Electrical Resistivity Tomography And Induced Polarization Study For Groundwater Exploration In The Agricultural Development Areas of Brunei Darussalam

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Abstract

Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) study was carried out for groundwater exploration at eight agricultural development areas in Brunei Darussalam. The study was undertaken to meet the growing demands of water supply in the Brunei agricultural sector, particularly for paddy field irrigation. A total of nineteen survey lines with survey lengths of up to 800 m and investigation depths of up to 150 m below ground level were conducted to delineate subsurface geological structures, formations and aquifer zones in the study area. Aquifer zones with resistivity values ranging from 1 to 100 ohm-m and chargeability values of less than 1 mV/V were detected in all surveyed locations. New groundwater well drilling was conducted at two of the surveyed sites based on interpretations of 2D resistivity and chargeability inversion models. Water well drilling encountered aquifer zones, which were primarily in sandy layers. Hydraulic tests revealed groundwater yields of 4.3 and 288 m³/day. Estimated transmissivity values of the aquifer units based on pumping tests are 0.53 and 109 m²/day, while their hydraulic conductivity values are 0.05 and 2.75 m/day. Estimated parameters of the aquifer units indicate weak to moderate groundwater yield for withdrawal and distribution for irrigation purposes at the investigated sites. The present study helped decision-makers take suitable measures for placing future irrigation wells and achieve significant groundwater exploration results in the study area.

Introduction

Groundwater is an essential source of freshwater that is used globally for domestic, industrial and agricultural purposes. In particular, groundwater use for agricultural development has grown exponentially over the past decade, especially in heavily populated areas such as South Asia, Africa and China (Shah et al. 2006; Giordano and Villholth 2007). However, competing demands and water scarcity often resulted in mismanagement of the water resources (Tamas 2003). In countries like China and India, concerns over groundwater quality are rising due to improper disposal of urban wastewater into natural streams or its reuse for irrigation, which ultimately seeps into groundwater (Watto et al. 2018). On the other hand, microbiological processes can break down even recalcitrant contaminants (Gödeke et al. 2008). Possible complex contamination scenarios may need a range of remediation and assessment measures (Marshall et al. 2019).

In Brunei, the government relies almost entirely on surface water resources, given the relatively sparse population of around 500,000 (DEPS 2020). However, industrialization and urbanization put more pressure on its surface and groundwater resources (Suhip et al. 2020). Furthermore, concern over the increase in water demand was highlighted through the Brunei Vision 2035, where the vision calls attention to the public utilities regarding continuous, adequate, and quality water (DEPS 2020). Moreover, climate variability causes greater unpredictability in precipitation, including periods of heavier rainfall as well as drought (Thornton et al. 2014). Groundwater recharge is also highly dependent on climate (Moeck et al. 2020). One study in Brunei found that climate changes were evident from increased rainfall.
intensity, pointing to the need for careful water management under a changing climate (Gödeke et al. 2020).

Groundwater abstraction in Brunei is currently limited to the local bottled water industry found within the Sungai Liang area of the Belait District (FAO 2011). This industry has been supplying bottled mineral water from its original artesian well for almost three decades. A previous study in Brunei investigated subsurface layers and groundwater levels using the seismic refraction method at the Berakas area in the Brunei-Muara District (Azhar et al. 2019). The study presented velocity profiles and seismic tomography for groundwater system evaluation. Furthermore, water samples from nearby springs revealed low pH values and high sulphate concentrations, likely due to localised acid sulphate soils present in the investigated area. Grealish and Fitzpatrick (2013) found that acid sulphate soils occur in Brunei within flat inland areas important for agricultural land. A resistivity study in Brunei by Azffri et al. (in press) found that the interpreted groundwater zone yields low resistivity values ranging from 5 to 100 ohm-m at the Labi agricultural site in the Belait District. Furthermore, a borehole drilling encountered sandy aquifer units in the investigated area. Further groundwater pumping revealed a moderate groundwater yield of 288 m³/day and estimated aquifer transmissivity of 109 m²/day.

