AQUIFER DELINEATION AND CLASSIFICATION USING 2-D RESISTIVITY IN VARIOUS GEOLOGICAL FORMATION

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AQUIFER DELINEATION AND CLASSIFICATION USING 2-D RESISTIVITY IN VARIOUS GEOLOGICAL FORMATION

by

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LIST OF SYMBOLS

a	Tortuosity
b	Potential electrode separation
C	Current electrode
F	Cementation factor
I	Current
k	Hydraulic conductivity
km	kilometre
m	metre
mm	milimetre
n	Ratio of nb over b
nb	Distance between current and potential electrode
P	Potential electrode
R	Resistance in Ohm
S	Fraction of the pore volume filled with groundwater
s	Second
T	Transmissivity
V	Voltage
ρ	Resistivity
ρ_a	Apparent resistivity
ρ_f	Resistivity of the formation
ρ_w	Resistivity of pore water
Ωm	Ohm-metre
%	Percentage
ψ	Porosity

>	Larger than
<	Smaller than

LIST OF ABBREVIATIONS

$CaCO_3$	Calcium carbonate
E	East
E-W	East-West
EM	Electromagnetic
ES	Electrode Selector
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IP	Induced Polarization
KFU	King Faisl University
MRSM	Maktab Rendah Sains Mara
N	North
NE	Northeast
N-S	North-South
Res2Dinv	Resistivity 2-D Inversion software
SAS	Signal Averaging System
SW	Southwest
VES	Vertical electrical sounding
VLF	Very low frequency
2-D	Two dimensional
3-D	Three dimensional

PENENTUAN DAN PENGKELASAN AKUIFER MENGGUNAKAN KEBERINTANGAN 2-D DALAM PELBAGAI FORMASI GEOLOGI

ABSTRAK

Sumber air adalah penting untuk semua kehidupan dan air bawah tanah merupakan salah satu sumber air terpenting di Malaysia. Salah satu daripada kaedah yang biasa digunakan untuk penerokaan air bawah tanah adalah pengimejan keberintangan 2-D. Kaedah ini digunakan untuk mengukur corak taburan keberintangan bahan-bahan bawah permukaan. Dalam kajian ini, kaedah keberintangan 2-D digunakan untuk cuba mengesan, mencari dan mencirikan potensi kewujudan akuifer di kawasan yang berlainan dengan formasi ciri geologi dan stuktur yang berbeza. Kajian terpilih telah dilaksanakan di Rasa di Selangor, Batang Merbau di Kelantan, Bukit Chondong, Guar Jentik dan Bukit Jernih di Perlis serta di Bukit Kodiang dan Merbok di Kedah. Kajian ini menggunakan susun atur Pole-Dipole bagi mendapatkan penembusan kedalaman maksimum. Lubang bor di Rasa dan Batang Merbau manakala singkapan geologi di Bukit Chondong dan Guar Jentik digunakan sebagai kolerasi. Interpretasi kajian telah diproses menggunakan perisian keberintangan Res2Dinv dan Surfer8 berbantukan kolerasi lubang bor dan singkapan geologi. Zon tepu air (1-100 Ωm) yang tertafsir daripada model keberintangan songsangan 2-D di Rasa dan Batang Merbau adalah akuifer dan terbukti daripada rekod lubang bor manakala hasil kajian di Bukit Chondong dan Guar Jentik menunjukkan kolerasi yang baik terhadap singkapan geologi. Ciri perlapisan bagi batu pasir dan batu lumpur boleh dibezakan berdasarkan kepada model keberintangan songsangan 2-D. Ciri perlapisan antara dua sifat bahan geologi yang berbeza mempunyai ciri yang berbeza. Sifat unit geologi yang dengan ciri-ciri formasi keporosan dan kebolehtelapan yang tinggi berpotensi membentuk zon kawasan tepu air manakala ciri lapisan batuan tak telap, bertindak sebagai lapisan mengekang atau perangkap air. Dalam pada itu, Bukit Jernih dan Bukit Kodiang berkemungkinan memiliki ciri-ciri akuifer kerana seperti dikenalpasti daripada model keberintangan songsangan 2-D. Iaitu berpotensi terdapat rongga, rekahan dan rejahan. Hasil kajian menunjukkan bahawa kawasan tersebut mempunyai zon anomali keberintangan yang rendah berbanding kawasan sekitar. Merbok terbentuk daripada mendapan lanar laut atau sungai yang dicirikan oleh lapisan lempung tidak terkonsolidat dan pasir. Kombinasi bahan-bahan tersebut terutamanya lempung tidak terkonsolidat telah mengurangkan kemungkinan kawasan tersebut menjadi akuifer. Akhirnya, nilai keberintangan digunakan untuk menganggarkan darjah keporosan bahan-bahan geologi kawasan berkenaan dengan menggunakan Persamaan Hukum Archie. Zon tepu, batuan terluluhawa, rekahan atau rongga yang berisi bahan-bahan geluh mempunyai keporosan >20% dan kawasan tersebut berpotensi membentuk akuifer atau bertindak sebagai penyaluran air jauh kedalam bumi.

