

ASSESSMENT OF SUBSURFACE FEATURES AND POTENTIAL OF GROUNDWATER DELINEATION USING 2-DIMENSIONAL ELECTRICAL RESISTIVITY IMAGING METHOD

NORSHIDAH YUNUS¹, NORDIANA MOHD MUZTAZA^{1*}, ISMAIL AHMAD ABIR¹, YASIR BASHIR², MUHAMMAD TAQUIDDIN ZAKARIA³, FARID NAJMI ROSLI¹, AHMAD AQIL AHMAD AZNAN¹, JOSEPH GNAPRAGASAN¹, RAMADHANSYAH PUTRA JAYA⁴, NAZRIN RAHMAN⁵, MUSTAPHA ADEJO MOHAMMED⁶, AYAACA DALTON TERKIMBI¹ AND MOHD HARIRI ARIFIN³

¹School of Physics, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia. ²Department of Geophysical Engineering, Faculty of Mines, Istanbul Technical University, 34469 Istanbul, Türkiye. ³Department of Earth Sciences and Environment, Faculty of Science & Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia. ⁴Faculty of Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, 26300 Kuantan, Pahang, Malaysia. ⁵Global GeoExperts Sdn. Bhd., 737-6-5, Kompleks Sri Sg. Nibong, Jalan Sultan Azlan Shah, 11900 Bayan Lepas, Pulau Pinang, Malaysia. ⁶Department of Physics, Federal University of Lafia, PMB 146, Nasarawa State, Nigeria.

*Corresponding author: mmnordiana@usm.my

<http://doi.org/10.46754/jssm.2025.06.001>

Submitted: 29 August 2024 Revised: 10 December 2024 Accepted: 15 December 2024 Published: 15 June 2025

Abstract: The application of geophysical methods is widely used for the assessment of subsurface geological features, including the determination of potential groundwater aquifers, understanding of stratigraphy sequences, and structural analysis. The demand for groundwater exploration is on the rise, encompassing needs for domestic, industrial, and agricultural purposes. However, unsuccessful groundwater exploration has occurred owing to a lack of comprehensive subsurface information. Groundwater, as an alternative water source, remains largely unexplored within the Penang Island. In relation to this, a thorough study on the geophysics and geology should be carried out. It is certainly not as simple as just digging a well to draw water. Current technologies widely used for groundwater exploration include geophysical methods, remote sensing, Geographic Information System (GIS), hydrogeological, and machine learning. Therefore, geophysical methods were applied to obtain subsurface information to determine and classify the materials using selected geophysical properties. Geophysical methods, particularly Electrical Resistivity Tomography (ERT) is a non-invasive technique that allows for accurate identification of aquifer boundaries, saturated zones, and is cost-effective. This research aims to assess the subsurface features and evaluate the delineation of potential groundwater zones using 2-D electrical resistivity imaging and serves as a preliminary guide for identifying suitable locations for groundwater exploration in Universiti Sains Malaysia, Penang Island, Malaysia. Eight resistivity survey lines (LR01-LR08) are conducted within the research area. The 2-D resistivity imaging survey was conducted using Pole-dipole array for LR02, LR03, LR04, LR06, LR07, and LR08 while Wenner Schlumberger array for LR01 and LR03 with 5 m minimum electrode spacing. The Wenner-Schlumberger array was chosen due to site constraints in placing the remote electrodes within the study area. The research area's geology is characterised by an underlying igneous rock, featuring a centrally positioned granitic range that extends in a north-south direction, accompanied by low-lying elevations ranging between 5 metres and 20 metres above sea level. For this research, an automated multi-electrode resistivity meter, the ABEM Terrameter SAS 4000 system is employed. The resistivity values underwent an inversion process using RES2DINV software to generate the electrical resistivity topography model. The resistivity profiles are cross plotted using Surfer 8 and Sketchup software to obtain the overview of resistivity anomalies continuity between the resistivity profiles. The results showed the resistivity values ranged from 1 Ωm to 20,000 Ωm . Subsurface materials were categorised into four types based on their resistivity value ranges: Water-saturated zones (1 Ωm to 300 Ωm),

weathered material (301 to 1,000 Ωm), weathered bedrock (1,001 to 4,500 Ωm), and fresh bedrock ($> 5,000 \Omega\text{m}$). Several faults and anomalies are interpreted as potential water-saturated zones for groundwater drilling purposes. They are the continuation of water-containing zones between LR02, LR05, and LR08 profiles. These zones are proposed as a suitable potential location for drilling for groundwater. This outcome could contribute to establishing a one-stop centre for hardrock groundwater resources and developing sustainable guidelines for their management in the granitic region of Malaysia.

Keywords: 2-D electrical resistivity imaging, groundwater, granitic, saturated zone, sustainable.

Introduction

Ensuring a clean water supply is crucial for public health, supporting various needs such as drinking, domestic use, sanitation, food production, and industrial activities. The Department of Irrigation and Drainage Penang oversees the regulation of Penang's water supply, with Perbadanan Bekalan Air Pulau Pinang (PBAPP) serving as the water operator. The key water sources for Penang include the Air Itam Dam, Teluk Bahang Dam, and the Muda River. As stated by PBAPP, the Muda River contributes to 80% of Penang's raw water supply. Nevertheless, the El Nino phenomenon and inadequate rainfall in 2021 led to a substantial reduction in the water levels of Muda River's (Perbadanan Bekalan Air Pulau Pinang, 2021). The Ayer Itam Dam and Teluk Bahang Dam similarly exhibit diminishing capacity due to this phenomenon. If such occurrences persist and extend for prolonged periods, the potential for water supply disruption is significant, given that USM relies entirely on PBAPP for its water supply.

As per the USM Financial Report, the main campus requires approximately 417 million litres of water a month (14MLD) for consumption. This substantial consumption leads to an annual expenditure of approximately RM1 million on water bill tariffs. Hence, this investigation was undertaken to explore alternative water sources for USM. Additionally, reducing expenses related to water bills can contribute to the optimal functioning of USM (Yunus *et al.*, 2023).

Groundwater is the water located beneath the Earth surface. It can be classified into two main categories: Water in alluvium and water

in rock. The existence of groundwater in alluvium originates from comets and asteroids that hit Earth millions of years ago. This type of groundwater accumulated in the Earth's atmosphere and transformed into precipitation. The precipitates then seeped into the alluvium to create a groundwater cycle which exists till today. This type of groundwater is prone to contamination from atmosphere/ground and is also dependent on season's (dry/wet); therefore, it is not sustainable for drinking and could introduce geohazard if the extraction is not controlled (Anuar & Muztaza, 2018).

In contrast, groundwater in rock formed billions of years ago during the formation of the Earth (~4.5 billion years). The formation of our Earth started with the circulation of rocks, dust and Helium gas (He), which were compacted into a ball of molten rock that trapped He inside.

Through He nuclear fusion process, Hydrogen (H) was formed followed by other type of gases including Oxygen (O_2) and heavy elements (Earle, 2006). Water was then formed as H and O_2 combined, which was then trapped in the rock and is called hardrock groundwater. The hardrock groundwater accumulated and migrated closer to the Earth's surface and resides inside porous and permeability rock bodies. At the same time, the hardrock groundwater is supported by water from precipitation through porosity and permeability of alluvium and rock (Figure 1). This hardrock groundwater is clean, rich with minerals, sustainable due to its massive quantity, independent of seasons, less/non geohazard problems, and is safe for consumption (Anuar & Muztaza, 2018).

