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ORIGINAL ARTICLE

Integrated geoelectrical resistivity, hydrochemical and soil property analysis methods to study shallow groundwater in the agriculture area, Machang, Malaysia

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Abstract Integrated geoelectrical resistivity, hydrochemical and soil property analysis methods were used to study the groundwater characteristics of sandy soils within a shallow aquifer in the agriculture area, Machang. A pilot test investigation was done prior to the main investigation. The area was divided into two sites. Test-Site 1 is non-fertilized; Test-Site 2 is the former regularly fertilized site. From the surface to depths of 75 cm, a lower average resistivity was obtained in Test-Site 2 (around 0.37 less than in Test-Site 1). The presence of nitrate and chloride contents in pore water reduced the resistivity values despite the low moisture content. The pH values for the whole area range from 4.11 to 6.88, indicating that the groundwater is moderately to slightly acidic. In the southern region, concentration of nitrate is considered to be high (>20 mg/l), while it is nearly zero in the northern region. In the south, the soil properties are similar. However, the geoelectrical model shows lower resistivity values (around 18 Ω m) at the sites with relatively high nitrate concentration in the groundwater (>20 mg/l). Conversely, the sites with low nitrate concentration reveal the resistivity values to be higher (>35 Ω m). Basement and groundwater potential maps are generated from the interpolation of an interpreted resistivity model. The areas that possibly have nitrate-contaminated groundwater have been mapped along with groundwater flow patterns. The northern part of the area has an east to west groundwater flow pattern, making it impossible for contaminated water from the southern region to enter, despite the northern area having a lower elevation.

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Introduction

Groundwater is among North Kelantan's most important natural resources. Good quality groundwater provides drinking water to urban and rural communities. Unfortunately, it might become contaminated when even seemingly harmless materials and waste materials introduced into the ground are improperly handled. Contamination involves excess amounts of nitrogen, phosphorus and many other chemicals.

In the study area and elsewhere, chemical fertilizers (Yang et al. 2006) are extensively used to enhance agricultural establishments such as for palm oil plantations. The fertilization process is conducted every 2 months using fertilizers of different chemical content. At the beginning of the year, 400 kg of urea with 60% nitrogen is used for a 2 ha palm plantation. Two months after that, another type of fertilizer with 15% nitrogen, 30% phosphorus and 55% potassium (NPK) is applied to further improve the production of palm. This process is repeated in the middle of the year and continues till the end of the year. In total, at least 800 kg of urea is used for the fertilization of palm trees in a 2 ha area per year.

Other agricultural activities within the study area include the cultivation of paddy plants and rubber trees. However, the intensity of the fertilization for paddy and rubber trees is much less than for palm oil. The farmers in the study area generally plant paddy only once a year, although in other areas some plant up to twice a year. Paddy planting consumes a mere 100 kg of urea per 2 ha a year. For rubber trees, 150 kg of urea is utilized for every 2 ha per year.

Contaminant leaching (especially nitrate) from agricultural soils has been widely studied (Almasri and Kaluarachchi 2004; Saadi and Maslouhi 2003). In this study, attention has been focused mainly on nitrate contamination in groundwater within sandy soils in the shallow aquifer. Clay soils are usually not considered to have actual high nitrate leaching potential (Almasri and Kaluarachchi 2004). Before performing the main investigation, a pilot test study in a selected site was performed to understand the different soil properties of an area that has been fertilized for a long time and a non-fertilized area.

Review of geology of the study area

The area covers approximately 98 km^2. It is about 45 km from the beach line. The southern and northern part is bounded by Kampong Tok Bok and Kampong Ketereh, respectively. The west and east side boundaries are bounded by the Kelantan River and the high hill, respectively (Fig. 1). The hill is a part of the Boundary Range Composite Batholith. It consists of two major components, the Machang Batholith which is about 100 × 20 km, with the smaller Kerai Batholith on the western flank (Cobbing and Pitfield 1992). Around the hill, a lot of exposed granite can be found, especially at the Sungai Buluh Quarry. Other exposed granite can also be found in Kampong Pulai Condong about 4 km to the west of the Machang Batholith Boundary Range. The area is covered by Quaternary sediments overlying granite bedrock. It is drained mainly by short rivers and streams, which flow into the South China Sea. The thickness of the Quaternary deposits varies from 20 m inland to about 200 m near the coast. The loose Quaternary sediments consist of alternating layers of coarse gravels to silts or mixtures of the two (Saim 1999). Figure 1 shows the location map of the research area. The RSO West Malaysia and Kertau 1946 are used as the coordinate system and datum in the map, respectively.

Methodology

A pilot test study was done prior to the main investigation. The geoelectrical resistivity, soil property analysis and hydrochemical methods were used in both investigations.

Pilot test study

The pilot test study was performed at Kampong Tok Bok. A detailed map including geoelectrical resistivity surveys and soil sampling location and photograph of the site investigation is given in Fig. 2. The area was divided into two: Test-Site 1 is the non-fertilized land, and Test-Site 2 is the regularly fertilized land. Test-Site 1 is of grassy fields, which are sometimes used by the local people as celebration grounds and by their farm animals for grazing. Test-Site 2 mainly consists of an old palm oil plantation. The field had been farmed recurrently for over 25 years (personal conversation with a local field supervisor). The palm oil plantation has not been fertilized since August 2007, since it is due to be replanted in the near future. The fertilization scheme for the palm oil plantation for trees more than 12 years old is shown in Table 1.

For both sites, the investigation methods are: a two-dimensional (2D) geoelectrical resistivity imaging survey, soil property analysis and water chemical analysis.

The 2D geoelectrical resistivity imaging surveys were performed at both sites using the ABEM Terrameter SAS4000 resistivity meter. The Wenner arrays were used on five lines within each test site with 1 m electrode spacing. The total profile length is 40 m. Processing of the data was achieved by a tomographic inversion scheme using the software RES2DINV (Loke 2007; Loke and Barker 1996). The focus of investigation is to compare the geoelectrical resistivity imaging results with soil properties and the water soil chemical content.

