Original Paper

GEOELECTRICAL RESISTIVITY METHOD FOR SALT/BRACKISH WATER MAPPING

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ABSTRACT

A 2D geoelectrical resistivity method was used for detecting and mapping occurrence of salt/brackish water in the subsurface, North Kelantan - Malaysia. The North Kelantan plain is covered with Quaternary sediments overlying granite bedrock. The drainage system is dendritic with the main river flowing into the South China Sea. The geoelectrical resistivity surveys made up of eleven resistivity traverses at four different sites. The zone of brackish water is very clearly seen in the resistivity inverse model with position around 20-30 m depth. This aquifer is referred to second aquifer. As the final result, a map with the possibility of salt/brackish and fresh water interface can be generated.

INTRODUCTION

Groundwater is an essential and vital resource in all countries. A number of factors can affect the quality of a groundwater reservoir, such as contamination by salt-water intrusion (Samsudin, *et al.,* 2007; Abdul, *et al.,* 2000; Harding, 1991) or by toxic industrial chemical waste (Barker, 1996). These pollutants pose common environmental problems that have created the need to find suitable methods for monitoring the extent of such environmental damage (Bernstone and Dahlin, 1996).

Occurrence of saltwater in the subsurface has been discussed in literature as a source of contamination. Saltwater intrusion can cause serious problems to coastal area. In natural condition, sources of saltwater contamination include connate water of marine origin, saline water of swales or river which hydraulically interacts with aquifer. In this paper, the efficiency of the geoelectrical resistivity method which is supported by gamma ray and water chemical data for the mapping of subsurface salinity is examined.

Geology and Hydrogeology of Study Area

The North Kelantan plain is covered with Quaternary sediments overlying granite bedrock. It is drained mainly by short rivers and streams which flow into the South China Sea. The central part of the plain is drained by the largest river in the region, the Kelantan River, and in the South East, it is drained by Pengkalan Datu River. The thickness of the Quaternary deposits varies from 25 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). There are two main aquifer. Shallow aquifer, mostly unconfined but occasionally confined or semi-confined, thickness normally 2-3 m and may reach up 17.5 m. This aquifer is first aquifer. Deep aquifer, mainly confined, its

thickness usually more than 15 m, this deep aquifer comprises three different layers, separated from each other by permeable strata of clay. This aquifer refer to second, third and fourth aquifer (Pfeifer and Tiedeman, 1986, Saim, 1999). **Fig. 1** show the location map of research area, Nort Kelantan – Malaysia. The RSO West Malaysia and Kertau 1946 are used as coordinate system and datum in the map.
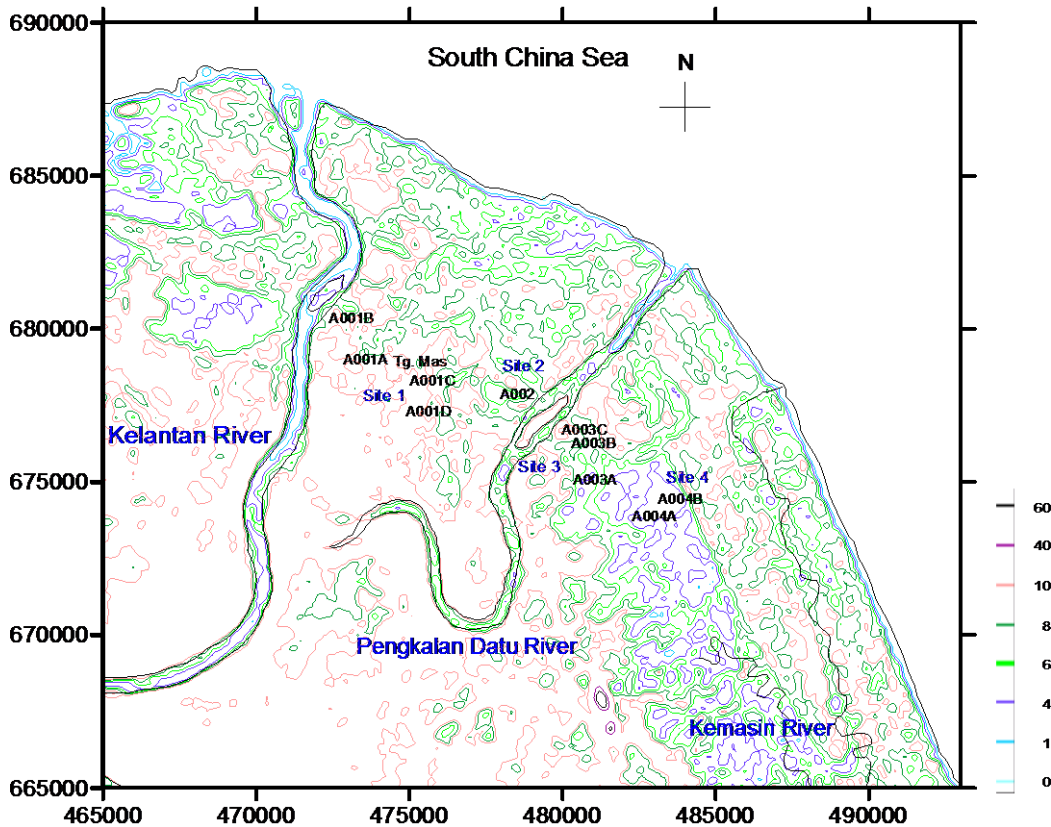

