Aquifer Characterization and Groundwater Potential Evaluation in Sedimentary Rock Formation

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Abstract. This study was conducted to characterize the aquifer and evaluate the groundwater potential in the formation of sedimentary rocks. Electrical resistivity and drilling methods were used to develop subsurface soil profile for determining suitable location for tube well construction. The electrical resistivity method was used to infer the subsurface soil layer by use of three types of arrays, namely, the pole–dipole, Wenner, and Schlumberger arrays. The surveys were conducted using ABEM Terrameter LS System, and the results were analyzed using 2D resistivity inversion program (RES2DINV) software. The survey alignments were performed with maximum electrode spreads of 400 and 800 m by employing two different resistivity survey lines at the targeted zone. The images were presented in the form of 2D resistivity profiles to provide a clear view of the distribution of interbedded sandstone, siltstone, and shale as well as the potential groundwater zones. The potential groundwater zones identified from the resistivity results were confirmed using pumping, step drawdown, and recovery tests. The combination among the three arrays and the correlation between the well log and pumping test are reliable and successful in identifying potential favorable zones for obtaining groundwater in the study area.

1. Introduction
The demand on water resources has been increasing rapidly accompanied with the issue of supplying adequate water to meet social needs as the most significant challenge. In Malaysia, the source of water for daily use comes from treated water from reservoir. The growth of population and the expansion of the industrial and agricultural sectors have significantly increased the demand for water. The problems arise when the water is insufficient to meet the demand or is polluted. Extensive development in various sectors has resulted in certain impacts on the high demand of clean water in some areas. In addition, climate change may be a contributor to the water supply problem as it changes the availability, quantity, and quality of water resources, thereby influencing the entire cycle of water supply. Currently, Malaysia and other Southeast Asian countries receive high intensities of rainfall during the monsoon season. In December 2014, the villagers in Kelantan and some parts of Terengganu in Malaysia faced water supply disruption after a water supply plant was affected by devastating floods [1]. Tube wells were then built to supply clean water. This incident proves that groundwater can be an alternative source of water supply.

Another factor that is often associated with the shortage of water is the El Niño phenomenon. El Niño is a natural phenomenon that occurs in the Pacific Ocean when warm waters of the western coast
of South America replace the cold nutrient-rich waters and causes impacts on the weather patterns, such as increase in temperature between 0.5 and 2 °C and reduction in the amount of rainfall [2].

This study focused on groundwater potential in the formation of sedimentary rocks, which are formed from the consolidation of sediments. Among the various types of sedimentary rock, shale constitutes the thickest and most extensive aquitards in the majority of sedimentary basins. Shale originates as mud laid down on ocean bottoms, in the gentle-water areas of deltas, or in the backswamp environments. Mud, from which shale is formed, can present porosities as high as 70%–80% prior to burial. However, after compaction, shale generally exhibits a primary porosity of less than 20% and less than 5% in some cases. This type of sedimentary rock possesses higher groundwater potential than other types of rock, such as igneous and metamorphic rock. The type of rock and its potential for groundwater prospect should be comprehensively examined as groundwater resources are important for the future demand of water in Malaysia.

2. Geological condition of study area

The site chosen for this research is Kampung Bukit Kerek in Kedah at the northern region of peninsular Malaysia. The area is located in Pendang District (coordinates: 6°3'0”–6°4'30”N, 100°34'30”–100°36'0”E) as shown in Figure 1. Pendang District spans over an area of 629 km² with a population of 112,000 people. The town is approximately 20 km from state capital Alor Setar and is a district and a parliamentary constituency. The district is primarily covered with paddy fields with agriculture as its main economic activity. This study area is a sparsely populated rural region with underdeveloped infrastructures.