Groundwater is the water that occupies the cracks and voids in the soil, sand, and rocks beneath the surface of the Earth. There are two main zones which are unsaturated and saturated zones. The unsaturated zone is found immediately below the land surface and within this zone one can find both water and air. The latter fills in the open spaces or pores. The region where water occupies these voids is referred to as a saturated zone or aquifer, with the upper boundary of this saturated zone being termed the water table. Precipitation, including rain, hail, or snow, infiltrates the ground through fractures and cracks until it reaches the bedrock, where its escape and its outward flow is impeded. The source of surface water and groundwater are the same and are interconnected.

Figure 1 shows the schematic diagram for the source of surface and groundwater. As rain falls onto the ground, water begins to infiltrate into the subsurface. The speed of water that soaks into or infiltrates the soil depends on soil type, land use, intensity, and length of the storm. Water infiltrates faster into sand than clay or silt, and almost no water filters into paved areas. Rainfall that cannot be absorbed into the ground accumulates on the surface, giving rise to runoff streams. As the soil becomes fully saturated, excess water gradually percolates through the unsaturated zone into the saturated zone, replenishing the groundwater. Subsequently, water flows through the saturated zone toward areas of groundwater discharge (Muztaza & Ismail, 2020).

A Malaysian government-commissioned report found Penang state to be the most water-vulnerable state in the country (Ranhill Consulting, 2011). This vulnerability stems from the state's heavy reliance on a single shared river system, the Muda River, to meet majority of its water requirements. In recent years, low water level warnings for the state dams have been increasing in frequency. In 2016 alone, Penang spent around \$110,000 on cloud-seeding operations to induce rainfall and refill the critically low dam water levels. As a heavily urbanised state with a rising population, it is imperative to prioritise the development of alternative water sources to ensure the preservation of the state's water security.

Kura *et al.* (2018) mentioned that no exploratory groundwater studies have been published for Penang Island. Petrick *et al.* (2023) delineate favourable and unfavourable groundwater potential zones in Penang Island and the assessment was performed through integration of remote sensing and Geographic Information System (GIS) techniques to produce groundwater potential map validated with 2-D Electrical Resistivity Tomography (ERT) field data. In Malaysia, groundwater potential mapping using remote sensing and GIS has been conducted for the Langat Basin in Selangor (Musa *et al.*, 2000; Manap *et al.*, 2013), Kedah state (Yahaya *et al.*, 2007), Perlis state (Yahaya *et al.*, 2007), and Perak state (Surip *et al.*, 2009). However, groundwater assessment using 2-D Electrical Resistivity Imaging was conducted by

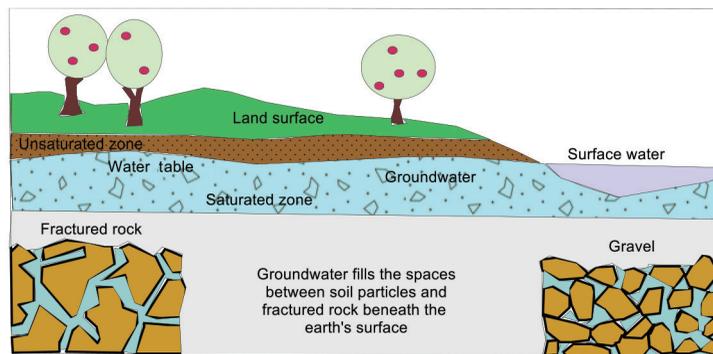


Figure 1: The schematic diagram of the origin of surface and groundwater
Source: Earle (2006)

Riwayat *et al.* (2009) and Zamari *et al.* (2019) at Johor, Azizan *et al.* (2018) (Perlis), Zeinab *et al.* (2015) (Melaka), Anuar and Muztaza (2020) (Perlis), and Razak and Muztaza (2022) (Kelantan).

Therefore, this article aims to delineate groundwater potential zones at Universiti Sains Malaysia (USM) on Penang Island. By employing ERT method, the study seeks to identify and map areas with high groundwater availability, which are crucial for sustainable resource management. This investigation serves as a preliminary assessment of groundwater resources on the island, providing valuable insights into their distribution and depth. The findings will not only enhance our understanding of the groundwater system in this region but also help future studies and water resource planning efforts, contributing to the sustainable management of water supplies in the face of increasing demand and environmental challenges.

The electrical resistivity methods are widely employed in geophysics for groundwater exploration due to their high data accuracy, extensive coverage capability, and environmentally non-destructive nature. This method was selected for its ability to provide detailed information over a broad area. Resistivity values are influenced by various factors, including earth-forming minerals, porosity, the quantity and characteristics of the pore fluid, and ground temperature (Burger, 1992; Society of the Exploration Geophysicist of Japan, 2014). High-resistivity values are frequently associated with igneous and metamorphic rocks, which are typically characterised by their dense and crystalline structures.

However, the specific resistivity measurements can vary significantly based on several factors, including the extent of fracturing within these rock types. When fractures are present, they can create pathways for groundwater movement, potentially altering the overall resistivity profile of the rock. If these fractures are saturated with groundwater, they may contribute to lower resistivity values

compared to completely dry or less fractured areas.

Conversely, in regions where the fractures are minimal or not filled with water, the high resistivity of the surrounding rock is often maintained. Understanding this relationship is critical for accurately interpreting geophysical survey results and identifying potential groundwater reservoirs within these geological formations (Loke, 1997; 1999). In contrast, sedimentary rocks typically exhibit low-resistivity values due to their high porosity and elevated water content (Loke, 1997; 1999). The subsurface materials and geological structures are interpreted and undergo an inversion process by comparing the apparent resistivity value measured during data acquisition and calculated by software to produce the inversion model representing the subsurface tomography (Loke, 1997).

Study Area

The research was conducted at the main campus of Universiti Sains Malaysia in Gelugor, located on Penang Island. The central region of Penang Island features a mountainous granitic range running in a north-south direction (Ahmad *et al.*, 2006). The coastal areas of Penang Island are underlain by the Simpang Formation, Beruas Formation, and Gula Formation. The Pleistocene Simpang Formation is composed of gravel, sand, clay, silt, and peat, interpreted as a terrestrial fluvial deposit. The Holocene Beruas Formation is a fluvial deposit comprising of sand, gravel, clay, silt, and occasionally peat. The lithology of the Gula Formation includes silt, clay, sand, gravel, and peat, often containing shell fragments (Hasan, 1990).

The geological map was generated using Surfer8 software with geological information obtained, as shown in Figure 2. The primary fault, which runs approximately in a North-South direction and divides the island was deduced by Tjia (1985) based on aerial photo lineaments. The faults in Penang are primarily dip-slip faults with a normal faulting component, associated with regional tectonic forces in the