Fig. 1. Location map of area study with line survey name and topography contour

Geoelectrical Resisitivity and Gamma Ray

Geoelectrical resistivity is often first encountered in physics when discussing the resistance of an ideal cylinder of length L and cross-sectional area A of uniform composition. The resistivity ρ appears as the material-specific constant of proportionality in the expression for the total resistance of the cylinder,

$$R = \rho L/A$$

The total resistance *R* may be obtained experimentally through Ohm's law, *R=V/I* , where *V* is the potential difference between the ends of the cylinder and *I* is the total current flowing through the cylinder. Edge effects are not considered. The resistivity of

the material, an intrinsic property of the material, is then related to experimentally measured extrinsic parameters by

$$\rho = (V/I)(A/L) = R_{app}K$$

In the second equation, the resistivity is given by the product of the apparent resistance $R_{app}=V/I$ and a geometric factor $K=A/L$ that carries information about geometry of the cylinder. This type of product of an apparent resistance and a geometry factor will appear again when the resistivity of the ground is determined. For the Wenner array which separated by equal intervals, denoted *a*, the apparent resistivity is given by (Telford, *et al.,* 1990):

$$R_{app} = 2\pi a(\Delta V/I)$$

Gamma-ray measurements detect variations in the natural radioactivity originating from changes in concentrations of the trace elements uranium (U) and thorium (Th) as well as changes in concentration of the major rock forming element potassium (K) (Baker, 2002). Since the concentrations of these naturally occurring radioelement vary between different rock types, natural gamma-ray logging provides an important tool for lithologic mapping and stratigraphic correlation. Gamma-ray logs are important for detecting alteration zones, and for providing information on rock types.

MATERIALS AND METHODS

The purpose of geoelectrical surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to

various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock.

The 2D electrical resistivity imaging surveys were performed at the proposed sites using the ABEM SAS1000 resistivity meter and multicore cable to which electrodes were connected at takeouts moulded on predetermined equal intervals. A computer-controlled system is then used to select the active electrodes for each electrode set-up automatically. This computer-controlled system was included in the instrument ABEM SAS1000 which was used in the survey. By using Wenner configuration, current was injected into C1 electrode to the ground and received from the ground through C2 electrode. The potential difference was measured between two inner electrodes, P1 and P2. The configuration was kept constant and moved along the profile until all possible measurements had been made with 1a electrode spacing (**Fig. 2**).
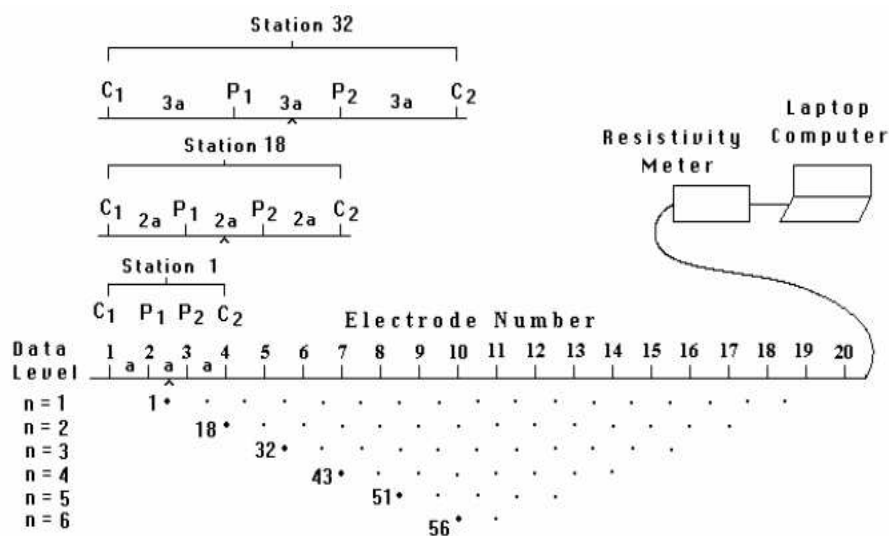

Fig.2. The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build up a pseudosection (Loke, 2000).

Processing of the data was achieved by a tomographic inversion scheme using the software RES2DINV (Loke, 2007). In this scheme, true resistivity distribution in the subsurface is obtained by a linearized least-squares inversion of apparent resistivity pseudosections acquired along profiles.

The result of geoelectrical resistivity data (after the processing) is presented in contour section of true resistivities

(**Fig. 2,3,4,5 and 6**). In the section, horizontal axis is the electrodes spacing and vertical axis is the depth.