AQUIFER DELINEATION AND CLASSIFICATION USING 2-D RESISTIVITY IN VARIOUS GEOLOGICAL FORMATION

ABSTRACT

Water resource is essential media for all living things and groundwater is one of the important water sources in Malaysia. One of the most used methods for groundwater exploration is 2-D resistivity imaging technique. The method is used to assess the resistivity distribution of the subsurface materials including groundwater. In this study, 2-D resistivity method has been used to detect, locate and characterize the potential aquifer at various places underlain by different geological rock and characteristics on the formation. The surveys have been carried out at Rasa in Selangor, Batang Merbau in Kelantan, Bukit Chondong, Guar Jentik and Bukit Jernih in Perlis, and Bukit Kodiang and Merbok in Kedah. The surveys were performed using Pole-Dipole electrode configuration in order to obtain maximum depth of signal penetration. There are boreholes in Rasa and Batang Merbau while outcrops at Bukit Chondong and Guar Jentik. The results were processed using Res2Dinv and Surfer8 software and were correlated with the boreholes and local geological outcrops. The saturated water bearing zone (1-100 Ωm) that had been interpreted from the 2-D inversion model of resistivity at Rasa and Batang Merbau were confirmed be the aquifer which proved by borehole records while the results at Bukit Chondong and Guar Jentik show well correlation with geological outcrops. The interbedding between sandstone and mudstone can be differentiated from the inversion model of 2-D resistivity. The interbedding between two different materials have different functions. The rock formation that shows porosity and permeability characteristics have potential to form underground reservoir while materials with low porosity and permeability act as confining layer or water cap. Moreover, Bukit Jerneh and Bukit Kodiang have aquifer potential characteristic as the presence of cavities, fractures rock and intrusive bodies were recognised from the inversion model of 2-D resistivity. The results show that that area which has low resistivity values compared to the surrounding. Merbok is overlain by thick sedimentation from marine or river which caused the area consists of unconsolidated clay and sand. The materials presence especially unconsolidated clay reducing the possibilities of the area to be an aquifer. Finally, resistivity data were postulated to measure the porosity of the subsurface materials using the Archie's Law Equation. The saturated water bearing zone, weathered permeable rocks, fractures zone or cavities that filled with loamy materials have a porosity of >20% and those areas have potential to be an aquifer or act as water transmission into the ground.

CHAPTER 1

INTRODUCTION

1.0 Background

The total water consumption in Malaysia can be divided into domestic, industry and agriculture use as shown in Figure 1.1. Most of the developed and developing countries rely on groundwater as the main drinking supply and for both agriculture and industrial use. Since the reliance on groundwater is high, it is important to ensure that there are significant quantities of water and high quality of water.

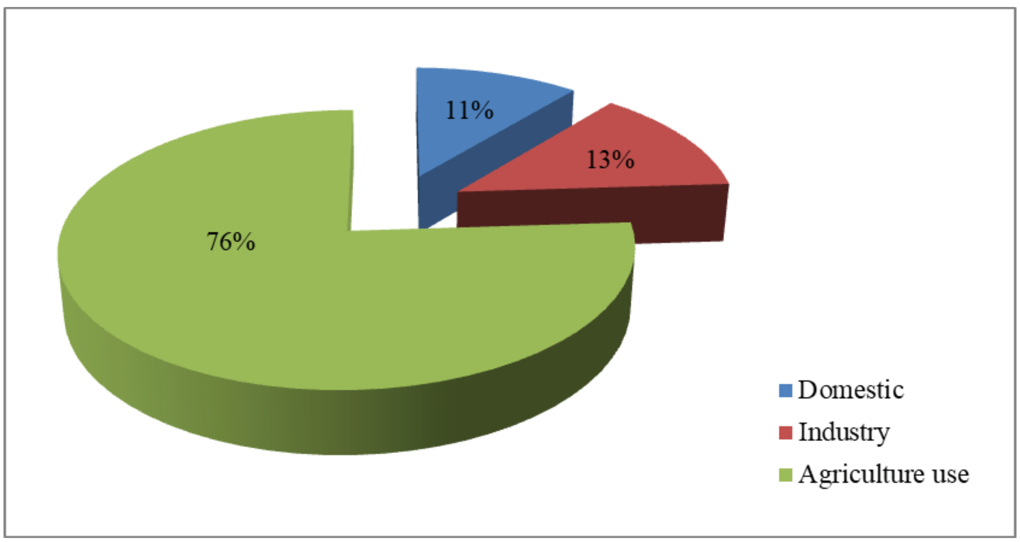

Figure 1.1: The water consumption in Malaysia for the year 1995 (Lim, 2008).

