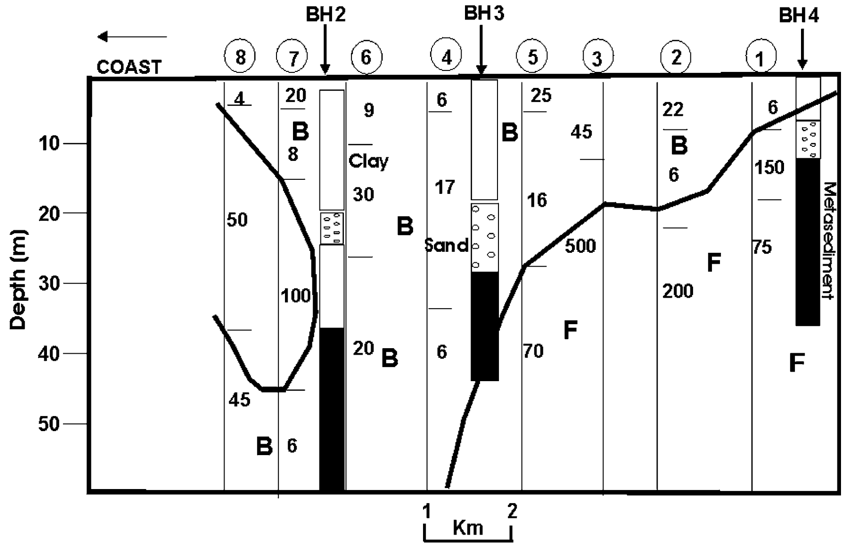


Fig. 9 Subsurface resistivity profile for survey line 3

were moving laterally towards the inland, the saltwater would first be detected in boreholes nearest the coast. However boreholes 3 and 14 located near the coast have chloride content indicating freshwater facies, whereas some boreholes as much as 20 km inland of the coast have chloride concentration exceeding 250 mg/L indicating brackish type of water. Another possible explaination for the high chloride content found in the inland boreholes is the infiltration of seawater into these aquifers through the river during high tide. This explains why profiles 1 and 3 showed the same results where the presence of fresh water is more prevalent than brackish water in the subsoil compared to profile 2 which was dominated by brackish groundwater zones and is completely heterogeneous. It is also possible that freshwater occurs in gravel lenses formed by Selangor river in its meandering to the coast. This could explain the presence of fresh water lenses within brackish groundwater zones.

Conclusion

The subsurface resistivity distribution obtained from the VES survey has been useful to characterize groundwater type in the study area. Based on the hydrochemical analysis of groundwater, it is concluded that the groundwater in the study area is classified as both fresh and brackish. Both fresh and brackish types of groundwater pumped from the boreholes appear to correlate with the interpreted fresh and brackish resistivity zones of the VES survey.

Acknowledgments We would like to thank members of UKM Geophysical Group for their cooperation in the geophysical field data collection and help in processing some of the data. We also wish to thank the Department of Mineral and Geoscience of Malaysia for providing borehole data used for the interpretation and finally the Malaysian Ministry of Science, Technology & Innovations for financing this project through RM7 (02-02-02-010) R&D project.

References

APHA, AWWA, WPCF (1995) Standard methods for the examination of water and wastewater, 19th edn. American Public Health Association, Washington

Archie GE (1942) The electrical resistivity log as an aid in determining some reservoir characteristics, AIME Tech. Paper 1422

Bachik AR (2000) Groundwater potential in Kuala Selangor-Batang Berjuntai Selangor. Geological Survey Dept report

Bugg SF, Lloyd JW (1976) A study of freshwater lense configuration in the Cayman Islands using resistivity methods. Q J Eng Geol 9:291–302

Choudhury K, Saha DK, Chakraborty P (2001) Geophysical study for saline water intrusion in a coastal alluivial terrain. J Appl Geophys 46:189–200

Fetter CW (2001) Applied hydrogeology. Prentice Hall Inc., New Jersey

Frohlich RK, Urish D (2002) The use of geoelectrics and test wells for the assessment of groundwater quality of a coastal industrial site. J Appl Geophys 50:261–278

Inman JR (1975) Resitivity inversion with ridge regression. Geophysics 40:798–817

Interpex Limited (1990) Resix user's manual of DC Resistivity Data Interpretation software. Golden, Colorado

Jackson PN, Taylor SD, Stanford PN (1978) Resistivity-porosity – particle shape relationship for marine sands. Geophysics 43:1250–1268

Johnston RH (1983) The saltwater-freshwater interface in the Tertiary limestone aquifer, southeast Atlantic outer-continental shelf of the USA. J Hydrol 61:239–249

Kaya GK (2001) Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey. Environ Geol 40:725–731

Keller GV, Frischknecht FC (1977) Electrical methods in geophysical prospecting. Pergamon Press, Oxford

Kelly EW (1976) Geoelectric sounding for delineating groundwater contamination. Groundwater 14:6–11

Koefoed O (1979) Resistivity soundings measurements. In:Geosounding principles, vol. 1, Elsevier, New York

Lashkaripour GR (2003) An investigation of groundwater condition by geoelectrical resistivity method: a case study in Korin aquifer, Southeast Iran. J Spat Hydrol 13(1):1–5

Nigmatullin RR, Dissado LA, Sontougin NN (1992) A fractal pore model for Archie's Law in sedimentary rock. J Phys D Appl Phys 25:32–37

Rafek AG, Samsudin AR (1989) Pemetaan lapisan lempung samudera dengan kaedah keberintangan geoelectrik di kawasan lebuh raya Tangkak—Pagoh, Johor. Sains Malaysiana 18(1):139–148

Rhoades JD (1982) Reclamation and management of salt-affected soils after drainage. Proc. First annual western provincial conf. rationalization of water and soil resources and management. Lethbridge, Alberta pp 123–197

Samsudin AR, Haryono, Hamzah U, Rafek AG (1997) Salinity study of coastal groundwater aquifers in North Kelantan, Malaysia. Geol Soc Malaysia Bull 41:159–165

Surip N (1994) Penggunaan kaedah-kaedah geofizik, hidrogeologi dan radioisotop dalam mengesan akuifer air masin kawasan Kuala Rompin dan Marang. Unpublished MSc theses National University of Malaysia

Sapari N, Awang MN (1996) Alluvial aquifer in Selangor: a threatened water resources. Prosiding Seminar Geologi dan Sekitaran: Impak dan Pengauditan. UKM, Bangi 85–101

Stauffer PH (1973) Quaternary deposits. In: Gobbett DJ, Hutchison CS (eds) Geology of The Malay Peninsula. Wiley, New York pp438

Urish DW, Frohlich RK (1990) Surface electrical resistivity in coastal groundwater exploration. Geoexplor 26:267–289

Wetzel RG, Likens GE (1991) Limnological analysis. Springer, Berlin Heidelberg New York p 391

Young ME, de Brujin RGM, Salim AA (1998) Exploration of an alluivial aquifer in Oman by time-domain electromagnetic sounding. Hydrogeol J 6:383–393

Zohdy AAR, Bisdorf RJ (1989) Programs for the automatic processing and interpretation of Schlumberger sounding curves in quick basic. U.S. Geological Survey Open File Report89–137–2, 64 p