In this study, groundwater exploration was conducted at eight agricultural development areas in Brunei (Fig. 1), Electrical Resistivity Tomography (ERT) and Induced Polarization (IP). The ERT and IP surveys helped delineate subsurface geological structures, formations and aquifer zones. The study revealed subsurface resistivity and chargeability variations in the study area. Interpreted 2D subsurface resistivity and chargeability inversion models delineated potential aquifer zones and subsequently identified suitable prospects for groundwater well drilling and construction of groundwater pumping wells in two of the surveyed areas. Hydraulic test results of the newly drilled groundwater pumping wells helped estimate the aquifer transmissivity and hydraulic conductivity for aquifer characteristics.

**Geological Settings And Survey Locations**

Brunei lies on the north coast of Borneo Island in Southeast Asia, with a total land area of 5,765 km². It is divided into four main districts: Brunei-Muara, Tutong, Belait and Temburong. Brunei’s climate is typical of the equatorial tropics, characterized by high rainfall and temperatures throughout the year. Rainfall shows a seasonal pattern with wet and dry seasons throughout the year. The wet seasons are from September to January and May to June, and the drier seasons are from February to March and July to August. The average annual rainfall from 2019 was 2909 mm. The temperature is relatively uniform throughout the year, ranging from 23.8 to 32.1°C (BDMD, 2021).

Brunei is drained by four main river basins, namely the Brunei, Tutong, Belait and Temburong Rivers (Chuan 1992). The Belait river basin (Fig. 1) is the largest, with an area of 2,700 km². Peat swamp forests dominate the lower catchment areas. Some areas in the upper catchment have been cleared for agricultural development areas. The Tutong river basin has an area of about 1,300 km² (Chuan 1992). The basin comprises a floodplain in the lower catchment areas, with the upper catchment is forested with
few areas cleared for agricultural development areas. The Brunei river basin flows into the Brunei Bay. The upper parts of the river are a major freshwater source for urban water. The Temburong basin is the smallest river basin in the study area, with 430 km².

Brunei's geology is closely linked to its neighbouring Malaysian states of Sarawak and Sabah, and many regional geological studies have been conducted (Liechti et al. 1960; Wilford 1961; Sandal 1996; Hutchison 2005). Tectonic events govern the geological setting in this region since the Cenozoic era (Hall 1997; Hall and Nichols 2002; Baillie et al. 2004). Overall compressional tectonics in the northwest Borneo margin formed deformation zones of mountainous terrains extending through central Borneo. Subsequent uplift and erosion of this mountainous range in the hinterland during the Early and Middle Miocene resulted in rapid sedimentation into basin depocenters, forming major deltaic systems in the region (Sandal 1996; Hutchison 2005).

The Champion and Baram delta systems have been major siliciclastic sedimentation locations in both onshore and offshore Brunei areas since the Miocene period (Saller and Blake 2003; Torres et al. 2011; Lambiase and Cullen 2013). Most sediments are gently deformed due to occasional compressional tectonics during the Miocene to Pliocene (Sandal 1996; Morley et al. 2003). Stratigraphic formations occur within depositional environments, from the coastal plain to deep marine (Tate 1974; Sandal 1996). In the study area, quaternary rock formations overlay older bedrocks of the Liang, Miri, Seria, Lambir, Belait, Setap and Meligan Formations (Fig. 2 and Fig. 3). The lithologies of the formations are mainly made up of alternating sand and shales. Coal occurrences have been recorded in the Liang and Belait Formations (Fig. 3; Osli et al. 2021).

In the present study, the survey locations were specifically situated within flat-lying or lowland areas with no significant geological structure outcrop seen on the surface. Topographical elevations of the survey locations range from 2 to 5 m above mean sea level. All the survey locations are situated within recent sediments deposited in sub-aerial alluvial floodplain environment (Tate, 1974).

**Methodology**

**Theory**

Geoelectrical resistivity methods have been widely used in groundwater exploration, engineering and environmental applications (Dahlin 1996; Keller and Frischknecht 1996; Sudha et al. 2009; Galazoulas et al. 2015; Lech et al. 2020). Electrical resistivity tomography (ERT) is one of the most commonly used geoelectrical resistivity methods to map subsurface electrical resistivity (Griffiths and Barker, 1993; Dahlin, 2001), which subsequently can be interpreted from a hydrological perspective (e.g., Saad et al. 2012; Ashraf et al. 2018; Aziman et al. 2018; Riwayat et al. 2018; Thiagarajan et al. 2018; Kumar et al. 2020a, b).