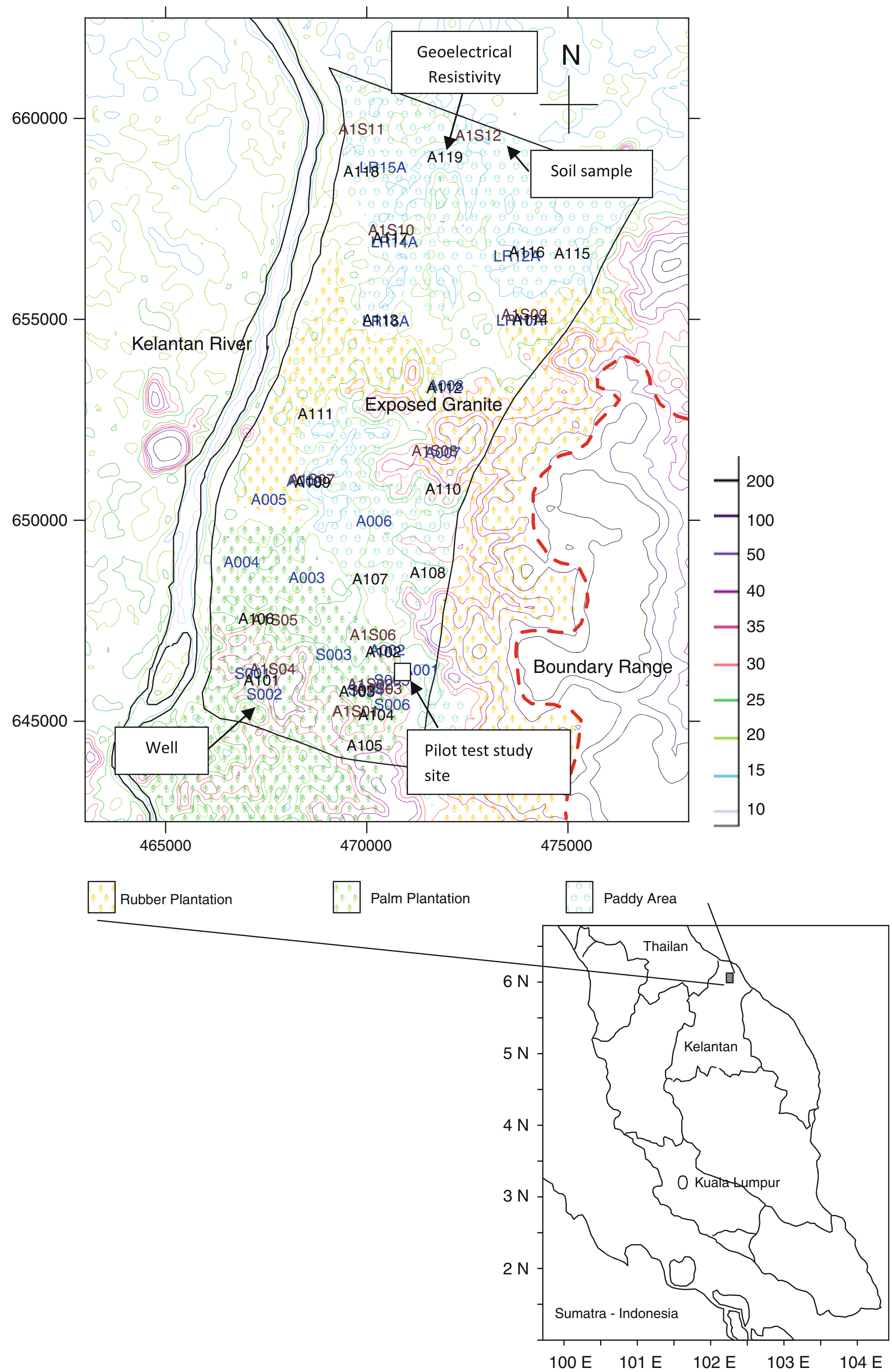
Grain size distribution for both sites was measured to distinguish the different soil properties. Soil samples were collected randomly from four point locations at each site (Fig. 2). Each location was taken from a depth of 0–1 m, at every 25-cm interval. The samples were then oven dried at 105°C for 24 h. The dried soil was sieved and classified according to the grain size classification scheme by Hamlin (1991). They are of gravel, sand, silt and clay.

A gravimetric method (Black 1965) was adopted to measure moisture content of four soil samples at each test site (Fig. 2). Each sample was taken from a depth of 0–1 m at an interval of 25 cm. The water content was determined gravimetrically by drying the samples at 105°C for 24 h.

Inverse auger methods (Van Hoorn 2007) were used to measure hydraulic conductivity at shallow depths above the water level. A hole with an 11.5-cm diameter and 60-cm depth was made at each location and filled with water up to the ground surface level. The rate of decreasing water level was initially intermittent, but eventually stabilized to a constant rate.

To analyze its chemical content in the vadose zone, soil water was collected at depths of 0.25, 0.50, 0.75 and 1 m (four samples at each depth) from four random locations (Fig. 2) using a 1900 Soil Water Samplers (manufactured by Soilmoisture Equipment Corp, USA). The samples were kept in plastic bottles of 40 ml at 4°C and 1 day later were analyzed using ion chromatography (IC) and inductively coupled plasma (ICP).

Fig. 1 Location of study area



Main investigation

2D electrical resistivity imaging surveys were performed at the selected sites as shown in Fig. 1. A total of 19 traverse lines were measured of lengths ranging from 80 to 400 m depending on the available space in the field.

A hydrochemical analysis was used to study the groundwater properties in this area. Special emphasis was given to the first aquifer (shallow aquifer) because it is the main source of domestic water. Samples of groundwater were collected from the existing wells. In situ parameters such as well depth, water level, total

Table 1 Fertilization scheme of palm oil plantation in the Test-Site 2 Kampong Tok Bok

No	Month	Fertilizer types	Content	Amount per 2 Ha
1	February	Urea	Nitrogen (60%)	400 kg
2	April	NPK	N(15%), P, K	600 kg
3	August	Urea	Nitrogen (60%)	400 kg
4	October	NPK	N(15%), P, K	600 kg
5	December	Dolomite	Dolomite	300 kg
6	When needed	KCl	K and Cl	200 kg
7	Anytime	Farmyard manure	Mixture	As available

dissolved solids, pH, conductivity, salinity and temperature were measured. Water samples of 500 ml were kept in plastic bottles and maintained at a temperature of 4°C and analyzed by IC and ICP to determine the ion contents. Well location, well depth and depth to water were obtained directly during the collection of the water samples.

Grain size distribution was measured offering a better understanding of the soil characters of the area (Das 2001). Soil samples were collected from a depth of 0–1 m, at intervals of 25 cm at certain locations (Fig. 1) to determine the grain size distribution.

Results and discussion

Pilot test study

Grain size distribution

The results of the soil property analysis (grain size and moisture content) on Test-Site 1 and Test-Site 2 are given in Table 2. The total percentage of sand at all sampling locations ranges from 91.77 to 99.15%. Maximum percentage values of sand-sized grain are observed in samples collected from a depth of 50 cm (Test-Sites 1 and 2). The percentage of gravel-sized grains increases with depth. In both sites and at any depth, the percentage of silt and clay content is low (1% in average), ranging from 0.32 to 1.60% and decreasing with increasing depth. Generally, the results show that there is no significant difference between the grain size distribution of the soils proceeding from both sites. Therefore, it can be concluded that both have the same soil and geologic conditions.

Moisture content

At Test-Site 1, the average moisture content ranges from 11.48 to 11.69% (Table 2). A highest percentage value was obtained at location A. At each location, maximum values of moisture content were obtained at the surface. Though moisture content increases slightly in the near subsurface for location A, the moisture content does not show a similar general trend.

The two test sites differ in average moisture content percentages. Test-Site 1 has an average of 11.60 with 0.09% standard deviation and Test-Site 2 averages 11.27 with 0.07% standard deviation. Differences in moisture content are attributed to the different rate of evaporation. Data for Test-Site 1 was acquired 1 day prior to data for Test-Site 2. However, the weather conditions of the 2 days of data acquisition were nearly the same (cloudy), thus resulting in a negligible difference of the moisture content in both sites.

Hydraulic conductivity

The measured hydraulic conductivity are 0.001079 and 0.001096 cm/s in Test-Site 1 and Test-Site 2, respectively. The difference between the measured values is negligible and therefore it can be concluded that the porosity and permeability of both test sites are similar.

Water chemical results

The chemical composition of extracted water at Test-Sites 1 and 2 is shown in Table 3. In both sites, among the detected cations, the content of K, Ca, and Na shows the highest range from 1.02 to 6.79 mg/l. The content of the other cations is lower than 1 mg/l. The results indicate that there is no relevant difference in the cation content of the soil water extracted from both sites.

The nitrate concentration ranges from 1.36 to 2.75 mg/l and 5.14 to 9.11 mg/l in the Test-Site 1 and Test-Site 2, respectively. The highest nitrate concentration is found at the surface level, decreasing with depth. The same trend is also recognized for chloride concentration. Meanwhile, sulfate and fluoride concentrations range from 0 to 5.01 mg/l and 0.14 to 0.52 mg/l, respectively. Thus, the results (Table 3) show that the concentration of nitrates and chlorides in Test-Site 2 are significantly higher than in Test-Site 1.