Other data including gamma ray log and chemical water content was used to support geoelectrical resistivity interpretation. Gamma ray data was derived from (Abdul, 1989) for subsurface lithology interpretation, whilst chemical water content

was from Jabatan Geosain and Mineral Kelantan – Malaysia.

RESULTS AND DISCUSSION

Site 1

In site 1, geoelectrical resistivity survey began from the Tanjung Mas well station. There was however no space to lay long cable for geoelectrical resistivity survey. A space along 100 meter was used to survey the data with 2.5 meter electrodes spacing. In the survey, the geoelectrical resistivity line was crossed with the monitoring well which had gamma ray data. The nearest line was adjusted to be 2 m away from the well to avoid affect of the well in the geoelectrical resistivity reading.

Fig. 3. shows the subsurface lithology derived from the interpretation of available gamma ray data in the monitoring well. It can be clearly seen that clay material can be found on the surface until around two meter depth. In Tanjung Mas well station, five monitoring well with variations of depth can be found. The well are KB6 with 129 meter depth, KB7 with 99 meter depth, KB8 with 88 meter depth, KB9 with 55.5 meter depth and KB10 with 31.5 meter depth.

The Wenner inverse model for this site can be seen in **Fig. 4**. The high resistivity values of about 200 ohm.m on the surface at position 0-20 meter mark and 80-100 meter mark correspond to clay material with very low water content (moisture content). It did not rain in the area for around 1 week before the survey was done.

Visually in **Fig. 4**. the correlation of subsurface lithology derived from the interpreted gamma ray data and Wenner inverse model is very good. It can be seen at the position 49 meter mark of Wenner inverse model, the resistivity value is around 14 ohm.m. It corresponds to the sand formation filled by freshwater in the interval depth. This interpretation can be supported by the interpreted gamma ray data informs that within the interval is fine sand formation. Based on the interpreted gamma ray data,

clay material can be found within an interval of around 9-12 meters in depth. At this interval the Wenner inverse model exhibits relatively high resistivity values of around 60 ohm.m.

At the position 18 meters marks with a depth around 6 meters, it can be noticed that the first aquifer (top aquifer) and the series of second aquifer are almost connected with each other. This can be seen from the resistivity values at that position which are around 25 ohm.m corresponding to more porous and more permeable material, which connects the first and second aquifer. This value can inform that the clay content in this zone has decreased. It is very possible that both aquifers are almost connected to each other.

Other surveys were also conducted in the surrounding area of the Tanjung Mas pumping well station (A001A, A001B, A001C and A001D). These lines consist of four wheel cable that required 61 electrodes. The total length of these set up equipment was 400 meter except A001B (240 m length) due to the lack in space. Unfortunately, in the surrounding area around these lines, there were no water sample to be collected.

