Groundwater Exploration through 2D Electrical Resistivity Tomography in the Labi Agricultural Site, Belait District, Brunei Darussalam

Siti Lieyana Azffri[1,3]*, Aziz Soffre Ali Ahmad[2], Mohammad Faizan Ibrahim[2], Amalina Abdul Khalid[3], James Jasmir Murphy[3], Stefan Herwig Gödeke[1]

[1]Universiti Brunei Darussalam, Bandar Seri Begawan, Brunei Darussalam
[2]Department of Agriculture and Agrifood, Bandar Seri Begawan, Brunei Darussalam
[3]Preston GeoCEM (B) Sdn Bhd, Bandar Seri Begawan, Brunei Darussalam
*Corresponding Author: lieyana.azffri@gmail.com

Abstract

Over the years, Brunei has relied on surface water as the primary water source for domestic, industrial and agricultural use. Increasing demands for irrigation water supply in its growing agriculture sector, has led to groundwater exploration at the Labi agricultural site driven by the Brunei Government. Electrical Resistivity Tomography (ERT) has been used extensively to delineate subsurface structures, formations and groundwater prospect zones. The technique was employed for the study area using the pole-dipole array configuration with a survey line of 300 m and a target investigation depth of 100 m from the surface. The 2D inverted resistivity model revealed a groundwater zone at depths of about 10 to 40 m from the surface with resistivity values ranging from 5 to 100 ohm-m. A borehole was drilled through this zone to a maximum depth of 80 m from the surface. The borehole drilling encountered multiple saturated layers of sand and sandstone between depths of 4 to 78 m. A pumping test showed the groundwater was able to be produced at a steady rate of 288 m³/day. The aquifer transmissivity estimated using the unsteady Cooper Jacob analysis was 109 m²/day, indicating moderate potential for groundwater usage in the study area for irrigation purposes. The resistivity survey, combined with borehole drilling and testing, provided insights into the groundwater hydrology at the Labi agricultural site. The present study helped decision-makers take suitable measures to place future irrigation wells and achieve significant groundwater exploration results in the study area and other regions with similar geological settings.

1. Introduction

Brunei Darussalam, or simply known as Brunei, is located on the north coast of Borneo Island in Southeast Asia. The country has a total land area of 5,765 km² with an estimated population of about 430,000 in 2021 (DEPS, 2021). Brunei is divided into four main districts: Brunei-Muara, Tutong, Belait and Temburong. The location map of Brunei and the study area are shown in Fig. 1.

The majority of the water supply in Brunei comes from surface water resources. Surface water accounts for 99.5 per cent of the total water supply used for domestic, industrial and agricultural, while the remaining 0.5 per cent comes from groundwater resources. Groundwater abstraction is currently limited to the local bottled water industry found in the Liang area (FAO, 2011).

Brunei is relatively unexplored with regard to its groundwater resources. Most recently, a study in Brunei investigated the shallow coastal aquifer in the Berakas area, Brunei-Muara District (Azhar, Abdul Latiff, Lim & Gödeke, 2019). Using velocity profiles and seismic tomography produced by the seismic refraction method, the study was able to delineate the subsurface stratigraphic layers and groundwater levels, and evaluate the local groundwater flow system.

The Brunei Government emphasises on developing agriculture and agri-food to ensure food supply security and enhance economic contribution to its GDP. However, Brunei's

Department of Agriculture and Agrifood identified the lack of irrigation water supply, especially during the dry seasons, as one of the obstacles faced by many of its farmers. The use of groundwater for irrigation purposes in Brunei has not been investigated before.

This study conducted groundwater exploration through geoelectrical resistivity at the Labi agricultural site, Belait District, Brunei, for irrigation purposes. The electrical resistivity tomography method (e.g., Ashraf, Yusoh & Abidin 2018; Riwayat, Ahmad Nazri & Zainul, 2018; Kumar, Rajesh, Mondal, Warsi & Rangarajan, 2020) was first employed to investigate the subsurface lithological formations, geological structures and resistivity variations in the study area. The 2D resistivity inversion model will delineate groundwater zones and locate a suitable site for borehole drilling. Resistivity data will be correlated with borehole lithology information. In addition, groundwater pumping tests will be conducted to provide estimates of the aquifer characteristics.

2. Study Area

The study area's climate is typical of the equatorial tropics characterised by high rainfall and temperatures throughout the year, with total average annual precipitation of 2909 mm. There are two periods of rainy season i.e., from October to January and May to July. Two periods of dry season are from February to March and June to August (BDMD, 2021).