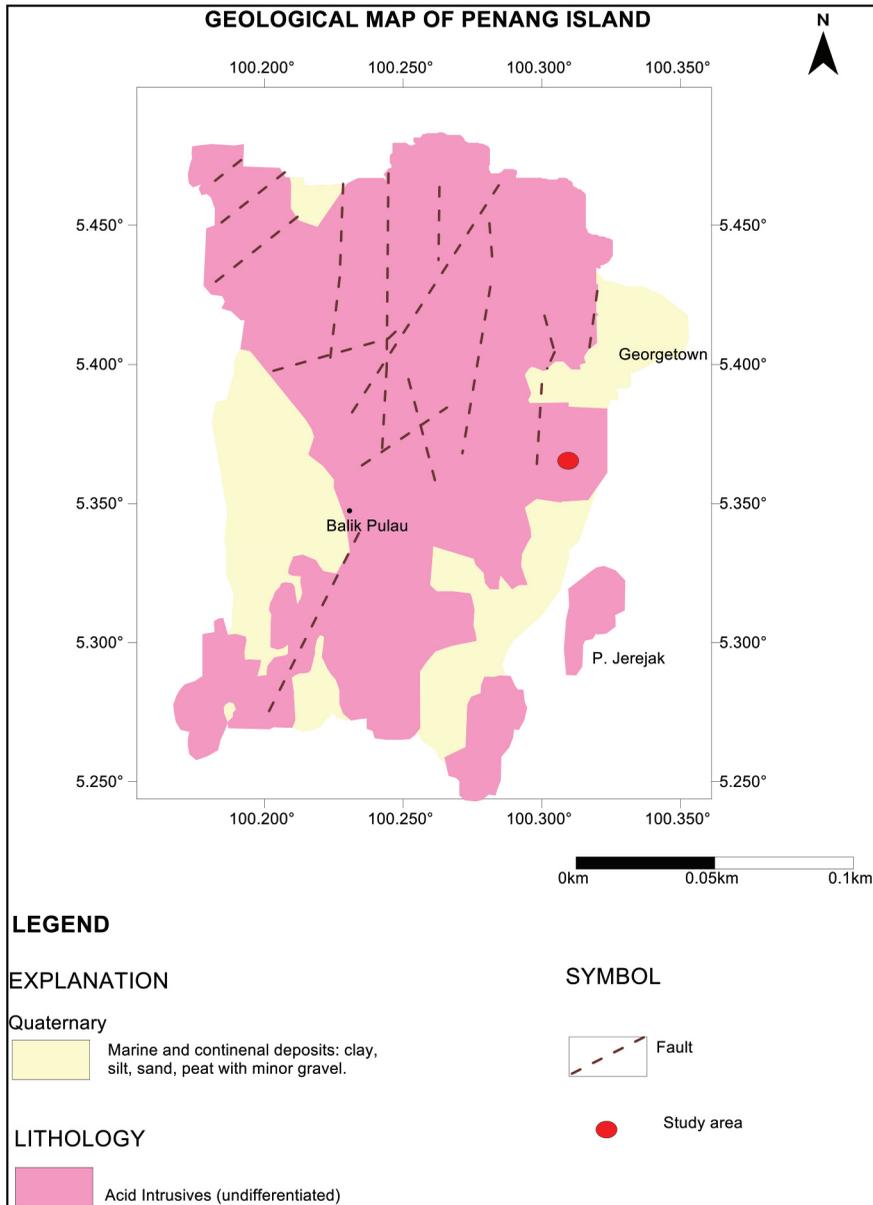


Figure 2: The geological map of Penang Island
 Source: Geological map of Peninsular Malaysia (1985)

region. Recent field investigations have revealed multiple pieces of evidence (such as a substantial quartz dyke/ridge-oriented North-South near Paya Terubung and exposed fault planes in the quarry face around Tg. Bunga) that supports the existence of this major fault.

The study area is Universiti Sains Malaysia’s main campus in Gelugor, Penang. The topography is plain, with elevations ranging from 4 metres to 11 metres. Eight surveys were conducted within the USM Campus, ranging between 200 m and 400 m (Figure 3). Survey



Figure 3: Location of research areas within the main campus of Universiti Sains Malaysia (USM)
 Source: Google Earth (2023)

line LR 01 is laid out behind the animal facility (L15) and the starting point of survey line LR 03 is laid out at 240 m of LR 01, extended behind Indah the Kembara student residence (K10). Survey line LR 02 is set up along the tennis court while 75 m of survey line LR 08 intersects at 200 m of LR 02. Survey line LR 04 is laid out along the Tasik Aman. Survey lines LR 05 and LR 06 were set up along the main road near the Bukit Gambier main entrance. Survey lines LR 07 were laid out between Tasik Aman and Tasik Harapan. Table 1 shows the information on field measurement of the electrical resistivity survey of the research area. The Wenner-Schlumberger array was chosen for RL1 and RL3 due to site

constraints in placing the remote electrode within the study area.

Methodology

A resistivity survey exhibits sensitivity to minor changes in resistivity, facilitating the identification of subsurface materials and the mapping of geological features like fractures, faults, and cavities. In the context of groundwater exploration in a granitic setting, the presence of fractures and faults heightens the likelihood of groundwater infiltrating the rock’s pore spaces. Additionally, the porosity of rocks plays a role in determining the degree of water saturation,

Table 1: Information on field measurement

| Survey Line | LR 01 | LR 02 | LR 03 | LR 04 | LR 05 | LR 06 | LR 07 | LR 08 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Survey length (m) | 400 | 200 | 200 | 200 | 390 | 340 | 200 | 400 |
| Electrode Configurations* | WS | PDP | WS | PDP | PDP | PDP | PDP | PDP |
| Estimated depth of data (m) | 70 | 70 | 35 | 70 | 125 | 125 | 70 | 125 |

*Note: pdp = Pole – dipole array, WS = Wenner Schlumberger array.

Table 2: The resistivity values of some types of water

| Types of Water | Resistivity |
|--|-------------|
| Precipitation | 30 – 1000 |
| Surface water, in areas of igneous rock | 30 – 500 |
| Surface water, in areas of sedimentary rock | 10 – 100 |
| Groundwater, in areas of igneous rock | 30 – 150 |
| Groundwater, in areas of sedimentary rock | > 1 |
| Seawater | ≈ 0.2 |
| Drinking water (max. salt content 0.25%) | > 1.8 |
| Water for irrigation and stock watering (max. sat content 0.25%) | > 0.65 |

Source: Keller and Frischknecht (1996)

thereby impacting the resistivity values for certain water types, as illustrated in Table 2 (Keller & Frischknecht, 1996).

The resistivity survey employs a measurement principle, where a controlled current is transmitted between two electrodes inserted into the ground while simultaneously measuring the potential between two other electrodes (ABEM, 2018). The calculation of resistance (R) is determined using Ohm’s Law, as expressed in Equation 1:

$$R = \frac{V}{I} \tag{1}$$

where:

R = Resistance, Ohm

V = Electric Potential, Volts

I = Current, Ampere

The equipment utilised in this survey includes an automated multi-electrode resistivity meter, the ABEM Terrameter SAS400 system, Electrode Selector (ES10-64C), Lund multicore

cables, stainless steel electrodes, and a jumper, as depicted in Figure 4. For data acquisition, two or four multicore cables with 21 take-outs each, along with stainless-steel electrodes, are interconnected using jumpers and then linked to the Terrameter SAS4000 system (ABEM, 2018). The length of the survey line varies according to the target data depth required and the accessibility of the area. At the same time, the electrodes are set up at constant intervals along each survey line. The resistivity array influences the data resolution, sensitivity to lateral and vertical changes, and the depth of data penetration. In this survey, the pole-dipole array was chosen for its effective vertical data coverage, whereas the Wenner-Schlumberger array exhibits moderate sensitivity to both vertical and lateral structures (Lowrie, 2007).