Geophysical methods can be applied for both groundwater resource mapping and for water quality evaluations. Near surface geophysics is usually applied for groundwater investigations. The application of near surface geophysics for groundwater include the mapping the depth and thickness of aquifers, mapping aquitards or confining units, locating preferential fluid migration paths such as fractures and fault zones and mapping contamination to the groundwater such as that from salt water intrusion. Reynolds (1997) covered in detailed about groundwater and near surface investigations. Many geophysical techniques have been applied to groundwater investigations. The potential field methods, gravity and magnetics have been used to map regional aquifers and large scale basin features. Seismic methods have been used to delineate bedrock aquifers and fractured rock systems. Electrical and electromagnetic methods applicable for groundwater studies as many of the geological formation properties that are related to hydrogeology such as the porosity and permeability of rocks can be correlated with electrical conductivity signatures.

Most geophysical techniques have been applied for groundwater characterization but the electrical and electromagnetics methods are the best in directly mapping and monitoring contaminated and clean groundwater. The knowledge of the aquifer characteristics is important in determining the potential of the aquifer. The 2-D resistivity method is an electrical method. The 2-D resistivity method has shown potential to explore and determine the aquifer characteristics (Lashkaripour et al., 2005). This is a method that studying the subsurface using the electricity. The 2-D resistivity method is measuring the resistivity distribution in the subsurface. Different materials in the subsurface have different resistivity values that can help in detecting the groundwater. It is a non-destructive and cost-effective method for locating the aquifer. This method is commonly being used to detect aquifer, which it can explore deeper penetration. The 2-D resistivity method is also applicable to the identification of subsurface formations, groundwater zones, groundwater salinity and anthropogenic contamination (Khaki et al., 2014).

1.1 Problem statement

The groundwater exploitation nowadays only successfully locate the aquifer but unable to know the type of the aquifer system. The aquifer found can be classified as confined or unconfined aquifer but the people unable to differentiate the type of the aquifer either it is confined or unconfined aquifer. The type of aquifer system is important in choosing the type of water well and in knowing the water amount estimation. Performing the 2-D resistivity method able to locate the aquifer if study the resistivity distribution of the subsurface with the geology and geomorphology of the suspected area while the amount of water discharge cannot be known from the method. The estimation of the amount of water discharge can be known if the porosity of the aquifer is known as the porosity of the aquifer can provide information about the subsurface water saturation.

Moreover, the lack of groundwater development is failed to recognize the potential of the groundwater resources and the misconception of groundwater exploitation is not sustainable. The lack of information about the groundwater storage or aquifer leads to well drilling failure. No trace water in well location will cause wasting money and time since a well drilling is expensive and consume a lot of time.

1.2 Research objectives

The objectives of this study are:

i. To determine and characterise the potential aquifer from the hydrogeological concept and 2-D resistivity subsurface imaging

ii. To correlate and analyse the 2-D resistivity data with borehole geology information and geological outcrops

iii. To estimate and verify the potential aquifer based on porosity data analysing

1.3 Scope of study

The aim of this study is to explore the potential aquifer occurrence involved a different type of subsurface geology. The potential aquifer study is usually supported by borehole information which expensive and consumed lots of time. In order to reduce cost and time, the porosity of the subsurface material is determined to verify the potential aquifer based on the Archie's Law. The porosity is calculated using the resistivity value from the 2-D resistivity inversion model. The porosity for every single datum point of inversion model of 2-D resistivity will be determined. Apart from resistivity survey, the geological information factors such as the age of the formation are important in choosing the value of tortuosity and cementation factors that will be applied during the calculation. However, the application of Archie's Law Equation in determining the porosity of the subsurface is limited in the area with high clay content.

This study was carried out at seven different sites, each located in Selangor, Kelantan, Kedah and Perlis. All the study sites are chosen with interest to find the potential aquifer. The 2-D resistivity method was utilised using ABEM SAS4000 and electrode selector ES10-64 for the data acquisition while Res2Dinv software was used for data processing (Loke, 1997). The 2-D resistivity results were then correlated with the borehole data and geological outcrops. The characteristics of the potential aquifer are discussed according to the results of the 2-D resistivity, the correlation between 2-D resistivity data with borehole data and the correlation between 2-D resistivity data with geological outcrops at the study sites. The determination of porosity is calculated using the equation from Archie's law. The equation of porosity is not applicable for Merbok as it has high clay content.

1.4 Layout of thesis

The contents of this thesis are organized as follows;

Chapter 2 explains the formation of the groundwater, aquifer and sedimentation and also discusses the theory of 2-D resistivity method, type of array used in this survey, the influence of geology and resistivity and resistivity values for various types of rocks and soils medium. Besides, Archie's Law also has been discussed in this chapter. The equation from Archie's Law was used in this survey to calculate the porosity of the subsurface materials. The previous study was also included in this chapter. Most of the previous studies are using 2-D resistivity method in detecting and locating aquifer or groundwater. Besides, the previous study about the geological formation of the study area also discussed in this chapter such as Kubang Pasu formation. The hydraulic conductivity and transmissivity were commonly calculated in the previous study, but not the porosity.