Resistivity model

The selected resistivity models of Test-Sites 1 and 2 are shown in Fig. 3. The same scale is used for all sections. In section TB01, a high-resistivity value ranging between

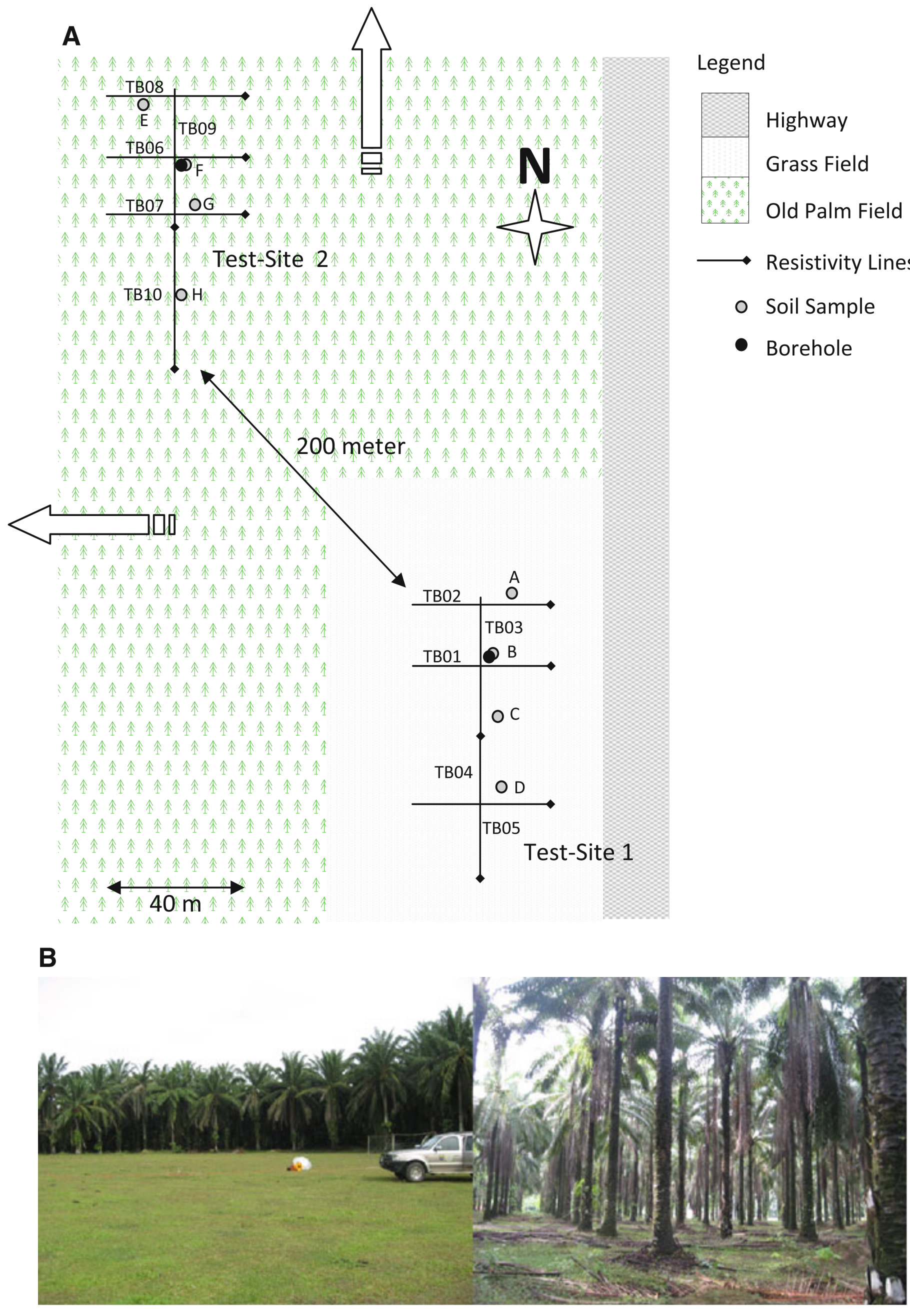


Fig. 2 Map showing line surveys and soil sampling location (**a**). Photograph of pilot test site (**b**)

2,000 and 6,000 Ω m is observed from the surface level to a depth of around 1.5 m, corresponding to the presence of compact sand with low moisture content. The same feature is also observed in other sections (TB02-TB05).

The measured water table was 3.60 m below the ground surface in the borehole that was drilled at the 19-m mark of line TB003. In the inverse model of the line TB003, resistivity values of approximately 500 Ω m corresponded to a unit of compact fully saturated sand.

Generally, at a depth of more than 4 m, zones that are probably more porous and more permeable can be seen in the section with values of around 150 Ω m. This value corresponds to the fully saturated zone.

The line TB03 crosses lines TB01 and TB02, and TB04 crosses TB05. The intersection point is marked with an arrow in Fig. 3. The results show consistency for every line crossing, leading to reliable subsurface interpretations.

Test-Site 2 is located northwest of Test-Site 1 in an old palm oil plantation. Geoelectrical surveys were conducted for five lines in this site. The inverse models of all lines (TB06-TB10) show relatively lower resistivity values (1,800 Ω m) from the surface to 1-m depth. This value

Table 2 Grain size distribution and moisture content of Test-Site 1 and Test-Site 2

S_ID	Gravel (%)	Sand (%)	Silt and clay (%)	(Moisture) (%)	S_ID	Gravel (%)	Sand (%)	Silt and clay (%)	(Moisture) (%)
Test-Site 1					Test-Site 2				
A-0	0.76	98.29	0.95	16.53	E-0	0.91	98.15	0.94	15.76
A-25	0.00	98.48	1.52	11.54	E-25	0.00	98.44	1.56	10.87
A-50	0.47	99.14	0.86	9.75	E-50	0.00	99.15	0.85	9.23
A-75	1.53	97.81	0.66	10.33	E-75	1.22	98.04	0.74	10.15
A-100	7.05	92.64	0.32	10.31	E-100	6.56	93.10	0.34	10.37
Average	1.96	97.27	0.86	11.69	Average	1.74	97.38	0.88	11.28
B-0	0.86	98.14	1.00	15.98	F-0	0.85	98.20	0.95	15.93
B-25	0.00	98.44	1.56	10.44	F-25	0.00	98.45	1.55	10.92
B-50	0.00	99.08	0.92	9.97	F-50	0.00	99.12	0.88	9.72
B-75	1.44	97.83	0.74	11.79	F-75	1.54	97.73	0.73	10.17
B-100	7.22	92.43	0.34	9.24	F-100	7.23	92.43	0.34	10.03
Average	1.91	97.18	0.91	11.48	Average	1.92	97.19	0.89	11.35
C-0	0.82	98.21	0.97	16.29	G-0	0.85	98.20	0.96	15.78
C-25	0.00	98.41	1.59	11.23	G-25	0.00	98.45	1.55	10.79
C-50	0.59	99.12	0.88	10.01	G-50	0.00	99.09	0.91	9.65
C-75	1.55	97.78	0.67	10.51	G-75	1.56	97.71	0.73	10.12
C-100	7.24	92.40	0.36	10.23	G-100	7.86	91.77	0.37	10.09
Average	2.04	97.19	0.89	11.65	Average	2.05	97.04	0.90	11.29
D-0	0.81	98.21	0.97	16.16	H-0	0.85	98.20	0.95	15.69
D-25	0.00	98.40	1.60	11.08	H-25	0.00	98.47	1.53	10.48
D-50	0.00	99.14	0.86	9.86	H-50	0.00	99.14	0.86	9.53
D-75	1.54	97.79	0.66	10.52	H-75	1.52	97.76	0.72	10.15
D-100	7.27	92.39	0.34	10.18	H-100	7.77	91.88	0.34	10.06
Average	1.93	97.19	0.89	11.56	Average	2.03	97.09	0.88	11.18

Table 3 Water extraction analysis result of Test-Site 1 (top half) and Test-Site 2 (bottom half)