Groundwater concerned with plates and bound syncline of platforms or large intermountain areas can be attributed to this type. The dominating thickness of sedimentary deposits changes in these conditions within 1–4 km and reaches 10–12 km or above in some structures. Sedimentary deposits of these structures maintain primary sedimentary porosity that determines their storage and permeability to a great extent. Formation of rocks with dominance of fractured porosity is typically composed of sedimentary carbonate and clay–carbonate and of deep (3–4 km and above) parts of structures; the processes of lithification of sedimentary rocks (e.g., sandstone, argillite, siltstone, and others) occur in these structures because of high temperature and pressure.

In the Muda Dam area of eastern Kedah, the formation called the Semanggol Formation underlies a sequence of probable post-Triassic redbeds unconformably. The contacts between the Semanggol and older formations are interpreted to be faults. In addition, isolated occurrences of Triassic limestones are common in northern Kedah. The Tertiary rocks throughout the Western Belt are represented by small basinal rocks of shale and other clastics with coal bands [3].

A hydrogeological characterization of a sedimentary rock formation can be achieved by estimating a set of aquifer parameters, such as the thickness, extent, and hydraulic conductivity of aquifer [4]. Aquifers differ in properties because these properties are function of rock types constituting them. Different rock materials constitute the basement complex and sedimentary aquifers [5]. In hard rock terrains, the aquifers are fractured rocks and weathered in-situ materials, while the sedimentary aquifers consist of sands and sandstones. The existence of fracture zone in a geologic medium helps in creating groundwater conduit medium and accumulating groundwater [6].
Due to conditions of sedimentation and low tectonic dislocation, hydrogeologic formations of sedimentary deposits typically exhibit layered structure of heterogeneity with aquifer–aquitard consecution. Sand, sandstone, fractured or karstic limestone, and dolomite are usually the main types of water-bearing rocks. Loam clays, carbonate-clayey rocks, gypsum-anhydride, and salt (at their occurrence outside of upper zone of intensive leaching) are typical low permeability rocks. The rocks, which are usually considered water-bearing aquifers, present a hydraulic conductivity of $10^{-6}$–$10^{-4}$ m/s or above. Typical low permeable rocks, such as aquitards, exhibit a hydraulic conductivity of $10^{-7}$ m/s or below. The so-called confined aquifers, which are confined by aquitards at the top and the bottom (except when the upper aquifer has free groundwater level), are related to the cross section of sedimentary rocks of this type.

3. Methodology

3.1 Equipment

Electrical resistivity surveys at the site were conducted using ABEM Terrameter LS System with its accessories. Additional equipment including a hammer for driving down the steel electrodes, GPS, and portable two-way radios were used to conduct the survey.

3.2 Methods for data collection

The principle of resistivity is based on four electrodes (i.e., currents, C1 and C2 potentials, P1, and P2) according to the study by the Schlumberger brothers in 1920. Using this method, the center point of the electrode arrays remains fixed, but the electrode spacing is increased to gain detailed information about the subsurface. Multiple types of arrays are used in the resistivity survey and their geometric factors are based on the change in spacing between electrodes.

The developments of multi-electrode resistivity equipment and data acquisition technique have made electrical resistivity imaging a standard tool in near-surface geophysical surveys. Electrical resistivity is measured in $\Omega$m (ohm m) and represented by $\rho$. This physical property represents the difficulty in passing an electric current through a volume of materials with a given length and cross-sectional area [7] as expressed below:

$$\rho = R(A/L),$$

(1)
where \( \rho \) is the resistivity, \( R \) is the electrical resistance, \( A \) is the cross-sectional area, and \( L \) is the length. The resistivity of a volume of material can be calculated by multiplying the electrical resistance with the cross-sectional area and divided by the length. The electrical imaging system is normally carried out with a multi-electrode resistivity meter system. In the survey, the number of electrodes used is typically from 25 to 100; these electrodes are laid out in a straight line with constant spacing. The active electrodes used for measurement are automatically selected by the computer system. The arrangement of the electrodes is shown in Figure 2.

Figure 2. Arrangement of electrodes for 2D electrical survey (Loke 2012).

The selection of array for a field survey depends on the type of structure to be mapped, the sensitivity of the resistivity meter, and the background noise level. In this study, the suitable arrays used for 2D imaging surveys were the Wenner, pole–dipole, and Schlumberger arrays [8].