A measuring tape was used to set the electrode spacing of each survey line and then the resistivity cable was laid on the survey line. Then, both resistivity cables were connected to

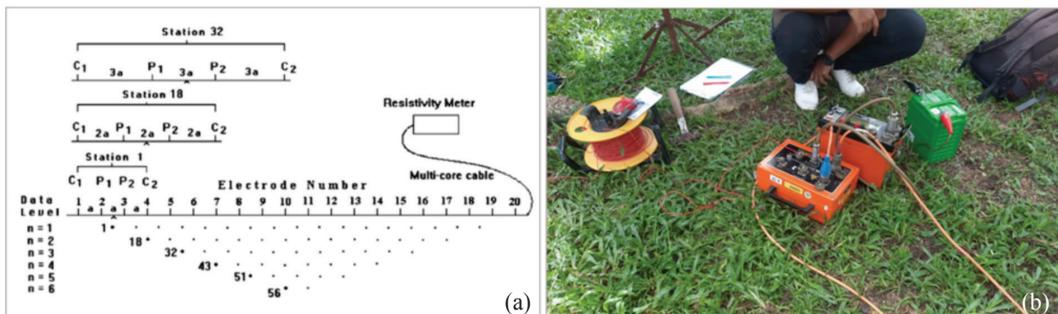


Figure 4: (a) shows the principle of the resistivity methods while (b) shows the resistivity field set up

an electrode selector which was interconnected with the Terrameter. Furthermore, 41 electrodes were planted into the ground and were connected to the resistivity cable using jumpers. The remote cable was set up far away from the survey line and the array used was Pole-Dipole, which needed C_2 electrode with infinity distance. The settings were fixed in the ABEM SAS4000 and when the other equipment had been set up correctly, the minimum and maximum outputs were 1 mA and 100 mA, respectively. Table 3 shows ABEM SAS4000 Terrameter data acquisition setting.

The Terrameter SAS4000 is connected to a compatible computer for the retrieval of recorded resistivity data. The obtained data was stored in a binary format with the file extension (.s4k) and was subsequently converted to a readable data format (.dat) for further processing. The data retrieved includes details such as survey name, electrode spacing, electrode array employed, total number of measured data, and the type of resistivity measurement. Each resistivity data files also contained information on electrode location, electrode spacing, and apparent resistivity (ρ_a) values for each measurement.

The resistivity data were subjected to an inversion process using RES2DINV software to generate the electrical resistivity pseudo section (Loke, 1999). The accuracy of the inversion outcome was directly related to the quality of the measured resistivity data, as indicated by the Root Mean Square (RMS error) in the inverted

resistivity models. This error is determined by calculating the residuals between the measured and computed apparent resistivity values (Sudha *et al.*, 2009).

Results and Discussion

An aquifer is characterised as a geological formation consisting of either rock or weathered material with ample permeability to enable the passage of water. Weathered materials such as gravel, sand, and even silt is generally considered effective aquifers. Additionally, well-fractured rocks have the potential to serve as competent aquifers. There are four existing boreholes available in USM. However, the position of this borehole is far from the survey line conducted. The borehole data revealed that there are three major subsurface formations consisting of clay, silty sand, and granitic bedrock as mentioned in Figure 5. The shallower granitic bedrock is recorded at BH04 with a depth of 7.5 m. The other average depth of the granitic top is 30 m. Table 4 summarises the subsurface formations encountered in the boreholes.

Fractures play a crucial role in determining the permeability of bedrock aquifers. It also showed a correlation between RQD and fractures. High RQD (between 75% and 100%) indicates rock with few fractures or closely spaced joints. Limited permeability makes the rock a poor aquifer unless significant secondary porosity (e.g., dissolution features)

Table 3: ABEM SAS4000 terrameter data acquisition setting

| Function | Setting | Value |
|----------------------|---------|---------|
| Current | Maximum | 100 mA |
| | Minimum | 1 mA |
| Mode | Auto | - |
| Acquisition delay | - | 0.3 sec |
| Acquisition time | - | 0.3 sec |
| Total cycle time | - | 3 sec |
| Stack | Maximum | 3 |
| | Minimum | 1 |
| Power line frequency | - | 50 Hz |



Figure 5: Summary of borehole records at USM

Table 4: The subsurface formations encountered in the boreholes

| Borehole No. | Depth of Borehole (m) | Top of Granitic Bedrock (m) |
|--------------|-----------------------|-----------------------------|
| BH 01 | 37.5 | 31.5 |
| BH 02 | 33.0 | 31.5 |
| BH 03 | 37.5 | 34.5 |
| BH 04 | 10.5 | 7.5 |

is present. Moderate RQD (between 50% and 75%) suggests moderately fractured rock. Fractures may provide pathways for water flow, creating a fair to good aquifer depending on the extent of interconnection. Low RQD (< 50%) represents highly fractured or crushed rock. High permeability due to abundant fractures, but the rock may also exhibit instability. The rock is also likely to act as a good aquifer if the fractures are interconnected and not filled with clay or other impermeable materials (Adrew & Cohen, 1995; Alhadar & Rachmansyah, 2021; Hasan *et al.*, 2022). Rocks such as granite and schist are generally poor aquifers because they have a very low porosity. However, if these rocks are highly fractured, they would make

good aquifers (Anuar, 2017; Razak & Muztaza, 2022).

Following the resistivity inversion profiles, the subsurface materials in the research area are categorised into four classes based on their resistivity value ranges. A low resistivity value is construed as water-saturated zones, with resistivity values ranging between 1 Ωm and 300 Ωm while a low to intermediate resistivity value is interpreted as a weathered material with resistivity values ranging between 301 Ωm and 1,000 Ωm (Keller & Frischknecht, 1996). Intermediate to high resistivity values are indicative of weathered bedrock, with resistivity values ranging between 1,001 Ωm

Table 5: Summarise subsurface materials according to their respective resistivity values range

| Resistivity Value (Ωm) | Subsurface Materials |
|--|-------------------------|
| 1 – 300 | Water saturated zone |
| 301 – 1,000 | Weathered material |
| 1,001 – 4,500 | Weathered granitic rock |
| > 5,000 | Fresh granitic bedrock |

and 4,500 Ωm , whereas fresh granitic bedrock is identified by resistivity values exceeding 5,000 Ωm (Azman *et al.*, 2017). Table 5 provides a summary of the classification of subsurface materials in the research area.

Figure 6 shows the resistivity profile of survey lines LR 03 and LR 06, respectively. The upper part of the resistivity inversion profile of survey line LR 03 Figure 6 (a) exhibits a low resistivity value zone (less than 300 Ωm) interpreted as a saturated zone until the depth of 15 m.

This is weathered material with resistivity value between 301 and 1,000 Ωm at LR03. Weathered material is a sediment characterised by loose or unstratified arrangement, with particles that are not cemented together can be found either at the surface or at various depths (Streckeisen, 1967; Loke, 1999; Yunus *et al.*, 2023). By comparing with the nearest borehole records (BH04), the soil formation consists of interbedded sandy silt, silty sand, and sand until the depth of 15 m which corresponded in line with the inversion profile.

Both silty sand and sand are types of sediments that can influence the potential for groundwater. Silty sand typically has moderate to high porosity, allowing it to hold a significant amount of water. Silty soil has medium-sized particles, providing better water retention than sandy soils. They have moderate water-holding capacity and drainage characteristics. The fine particles in silty sand create spaces between them, contributing to porosity. Sand is known for its high porosity due to its coarse nature. The larger particles in sand create larger pore spaces, allowing for greater water storage (Anuar, 2017). Silty sand and sand are known

for having a high permeability. The larger pore spaces between sand particles allow water to flow between them more freely, increase the rate of water movement and have higher infiltration rates than fine textured soils, making it easier for groundwater to move through (Brears, 2017).