Chapter 3 discusses methodology where the 2-D resistivity method studies the resistivity distribution in the subsurface. The survey was carried out at seven different sites, there are two survey lines in Selangor (Rasa), four survey lines in Kelantan (Batang Merbau), three survey lines in Perlis (Bukit Chondong, Guar Jentik and Bukit Jerneh) and five survey lines in Kedah (Bukit Kodiang and Merbok). Two boreholes were performed in Selangor and Kelantan while two geological outcrops found in Perlis (Bukit Chondong and Guar Jentik). Moreover, data acquisition describes the technique and apparatus used in the survey were also discussed. The data processing used the Res2Dinv software while Microsoft Excel was used to calculate the porosity percentage using Archie's Equation and Surfer8 software used to analyse and plot the porosity.

Chapter 4 highlights and discuss the results and finding accordingly of each site of 2-D resistivity survey results. Firstly, the potential of each aquifer was discussed according to the hydrogeological concept and 2-D resistivity subsurface imaging. The discussion includes the evidence found during the data acquisition. The general characteristics of each potential aquifer were elaborated in this chapter. Secondly, the inversion model of 2-D resistivity in Rasa and Batang Merbau were discussed and correlated to borehole log profile while Bukit Chondong and Guar Jentik were discussed and correlated with local geology outcrops. Finally, the porosity imaging and 2-D porosity imaging were generated based on the porosity of the subsurface was calculated.

Finally, in Chapter 5, the conclusion on the finding and application of the 2-D resistivity method in characterizing the aquifer were discussed and the recommendations included in this chapter for the future research.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) from which groundwater can be exploited using a water well (Karamouz et al., 2011). Sedimentary rock is the most common geological structure for groundwater to accumulate. Sedimentary aquifers consist from loose to coarse-grained deposits such as sandstone and hard fractured sedimentary rocks such as limestone or dolomite.

The 2-D resistivity method is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. This method also referred to as a galvanic electrical method which sometimes useful for determining shallow and deep geologic and hydrogeology conditions (Sultan, 2012). The 2-D resistivity method works by applying direct current to the surface and measure the electrical resistance. The 2-D resistivity method is a non-destructive ground survey method and its main advantage is to produce the subsurface resistivity distribution. This method has many applications in a number of fields. It provides accurate depth information of suspected target through visualisation. The depth information is important to detect the aquifer. The sedimentary rocks usually are more porous and have higher water content, which results in lower resistivity values. Wet soils and fresh groundwater have even lower resistivity values (Loke, 1999).

2.1 Groundwater

Groundwater is water that is found in the subsurface occupying all the voids in cracks and spaces in soil and rocks. The area where water fills these spaces is known as a saturated zone or aquifer. The top of the saturated zone is called water table. The groundwater occurs almost everywhere beneath the surface. The precipitation from the surface infiltrates into the ground through the fractures and cracks until it reaches the bedrock that prevents from escape and flowing away. Generally, the velocities of groundwater flow are low and its magnitude is less than the velocities of stream flow (Frank and Joni, 2012). The source of surface water and groundwater are actually from the same resource and they are interconnected. Figure 2.1 shows the hydrological cycle for the source of surface and groundwater. Groundwater can be found either from the alluvial aquifer (sand and gravel) or hard rock aquifers (sedimentary rocks or limestone).

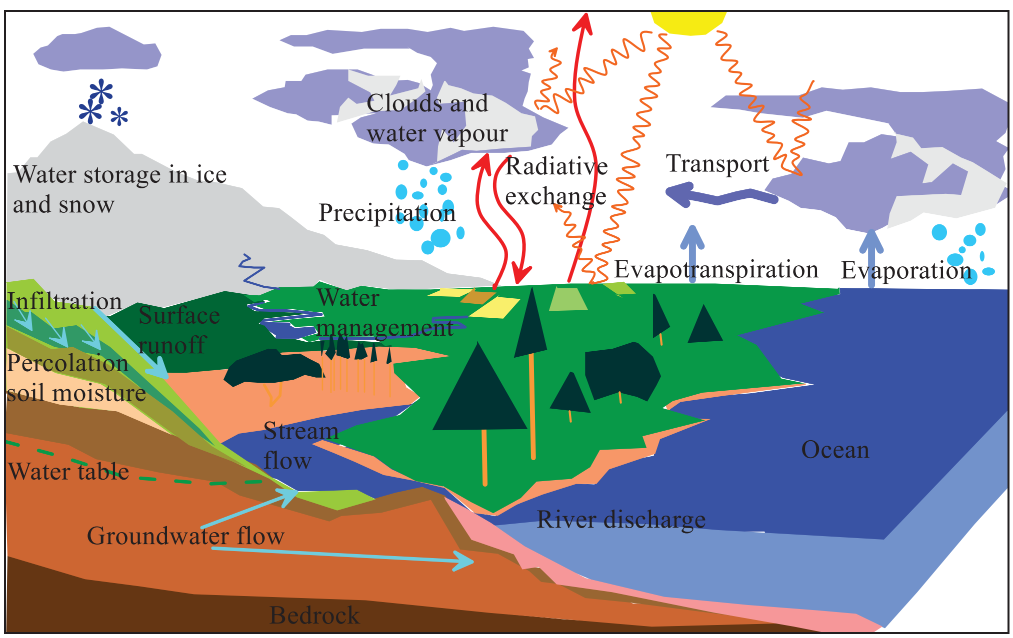

Figure 2.1: Hydrological cycle (modified from NASA GSFC Water and Energy Cycle web site).