Figure 3. Plan view of the 2D ground resistivity investigation area with the survey alignments at Kampung Bukit Kerek, Pendang Kedah.
Figure 4. (a) Resistivity line for west direction (b) Resistivity line for east direction

Table 1. Survey alignments for each array.

| Array      | Length (m) | Coordinate (starting point) | Coordinate (end point) |
|------------|------------|----------------------------|------------------------|
| Pole–Dipole| 800        | 06°03'31.6"N 100°34'56.2"E | 06°03'20.0"N 100°35'19.0"E |
|            | 400        | 06°03'28.4"N 100°35'01.6"E | 06°03'22.9"N 100°35'09.5"E |
| Schlumberger| 800        | 06°03'31.6"N 100°34'56.2"E | 06°03'20.0"N 100°35'19.0"E |
|            | 400        | 06°03'28.4"N 100°35'01.6"E | 06°03'22.9"N 100°35'09.5"E |
| Wenner     | 800        | 06°03'31.6"N 100°34'56.2"E | 06°03'20.0"N 100°35'19.0"E |
|            | 400        | 06°03'28.4"N 100°35'01.6"E | 06°03'22.9"N 100°35'09.5"E |

4. Result

Data processing converts the raw data by use of computer software. However, software application only produces resistivity to the image. The processed data should be interpreted and evaluated on the basis of engineering justification and comparison with reliable data sources available (borehole data from the site) to obtain accurate and reliable result.

A large variety of data sets were collected over the heterogeneous geological conditions; thus, no single inversion method can produce the optimum results in all the models. RES2DINV program was used to analyze the raw data collected at the field in .DAT format. The resistance measurements were reduced to the apparent resistivity values by the inversion process. The inversion of the resistivity and IP data was conducted by least-square method involving finite element and finite difference methods. The inversion process was done to obtain three types of resistivity section: calculated apparent resistivity, measured apparent resistivity, and inverse model resistivity.

Apart from the length of survey line, the type of array used is also important and can significant influence the established resistivity model. The three main array configurations were the pole–dipole, Schlumberger, and Wenner arrays in this study. The apparent resistivity measured by the array depends on the geometry of the electrodes. The majority of resistivity surveys use two current electrodes and two potential electrodes. As a precaution, the two arrays need a solid contact between the electrodes and the ground; otherwise, numerous errors will be produced, thereby jeopardizing the analysis
procedure. After the system was set up in this study, the software checked for sufficient ground contact across the entire electrode spread.

The software program automatically created a 2D model by dividing the subsurface into rectangular blocks and chose optimum inversion parameters for the data; these parameters were the damping factor, vertical to horizontal flatness filter ratio, convergence limit, and number of iterations. The program calculated the apparent resistivity values of the model blocks by use of either a finite difference or a finite element method and compared the results with the measured data. The resistivity of the model blocks was adjusted iteratively until the calculated apparent resistivity values of the model agreed with the actual measurements [9].

The final output from RES2DINV displayed three sections: measured and calculated apparent resistivity pseudosections and the inverse model resistivity section. The use of pseudosections is a qualitative way of presenting the spatial variation in the measured or calculated apparent resistivity in the cross section and does not reflect the true depth. The inverse model section shows the true depth and true formation resistivity. The topography can only be included in the inverse model section. Figures 5 and 6 show the electrical resistivity imaging at the survey site for Line 1 (800 m) and Line 2 (400 m). The correlation for this analysis was made on the basis of the data comparison between the materials drilling from the borehole at the site and electrical resistivity values from the electrical resistivity model in Table 3. By understanding that the differences of lithology are followed by those of resistivity, resistivity surveys can be useful in detecting bodies of anomalous materials or in estimating groundwater potential zones.

![Electrical resistivity imaging](image)

**Figure 5.** Electrical resistivity imaging at the survey site for Line 1 (800 m).
Figure 6. Electrical Resistivity imaging at the survey site for Line 2 (400 m).