The electrical resistivity method estimates the variation in the ground's resistivity by injecting direct current into the ground (Fig. 4) through a set of current electrodes (C1 and C2) and measuring the
resulting voltage differences at the potential electrodes (P1 and P2). The resistivity is determined from Ohm's law using the voltage differences for a known current and correcting the current geometrical pathway through the earth. From the current ($I$), voltage ($V$) and geometric factor ($k$), the apparent resistivity ($\rho_a$) was calculated using the following Eq. 1 (Telford et al. 1990; Dahlin 2001; Binley et al. 2015):

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

Resistivity interpretations have proved helpful for detecting geological units of unconsolidated sediments and groundwater prospects (e.g., Saad et al. 2012; Ashraf et al. 2018; Aziman et al. 2018; Riwayat et al. 2018; Thiagarajan et al. 2018; Kumar et al. 2020a, b). Igneous and metamorphic rocks, depending on the degree of fracturing and the percentage of the fractures filled with groundwater, generally have higher resistivities than sedimentary rocks, which are usually more porous and have higher water content. For example, the resistivity of granite ranges between 5,000 to 10,000 ohm-m depending on the degree of fracturing and moisture content (e.g., Kumar et al. 2020a, b), whereas the resistivity of sand and clay materials ranges within 1 to 1,000 ohm-m (e.g., Saad et al. 2012; Ashraf et al. 2018). Furthermore, clay has significantly lower resistivity values than sand. The resistivity values of clay range between 1 to 100 ohm-m, whereas the resistivity values of sand range between 60 to 1000 ohm-m (Keller and Frischknecht, 1996). The degree of overlap in different resistivities of different types of materials and waters is dependent on several factors such as porosity, degree of water saturation and concentration of dissolved salts (Samouëlian et al. 2005; Hazreek et al. 2015; Annuar and Nordiana 2018). Keller and Frischknecht (1996) found that groundwater yields low resistivity values ranging from 10 to 100 ohm-m depending on the concentration of dissolved salts.

Due to the ambiguity of resistivity values with overlapping resistivity ranges, several researchers have used an integrated geophysical approach combining resistivity with the induced polarization (IP) technique to solve complicated geological and hydrological problems (e.g., Goldman and Neubauer 1994; Amaya et al. 2016; Kumar et al. 2016a, b; Rehman et al. 2016). The IP method uses the voltage decay characteristics to study the soil's induced polarization, also known as the chargeability (Telford et al. 1990; Keller and Frischknecht 1996; Kearey et al. 2002). Subsurface chargeability measurements have been used to determine high clay content in sedimentary settings. The clay particles have a negative charge that can attract positive ions from the electrolyte contained in the cavities of rocks (Telford et al. 1990). High chargeability measurements have been observed for fine-grained sediments such as clay, while deposits with larger particle size like sand and gravel typically yield lower chargeability values (Keller and Frischknecht 1996; Slater and Lesmes 2002; Alabi et al. 2010; Amaya et al. 2016).

Hydraulic tests of groundwater wells are crucial for understanding the aquifer potential in any hydrogeological setting (Ashraf et al. 2018; Aziman et al. 2018; Kumar et al. 2020b). Transmissivity and hydraulic conductivity are two key hydraulic parameters that can help determine the aquifer characteristics (e.g., Mogaji et al. 2011; Shen et al. 2015; Wu et al. 2017). Furthermore, the records of
time-drawdown data have been used to evaluate the aquifer transmissivity and hydraulic conductivity. The Cooper-Jacob solution assumes that the aquifer is confined, homogenous, isotropic and of uniform thickness over the area of pumping. The assumption discussed in Fetter (2001) for determining aquifer parameters from time-drawdown data is that the pumping well is screened throughout the entire thickness of the aquifer being tested. Using the Cooper-Jacob straight-line time-drawdown method, the aquifer transmissivity was calculated using Eq. 2 (Cooper and Jacob 1946):

\[ T = \frac{2.3Q}{4\pi(h_0 - h)} \]  

Where \( Q \) is the pumping rate and \( h_0 - h \) is the calculated change in drawdown between initial and final drawdown.

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

\[ K = \frac{T}{b} \]  

Data acquisition and processing

Data acquisition was conducted with a combined measurement of resistivity and chargeability. A total of 19 survey lines from eight agricultural sites were carried out in the study area (Table 1). Information such as aerial, topographical and geological maps is required when considering resistivity surveying suitability (to select profile lines). The selection of survey locations was predominantly planned based on area availability and accessibility. The survey locations were generally free from obstacles, such as houses, crops or fences. In some areas, permission from landowners was needed to perform the surveys on their land.