In Malaysia, more than 90% of the freshwater resources come from groundwater. There are about 5000 billion m^3 of groundwater that still in storage and unexploited (Azuhan, 1999) as shown in Table 2.1. Therefore, in order to overcome the water shortage during the dry season, the groundwater can be the resources for water supply.

Table 2.1: Water resources in Malaysia (Azuhan, 1999).

Water resources	**Quantity (billion $m^{3)}$**
Annual rainfall	990
• Surface runoff	566
• Evapotranspiration	360
• Groundwater recharge	64
Surface artificial storage	25
Groundwater storage	5000

2.2 Aquifer

An aquifer is a place that stores the groundwater. The groundwater in the aquifer can move easily as the water moves through the moderately to highly permeable rocks. The aquifer typically made of permeable materials such as gravel, sand, sandstone or fractured rocks, for example, limestone and granite. It is because the materials have many connected spaces that allow water to flow through. However, the groundwater cannot flow through clay and shale, though they have many small pores. It is because the pores are not connected to each other and become low-permeable (James et al. 2007).

The groundwater may occur either in confined (artesian) or unconfined (water table) aquifer. A confined aquifer is an aquifer that overlain by materials with low permeability compared to the materials of the aquifer that can prevent the water from moving upward. The water within this confined aquifer has additional pressure, thus the water usually tapped by a well as the water will rise up to the top of the aquifer which is the potentiometric surface level. Otherwise, an unconfined aquifer is an aquifer with the water table at the upper surface. The permeable rocks below the water table are saturated under the normal conditions and the pressure at the water table is at atmospheric pressure (Eric, 1984) as shown in Figure 2.2.

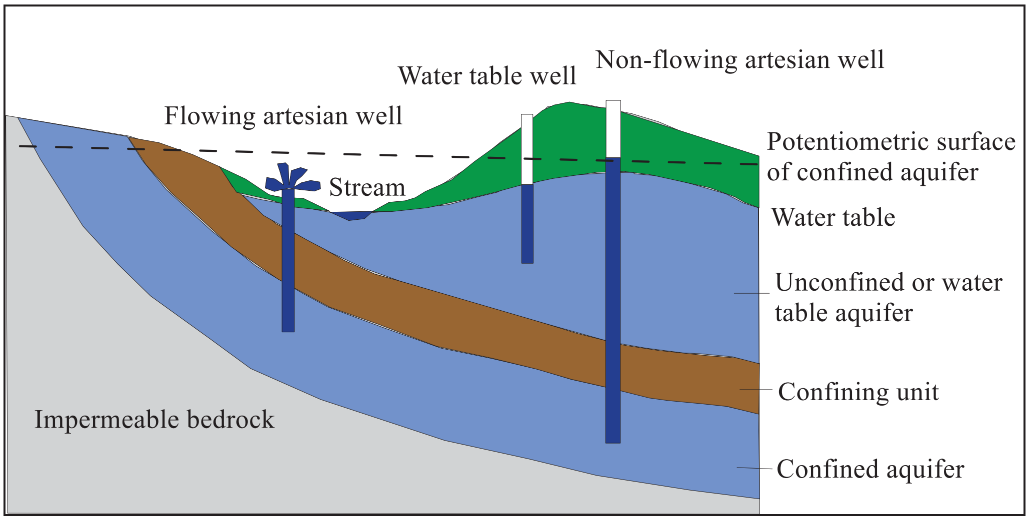

Figure 2.2: Aquifer diagram (modified from Purdue Research Foundation, 1996).

2.2.1 Fractured aquifer

Groundwater flow in a fractured aquifer is different from groundwater that flows in the aquifer with a porous medium which consists of sand (Nielsen, 2007). The flow moves from the recharge zone to the discharge zone. Fractures form an irregular pattern of interconnected or isolated conduits of groundwater. The fractured aquifer stores and transmits groundwater. The ability of the fractured rock to produce water depends on the size and opening of fractures, the connectivity of the fractures, the number of fractures and the connection to the recharge zone (Kasenow, 2006).

The well that drilled at the fractured rock may have very high yields of water. The fractures that are not connected to each other will not produce a sustained well yield while the fractures that are connected will act as a channel and therefore produced a sustained well yield. Besides that, the multiple fractures in porous sedimentary rock also may produce a sustained well yield. This is due to the double porosity system, which are porosity of the sedimentary rock and porosity of the fractures (Kasenow, 2006). It is important to construct wells where the fractures are numerous and interconnected.