The sharp contrast of round structural features exhibits a high resistivity value of more than 5,000 Ωm is interpreted as fresh granitic bedrock. This zone is located between 55 m and 85 m and between 110 m and 160 m, with a depth ranging from between 10 m and 15 m. However, there is a lateral variation in resistivity, probably due to a fault. Fresh rock (unfractured) has higher resistivity while fractured rock has lower resistivity. The higher the degree of fracturing, the lower the resistivity value. The potential fault zone is located at between 85 m and 115 m and extends to a depth of 100 m. The intrusive bodies or fractured zone has low-resistivity value compared to the surrounding as a result of being a channel for water to infiltrate from the surface. Moreover, the precipitation from the surface seeps into the subsurface through the fracture zone as the it has high solubility (Engfer & Rongstad, 1991; Saad *et al.*, 2012) that can lead to more fractures and creates interstices for water flow.

The inversion profile of survey line LR 06 [Figure 6 (b)] exhibits similar features to the inversion profile of survey line LR 03. The upper part predominantly consists of an unconsolidated layer extended to 25 m. This inversion profile also shows a similar sharp structural high resistivity zone with undulating depth from 10 m to 25 m. The head rock of fresh granitic bedrock is located at a distance of between 45 m and 220 m and between 270 m and 340 m. The low

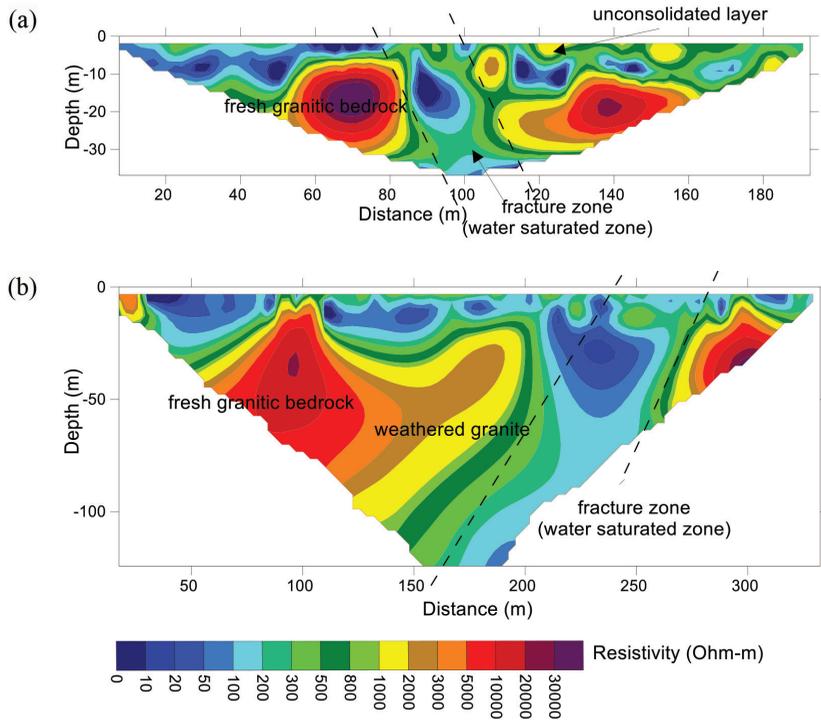


Figure 6: Interpreted electrical resistivity profiles of (a) Survey Line LR 03 and (b) Survey Line LR 06

resistivity value zone, interpreted as a fault zone, is located from 200 m to 270 m, and extends to 100 m. Features facilitating fluid flow such as faults and lithologies with higher porosity are identified by low-resistivity anomalies (Kumar, 2012; Ammar & Kamal, 2018).

Figure 7 (a) shows the low to intermediate resistivity value layer along the survey line of LR 02, interpreted as an unconsolidated layer extended to a depth of 10 m. Gravel, sand, and silt are categorised as weathered materials due to their loose, unbounded nature, and varying particle sizes. These materials can be easily transported by natural forces such as wind, water, and gravity. They generally have high permeability, allowing water and other fluids to pass through relatively easily, though the degree of permeability varies with particle size.

The underlain layer is an intermediate to high resistivity value that oscillates between 1,001 Ωm and 4,500 Ωm representing the weathered granitic layer. Between 120 m and 170 m, a high resistivity zone is interpreted as fresh granitic

bedrock. Next, a low resistivity value zone (less than 300 Ωm) is extended along this survey line, which is interpreted as being a water-saturated zone. These are geological formations within the saturated zone that can store and transmit significant quantities of groundwater. This is due to the area being typically composed of materials like gravel, sand, and fractured rock, which have high permeability as shown in Figure 5. The underlain layer shows the increasing resistivity value representing the fresh granitic bedrock.

Figure 7 (b) shows the resistivity inversion profile of survey line LR 05, which shows a similar pattern of resistivity value distribution as survey line LR 02. The upper layer exhibits heterogeneity, displaying a notable variation of the subsurface material with a resistivity value of less than 300 Ωm . The underlain layer is interpreted as being composed of fresh granitic bedrock with resistivity value oscillate starting from 5,000 Ωm onwards. The large low resistivity value zone is located from 110 m to 250 m, interpreted as a water-saturated zone.

Figure 7 (c) shows the inversion profile of survey line LR 08. This profile illustrates a gradual rise in resistivity values as depth increases. Low resistivity water-saturated zones with a value less than 300 Ωm are found at shallower depths of between 25 m and 175 m. The underlain layer is a high resistivity value zone interpreted as a fresh granitic bedrock. The fresh granitic bedrock has an undulating depth of 50 m and extends to 125 m.

the resistivity value gradually increasing with depth. The upper layer of resistivity profiles of survey line LR 01 is a weathered material with a resistivity value of between 300 Ωm and 1,000 Ωm from the surface until a depth of 20 m. By comparing the nearest borehole log (BH01), the type of soil formation consists of an alternating layer of sandy silt and sandy sand until the depth of 31.5 m, and the top of granitic bedrock is found from a depth of 31.5 m. Silty sand typically exhibits moderate to high porosity, enabling it to retain a substantial

Figure 8 (a) shows the resistivity inversion profile of survey line LR 01. The results show