No	Sample ID	Chloride (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Fluoride (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	Al (mg/l)	Fe (mg/l)
1	TB001-25	10.262	2.752	0.491	0.152	1.953	2.973	0.571	4.956	0.196	0.037
2	TB001-50	8.576	2.451	3.358	0.137	1.231	2.567	0.713	4.030	0.097	0.032
3	TB001-75	7.775	2.579	5.008	0.373	1.558	2.188	0.538	3.920	0.068	0.012
4	TB001-100	5.935	1.357	0.000	0.155	1.020	1.279	0.395	2.794	0.043	0.008
	Average	8.137	2.285	2.214	0.204	1.441	2.252	0.554	3.925	0.101	0.022
1	TB006-25	20.502	9.116	0.000	0.432	2.545	3.957	0.288	4.340	0.600	0.274
2	TB006-50	13.103	6.777	3.031	0.398	2.479	3.941	0.333	4.611	0.406	0.056
3	TB006-75	10.259	6.104	0.000	0.523	1.929	3.139	0.264	6.769	0.741	0.087
4	TB006-100	9.819	5.136	1.644	0.044	1.162	1.439	0.150	2.207	0.083	0.011
	Average	13.421	6.783	1.169	0.349	2.029	3.119	0.259	4.488	0.458	0.107

(colored yellow) does not appear in the inverse model of Test-Site 1.

Zones with fairly high-resistivity values (more than 8,000 Ω m) in sections TB06, TB07 and TB08 (Test-Site 2) correspond to certain features indicating the presence of compact material. These features (high-resistivity values) are weathered boulders found after drilling with a hand auger.

Line TB09 crosses lines TB06, TB07 and TB08 at the 16.5 m mark. The inverse model shows quite good correlation between each of the crossing lines. More porous and permeable zones exhibit resistivity values of about

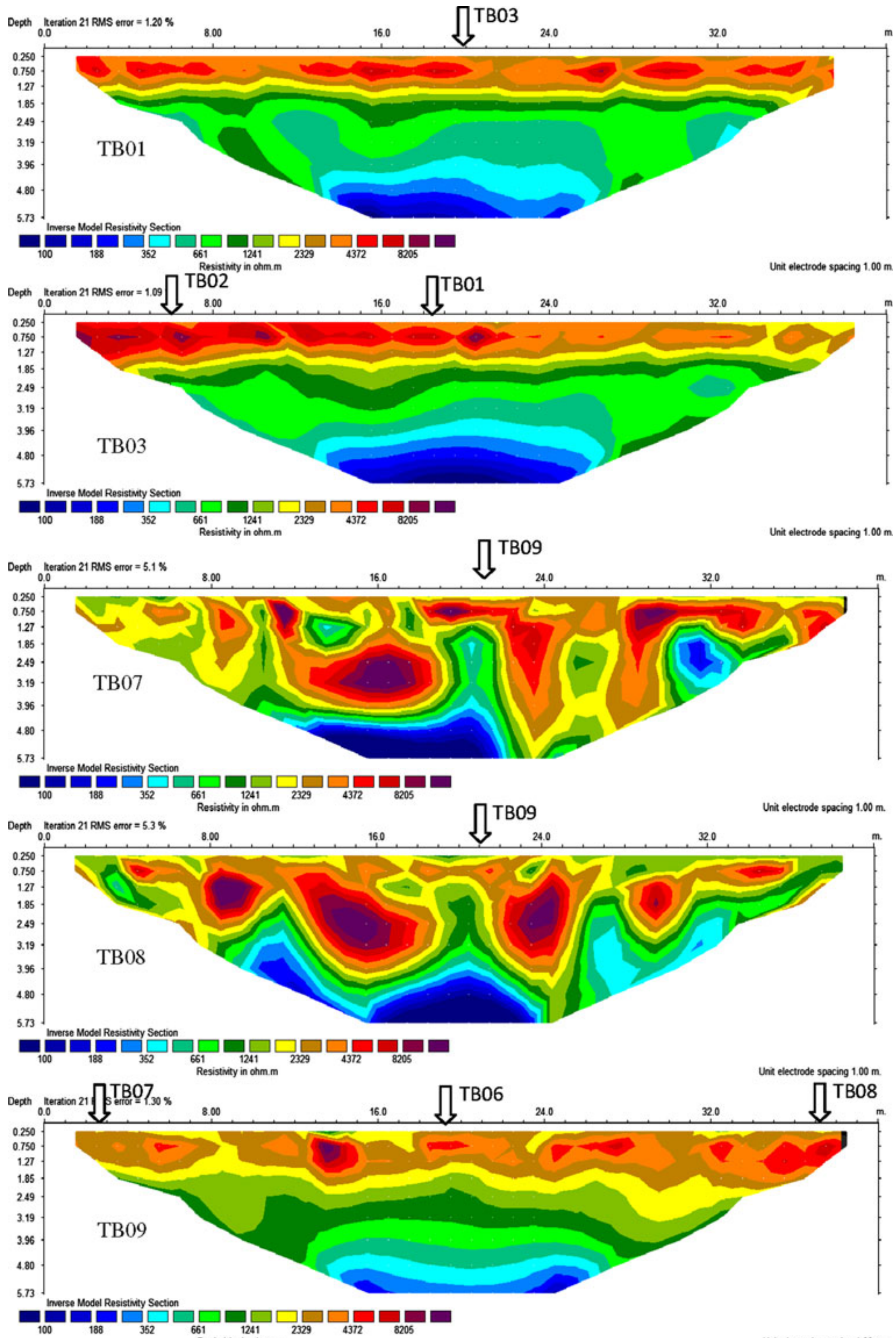


Fig. 3 Selected resistivity inverse model of Test-Site 1 and Test-Site 2

150 Ω m at depths of more or less than 3 m below the ground surface. The water table was found at a depth of 3.48 m in a borehole that was drilled using a hand auger at the 20-m mark along the TB009 line. In the inverse model of line TB009, resistivity values of around 500 Ω m correspond to the fully saturated compact sand unit.

Correlation of soil parameters, chemical content of extracted water and geophysical parameters

To simplify the analysis, reverse values of the resistivity model were extracted from both sites and are listed in Table 4. It shows the statistical summary of the extracted

Table 4 Statistical values of resistivity extraction derived from the surface to 75-cm depth

	Inverse resistivity model (Ω m)					Soil properties				
	Line name	Mean resist	SD	Max	Min	Gravel (%)	Sand (%)	Silt and clay (%)	Moisture (%)	K (cm/s)
Test-Site 1	TB001	4042.62	1245.367	8021	2084.3	1.95 (2.74)	97.20 (2.47)	0.88 (0.41)	11.59 (2.45)	0.001079
	TB002	4950.52	1275.909	8496.8	2873.5					
	TB003	4303.951	1358.411	9065	1932.4					
	TB004	3995.408	1201.233	6783.1	1466					
	TB005	4003.477	1328.22	8940.9	1980.5					
Test-Site 2	TB006	2597.096	1300.075	7825.7	290.5	1.93 (2.84)	97.17 (2.55)	0.89 (0.39)	11.27 (2.35)	0.001096
	TB007	2270.121	1127.833	6605	944.42					
	TB008	2718.001	1326.222	7173	933.97					
	TB009	2872.892	719.566	4636.3	885.07					
	TB010	3027.621	936.733	5881.7	1375.9					

On the right side, soil properties values within the Test-Site 1 and Test-Site 2 show the mean and standard deviation (in bracket)

resistivity models for both sites (left-hand side) and average of selected soil properties (right-hand side). The maximum average resistivity values from the surface to a 75-cm depth for both sites is 4950.52 Ω m (TB002) and 3027.63 Ω m (TB010). All the resistivity values in Test-Site 1 are higher than in Test-Site 2 (Fig. 3). The similarity composition of gravel, sand, silt and clay (soil grain size) indicates similar geological conditions at both sites. Furthermore, based on the hydraulic conductivity data, the porosity and permeability values of Test-Site 1 are approximately equal to Test-Site 2. Although the moisture content at Test-Site 2 is lower than Test-Site 1, the resistivity value in Test-Site 1 is higher than in Test-Site 2. The lower average resistivity of Test-Site 2 is believed to be caused by the higher nitrate and chloride concentrations in the near subsurface. Even if fertilizing activities had been stopped since last year, residual chloride and nitrate still remain in the soil. The negative charges of nitrate and chloride ions caused a decrease of the medium's resistivity. This is the reason why there is a 36.6% decrease in average resistivity from the surface to depths of 75 cm for Test-Site 2.