Table 1 Survey parameters for each resistivity survey line (sites 1-8).
Two sets of data were acquired between the years 2018 and 2020. The first set of data acquisition was carried out in 2018 using the ABEM Terrameter LS2 resistivity meter covering a lateral distance of 800 m with eighty stainless-steel electrodes arranged at an equal length of 10 m (Line 1–11). This set of data acquisition was conducted using the gradient array configuration. The gradient array configuration uses two current electrodes and two potential electrodes, placed with equal spacings (Fig. 4). The gradient method is suitable for multichannel acquisition due to dense and fast data point collection (Dahlin and Zhou 2006; Loke 2012; Aizebeokhai and Oyeyemi 2014). With the multichannel acquisition, resistivity measurements continue down the row of electrodes until the whole survey line is measured. The second set of data acquisition was conducted from 2019 through to 2020 using the ABEM SAS4000 resistivity meter covering a lateral distance of 400 m (Line 12–19). The line uses sixty-one electrodes with 5 m spacings for the inner cables and 10 m spacings for the outer cables. This set of data acquisition was conducted using the pole-dipole array configuration. For the pole-dipole array configuration, one transmitting current electrode, also known as the infinity electrode, was moved to an effective infinity distance, approximately five times the survey depth (Fig. 4). Simultaneously, the other current electrode is placed in the vicinity of the two potential electrodes. The pole-dipole method is suitable for deep earth investigation, making it a popular option among researchers (Saad et al. 2012; Annuar and Nordiana 2018; Ashraf et al. 2018; Kumar et al. 2020a).

Raw data were processed and inverted using the ZONDRES2D software (in DAT format). Resistivity and chargeability inversion models were obtained from the inversion process (Loke and Barker 1996). The inversion process averaged the resistance measurements to apparent resistivity values and the apparent chargeability time window measurements to integral chargeability values. The Gauss-Newton inversion
method was used to determine the appropriate resistivity values (Griffith and Barker 1993; Loke and Barker 1996; Dahlin 2001; Loke and Dahlin 2002). 2D pseudo-sections were generated to help delineate subsurface geological structures, formations and aquifer zones in the surveyed areas. All the pseudo-sections displayed present RMS errors of not more than 5%, which indicates the measured data are fitted with the computed apparent resistivity; the number of iterations for each survey was ten.

**Groundwater well drilling and hydraulic tests**

Groundwater wells were drilled at site-1 in the Brunei-Muara District (Well-B1) and site-5 in the Belait District (Well-L1) through the aquifer zones inferred from resistivity and chargeability interpretations. Borehole drilling was conducted using a straight rotary method. The hole was advanced by rotating a drill string consisting of a series of hollow drill rods to the bottom attached to a 10-inch drill bit. Water-based drilling fluid under pressure was introduced into the bottom of the hole through the hollow drill rods and passages into the bit. The drilling fluid served the dual function of cooling the rotating bit as it entered the borehole and removing the rock cuttings from the bottom of the hole. The rock cuttings move through the annular space between the drill rods and the walls of the hole as they returned to the surface. Rock cuttings were collected at an interval of 3 m, primarily for soil identification purposes. 6-inch diameter UPVC casings and screens with 1.5 mm openings were used to construct the groundwater pumping wells. A gravel pack filter was installed between the aquifer and UPVC screens.

A 4-inch submersible pump was installed inside the well to continuously pump water out from the well through a 2-inch riser pipe for hydraulic testing. The pumping well responses in terms of the water discharge and changes in water depth were recorded using a volume meter connected at the outlet pipe on the surface and a water depth meter installed inside the well annulus. None of the newly drilled water wells had yet a nearby observation well that could have been used for time-drawdown observation due to pumping. Hydraulic tests of the newly drilled wells were investigated using time-drawdown data gathered from the pumping well. A five-step drawdown test with different flow rates, constant discharge test and recovery test was carried out in this investigation.