The Labi agricultural site is about 30 km inland from Seria town in Kampong Rampayoh, Mukim Labi, Belait District. The site has two separate lots, Lot A and Lot B. Groundwater exploration was conducted at Lot A, which covers about 45 ha of cultivable land. The site is generally flat, with no significant outcrops and geological features seen on the surface. Topographical elevation of the site ranges from 7 to 30 m above mean sea level. Drainage systems are controlled by the Rampayoh river which flows from east--southeast to west-northwest directions of the study area (Fig. 1).

Previous soil studies conducted at the site by Brunei's Department of Agriculture and Agrifood revealed soils consisting of peat, clay, and silty clay up to 15 m below the ground surface (DAA, 2018). No further information on the deeper geological strata was available.

3. Regional Geological Setting

The geology of Borneo Island is a result of a series of complex regional tectonic events since the Cenozoic era (Hall & Nichols, 2002; Baillie, Darman & Fraser, 2004). According to Baillie et al. (2004), the island's evolution resulted from two major tectonic events; the South China Sea opening and the Australian plate's northward movement. Consequently, overall compressional tectonics have formed deformation zones of mountainous terrain extending through the island's central part. High weathering and erosion rates of the mountainous terrain contributed to development of many known delta systems around the island.

The study area lies within the Champion delta system. This delta developed during the Middle Miocene to Early Pliocene. Rock strata in the area consist of thick sand-shale sequences deposited during the delta development (Torres, Gartrell & Hoggmascal, 2011; Lambiase & Cullen, 2013). Quaternary deposits possibly overlie older bedrocks of the Miri and Lambir Formations in the study area (Fig. 2; Sandal, 1996). The Quaternary deposits are mainly unconsolidated rocks made up of clay, sand, silt and in places overlain by peat (Suhip, Gödeke, Cobb & Sukri, 2020). The underlying Miri Formation is of the Middle to Late Miocene age. The lower part of the formation is argillaceous, while sandstones dominate the upper part. The Lambir Formation of Early to Middle Miocene age consists of sandstone and shale with minor limestone and marl intercalations.

4. Methodology

4.1 Electrical Resistivity Tomography

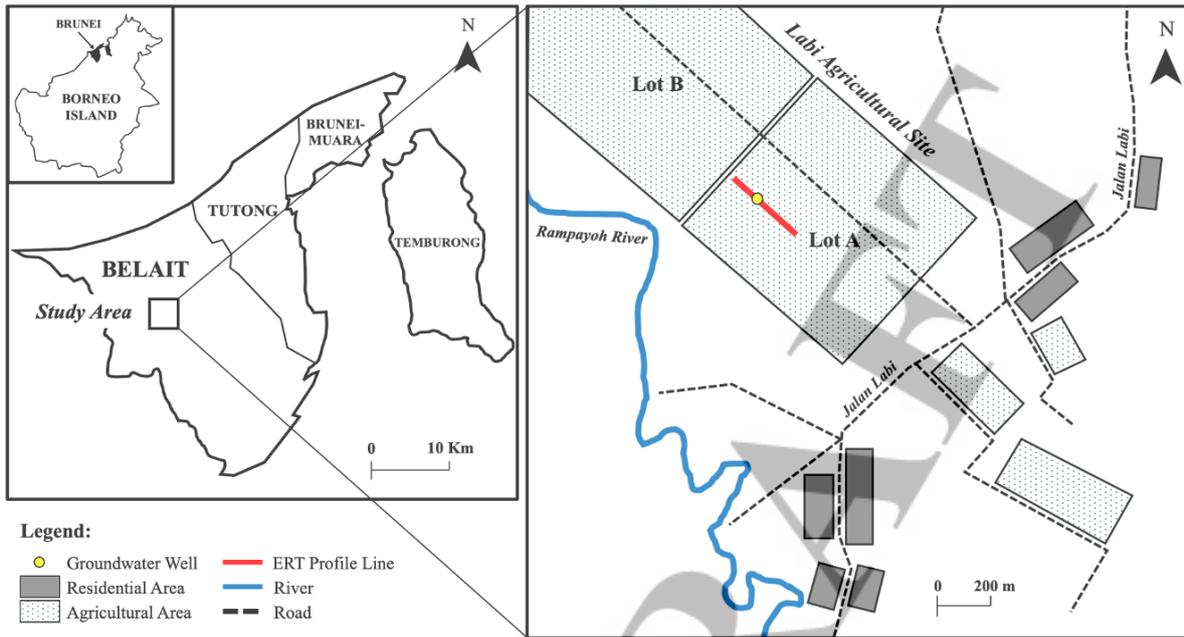Electrical Resistivity Tomography (ERT) is a geophysical survey method widely used to