2.3 Sedimentation

An aquifer can develop from the sedimentation of the marine in the earlier age. The sedimentation process is controlled by the depositional process from the marine. The sediments; rocks, soil and mineral from weathering process were transported from the ocean to the lower area and strongly influenced by the regional geology (Saad et al., 2016). The transportation of the hydrogenous from the ocean is due to the long shore drift from the tidal current to formed range of landforms. There are various factors that control the depositional process; fluvial discharge including water volume, time variation, tidal process and river mouth process (Saad et al., 2016). The sediments from the marine or near shore are well sorted with fine-grained distribution due to current velocity and particle diameter (Dominic et al., 2010).

On the other hand, the sedimentation from the higher land may results the ocean became shallower and disappearing with time. Geological of that area underlain by sedimentary rock of sandstone and mudstone as a result of the seafloor were covered with mud and sand layer during the higher rates of erosion in the early age, while limestone and dolostone are formed during slow rates of erosion which the shallow marine shelf composed of calcium carbonate shells and skeletal parts of invertebrates and algae that grow rapidly in the warm and shallow sea water. The type and texture of the original sediment, changes during post-depositional burial and transformation of sedimentary rock, dissolution and fracturing are the factors that result in different of porosity and permeability (Cow Creek Groundwater Conservation District, 2007).

2.4 Resistivity theory

The 2-D resistivity method works through the measurement of potential differences at points on the Earth's surface that is produced by injecting current into the subsurface.

The electrical is applied to a pair of current electrodes (C_1 and C_2) and the potential difference is measured between one or more pairs of potential electrodes (P_1 and P_2) (Muztaza et al., 2012). Figure 2.3 shows four electrodes configuration in a two-layer model of resistivity, ρ_1 and ρ_2 including current (I), voltage (V), the current electrode (C) and potential electrode (P).

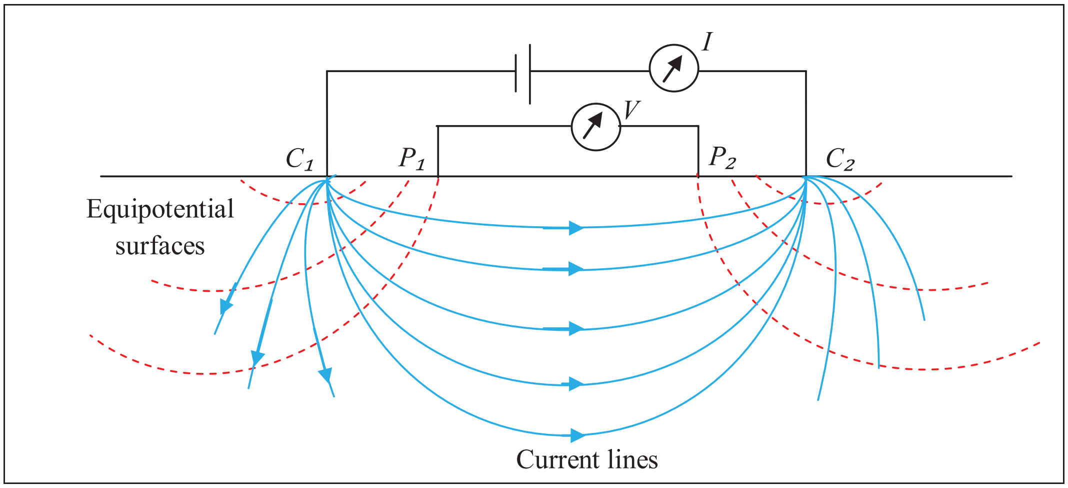

Figure 2.3: Four electrodes configuration in a two-layer model of resistivity, ρ_1 and ρ_2 (modified from Said, 2007).

2.5 Arrays

The resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties of the ground and also in the detection of three-dimensional bodies of anomalous electrical conductivity. It is routinely used in engineering and hydrogeological investigations to investigate the shallow subsurface geology (Kearey et al., 2002). There are many arrays uses in the 2-D resistivity method such as Pole-Dipole, Pole-Pole, Dipole-Pole, Wenner, Wenner-Schlumberger and Schlumberger. However, only Pole-Dipole array will be explained for further discussion because the array adapted for this research is a Pole-Dipole survey. Pole-Dipole is adopted because of its ability to penetrate deep into the ground, which is suitable for groundwater exploration. Groundwater usually found in a deeper geological formation.

2.5.1 Pole-Dipole

The arrangement of current and potential electrodes for the Pole-Dipole array is shown in Figure 2.4. The potential electrode has a constant electrode separation (b) and the distance between current and potential electrode is (nb) but one of the current electrodes is at an infinite distance. Usually, it is positioned at about five to ten times survey length (Loke, 2001).