Main investigation

The hydrochemical content and well physical parameters are given in Table 5. Ninety percent of the groundwater in the shallow aquifer possesses hydrogen ion concentrations (pH) that are moderately acidic (4–6.5), whereas the remaining five have pH values of 6.5–7.8 indicative of a more neutral environment; 30% of the water samples have pH values of 5, considered not good for human consumption if untreated.

Magnesium ion (Mg^{2+}) concentration is generally low (0.26–2.42 mg/l). The availability of magnesium ions in the groundwater can be explained by the occurrence of ferromagnetic minerals such as goethite and limonite in the alluvium formation. The magnesium content of groundwater in the area is suitable for human use.

The sodium (Na) and potassium (K) contents in the water samples are remarkably low. The concentration of Na and K range from 0 to 13.19 mg/l and 1.17 to 7.58 mg/l, respectively. The possibility of a contributing factor is the weathering of feldspars and leaching of clay minerals (Egbunike 2007; Hounslow 1995). Potassium, an important fertilizer component, is strongly held by clay particles in the soil. Therefore, leaching of potassium through the soil profile and into groundwater is important only in coarse-textured soils. Potassium is common in many rocks. Most of the potassium in the rocks is relatively soluble and thus concentrations in groundwater increase with time. Sodium is more mobile in soil than potassium and it is often used as an indicator of impacts of shallow groundwater to humans. Important sources of sodium include fertilizing activities and animal waste. Sodium is also a common chemical in minerals. Like potassium, sodium is gradually released from the rocks. The concentrations thus increase with time.

The chloride concentration in the groundwater was reported to be relatively low because chloride does not show any correlation with the components of pore water derived from mineral dissolution. The concentration of chloride in rain water and subsequently by evapotranspiration may be an important source of chloride (Egbunike 2007) in the area. Another common source of chloride in groundwater is the leaching of chloride in fertilizer over long periods of time. The influence of the fertilizing factor for the chloride content in the groundwater around the southern part of the study area is found in water samples from the borehole at A006. The chloride concentration is 12.10 mg/l and lies within the accepted limits for human consumption.

Table 5 In situ parameters and results of groundwater samples within the study area

No	Sample ID	Location X (m)	Location Y (m)	Well depth (m)	Ground level (m)	Depth to water (m)	Water level (a.m.s.l) (m)	TDS (mg/l)	Conductivity (μS/cm)	Salinity 0/00	T (^{0}C)	pH
1	A001	471343	646277	<7	28	2.56	25.44	76	159	0	27.8	4.77
2	A002	470511	646770	<7	24	2.1	21.9	323	654	0.1	30.5	5.98
3	A003	468507	648571	5	22	1.96	20.04	407	830	0	29.4	4.93
4	A004	466884	648964	<7	21	0.86	20.14	76	159	0	29.2	4.63
5	A005	467562	650522	<7	22	0.98	21.02	78	163	0	29.1	5.72
6	A006	470178	649987	<7	18	0.67	17.33	151	313	0	27.4	5.75
7	A007	471890	651687	<15	40	10.62	29.38	57	120	0	28.5	6.14
8	A008	471962	653352	<7	24	1.35	22.65	83	173	0	31.7	4.86
9	A009	468452	650985	<7	20	0.91	19.09	50	104	0	34.4	5.72
10	LR10A	473804	654980	<7	19	1.02	17.98	183	381	0	42.2	5.77
11	LR12A	473733	656574	<7	14	0.23	13.77	84	170	0	31.1	6.4
12	LR14A	470689	656930	5	17	0.65	16.35	89	180	0	25.7	6.42
13	LR15A	470404	658785	6	28	2.11	25.89	64	130	0	28.7	6.22
14	LR16A	470475	654957	<7	17	0.61	16.39	106	217	0	27.2	4.11
15	S001	467159	646187	5	24	1.43	22.57	370	751	0	28.3	6.88
16	S002	467455	645676	5	26	1.92	24.08	247	501	0	28.3	5.98
17	S003	469175	646657	3	28	2.38	25.62	49	98	0	30.5	5.09
18	S004	469982	645778	7	38	2.46	35.54	60	121	0	28.1	4.49
19	S005	470622	646025	5	29	1.22	27.78	35	70	0	28.5	6.19
20	S006	470630	645415	<7	33	2.96	30.04	48	97	0	30.1	6.42
												6–8

Sample ID	Chloride (mg/l)	Nitrate (mg/l)	Sulfate (mg/l)	Fluoride (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	Al (mg/l)	Fe (mg/l)	CO_3 (mg/l)	HCO_3 (mg/l)
A001	5.86	2.77	5.915	0	1.309	4.782	0.304	7.912	0.045	0.054	0.000	85.320
A002	11.66	22.28	1.716	0.058	1.693	24.790	0.588	5.124	0.015	0.006	0.000	47.160
A003	17.60	28.79	0.25	0	2.181	19.540	1.887	10.010	0.000	0.220	0.000	52.56
A004	6.75	12.90	0.622	0	1.785	3.295	0.447	6.057	0.331	0.023	0.000	62.230
A005	4.11	3.84	3.544	0.049	2.505	8.306	0.622	3.581	0.122	0.058	0.000	12.510
A006	12.10	4.46	4.154	0	3.228	12.210	0.536	10.550	0.072	0.055	1.760	73.340
A007	2.14	0.00	1.213	0	1.329	2.469	0.327	3.059	0.025	0.540	0.000	2.700
A008	3.51	2.18	1.443	0	1.172	3.681	0.258	3.078	0.059	0.021	0.000	1.300
A009	7.21	12.58	0	0.22	1.487	3.628	0.698	11.240	0.130	0.025	1.600	23.800
LR10A	11.16	0.00	7.953	5.643	2.303	2.972	0.326	0.000	0.072	0.000	0.000	195.200
LR12A	2.43	0.00	0.263	0.032	4.151	3.048	0.888	3.227	0.130	1.993	0.000	7.000
LR14A	4.36	0.00	0.212	0.000	7.581	2.739	1.094	1.715	1.505	0.541	0.000	10.100
LR15A	1.83	0.00	0.000	0.073	3.797	3.340	0.915	1.183	0.448	0.164	0.000	13.200
LR16A	9.90	0.00	0.663	0.052	5.547	3.309	1.127	3.609	1.338	0.280	0.000	0.000
S001	12.28	24.18	0.318	0.000	2.534	6.025	1.558	7.835	0.000	0.032	0.000	0.000
S002	8.18	18.93	5.571	0.000	5.044	22.250	2.418	13.190	0.034	0.146	4.800	80.600
S003	5.23	6.83	1.605	0.000	1.457	6.211	0.433	8.004	0.304	0.029	0.000	4.200
S004	8.15	6.06	12.339	0	4.343	6.238	1.048	10.350	0.266	0.001	0.000	7.300
S005	3.65	9.72	1.394	0.000	2.064	3.917	0.666	4.831	0.144	0.004	0.000	4.500
S006	2.11	0.34	0.237	0.000	4.616	4.146	0.575	3.949	0.082	0.122	0.000	12.000
	250	45	400	1.5			150	200	0.2	0.3		

In the bottom row of the table, limit concentration for domestic use by the USA EPA (1980) and World Health Organization (WHO) (1984)