Fig. 1: Map of Brunei showing the location of the study area, ERT profile line and groundwater well.
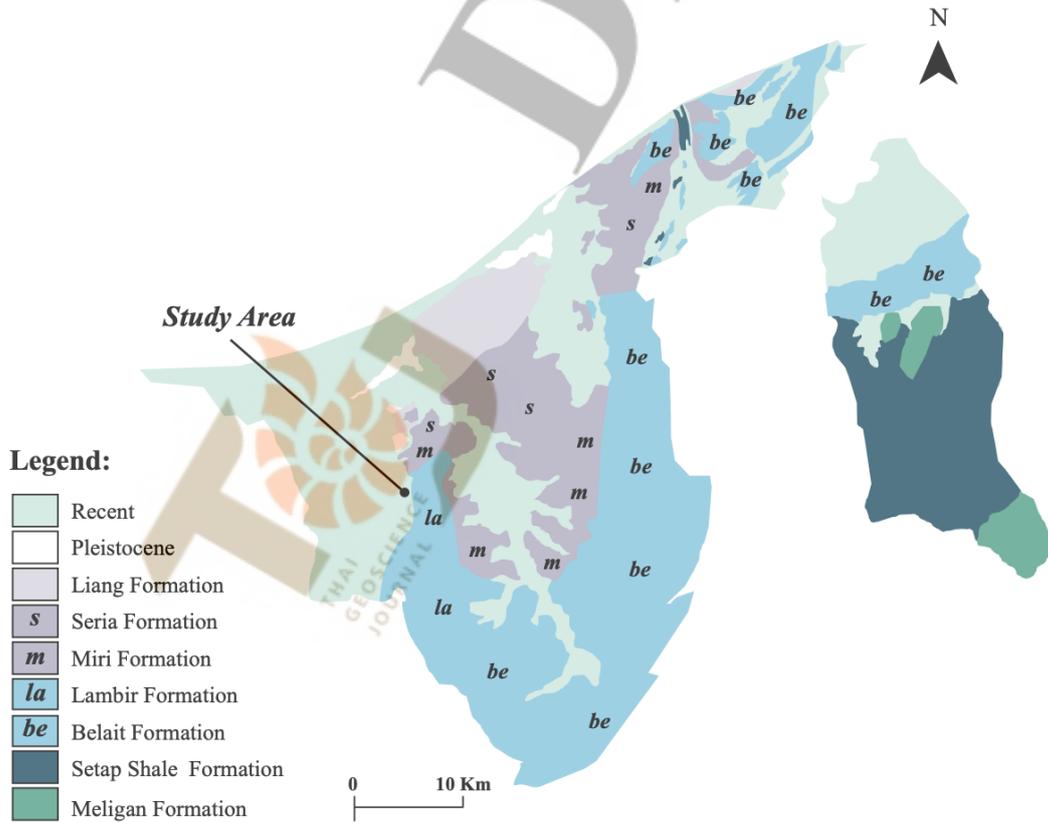

Fig. 2: Geology map of Brunei and the study area (modified after Sandal, 1996).

obtain subsurface information. It is a non--destructive and reliable method typically used for groundwater exploration (Saad, Nawawi & Mohamad, 2012; Annuar & Nordiana, 2018; Ashraf et al., 2018; Aziman, Hazreek, Azhar, Fahmy, Faizal, Sabariah, Ambak & Ismail, 2018; Riwayat et al., 2018; Kumar et al., 2020). Others used this method to solve geotechnical and environmental problems (Sudha, Israil, Mittal & Rai, 2009; Zawawi, Syafalni & Abustan, 2011; Galazoulas, Mertzanides, Petalas & Kargiotis 2015; Lech, Skutnik, Bajda & Markowsk-Lech, 2020).

The electrical resistivity method utilises the differences in electric potential to identify subsurface materials. The measurement of subsurface resistivity is performed by injecting electric current into the ground through two current electrodes (C1 and C2 in Fig. 3) and measuring the resulting voltage difference at two potential electrodes (P1 and P2). From the current (I), voltage difference (V) and a geometric factor (k), the apparent resistivity (ρ_a) is calculated using Eq.1:

$$\rho_a = \frac{kV}{I} \qquad (1)$$

The resistivity survey was carried out in this study by using the ABEM SAS4000 resistivity meter and ABEM ES10-64 multi-electrode system. The resistivity survey line covered a lateral distance of 300 m in the NW-SE direction in the study area. Sixty-one electrodes were deployed along the survey line with an interval ranging between 5 m and 10 m. The configuration of the resistivity survey used was the pole-dipole array (Fig. 3). The pole-dipole array offers a good horizontal data and depth coverage (Saad et al., 2012; Annuar & Nordiana, 2018; Ashraf et al., 2018; Kumar et al., 2020). A total of 1172 data points were acquired during the field survey. Raw data were inverted using the ZONDRES2D software to produce a 2D inverted resistivity model of the subsurface. The Gauss-Newton inversion method was used to determine the appropriate resistivity values. The Root Mean Square (RMS) error and iteration criteria of the resistivity data inversion model are 5%, and 5, respectively.