Wenner inverse model of line A001A and A001B can be found in **Fig. 5.** The line of A001B is the nearest survey done to the Kelantan River. In the Wenner inverse model of A001A, the minimum values of true subsurface resistivity is 16.1 ohm.m that correspond to fresh water. This can be seen in the interval depth from 20 – 28 meter deep. More compacted material which alternates to softer material is revealed on the top. It can be explained by the occurrence of relative high and low resistivity values respectively. The highest resistivity values reveal in the area with a depth of around 7 meters and 50 meters. That means more compacted and less porous material such as clay material can be defined in that area. This can be clarified with the occurrence of clay material based on the interpreted gamma ray data in Tanjung Mas well located around 1.3 km from the line.
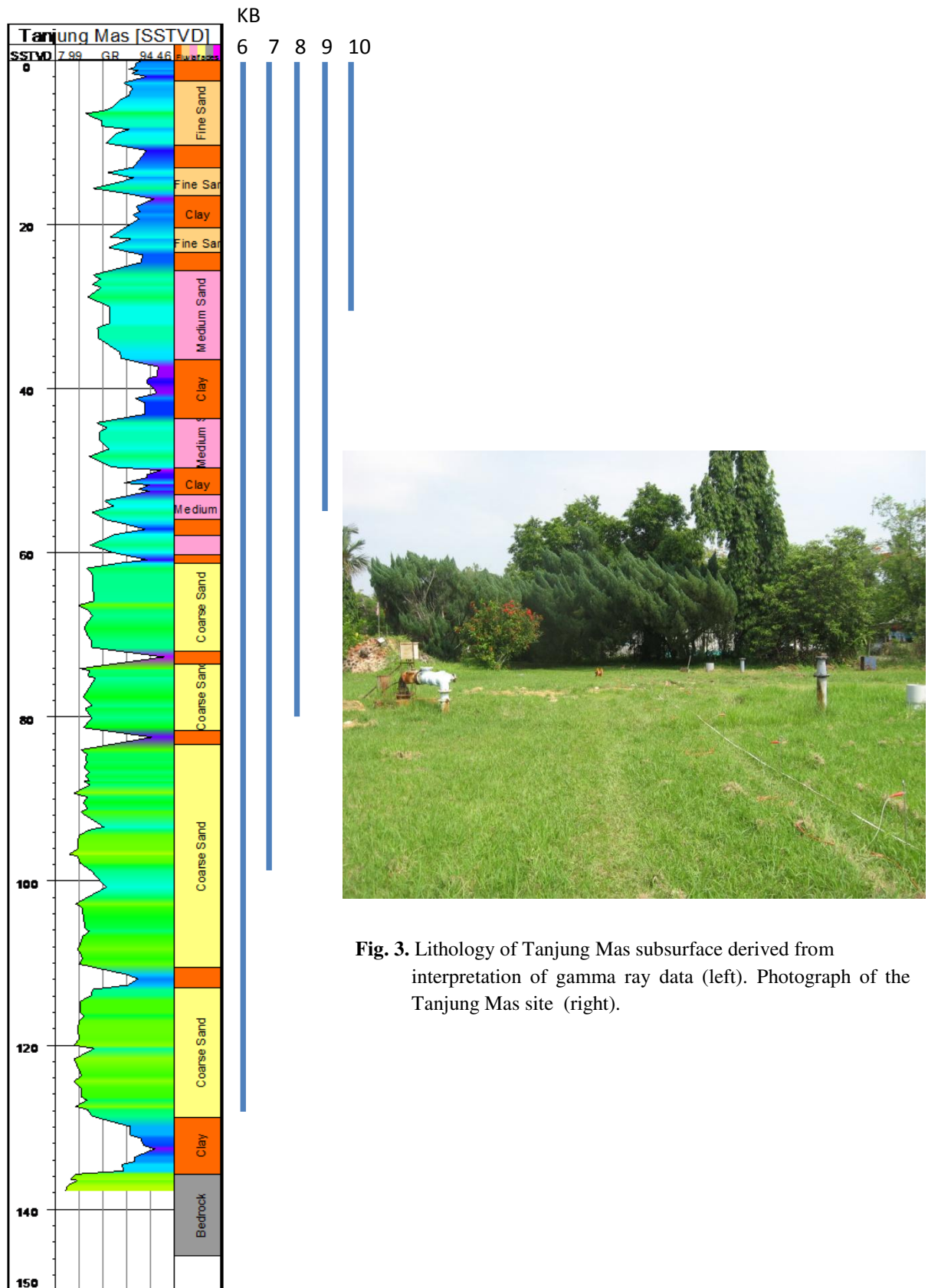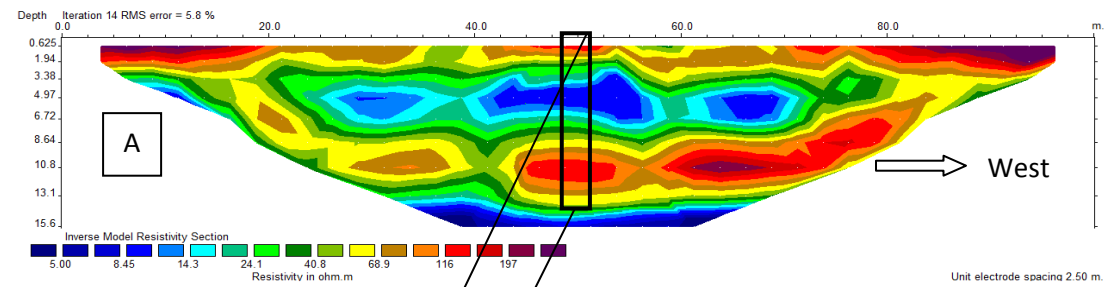
Fig. 3. Lithology of Tanjung Mas subsurface derived from interpretation of gamma ray data (left). Photograph of the Tanjung Mas site (right).
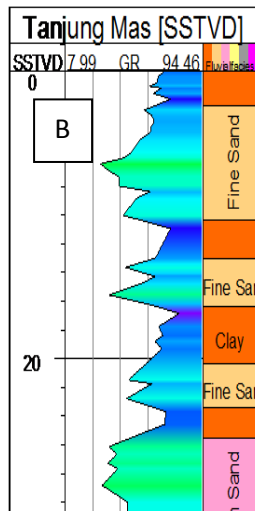
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Water table = 3.25 meter

Fig. 4. Wenner inverse model of line Tg Mas in Tanjung Mas well station (A), Lithology of Tanjung Mas subsurface derived from interpretation of gamma ray data (B). (gamma ray data derived from Abdul Rashid 1989)

In the Wenner inverse model of line A001B (**Fig. 5.**), the boundary between brackish and fresh water is very clear, occurring in the centre of the line survey. This is indicated by the presence of a resistivity value of less than 7 ohm.m with a depth of around 18 meters deep at the right side of the survey line, and the value of more than 10 ohm.m at the same depth at the left side. However, the left side is closer to the Kelantan River, and the right side is to the sea ward.

Fig. 5 shows Wenner inverse model of line A001C. It can be seen that the minimum values of true subsurface resistivity is 5.51 ohm.m which corresponds to brackish water in the interval depth of 18 – 26 meter. Occurrence of relative high and low resistivity values on the top correspond to more compacted material which alternates to

softer material. At around the 265 meters mark, very soft material is exhibited. It is very possible for water to infiltrate from the surface to the next aquifer by this path.