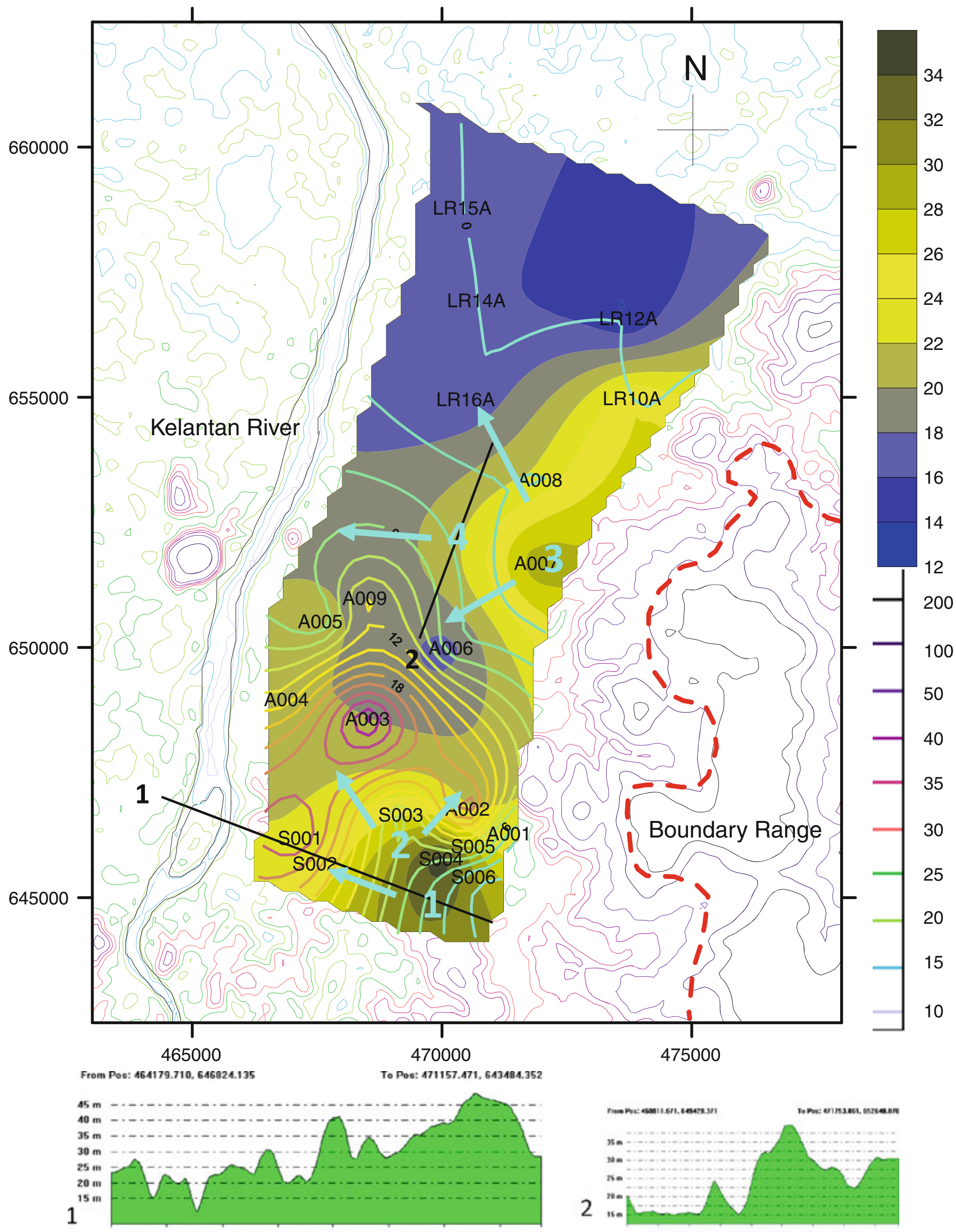


Fig. 4 Combination map of three sets of contour data. The *solid contour* represents the water level relative to the mean sea level (unit in meter) and the line contour above the *solid contour* is nitrate concentration in the shallow aquifer (less than 11 m deep) with well ID marks. The remaining *contour lines* are surface elevations. Cross section at lines 1 and 2 is plotted at the *bottom*

The concentration of nitrate in the northern part of the mapped area is generally low (less than 5 mg/l). It falls within the accepted limit for human consumption. In the southern part (palm oil plantation area), especially where the surface water flow ends (around A002, A003, A004, S001 and S002), the nitrate concentration is relative higher (more than 20 mg/l). The nitrate concentration in water is safe for drinking if less than 45 mg/l (US EPA 1980). The potential source of nitrate in the area may include fertilizing activities, animal excrement and probably the atmosphere.

Aluminum ion (Al^{3+}) content in the study area varies from 0.00 to 1.51 mg/l and is within the accepted limit for human consumption. There are only two groundwater samples (LR016A and S001) in which bicarbonate are absent. The presence of bicarbonates in the shallow aquifer within the study area is probably due to agricultural activities that utilize carbonate powder (neutralizing agent) for various purposes such as for normalizing land pH level. Sulfate (SO_4) concentration ranges from 0 to 12.34 mg/l, which is considered low and lies within the accepted limit for human consumption.

Overall, correlation between conductivity and other water chemical content can be calculated statistically using the Pearson product–moment correlation (Till 1974). Based on the data in Table 5, the correlation coefficient between