Resistivity values of some typical rocks, soil materials, saturated zones and water are shown in Table 1 and Table 2 (Keller & Frischknecht, 1996). Furthermore, overlapping resistivity values are dependent on several factors such as porosity, degree of water
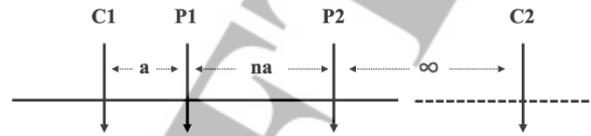

Fig. 3: The arrangement of electrodes for 2D electrical resistivity survey using the Pole-Dipole array configuration; 'a' and 'na' are the distances between the electrodes (Loke, 2012).

saturation and concentration of dissolved salts (Samouëlian, Cousin, Tabbagh, Bruand & Richard, 2005).

4.2 Borehole Drilling and Pumping Test

New borehole drilling accomplished at the study area was based on the interpretation of ERT data. A borehole was drilled using a mud rotary method to a depth of 80 m below the ground surface. The diameter of the drill bit was 10 inches. Materials drilled at the bottom of the borehole mixed with drilling fluid were sampled as they emerged at the top of the hole with a sampling interval of 3 m. 6-inch diameter UPVC casings up to 80 m and slotted screens with 1.5 mm openings were used to construct the groundwater pumping well. The slotted screens were installed at 18 to 28 m and 48 to 78 m depths below the ground surface. A gravel pack filter was installed between the aquifer and UPVC screens. The pumping test was carried out by installing a 1.5 HP submersible pump into the groundwater well at 65 m depth and continuously pumping water out from the well through a 2-inch riser pipe. The well responses in terms of water level change and water discharge rate were recorded. These were measured by using a water level meter installed inside the well and a volume meter connected at the outlet pipe on the surface. A constant rate pumping test was carried out for 24 hours, with an initial water table of 21.4 m and final water table of 22.9 m

Table 1: Resistivity values of common rocks and soil materials (Keller & Frischknecht, 1996).

Material	Resistivity (Ωm)
Alluvium	10 – 800
Sand	60 – 1000
Clay	1 – 100
Groundwater (fresh)	10 – 100
Sandstone	8 – 4,000
Shale	20 – 2,000
Limestone	5,000 – 1,000,000

Table 2: Resistivity values of different water types (Keller & Frischknecht, 1996).

Type of water	Resistivity (Ωm)
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
Freshwater	10 – 100
Drinking water (max. salt content 0.25%)	> 1.8
Water for irrigation and stock watering (max. salt content 0.25%)	> 0.65

below ground level, before allowing the well to recover naturally.

4.3 Aquifer Transmissivity and Hydraulic Conductivity

In this study, the Cooper-Jacob straight-line time-drawdown method was used to analyse the pumping test data. Several assumptions were considered. The Cooper-Jacob solution assumes that the aquifer is confined, homogenous, isotropic and of uniform thickness over the area of pumping. In addition, we assumed that the pumping well is screened throughout the entire thickness of the aquifer being tested (e.g., Fetter, 2001).

Transmissivity is defined as the rate of flow under a unit hydraulic gradient through a cross--section of unit width over the whole saturated thickness of the aquifer (Bear, 1979). From the pumping rate (Q) and changes in drawdown ($h_0 - h$) of the water level, the transmissivity (T) is calculated from Eq.2 (Cooper & Jacob, 1946):

$$T = \frac{2.3Q}{4\pi(h_0 - h)} \qquad (2)$$

High aquifer transmissivity values are desirable for groundwater irrigation. Standard numerical values for transmissivity and classification of the aquifer are given in Table 3 (De Wiest, 1965; Sen, 2015).

From the calculated transmissivity (T) and the aquifer thickness (b), the hydraulic conductivity (K) was calculated using Eq. 3:

$$K = \frac{T}{b} \qquad (3)$$

5. Results and Discussion

5.1 2D Inverted Resistivity Model and Groundwater Zone

An electrical resistivity study was carried out at the Labi agricultural site to delineate subsurface geological formations, structures and potential groundwater zones. The study area's 2D resistivity inversion model revealed the resistivity variations to 100 m depth below the ground surface (Fig. 4). Resistivity values in the model range from 5 to 700 ohm-m. Two resistivity layers were interpreted. The first layer is considered as the topsoil, with resistivity values ranging from 100 to 700 ohm-m. The

Table 3: Aquifer classification based on Transmissivity values.