Wenner inverse model of line A001D can be seen in **Fig. 5.** In the model, from the surface to a depth of 4 meter lower resistivity value (around 30 ohm.m) can be found corresponding to the possibility of the top aquifer. At the next depth (4-10 m), more values of resistivity are revealed. This correlates to less porous material. In the second aquifer, it can be interpreted that freshwater is occupying this zone. This is indicated by the lowest resistivity values in the zone of 8.37 ohm.m. However, the dominant resistivity values is around 30 ohm.m.
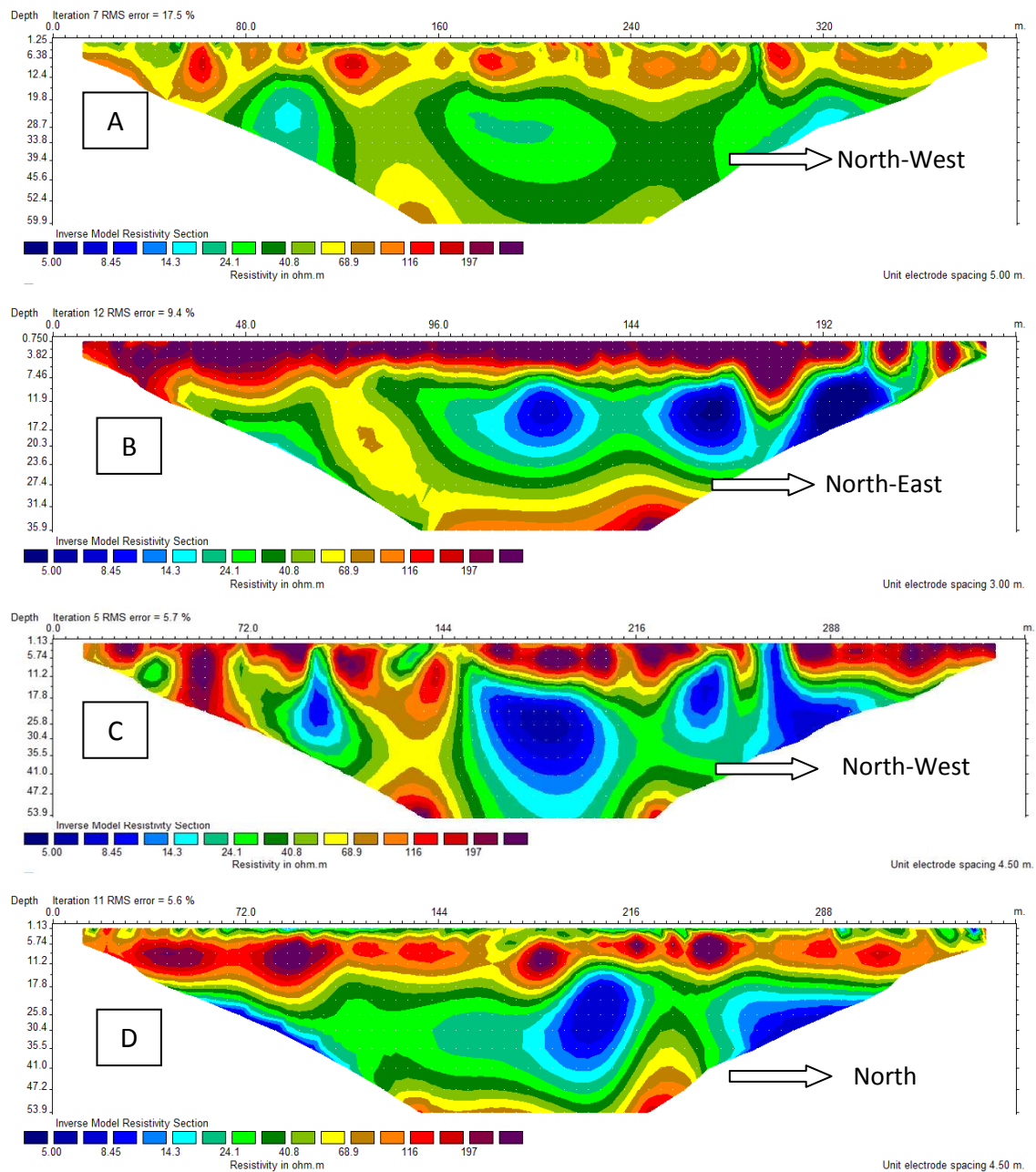
Fig. 5. Wenner inverse model of line A001A (A), line A001B (B), line A001C (C) and line A001D (D)

Site 2

The site second was situated to the west of the Pengkalan Datu River. Within this area, only one line was conducted due to the lack of space. The resistivity survey line A002 was conducted around 1 km from the river. The survey line A002 has an almost west-east orientation. The line was conducted on a surface with an elevation of 12 meters.