**Results**

**Interpretations of 2D resistivity and chargeability inversion models**

Electrical resistivity tomography and induced polarization revealed subsurface resistivity and chargeability variations in the study area with resistivity values from 1 to 500 ohm-m and chargeability values from 0 to 10 mV/V to a depth of about 150 m from the surface. Aquifer zones were also detected at varying depths in all surveyed locations with resistivity values ranging from 1 to 100 ohm-m (Table 2). Few shallow boreholes (< 30 m) with lithology information exist within the study area. Lithology correlations with resistivity models were possible. However, they are limited to shallow depths. Two new boreholes were drilled in two selected sites to investigate the deeper rock strata and groundwater
availability. The two pilot wells, namely Well-B1 and Well-L1, were placed explicitly in water-scarce agricultural areas used for paddy plantation. The two sites are Bebuloh (site-1) and Lot Sengkuang (site-5). These two sites were found to have favourable groundwater prospects based on resistivity and chargeability interpretations. The detailed interpretation and results of two ERT and IP profiles are presented in this paper, delineating subsurface geological structure, formations and aquifer zones of the area.

**Line 12 (Site-1)**

**Table 2** Resistivity surveys of sites 1-8 with depth and resistivity of aquifer zone.

| Survey location | Survey line | Depth of aquifer zone from the surface (m) | Resistivity of aquifer zone (ohm-m) |
|-----------------|-------------|------------------------------------------|-----------------------------------|
| Site-1          | ERT 1-3     | 20-30                                    | 1 - 100                           |
|                 | ERT 12      | 10                                       | 1 - 100                           |
|                 | ERT 19      | 20                                       | 1 - 50                            |
| Site-2          | ERT 4-8     | 20-40                                    | 1 - 100                           |
|                 | ERT 13      | 50                                       | 5 - 100                           |
| Site-3          | ERT 14      | 20-30                                    | 1 - 100                           |
| Site-4          | ERT 15      | 20                                       | 1 - 50                            |
| Site-5          | ERT 16      | 20-40                                    | 5 - 100                           |
| Site-6          | ERT 9       | 20                                       | 1 - 100                           |
| Site-7          | ERT 10-11   | 10-20                                    | 1 - 100                           |
| Site-8          | ERT 17-18   | 10-20                                    | 1 - 100                           |

Inverse model resistivity of ERT 12 revealed resistivity variations to a depth of 110 m from the surface (Fig. 5). Two subsurface layers differentiated by resistivity values were deduced. The first layer is interpreted as the topsoil and is distinctive of resistivities ranging from 1 to 140 ohm-m. A second layer distinct of resistivities ranging from 1 to 100 ohm-m is interpreted as the aquifer zone. The saturated zone is about 10 m below ground level. Inverse model chargeability of IP 12 revealed low chargeability values of the aquifer zone of less than 1 mV/V. High chargeability values ranging from 5–10 mV/V were observed in the topsoil layer and are assumed to be composed of fine-grained materials such as clay. Groundwater Well-B1 was drilled to about 96 m from the surface at site-1 (line 12) based on the resistivity and chargeability interpretations.

**Line 16 (Site-5)**
Inverse model resistivity of ERT 16 revealed resistivity variations to a depth of 100 m from the surface (Fig. 6). Two subsurface layers were deduced based on resistivity values. The first layer is interpreted as topsoil with resistivities ranging from 100 to 500 ohm-m. The second layer with resistivities ranging from 1 to 100 ohm-m was observed at a depth of about 20 to 40 m below ground level. This layer is interpreted as the aquifer zone. Inverse model chargeability of IP 16 indicated chargeability values at line 16. High chargeability values ranging from 5–10 mV/V were observed at a depth of about 40 to 50 m from the surface, possibly extending towards greater depths and are assumed to be composed of fine-grained materials such as clay. Groundwater Well-L1 was drilled to 80 m from the surface at site-5 (line 16) based on the resistivity and chargeability interpretations.

**Borehole lithology correlation with resistivity datasets**

Two pilot wells were drilled at site-1 and site-5 based on the resistivity and chargeability data interpretations (line 12 and 16). Borehole lithology of Well-B1 and Well-L1 were correlated with resistivity models and are shown in Fig. 7. Both the newly drilled wells encountered aquifer zones while drilling, which was primarily in sandy layers. The borehole lithology information revealed the inhomogeneity of the soil materials in the study area, mainly composed of multiple alternating sand and clay layers. Furthermore, the layers cannot be clearly distinguished in terms of their resistivities. However, it can be inferred that the overall higher clay content at Well-B1 yields lower resistivity values ranging from 1 to 30 ohm-m, whereas higher sand content at Well-L1 yields higher resistivity values ranging from 5 to 200 ohm-m.