Transmissivity (m²/day)	Aquifer Classification
<5	Negligible
5 – 50	Weak
50 – 500	Moderate
>500	High

second layer is interpreted as groundwater zone, with resistivities ranging from 5 to 100 ohm-m. This groundwater zone underlies the topsoil at depths of about 10 to 40 m below ground level extending to about 100 m below ground level and possibly to greater depths. Resistivity values of less than 100 ohm-m are typical of soils below the water table due to groundwater effects (Keller & Frischknecht, 1996; Samouëlian et al., 2005; Annuar & Nordiana, 2018; Saad et al., 2012; Ashraf et al., 2018; Riwayat et al., 2018). In contrast, resistivity values of soils above the water table are typically higher as they tend to be much drier (Riwayat et al., 2018).

5.2 Borehole Lithology and Resistivity Correlation

A new borehole was drilled up to 80 m below the ground surface at a horizontal distance of 50 m northwest of the ERT profile line (Fig. 4). Borehole drilling encountered multiple saturated layers of sands and sandstones between the depth of 4 and 78 m. Interbedded layers of clay and mudstone were also recorded throughout the borehole log. Lithological description of the borehole are shown in Fig. 5. Resistivity survey combined with borehole lithology information can be helpful to validate geological anomalies and groundwater zones (Saad et al., 2012; Annuar & Nordiana, 2018; Ashraf et al., 2018; Aziman et al., 2018; Kumar et al., 2020). Our findings indicate that due to the inhomogeneous properties of the soil materials comprising mainly alternating sand and clay, the resistivity values often overlap, resulting in an ambiguous interpretation. Therefore, future studies should include drilling test wells to reduce interpretation ambiguities and further determine the soil properties in the surveyed area.

5.3 Borehole Pumping Tests and Aquifer Characterisation

Borehole pumping tests are vital for understanding the aquifer performance in various hydrogeological settings (Ashraf et al., 2018; Aziman et al., 2018). The pumping test was conducted to investigate water table responses and groundwater availability in the study area. The constant rate pumping and recovery time-drawdown data from the newly drilled borehole are shown in Fig. 6. The water level measurements from the open borehole showed that the static water level is approximately 4.5 m below the ground surface, suggesting a shallow water table in the area. The results of the pumping test with a constant rate showed that the maximum drawdown was 1.52 m after 24 hours of the test. During the recovery test, the water table was recovered to the final drawdown of 0.02 m, 4 minutes after pumping stopped. The pumping test results indicate that the groundwater could be pumped at a steady rate of 288 m³/day (12 m³/hr). Thus, the results suggest that the well has sufficient groundwater for withdrawal and distribution for irrigation purposes.