Table 2. Resistivity of common rocks and soil materials (Keller and Frischknect, 1966).

| Material             | Resistivity (Ωm) |
|----------------------|------------------|
| Alluvium             | 10 to 800        |
| Sand                 | 60 to 1000       |
| Clay                 | 1 to 100         |
| Groundwater (fresh)  | 10 to 100        |
| Sandstone            | 8 to 4000        |
| Shale                | 20 to 2000       |
| Limestone            | 50 to 4000       |
| Granite              | 5000 to 1,000,000|
Table 3. Resistivity correlation with borehole log.

| Borehole Logging | Lithology and Depth (m) | Resistivity Value (Ωm) |
|------------------|-------------------------|-----------------------|
| **Clay (0–6)**   | Low Resistivity Zones   | (<150)                |
| **Light gray sand (6–12)** | Low Resistivity Zones   | (<150)                |
| **Fresh shale with quartz veins (12–30)** | Moderate Resistivity Zones | (more than 150 but less than 3,000) |
| **Fresh quartz veins (30–36)** | Moderate Resistivity Zones | (more than 150 but less than 3,000) |
| **Fresh shale with quartz veins (36–55)** | Moderate Resistivity Zones | (more than 150 but less than 3,000) |
| **Fresh quartz veins (55–65)** | Moderate Resistivity Zones | (more than 150 but less than 3,000) |
| **Fresh shale with quartz veins (65–70)** | Moderate Resistivity Zones | (more than 150 but less than 3,000) |

5. Discussion
For Line 1 (800 m), the maximum depths from the inverse model resistivity section was 200, 180, and 140 m for the pole–dipole, Schlumberger, and Wenner arrays, respectively. The results show that the RMS errors for the pole–dipole, Schlumberger, and Wenner arrays are 8.8%, 3.5%, and 2.5%, respectively. All RMS values are in the range of permissible limit; thus, no further refinement is needed. For Line 2 (400 m), only two arrays (i.e., the Wenner and Schlumberger arrays), were analyzed. The reason is that the RMS error for the pole–dipole (above 50%) is far beyond the permissible limit. Therefore, the data for the pole–dipole array cannot be used for further analysis although model refinement to reduce RMS error is done.

For Line 2 (400 m), the maximum depths from the inverse model resistivity section were 80 and 100 m for the Schlumberger and Wenner arrays, respectively. The results show that the RMS errors for the Schlumberger and Wenner arrays are 1.61% and 1.75%, respectively. The RMS value of the two arrays is below 5%; thus, no further refinement is needed.

6. Conclusion
Pumping test was conducted to verify the electrical resistivity result, and step drawdown test was also carried out immediately after the completion of the well construction. Submersible pumps were used to pump the water from the tube wells, and the discharge rates were measured with a weir tank. The valve was installed to control and vary the discharge rates. Step drawdown test is a single well test in which the water is pumped at a low constant discharge rate until the drawdown within the well stabilizes. This test was used to assess the tube well performance, and the data were analyzed using the graphical method and regression technique. The step drawdown test results showed that the maximum drawdown is 4.92 m after 72 h of test. For the recovery test, the drawdown is 0.62 m after 5 h of test. From this result, tube well is found to have high potential of being a groundwater source. The wells drilled in the study area are categorized as high productive wells with yield volume greater than 150 m³/h.

The pumping test results demonstrate the practical utility of a newly developed relationship for determining aquifer characteristics (specific storage coefficient and hydraulic conductivity) from analysis of cavity-well hydraulics. Two fractured zones are found. One is located at the depth of 20–25 m in the shale layer, and the other is located at the depth of 55–65 m in the fresh quartz vein. The well is located in excellent and good potential zones with yield capacities of 13210 and 31283 gal/h for the first and second layers, respectively. Groundwater in the form of confined aquifer is obtainable between
a depth of 20–25 and 55–65 m. The resistivity of the aquifer layer is <150 Ωm. In summary, well can be a source of groundwater.

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