In the Wenner inverse model of line A002 (**Fig. 6**), there is no significant low resistivity value. The lowest resistivity value is 12.2 ohm.m, which indicates that the formation is filled with freshwater at a depth 12 meters and 160 meter mark. It can be seen that the formation at position up to 140 meters mark change to less porous material. This is indicated by a higher resistivity value within the zone. Unfortunately, in this site there were no groundwater samples to be taken due to neither a well nor a piezometer located in the site.
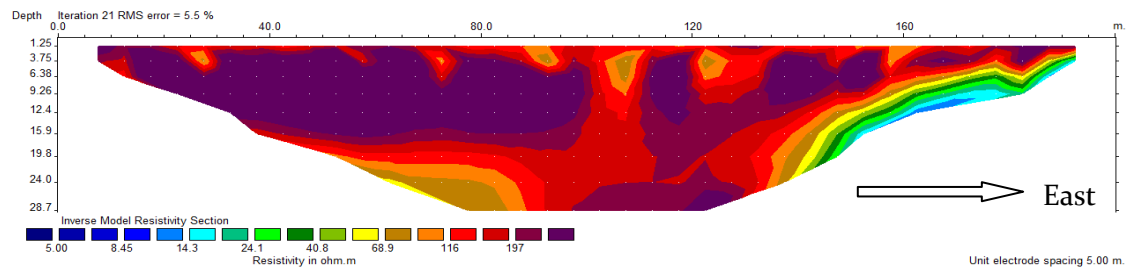
Fig 6. Wenner inverse model of line A002.

Site 3

The next site is situated to the east of the Pengkalan Datu River. Three geoelectrical resistivity survey lines (line A003A, line A003B and line A003C) were conducted around 7 km from the nearest beach. The lines were conducted beside an artificial drainage system around the paddy field. Among the three lines, the line A003A was the furthest from the Pengkalan Datu River,

followed by the line A003B and the nearest line to the Pengkalan Datu River was line A003C (see the map in **Fig. 7**).

The Line A003A (**Fig. 7**) was surveyed with a southwest-northeast orientation. It can be seen that there is a trend of lower resistivity values with a depth of 20 meters in the northeast part (seaward). On the surface of the Wenner inverse model, around the 330 meters mark, there is a higher possibility of surface water infiltrating the first aquifer.
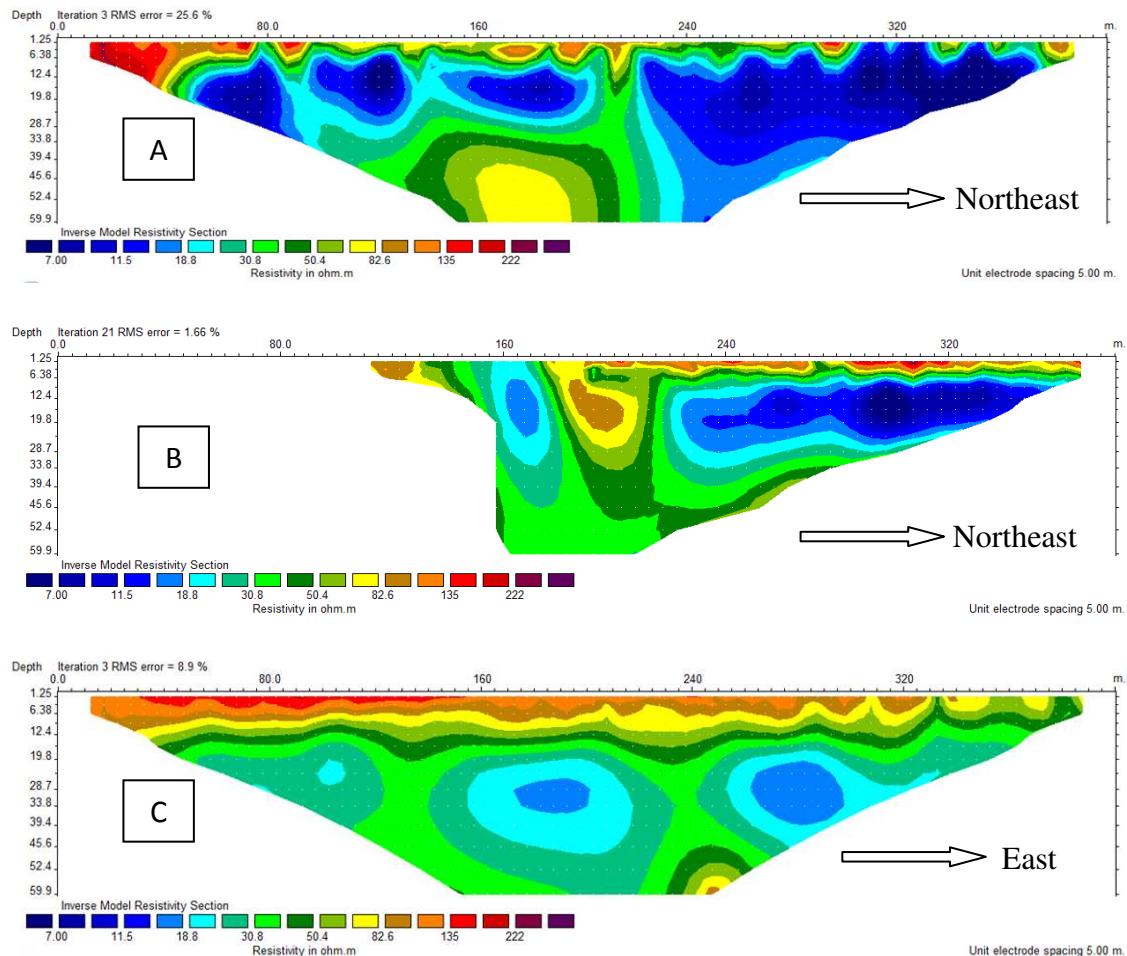