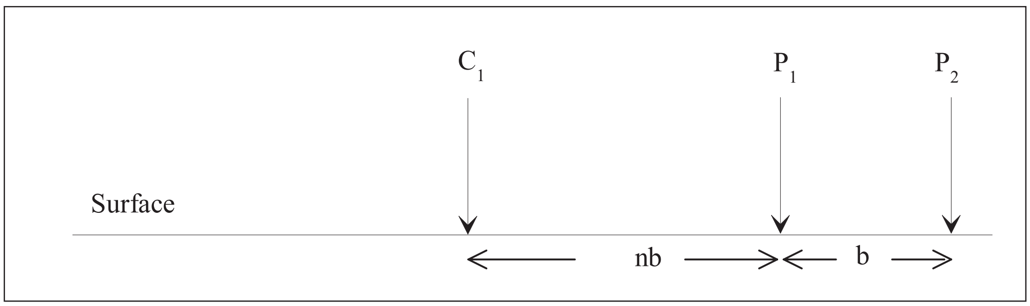

Figure 2.4: The arrangement of current and potential electrodes for the Pole-Dipole array.

This geometry is used because it reduces the distortion of equipotential surfaces (Smith, 1986). The measured apparent resistivity, ρ_a is given by Equation 2.1.

$$\rho_a = 2\pi nb(n+1)R \qquad (2.1)$$

where,

n : Ratio of nb over b
b : Distance between two electrode
R : Resistance (Ω)

2.6 Influence of geology and resistivity

Resistivity surveys will show the subsurface resistivity distribution and it is important to study the resistivity value of subsurface materials when dealing with resistivity survey. The knowledge about the subsurface and geology of the surveyed area is important during resistivity interpretation. Different rocks may different resistivity value. Igneous and metamorphic rocks commonly have high resistivity values depending on the degree of fracturing and percentage of the fractures filled with groundwater, but sedimentary rocks tend to have low resistivity due to high porosity and high water content (Loke, 1999).

2.6.1 Rock classification

There are three types of rock, igneous, sedimentary and metamorphic rocks. Igneous rocks are the solidification of magma or molten rock over a period of time (Chase and Pawlik, 2002). Igneous rocks that form from red hot lava above the Earth's surface are called extrusive rocks while those that form from magma that cooled below the surface are called intrusive rocks. They cool very slowly and become visible only when the rocks and soil above them erode.

Sedimentary rock is the most common rock found on the Earth's surface. Sedimentary rocks are formed from the broken down pieces of other rocks or debris cemented together by intense pressure and minerals deposited by water. The sediments are deposited when weathered rock is moved from one place to another by the wind, running water, the sea or glaciers. The fine particles of dirt begin to cover the surface and usually, these small rock particles end up by suspended in water and sink to the bottom of lakes, streams and the ocean. Then, the layer of sediment on the bottom of lakes and ocean becomes deeper and the weight of all the sediment becomes immense, pushing down on lower layers of sediment with tremendous force. Finally, the sedimentary rock is formed when some of the minerals act as cement. Physical properties of sedimentary rocks such as good porosity and permeability (Tucker, 1991).

When heat and pressure are applied to either igneous rocks or sedimentary rocks at the deeper part of the Earth, the rocks will become metamorphic rocks. This heat and pressure, change their structure substantially. The rocks are partially melted and the chemicals within them are altered (Lynch and Lynch, 2016).

The sedimentary rocks that have very fine-grained are clay, mudstone and siltstone. Their characteristics such as hardness depend on their geological age and the duration they have been buried and altered by tectonic events. Burial in thick sedimentary deposits causes the mudstone become compacted and hardened. Mudstone can be seen in various colours. Normally, grey colour indicates the mudstone has a high content of clay with a small amount of non-oxidized, ferrous iron-rich minerals while brown or red mudstone may contain oxidised ferric iron minerals. Besides, the mudstones that have a high content of clay mineral may form in pale-grey, pale-green or white colour (Merriman et al., 2003). Table 2.2 shows the grain sized for some common sedimentary rocks.

Table 2.2: Grain sized for some common sedimentary rocks (Hallsworth and Knox, 1999).

<table>
<tr><th>Particle Size (mm)</th><th>Sedimentary Components</th><th>Unconsolidated Rocks</th><th>Consolidated</th></tr>
<tr><td>265</td><td>Boulders</td><td rowspan="2">Boulders</td><td rowspan="4">Conglomerate</td></tr>
<tr><td>65</td><td>Cobbles</td></tr>
<tr><td>16</td><td>Pebbles</td><td rowspan="2">Gravel</td></tr>
<tr><td>4</td><td>Granules</td></tr>
<tr><td>2</td><td>Very-coarse-sand</td><td rowspan="5">Sand</td><td rowspan="5">Sandstone</td></tr>
<tr><td>1</td><td>Coarse-sand</td></tr>
<tr><td>0.5</td><td>Medium-sand</td></tr>
<tr><td>0.25</td><td>Fine-sand</td></tr>
<tr><td>0.125</td><td>Very-fine-sand</td></tr>
<tr><td>0.032</td><td>Silt</td><td rowspan="2">Mud /Clay</td><td rowspan="2">Siltstone/Mudstone /Shale (Slate)</td></tr>
<tr><td>0.004</td><td>Clay</td></tr>
</table>