The pumping test provided estimates of the aquifer transmissivity and hydraulic conductivity. The sandy aquifer is assumed to be confined for estimating aquifer characteristics. The thickness of the aquifer is 40 m. Based on the unsteady Cooper-Jacob time-drawdown method, the estimated transmissivity value is 109 m²/day, showing moderate potentiality for groundwater usage in the study area for irrigation purposes (Table 3). Based on the aquifer transmissivity and thickness, the calculated hydraulic conductivity is 2.75 m/day, which is typically associated with alluvial deposits (Spitz & Moreno, 1996).
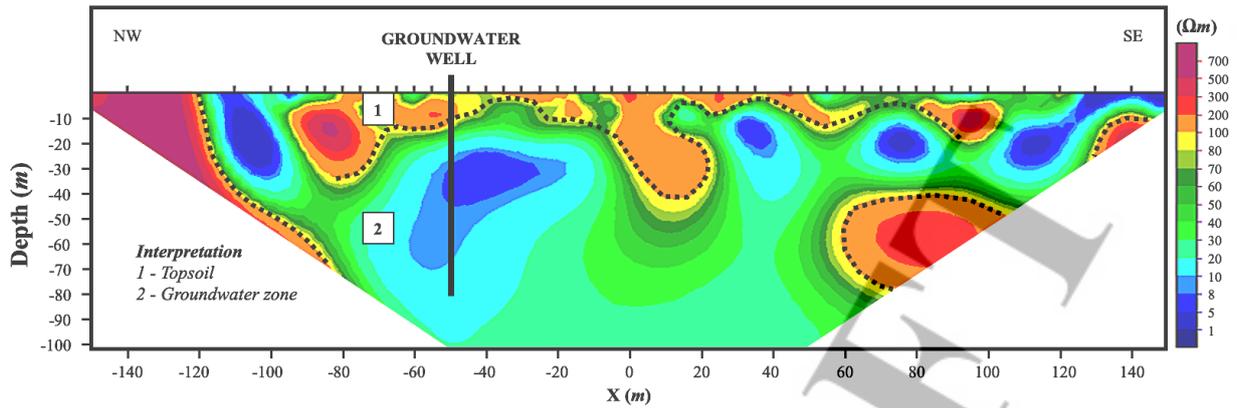
Fig. 4: 2D inverted resistivity model of ERT profile line at the Labi agricultural site showing the groundwater zone and location of groundwater well.
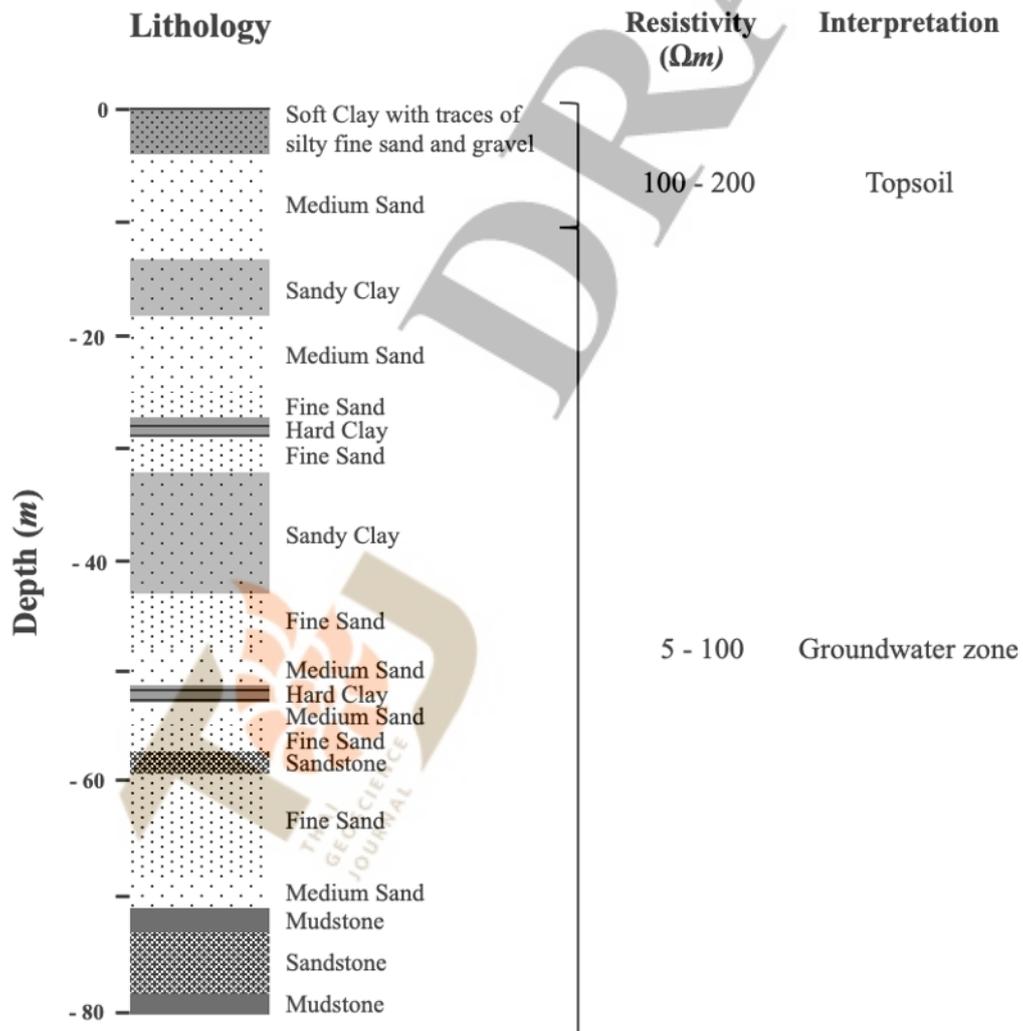