Fig. 7. Wenner inverse model of line A003A (A) and line A003B (B) line A003C (C)

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For the Wenner inverse model of line A003B (**Fig. 7**), unfortunately, data for this line was insufficient in the first half of the line due to some problems with the switch of the cable connector. The line was surveyed at around 4:00 PM. However, some feature for second aquifer can be found there. The low resistivity value appears in the zone next to the 240 meters mark. In the central region of the line section, the interface of brackish-fresh water has a very clear image.

The last line, A003C's Wenner inverse model can be seen in **Fig. 7.** The line orientation was from the Pengkalan Datu River seaward. It can be clearly seen in the second aquifer, that the occurrence of fresh water is very possible due to the resistivity value of around 18.5 ohm.m. The resistivity values increase with movement towards Pengkalan Datu River.

Site 4

The last site is situated to the southeast of site 1. The resistivity survey lines (line A004A and line A004B) were conducted almost perpendicular to the beach axis. The line A004A was located at about 4.5 km west of the beach line. The line A004B was around 1.5 km southwest of line A004A. It was noted that line A004B was almost perpendicular to line A004A. A total of 61 electrodes were laid out in each line A004A and line A004B respectively.

The circular region of low-resistivity values (less than 7 ohm.m) at around 25 meters depth in the Wenner inverse model line A004A and A004B (**Fig. 8**) corresponds to brackish water (Robinson, 1988). The concentration of salt/brackish water in this position of the section could be due to the concentration of marine deposits in that area (Samsudin, *et al.,* 2007).
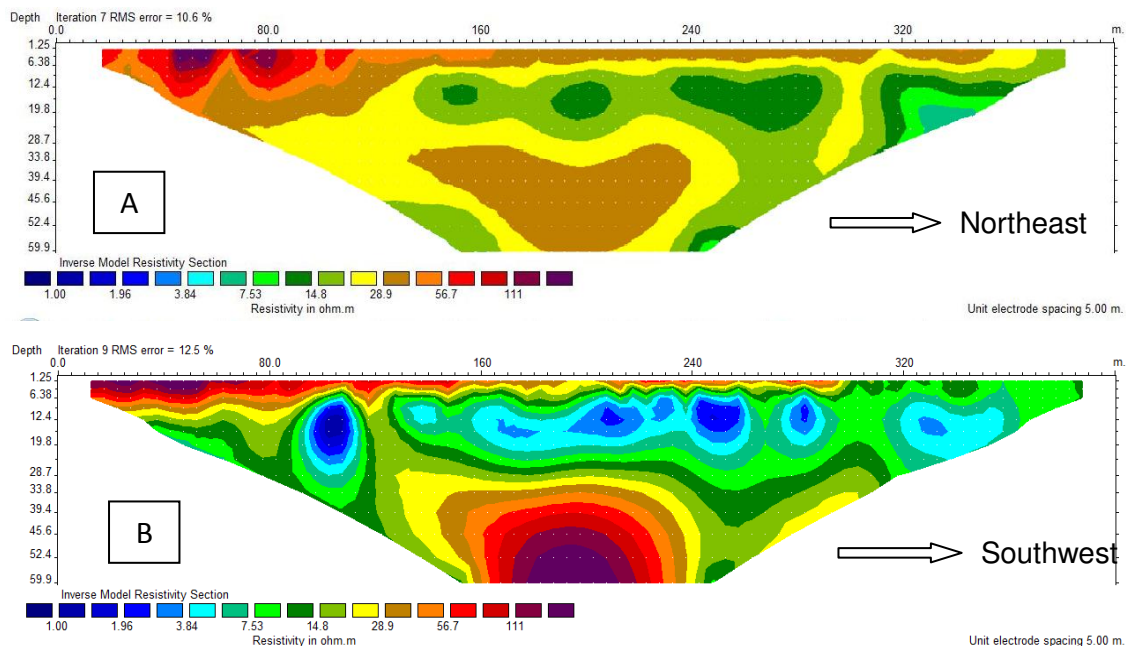

Fig.8. Wenner inverse model of line A004A (A) and line A004B (B).