Limestone is a sedimentary rock that consists of calcium carbonate ($CaCO_3$) or double carbonates calcium (dolomite) and magnesium such as fossils, fossils debris and shell fragments. Limestone mostly found in lakes, rivers and ocean (Dunham, 1962). The rock formed from calcite skeleton derived from microscopic organisms in the shallow sea with the outer part consists of silt and clay that help to protect the rock (Boynton, 1980). Most of the limestone forms in shallow, calm and warm marine water because, in that area, the organisms can easily form calcium carbonate shells and skeletons. Then, the organisms die and left their shell and skeletal. Later, it will accumulate as sediment that might be lithified into limestone. Besides that, limestone also can form through evaporation such as stalactites, stalagmites and other cave formations. The water that seeping from the ceiling of a cave might evaporate before falling down to the cave floor. During the water evaporates, there is calcium carbonate that was dissolved in the water and deposited on the cave ceiling called stalactites and stalagmites are droplets that drop on the cave floor and evaporates. Along the process, many other minerals entrained impurities and change the limestone's original colour to milky white, light grey, dark grey, brown, red and black (Pettijohn, 1975).

2.6.2 Resistivity of typical rocks and soil

The resistivity value of each type of rocks are different for example, igneous rocks tend to have highest resistivity values while sedimentary rocks tend to have highest conductive values due to high porosity content. On the other hand, metamorphic rocks have intermediate, but overlapping resistivity values. Table 2.3 shows the resistivity values of some of the typical rocks and soil materials and Table 2.4 shows the resistivity values for some types of water.

Table 2.3: The resistivity values of common rocks and soils (Keller and Frischknecht, 1996).

Material	Resistivity (Ωm)
Alluvium	10 to 800
Sand	60 to 1000
Clay	1 to 100
Groundwater	10 to 100
Sandstone	$8 – 4x10^3$
Shale	$20 – 2x10^3$
Limestone	$50 – 4x10^3$
Granite	5000 to 1,000,000

Table 2.4**:** The resistivity values of some type of waters (Keller and Frischknecht, 1996).

Type of water	**Resistivity (Ωm)**
Precipitation	30 – 1000
Surface water (Igneous rock)	30 – 500
Surface water (Sedimentary rock)	10 – 100
Groundwater (Igneous rock)	30 – 150
Groundwater (Sedimentary rock)	> 1
Seawater	≈ 0.2
Drinking water (max salt content 0.25%)	>1.8
Water of irrigation and stock watering (max salt content 0.25%)	>0.65

2.7 Archie's Law

The porosity of the subsurface materials can be calculated from Archie's Law (Equation 2.2):

$$\rho_f = \rho_w \, a \, \psi^{-F} S^{-2} \tag{2.2}$$

Where ρ_f is the formation resistivity, ρ_w is resistivity of the pore-water, ψ is the porosity and S is the fraction of the pore volume that is filled with groundwater. The exponents a and F are the tortuosity and cementation factors respectively. The aquifer is fully saturated and therefore S is equal to one (Thomas, 2002). Table 2.5 is the suggested value for constant a and F that be used in Archie's formula when the lithology of the rock is known.

The equation is applicable for certain types of rocks and sediments, especially those that have low clay content. It is not suitable for rocks or sediments containing a high clay content. There is a more complex equation have been proposed for rocks with high clay content (Olivar et al., 1990).

Table 2.5: The suggested value for constant a and F to use in Archie's formula when the lithology of the rock is known (Keller, 1987).

Description of rock	**a**	**F**
Weakly cemented detrital rocks, such as sand, sandstone and some limestones with a porosity range from 25 to 45%, usually Tertiary in age	0.88	1.37
Moderately well-cemented sedimentary rocks, including sandstones and limestones with a porosity range from 18 to 35%, usually Mesozoic age	0.62	1.72
Well-cemented sedimentary rocks with a porosity range from 5 to 25%, usually Paleozoic in age	0.62	1.95
Highly porous volcanic rocks, such as tuff, aa and pahoehoe, with porosity in range 20 to 80%	3.5	1.44
Rocks with less than 4% porosity, including dense igneous rocks and metamorphosed sedimentary rocks	1.4	1.58

2.7.1 Porosity and permeability

Porosity and permeability will affect the formation of the aquifer. Porosity is the space that can store the water while permeability is the movement of the water that can pass through rock or soil (Brears, 2017). There are three types of porosity, which are intergranular porosity, fracture porosity and solution porosity. Firstly, intergranular porosity is influenced by sorting, grain packing and grain size. The well sorted and well roundness grain tend to have high porosity than unsorted and not rounded grain. Secondly, fractured porosity is due to the tectonic event or the weathering process and mostly the fractured porosity developed along the bedding planes. Lastly, solution porosity happened to some minerals that soluble in water such as limestone that readily eroded or dissolved by rainwater. Furthermore, the most important factor in porosity is the cementation type. Clay-sized minerals as cement tend to have lower porosity than other cleaner sediments (Earle, 2006). Permeability usually is used to relate with porosity. The grain size and sorting of the grain also will influence the permeability. The well-sorted sediment will have high permeability while poorly sorted has low permeability. Besides, the interconnected