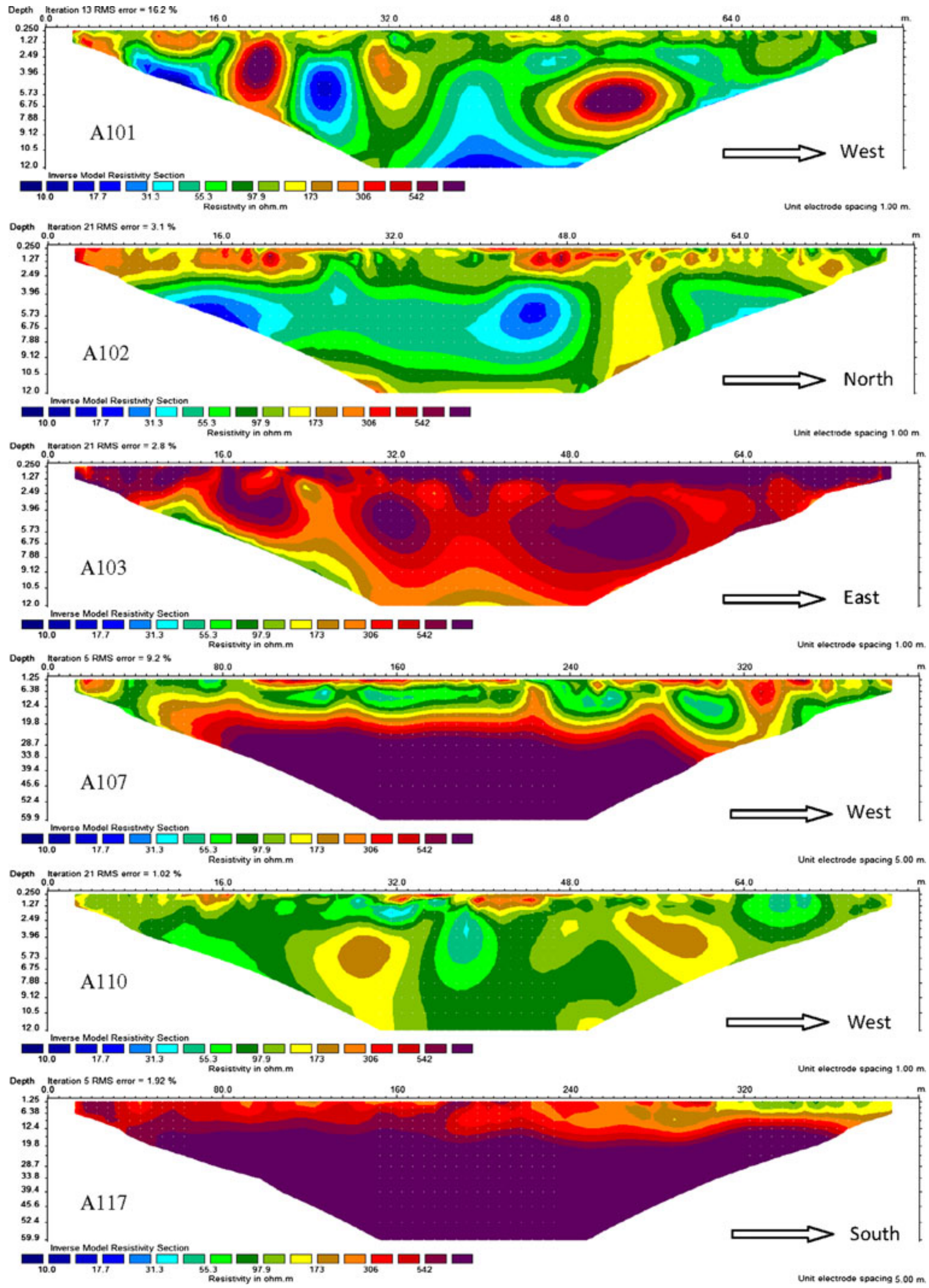


Fig. 5 Selected resistivity inverse model

conductivity and TDS is 0.99, conductivity and chloride is 0.82, conductivity and nitrate 0.80, and conductivity and sulfate is 0.04. Based on this, it is concluded that the amount of nitrate and chloride in the groundwater will influence total conductivity readings.

Figure 4 exhibits the well location for groundwater sampling. It also shows the nitrate concentration contour from 20 well samples and the water levels relative to mean sea level. Relatively high concentrations of nitrate can be found in wells in the palm oil plantation zone. The remaining rubber tree fields and paddy fields generally show low nitrate concentrations.

In the well with sample ID A009, the concentration of nitrate is considered to be high (12.58 mg/l), although there is no palm oil plantation around the well. Here, there are minor agricultural activities, including corn plantation. For these activities, chemical fertilizer is not utilized. Only organic fertilizers like cow manure are used.

A map of well water level relative to mean sea level and vector direction of groundwater movement is given in

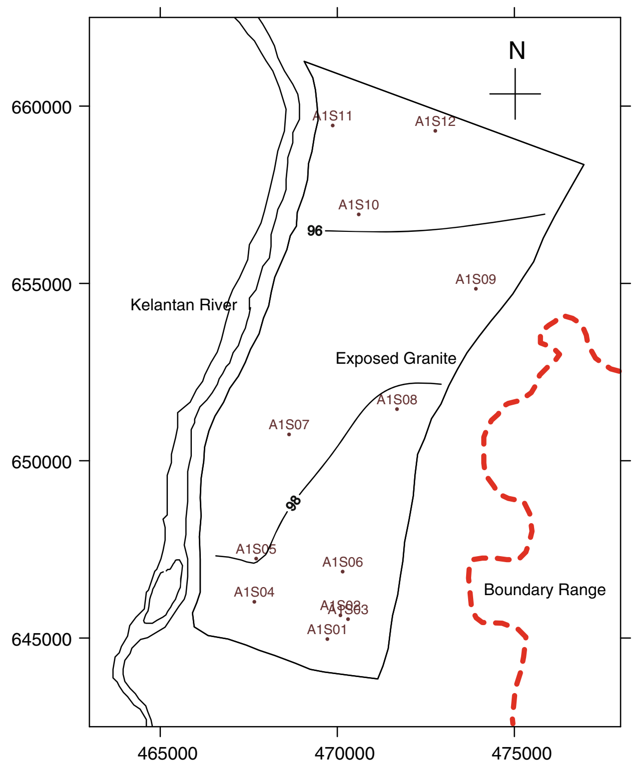


Fig. 6 Percentage weight map of gravel and sand

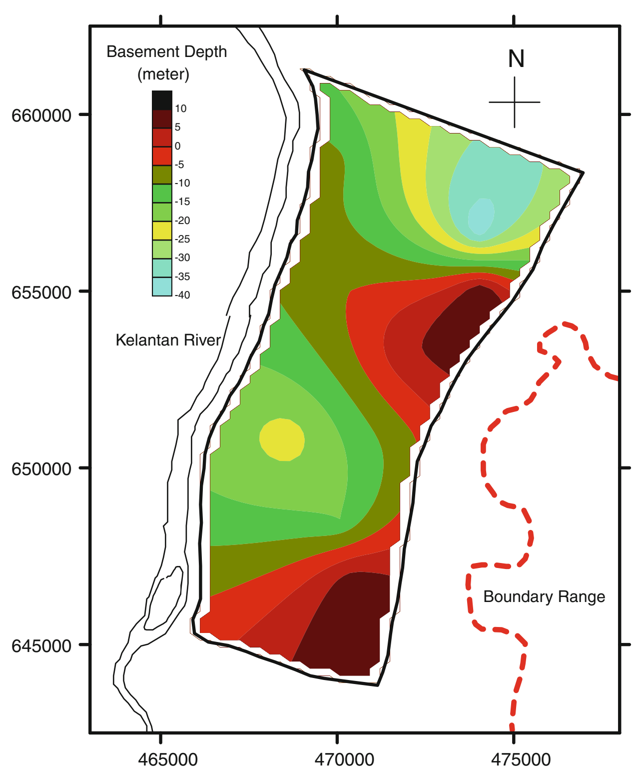


Fig. 7 Basement map derived from interpreted resistivity model

Fig. 4. The area is defined into three zones based on its topography. Zone 1 is highest topography area bounded by the X;Y coordinates from 465000;645000 to 473000; 650000. Zone 2 is a middle topography area, which is bounded by coordinates of 465000;650000 to 655000; 475000, while Zone 3 is the lowest topography area with coordinates ranging from 468000;655000 to 660000; 478000.

The groundwater at the southeastern part of Zone 1 flows from Boundary Range Hill to northwest in Kampung Tok Bok. Boundary Range Hill is at more than 250-m elevation whereas Kampung Tok Bok is at an elevation around 35 m above mean sea level. At the southwestern part of Zone 1, the groundwater around the wells WA101 and WA102 flows toward the Kelantan River. Generally, groundwater movement within Zone 1 is from southeast to northwest.

In Zone 2, groundwater flow originates from Boundary Range Hill toward Kampong Merbau Condong. As in Zone 1, the groundwater flow is from elevation 250 m at the Boundary Range Hill to about 30 m above mean sea level at the Kampong Merbau Condong. In Kampung Merbau Condong the groundwater flows in three directions: southeast–northwest, east–west and northeast–southwest. The general groundwater flow direction is, however, from the southeast to the northwest, toward the Kelantan River which is elevated at 15 m above mean sea level.

The northeastern part of Zone 3 has the lowest groundwater level of the study area. It is at a lower elevation than the Kelantan River. Thus, in this zone the groundwater does not flow toward the Kelantan River. Instead, the groundwater flows downward into the lower aquifer.

It can thus be generalized that the direction of groundwater movement is influenced by elevation, moving from highland to lowland areas. This factor may affect the potential distribution of nitrate concentration within an area. Groundwater in lower elevation which is covered by palm oil plantation tends to have higher nitrate concentrations (S001, S002, A002, A003, and A004) whereas groundwater in higher elevation areas (S003 and S004) have lower nitrate concentration.