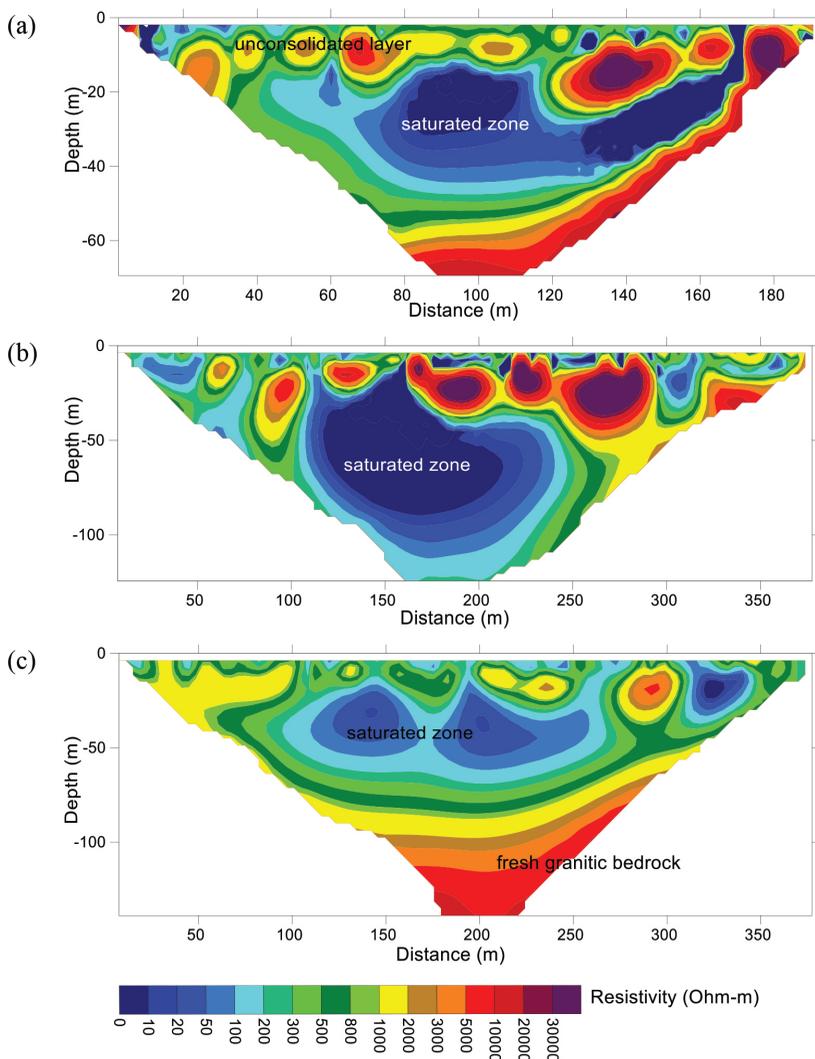


Figure 7: Interpreted electrical resistivity profiles of (a) Survey Line LR 02, (b) Survey Line LR 05, and (c) Survey Line LR 08

amount of water. The fine particles in silty sand create interstitial spaces, thereby enhancing its porosity. Sand is renowned for its high porosity owing to its coarse texture. The borehole record parallels the inversion profile, where the high resistivity value (5,000 Ωm) is fresh granitic bedrock. There is no indication of the fractured zone that can be determined from the profile, indicating no potential for a groundwater aquifer in this area.

Survey line LR 04 resistivity value ranging between 1 Ωm and 300 Ωm is the saturated zone [Figure 8 (b)]. The range of the saturated zone corresponds to areas where the subsurface materials are saturated with water. In the given lithological setting, the weathered layer might

include silty sand, sand, and gravel layers that are below the water table or in regions with high groundwater presence with resistivity value of 301 Ωm -1,000 Ωm. The high resistivity value observed along the survey line exhibits a distinct structure resembling a granitic rock intrusion. However, the continuation of the low resistivity zone at a depth of 70 metres, extending from a point 100 metres away from the survey line, could not be determined due to the limited depth of the available data. Survey line LR 07 [Figure 8 (c)] shows a similar resistivity profile to survey line LR 04. The upper layer of the profile is dominated by a low resistivity value zone (less than 300 Ωm). Granitic bodies with high resistivity extend along the survey line.

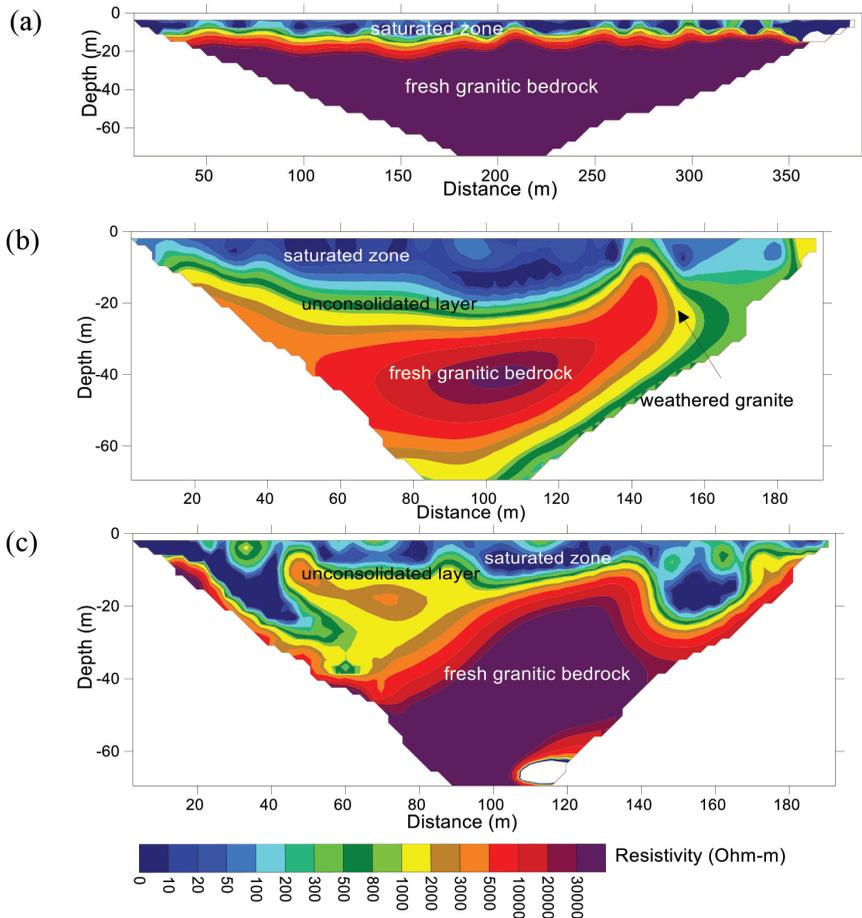


Figure 8: Interpreted electrical resistivity profiles of (a) Survey Line LR 01, (b) Survey Line LR 04, and (c) Survey Line LR 07

Resistivity data is an essential tool for geophysical surveys, providing insights into the subsurface materials based on their ability to conduct electrical current. Different materials exhibit distinct resistivity values, which can be correlated to their lithological characteristics. Table 6 shows a detailed analysis of the resistivity data in relation to the lithological setting of the site.

Water saturated zone 1 Ωm - 300 Ωm indicates zones with high water content, typically less than 20 metres deep. Such areas are prime targets for groundwater extraction due to the presence of saturated, porous materials that can store and transmit significant amounts of water. The unconsolidated layer with resistivity value of between 301 Ωm and 1,000 Ωm consist of silty sand, sand, and gravel. These materials, though not fully saturated, still have significant porosity and permeability, which can contribute to groundwater storage. They are important for recharge areas and can act as secondary

aquifers. Fractures at the study area may create pathways for water to move through otherwise impermeable granitic rock. The degree of connectivity between fractures influences the groundwater flow. Highly connected fractures form extensive networks that can significantly enhance groundwater movement and storage.

Conclusions

The application of 2-D electrical resistivity methods has proven successful in evaluating subsurface features and delineating groundwater potential zones within a granitic hard rock formation at USM. Based on the resistivity profiles, it can be inferred that the subsurface materials comprise unconsolidated layers, water-saturated zones, weathered granitic bedrock, and fresh granitic bedrock.

From the cross plot of resistivity profiles of survey lines LR 03 and LR 06 (Figure 9), there is an extension of the fracture feature with

Table 6: Resistivity values to infer the distribution and extent of different lithological units

| Resistivity Value (Ωm) | Subsurface Materials | Lithological Units |
|--|-------------------------|--|
| 1 – 300 | Water saturated zone | This range corresponds to areas where the subsurface materials are saturated with water at depth less than 20 m. In the given lithological setting, this might include silty sand, sand, and gravel layers that are below the water table or in regions with high groundwater presence. |
| 301 – 1,000 | Weathered layer | Unconsolidated materials such as silty sand, sand, and gravel that are above the water table or have partial saturation (up to 30 m). These layers are porous and can hold varying amounts of water, affecting its resistivity. |
| 1,001 – 4,500 | Weathered granitic rock | Original granite has undergone a weathering process, creating a layer that is more fractured and less dense than fresh granite. This weathered layer still retains some degree of resistivity due to its mineral composition. Fractures in granitic rock significantly enhance the rock’s ability to store and transmit groundwater. |
| > 5,000 | Fresh granitic bedrock | The most resistive material in the lithological setting varies at 7 m to 30 m depth. Granite is a hard, crystalline rock with very low porosity and permeability, resulting in high resistivity readings, signifying intact and unaltered bedrock. |

the northwest-southeast direction. Fractures in granitic bedrock facilitate water accumulation, turning the saturated zone into a potential groundwater aquifer. The potential for extending the aquifer to depths exceeding 125 metres can be assessed for future deeper groundwater exploration. This fracture zone is recommended as a potential location for drilling groundwater exploration. Figure 10 shows the cross plot of resistivity profiles of survey lines LR 02, LR 05, and LR 08. They are the continuation of water water-containing zones between the profiles. These zones are proposed as a suitable potential location for drilling location for groundwater exploration.