The monitoring well (KB-32/33/34/35) are located around 2500 meter southeast from the end of line A004A. Although it is very far from the survey line, but the well data can be used to help subsurface resistivity interpretation. The well depth of KB-35 is 29.2 meters and its chloride content is 83.945 mg/l (data derived from Jabatan Mineral and Geosains Malaysia). The Wenner inverse model (line A004A) shows resistivity values of 20 ohm.m at around this depth. The value of the resistivity and chloride content supports each other indicating occurrence of fresh water.

Based on the entire Wenner inverse model and its interpretation that was discussed above, the possibility of salt/ brackish-fresh water interface can be mapped

as shown in **Fig. 9.** The blue line is the contour of resistivity with value of 7 ohm.m within a depth interval of around 20 to 30 meters. These values can be found within a radius of around 6-7 km from the nearest beach line. The line is interpreted as the interface of salt/brackish-freshwater.
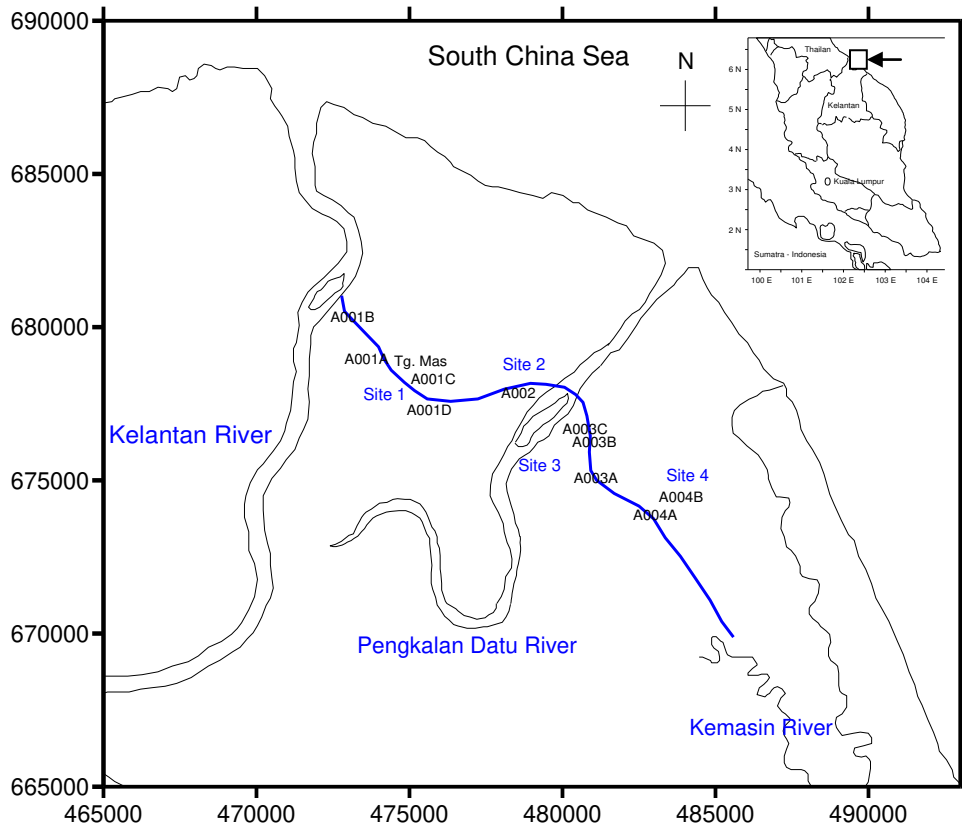

Fig. 9. The map with a line of salt/brackish-fresh water interface in the interval depth of 20 to 30 meters.

In the surrounding of Pengkalan Datu River, the blue line (salt/brackish-freshwater interface) bends in the direction of the river flow. This indicates that there is a possibility of groundwater in the aquifer being recharged by the water of the Pengkalan Datu River. In the surrounding Kelantan River, the blue line is also predicted to be bending in the direction of the river flow. In the area surrounding the Kelantan and Pengkalan Datu River, higher resistivity values in the Wenner inverse model indicates the presence of fresh groundwater in the aquifer that is influenced by the river water.

CONCLUSION

Gamma ray data has very high resolution vertically. It can distinguish formation below the surface by detail. Interpreted gamma ray data is very useful as calibration for geoelectrical resistivity interpretation in term of its lithology. The illustrated case studies show that electrical resistivity imaging is a valuable method for studies in the coastal environments. The zone of sand and clay is very clearly seen in the resistivity inverse model. In this study, the geoelectrical resistivity method is successfully imaging the subsurface with salt/brackish and fresh water zone. It has proved to be a useful tool for delineating the boundary between fresh water and salt water because of its inherent capability to detect the changes in pore-water electrical conductivity. The fresh-water/ saline-water boundary is almost two-dimensional and is a good target for 2D electrical imaging surveys. The zone of brackish water which has a resistivity value less than 7 ohm.m is very clearly seen in the Wenner inverse model with position around 20 to 30 m depth.

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