A selected geoelectrical resistivity model is given in Fig. 5. The locations of the surveys were as follows: lines A101, A102, A103, A104, A105 and A106 were located within the palm oil plantation and lines A110 and A114 were located on the proposed housing site and grass field. Geological and soil conditions are considered to be similar for all survey locations. Figure 6 shows the percentage weight of sand and gravel obtained from the surface to a depth of 1 m using a hand auger. Lines A107, A108, A109, A111, A112, A113, A115, A116, A117, A118 and A119

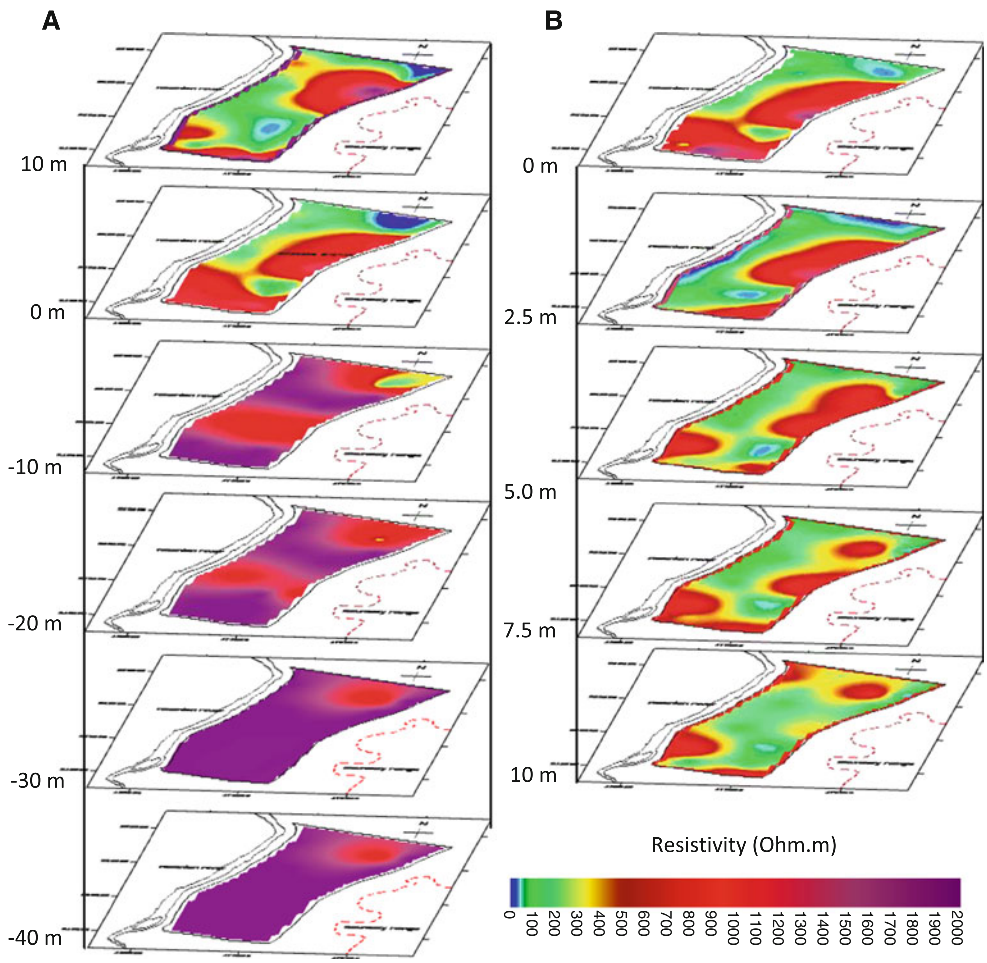


Fig. 8 Resistivity distribution relative to mean sea level (**a**) and resistivity distribution from the surface to a depth of 10 m (**b**)

were located within the site around an area of paddy field and rubber trees.

In the resistivity model of lines A101 and line A102 (Fig. 5), a lower subsurface resistivity value of around 18 Ω m can be found at a depth of about 3 m, although these lines were conducted on the zone with coarse-grained size and low moisture content. Along line A101 and line A1002, a relatively high nitrate concentration in the groundwater was found. The hydrochemical result from wells S001 and S002, with a depth of around 5 m showed that the nitrate concentration is 24.18 mg/l along line A101. The other lines, which were conducted in the palm oil plantation, were A103 and A104. The resistivity model for line A103 indicates that, at a depth of around 3 m, the possibility of groundwater accumulation can be seen at 52.39 Ω m resistivity values (minimum values in the section), while the nitrate concentration found around this area is less than 5 mg/l (wells S005 and S006).

Generally, in the zone where the surface water ends, subsurface and surface resistivities have been found to be relatively lower than in other palaces within the palm oil plantation. This fact shows that the presence of nitrate in the groundwater reduces the medium resistivity value.

In the resistivity model of line A107 and line A117 (Fig. 5), there is an anomaly with high values of more than 500 Ω m. This is seen in the profile at a depth of 20 and 25 m for both lines A107 and line A117, respectively. This anomaly can also be found in the other resistivity model (not shown in this paper). These anomalies are believed to be due to the occurrence of shallow basement. Based on all the resistivity models, the basement beneath the surface for the whole area can be mapped (Fig. 7), from which it can be seen that the groundwater at the southern region is blocked by the basement at the middle region, making it impossible for contaminated water from the southern region to flow into the northern area although elevation in the northern region is lower.

To better show the shape and distribution of the potential aquifer, a simplified 3D electrical resistivity model has been developed. Figure 8 shows a 3D electrical resistivity slice image for certain depth obtained from the sequence of 2D sections. The 3D resistivity data in Fig. 8 has been generated using a Kriging interpolating technique. It may be emphasized that the electrical images are the result of a tomographic 3D data inversion. Furthermore, the resolution of the 3D image is strongly limited by the low number of the inverse model profiles compared with the extension of the surveyed area (98 km^2), but it represents a simple and optimum tool to have more information about the shape of the aquifer.

At a depth to 5 m, a good correspondence between the magnitudes of the resistivity image to the higher surface topography has been observed (Fig. 8a). At the peak of the hill, the resistivity value is relatively higher because the moisture content is lower and dense material exists on it. The potential aquifer is at about 10-m depth above the mean sea level (Fig. 8a). This is inferred by the relatively lower resistivity values that appear to a depth of 0 m. To a depth of -10 m, the resistivity slices show a regular and closed geometry of the basin floor along the southeastern part; instead, it has an irregular shape of the basin along the northwestern part. It represents a tool for better visualization of the geometry of the groundwater potential and pre-Quaternary bedrock. Figure 8b shows the resistivity distribution from the surface to a depth of 10 m. In this figure, distribution of shallow groundwater potential is more straightforward. Higher resistivity values appear at the site of relatively elevated areas. At a depth of 2.5 m, some areas exhibit relatively lower resistivity values of around 250 Ω m. In the site with denser (more compact) soil material, the water table was found at this depth. At a slice depth of 5 and 7.5 m, two lower anomalies appear at the sites in a palm oil plantation. These sites are the area at which the water surface ends (catchment area). These anomalies are believed to be due to the relatively higher nitrate concentration in groundwater.

Conclusion

Geoelectrical resistivity and hydrochemical methods were successful for studying shallow groundwater aquifer characters within agricultural areas. In the pilot test study, it was found that in areas around the palm oil plantation, the nitrate concentration was higher compared to the area with no palm oil plantation. The application of chemical and natural fertilizers is the reason for the high nitrate concentrations found in palm oil plantations. In the zone with higher nitrate concentration, subsurface geoelectrical resistivity values were lower, although the moisture content was lower and soil properties were similar. The subsurface resistivity value is higher in the zone with lower nitrate content, although moisture content is higher.

In the main study, groundwater with a high level of nitrate concentration has been mapped along with groundwater flow patterns within shallow aquifers. The contaminated water from the southern region cannot enter the northern area despite the northern area having a lower elevation. This is due to pre-Quaternary bedrock preventing groundwater flow to the northern area in the middle part of the study area. The southern and middle parts of the study area have an east–west groundwater flow pattern.

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