USM is situated near the boundary of two types of igneous rocks with a coarse grain size, indicative of greater porosity. This increased porosity facilitates water seepage during precipitation. Furthermore, the area exhibits at least two sets of fractured/fault systems. These characteristics suggest a promising potential for groundwater exploration in this location. This paper addresses the potential groundwater to be explore at USM and serves as preliminary

guidance for identifying suitable locations for groundwater exploration. This result may contribute to the development of a one-stop centre for hardrock groundwater resources and the establishment of guidelines for the development and management of hardrock groundwater resources in the granitic region of Malaysia.

Acknowledgements

The authors express their gratitude to the technical staff of the Geophysics Laboratory and postgraduate students at the School of Physics, Universiti Sains Malaysia for their valuable assistance during the data acquisition process. They would like to acknowledge the Ministry of Higher Education Malaysia through the Fundamental Research Grant Scheme with Project Code: FRGS/1/2022/STG08/USM/03/1 entitles “Performance-Based Multimodal Geophysical Design for Soil Dynamic Properties to Improve Visualisation of Subsurface Conditions”. The authors would like to extend their thanks to Global GeoExperts

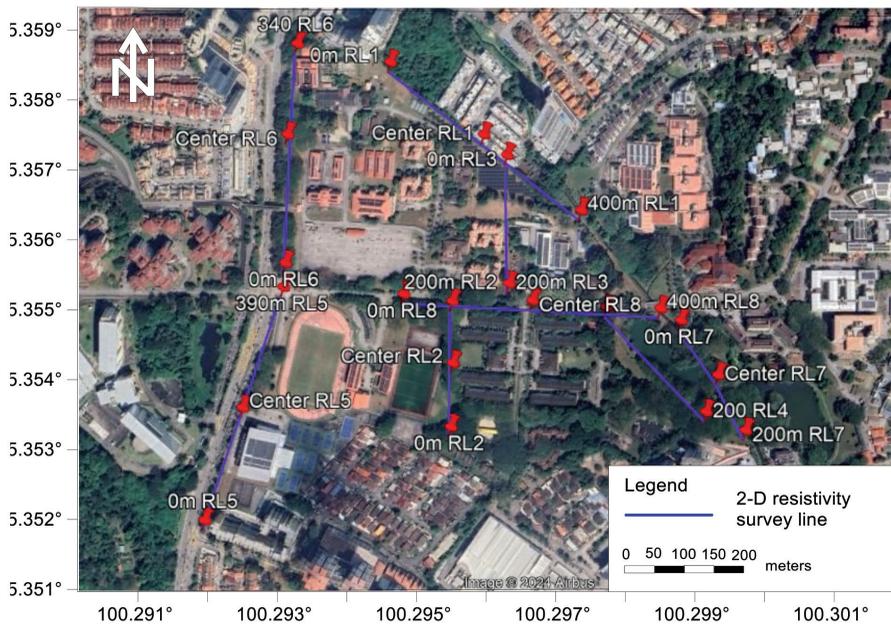


Figure 9: From the correlation of inversion profiles of survey lines LR 03 and LR 06, there is a linear structural possible fault structure with a direction of northwest-southeast

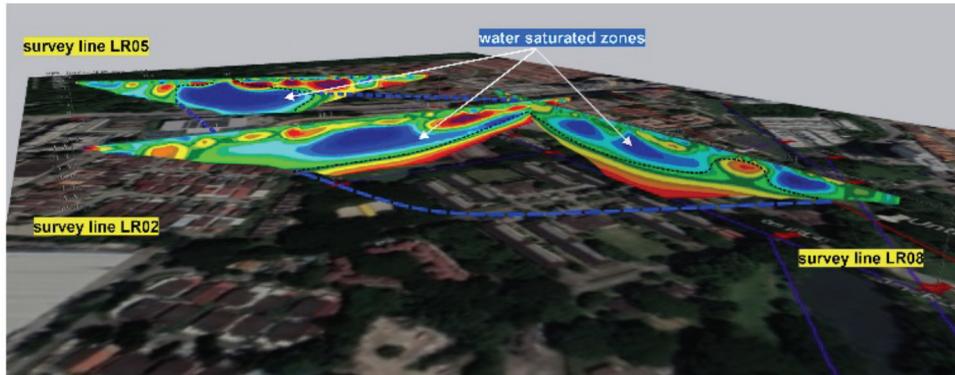


Figure 10: The continuation of water-saturated zones can be determined for the cross plot of inversion profiles of survey lines LR 02, LR 05, and LR 08

Sdn. Bhd. for awarding the tidustry grant titled “Groundwater Exploration Using Electrical and Induce Polarisation Methods” under account number R504-LR-GAL007-0000000266-G121.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

- Ahmad, F., Yahaya, A. S., & Farooqi, M. A. (2006). Characterisation and geotechnical properties of Penang residual soils with emphasis on landslides. *American Journal of Environmental Sciences*, 2(4), 121-128. <https://doi.org/10.3844/ajessp.2006.121.128>
- Alhadar, H., Rachmansyah, A., & Suryo, E. A. (2021). Rock Slope Stability of Ponorogo - Pacitan Road Km 232.5 using Rock Mass Rating (RMR) and RocPlane software. *Rekayasa Sipil*, 15(3), 199-207. <https://doi.org/10.21776/ub.rekayasasipil.2021.015.03.6>
- Ammar, A. I., & Kamal, K. A. (2018). Resistivity method contribution in determining of fault zone and hydro-geophysical characteristics of carbonate aquifer, eastern desert, Egypt. *Applied Water Science*, 8(1), Article 1. <https://doi.org/10.1007/s13201-017-0639-9>
- Andrew, J. B., Cohen. (1995). *Hydrogeologic characterisation of fractured rock formations: A guide for groundwater remediators*. Earth Sciences Division, Ernest Orlando Lawrence, Berkeley, National Laboratory University of California Berkeley, CA 94720. <https://doi.org/10.2172/219408>
- Anuar, U. M. (2017). Aquifer delineation and classification using 2-D resistivity in various geological formation (Master’s dissertation, Universiti Sains Malaysia).
- Anuar, U. M., & Muztaza, N. M. (2018). Aquifer detection using 2-D resistivity method and porosity calculation. *Jurnal Teknologi (Sciences & Engineering)*, 80(6), 149-158.
- Azizan, F. A., Aznan, A. A., Ruslan, R., Nazari, M., & Jaafar, M. N. (2018). Groundwater assessment using geophysical survey at Insat, Perlis, Malaysia. *IOP Conference Series: Materials Science and Engineering*, 429(1), 012026. <https://doi.org/10.1088/1757-899X/429/1/012026>
- Azman, M. I. M. F., Yusof, A. H. M., Ismail, N. A., and Ismail, N. E. H. (2017). Slope monitoring by using the 2-D resistivity method at Sungai Batu, Pulau Pinang, Malaysia. *AIP Conference Proceedings*, <https://doi.org/10.1063/1.4990910>.