Fig. 5: Borehole lithology of the groundwater pumping well at the Labi agricultural site and correlation with resistivity interpretation.
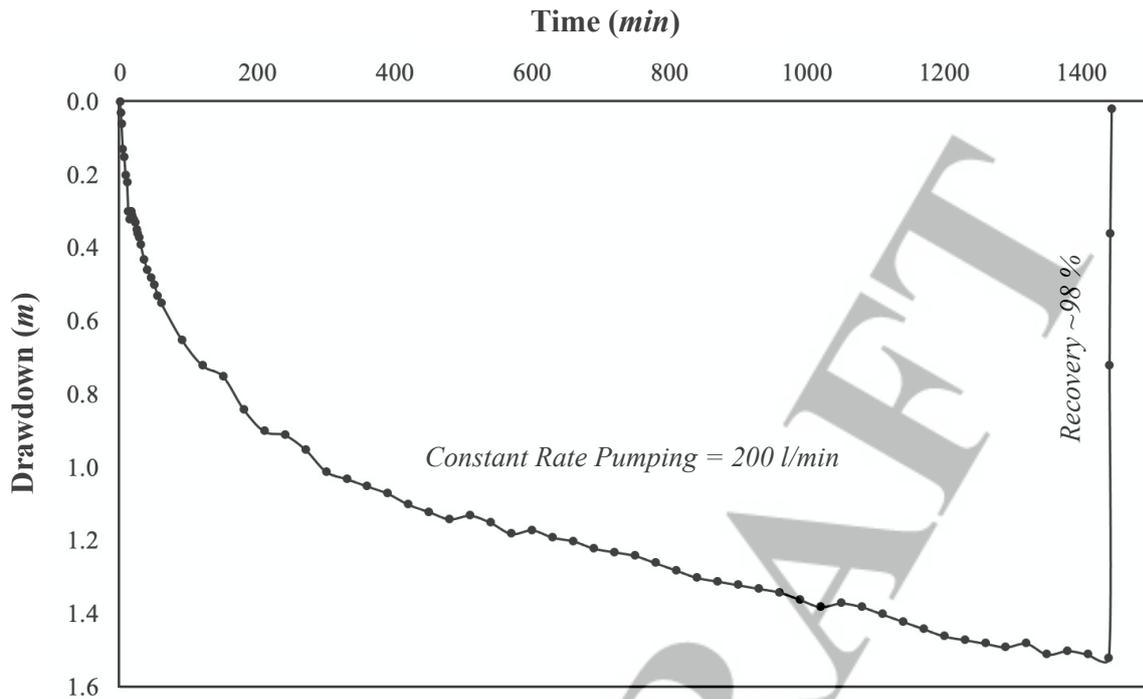
Fig. 6: Time-drawdown cross-plot of the groundwater pumping well at the Labi agricultural site showing the constant rate pumping and recovery curves.

6. Conclusions

Electrical resistivity tomography was conducted to delineate groundwater zones at the Labi agricultural site, Belait District, Brunei. Resistivity values ranging from 5 to 700 ohm-m were observed in the study area. The 2D inverted resistivity model showed two distinctive subsurface layers: the topsoil and the groundwater zone. The identified groundwater zone was characterised by distinctive resistivities ranging from 5 to 100 ohm-m. Based on these resistivity datasets, a suitable drilling target was identified.

The 2D inverted resistivity model was correlated with borehole lithology from the executed target well to 80 m depth. Borehole drilling encountered multiple saturated layers of sand and sandstone at depths of 4 to 78 m from the ground surface. In a pumping test, groundwater was produced at a steady rate of 288 m³/day. The pumping test indicated that the well could be used for irrigation purposes. The aquifer characterisation based on the pumping test analysis revealed an estimated transmissivity of 109 m²/day and a hydraulic conductivity of 2.75 m/day.

The resistivity datasets and borehole lithology have been very useful for a realistic conceptualisation and understanding of the study area's aquifer system. The present study helped decision-makers take suitable measures to place future irrigation wells and to achieve significant groundwater exploration results in the study area and other regions of similar geological settings. Future activities will involve the placement of a groundwater monitoring well in the direct vicinity of the pumping well.

References

Annuar, U. M., & Nordiana, M. M. (2018). Aquifer detection using 2D resistivity method and porosity calculation. Jurnal Teknologi (Sciences & Engineering) 80:6, 149-158.

Ashraf, M. A., Yusoh, R. S., & Abidin, M. H. (2018). Aquifer characterisation and groundwater potential evaluation in sedimentary rock formation. Journal of Physics: Conference Series Volume 995.

Azhar, A. S., Abdul Latiff, A. H., Lim, L. H., & Gödeke, S. H. (2019). Groundwater investigation of a coastal aquifer in Brunei Darussalam using seismic refraction. Environmental Earth Sciences 78:220.

Aziman, M., Hazreek, Z. A., Azhar, A. T., Fahmy, K. A., Faizal, T. B., Sabariah, M., . . . Ismail, M. A. (2018). Electrical resistivity technique for groundwater exploration in Quaternary deposit. Journal of Physics: Conference Series Volume 995.

Bailie, P., Darman, H., & Fraser, T. H. (2004). Deformation of Cenozoic basins of Borneo and West Sulawesi. Proceedings of Deepwater and Frontier Exploration In Asia & Australasia Symposium. Jakarta: Indonesian Petroleum Associations.