- Brears, R. C. (2017). *Urban Water Security: Challenges in Water Management*, John Wiley and Sons, Ltd. United Kingdom, ISBN: 9781119131724.
- Burger, H. R. (1992). *Exploration geophysics of the shallow subsurface*, Prentice Hall P T R, 60-75, Upper Saddle River, New Jersey 07458.
- Earle, S. (2006). *Hydrogeology*. Malaspina University College. Chapter 1, 1-1, Vancouver, British Columbia, Canada.
- Engfer, J. P., and Rongstad, J. M. (1991). *Aquifer characteristics of sedimentary rock types, Jackson County Geologic Atlas*, Water Resources Centre, Mankato State University, 4-5.
- Geological map of Peninsular Malaysia, based on 8th edition geological map, 1985, Minerals and Geoscience Department, Malaysia.
- Google Earth, 2023.
- Hasan, M., Shang, Y., Shao, P., Yi, X., and Meng, H. (2022). Geophysical Research on Rock Mass Quality Evaluation for Infrastructure Design, *Earth and Space Science*, 9, e2021EA002017, <https://doi.org/10.1029/2021EA00>
- Hassan, K. (1990). A summary of the Quaternary geology investigations in Seberang Prai, Pulau Pinang, and Kuala Kurau, *Bull. Geolog. Soc. Malaysia*, 47-53.
- Instruction Manual Terrameter SAS 1000/40000. 2018. ABEM Instrument AB.
- International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(4/W16), 711-718. <https://doi.org/10.5194/isprs-archives-XLII-4-W16-711-2019>
- Keller G. V., and Frischknecht, F. C. (1996). *Electrical methods in geophysical prospecting*, Pergamon Press Inc., Oxford.
- Kumar, D. (2012). Efficacy of electrical resistivity tomography technique in mapping shallow subsurface anomaly, *Journal of the Geological Society of India*, 80(3), 304-307.
- Kura, N. U., Ramli, M. F., Sulaiman, W. N. A., Ibrahim, S., and Aris, A. Z. (2018). An overview of groundwater chemistry studies in Malaysia, *Environmental Science and Pollution Research*, 25, 7231-7249.
- Loke, M. H. (1997). The inversion of two-dimensional resistivity data. Unpubl. PhD thesis, University of Birmingham.
- Loke, M. H. (1999). *Electrical Imaging Surveys for Environmental and Engineering Studies*, ABEM, Geometric, 3-4.
- Loke, M. H. (2000). *Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys*. ABEM, Geometric.
- Lowrie, W. (2007). *Fundamentals of Geophysics*. Published.
- Manap, M. A., Sulaiman, W. N. A., Ramli, M. F., Pradhan, B., and Surip, N. (2013). A knowledge-driven GIS modeling technique for groundwater potential mapping at the Upper Langat Basin, Malaysia, *Arabian Journal of Geoscience*, 6, 1621-1637.
- Musa, K. A., Akhir, J. M., and Abdullah, I. (2000). Groundwater prediction potential zone in Langat basin using the integration of Remote Sensing and GIS, *Geospatial World*. <https://www.geospatialworld.net/article/groundwaterprediction-potential-zone-in-langat-basin-using-the-integration-of-remotesensing-and-gis/>
- Muztaza, N. M., and Ismail, N. I. (2020). *2-D Resistivity and Characterisation of Shallow Aquifers in Tropical Peninsular Malaysia*, Penerbit Universiti Sains Malaysia, e-ISBN: 978-967-461-461-4.
- Perbadanan Bekalan Air Pulau Pinang (PBAPP), 2021, <https://pba.com.my/>
- Petrack, N., Jubidi, M. F., and Ahmad Abir, I., (2023). Groundwater Potential Assessment of Penang Island, Malaysia, Through Integration of Remote Sensing and GIS

- with Validation by 2D ERT, *Natural Resources Research*, 32, 523-541. <https://doi.org/10.1007/s11053-023-10164-w>
- Ranhill Consulting Sdn. Bhd. (2011). Review of the national water resources (2000–2050) and formulation of national water resources policy, vol. 9: Pulau Pinang. [https://www.water.gov.my/jps/resources/PDF/Hydrology%20Publication/Vol9Pulau Pinang.pdf](https://www.water.gov.my/jps/resources/PDF/Hydrology%20Publication/Vol9Pulau%20Pinang.pdf)
- Razak, M. H., and Muztaza, N. M. (2022). Evaluation of Aquifer Potential Using 2-D Resistivity and Induced Polarisation in Machang, Kelantan, Malaysia, *Journal of Sustainability Science and Management*, 17(1), 259-270.
- Riwayat, A. I., Ahmad Nazri, M. A., and Zainal Abidin, M. H. (2018). Detection of Potential Shallow Aquifer Using Electrical Resistivity Imaging (ERI) at UTHM Campus, Johor Malaysia, *Journal of Physics: Conference Series*, 995(1), <https://doi.org/10.1088/1742-6596/995/1/012103>
- Saad, R., Nordin, M. N. M., and Mohamad, E. T. (2012). Groundwater Detection in Alluvium Using 2-D Electrical Resistivity Tomography (ERT), *Electronic Journal of Geotechnical Engineering*, 17(Bund D), 369-376.
- Society of the Exploration Geophysicist of Japan. (2014). Application Manual of Geophysical Methods to Engineering and Environmental Problems, EAGE.
- Streckeisen, A. L. (1967). Classification and nomenclature of igneous rocks, *Neues Jahrbuch für Mineralogie Abhandlungen*, 107, 144-240.
- Sudha, K., Israil, M., Mittal, S., and Rai, J. (2009). Soil characterisation using electrical resistivity tomography and geotechnical investigations, *Journal of Applied Geophysics*, 67, 74-79.
- Surip, N., Musa, K. A., and Abidin, A. R. Z. (2009). GIS-based weightage overlay for groundwater potential study in Perak, Malaysia, [Paper presentation], Geosea 2009, Eleventh Regional Congress on Geology, Kuala Lumpur, Malaysia.
- Tjia, H. D. (1971). Lineament pattern on Penang Island, West Malaysia, *Journal of Tropical Geography*, 32, 56-61.
- Yahaya, A. N., Issa, A. K., Yusof, K. W., and Arof, Z. A. (2007). *Exploration of groundwater by integrated modeling using remote sensing and geographical information System in Kedah and Perlis, Pilot study and data Analysis*, Map Asia, Kuala Lumpur.
- Yunus, N., Muztaza, N. M., Abir, I. A., Bashir, Y., and Zakaria, M.T. (2023). Delineation of Groundwater Potential Zones Using 2-Dimensional Electrical Resistivity Imaging at Universiti Sains Malaysia, Penang, Malaysia, *Indian Journal of Power and River Valley Development*, 73(3&4), 71-76.
- Zamari, M. A., Musa, T. A., Mohamad, E. T., Musliman, I. A., and Aris, W. A. W. (2019). Geospatial Approach for Groundwater Exploration at UTM Johor Bahru Campus.
- Zeinab, A., Samsudin, A., Yaacob, W. Z., and Yaakub, J. (2015). Groundwater Exploration Using 2-D Geoelectrical Resistivity Imaging Technique at Sungai. Udang, Melaka, *Journal of Earth Science and Engineering*, 2, 634-630.