BDMD (2021). Climate. Retrieved from Brunei Darussalam Meteorological Department: www.bruneiweather.com.bn

Bear, J. (1979). Hydraulics of Groundwater. McGraw-Hill, New York, 569 p.

Cooper, H. H., & Jacob, C. E. (1946). A generalised graphical method for evaluating formation constants and summarising well-field history. Transactions, American Geophysical Union 27:526-34.

DAA (2018). Full Report of Electrical Imaging (Resistivity) and Soil Sampling in Brunei Darussalam. Bandar Seri Begawan: Department of Agriculture and Agrifood.

De Wiest, R.J.M. (1965). Geohydrology. John Wiley, New York.

DEPS (2021). Population. Retrieved from Department of Economic Planning and Statistics, Ministry of Finance and Economy: www.deps.gov.bn

FAO (2011). AQUASTAT Country Profile - Brunei Darussalam. Rome, Italy: Food and Agriculture Organisation of the United Nations (FAO).

Fetter, C. W. (2001). Applied Hydrogeology Fourth Edition. New Jersey: Pearson Education International.

Galazoulas, E. C., Mertzanides, Y. C., Petalas, C. P., & Kargiotis, E. K. (2015). Large scale electrical resistivity tomography survey correlated to hydrological data for mapping groundwater salinisation: A case study from multilayered coastal aquifer in Rhodope, Northeastern Greece. Environmental Process 2, 19-25.

Hall, R., & Nichols, G. (2002). Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis. In S. J. Jones, & L. Frostick, Sediment flux to basins: causes, controls and consequences (pp. 5-22). Geological Society London, Special Publications.

Keller, G. V., & Frischknect, F. C. (1996). Electrical methods in geophysical prospecting. Oxford: Pergamon Press Inc.

Kumar, D., Rajesh, K., Mondal, S., Warsi, T., & Rangarajan, R. (2020). Groundwater exploration in limestone-shale-quartzite terrain through 2D electrical resistivity tomography in Tadipatri, Anantapur district, Andhra Pradesh. Journal of Earth System Sciences, 129(1).

Lambiase, J. J., & Cullen, A. B. (2013). Sediment supply systems of the Champion "Delta" of NW Borneo: Implications for deepwater reservoir sandstones. Journal of Asian Earth Sciences 76, 356-371.

Lech, M., Skutnik, Z., Bajda, M., & Markowska-Lech, K. (2020). Applications of electrical resistivity surveys in solving selected geotechnical and environmental problems. Applied Sciences 10:2263.

Loke, M. H. (2012). Tutorial: 2D and 3D electrical imaging surveys. 172.

Riwayat, A. I., Ahmad Nazri, M. A., & Zainul, M. H. (2018). Application of Electrical Resistivity Method (ERM) in Groundwater Exploration. Journal of Physics: Conference Series, Volume 995.

Saad, R., Nawawi, M. N., & Mohamad, E. T. (2012). Groundwater detection in alluvium using 2-D Electrical Resistivity Tomography (ERT). Electronic Journal of Geotechnical Engineering, 369-376.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., & Richard, G. (2005). Electrical resistivity survey in soil science: a review. Soil & Tillage Research 83, 173-193.

Sandal, S. T. (1996). The geology and hydrocarbon resources of Negara Brunei Darussalam. Bandar Seri Begawan: Brunei Shell Petroleum.

Sen, Z. (2015). Practical and applied hydrogeology 1st Edition. Elsevier, 43-97.

Spitz, K., & Moreno, J. (1996). A practical guide to groundwater and solute transport modelling. New York: Wiley.

Sudha, K., Israil, M., Mittal, S., & Rai, J. (2009). Soil characterisation using electrical resistivity tomography and geotechnical investigation. Journal of Applied Geophysics 67, 74-79.

Suhip, M. A. A. B. H., Gödeke, S. H., Cobb, A. R., & Sukri, R. S. (2020). Seismic refraction study, single well test and physical core analysis of anthropogenic degraded Peat at the Badas Peat Dome, Brunei Darussalam. Engineering Geology, 273(January).

Torres, J., Gartrell, A., & Hoggmascal, N. (2011). Redefining a sequence stratigraphic framework for the Miocene to present in Brunei Darussalam: roles of local tectonics, eustacy and sediment supply. International Petroleum Technology Conference. Bangkok.

Zawawi, M. H., Syafalni, & Abustan, I. (2011). Detection of groundwater aquifer using resistivity imaging profiling at Beriah landfill site, Perak, Malaysia. Advanced Materials Research Volume 250-253, 1852-1855.