Well-B1 is mainly composed of clay and sand with traces of decomposed peat at the top layer. The predominance of clay deposits with resistivity values of 3 to 30 ohm-m may be explained by the deposition of fine-grained materials in an alluvial floodplain, specifically a lacustrine environment. Well-L1 is mainly composed of fine to medium sand, clay, sandstone and mudstone. The top part of the lithology log mainly consists of fluviatile deposits (clay, sand and gravel) with resistivity values between 60 to 200 ohm-m. The lower part of the lithology log with resistivities ranging between 5–60 ohm-m appears to be associated with alluvial deposits (mix of clay and sand).

**Hydraulic tests for aquifer characteristics**

At Well-B1, the UPVC screens were installed at the saturated clayey sand layer at depths of 84 to 95 m below ground level (Fig. 7). The constant rate pumping test at Well-B1 was carried out for 4 hours with a steady pumping rate of 4.3 m³/day and a maximum drawdown of 3.63 m. At Well-L1, the UPVC screens were installed be at sand and sandstone layers at depths of 18 to 28 m and 48 to 78 m below ground level (Fig. 7). The constant rate pumping test at Well-L1 was carried out for 24 hours with a steady pumping rate of 288 m³/day and a maximum drawdown of 1.52 m.
The time-drawdown cross-plot of Well-B1 and Well-L1 are shown in Fig. 8. Their calculated hydraulic parameters are shown in Table 3. The unsteady Cooper-Jacob time-drawdown analysis revealed the estimated aquifer transmissivity values of 0.53 and 109.8 m²/day at Well-B1 and Well-L1, respectively. The estimated hydraulic conductivity of the clayey sand unit (with an estimated aquifer thickness of 11 m) at Well-B1 is 0.05 m/day. Lower hydraulic conductivity values are typically associated with fine-grained materials such as clay deposits (Spitz and Moreno 1996). The hydraulic conductivity for the sandy units (with an estimated aquifer thickness of 40 m) at Well-L1 is 2.75 m/day. Based on the time-drawdown data and estimated hydraulic parameters of the aquifer, weak to moderate groundwater yield is expected for withdrawal and distribution in the investigated agricultural areas for irrigation purposes.

Table 3 Aquifer characteristics estimated through hydraulic tests of newly drilled groundwater wells.

| Well | Pumping duration (mins) | Initial and final water depth (m) | Discharge rate (m³/day) | Transmissivity (m²/day) | Hydraulic conductivity (m/day) |
|------|-------------------------|----------------------------------|-------------------------|-------------------------|-------------------------------|
| B1   | 240                     | 44.5 / 48.2                      | 4.3                     | 0.53                    | 0.05                          |
| L1   | 1440                    | 21.4 / 22.9                      | 288                     | 109.8                   | 2.75                          |

Discussion

Geophysical study and results of the 2D inverted resistivity model at eight agricultural development areas and their interpretations of hydrogeology revealed aquifer zones in all the surveyed locations found at varying depths with variation in apparent resistivities. The 2D inverted resistivity models delineated the subsurface geological formations and structures in the study area, showing resistivity contrasts between topsoil and aquifer zones. The resistivity of the topsoil layer ranges from 1 to 500 ohm-m, and the chargeability values range from 0 to 10 mV/V. High chargeability values were assumed to be composed of fine-grained materials such as clay. The resistivity of the aquifer zone ranges from 1 to 100 ohm-m, and the chargeability values are less than 1 mV/V. Based on the resistivity and chargeability interpretations, two new groundwater wells were drilled at site-1 (line 12) and site-5 (line 16). Based on the 2D resistivity and chargeability data interpretation and the yields of the newly drilled boreholes, it was found that site-5 has a higher potentiality for groundwater exploitation compared to site-1. Borehole drilling of groundwater Well-L1 encountered multiple saturated sand layers with a moderate groundwater yield of 288 m³/day. Well-L1 is currently used for groundwater withdrawal and distribution for irrigation purposes at site-5. Borehole drilling of groundwater Well-B1 encountered a saturated clayey sand layer with a poor groundwater yield of 4.3 m³/day. Therefore, Well-B1 was not used for groundwater withdrawal for irrigation at site-1. Our findings indicate that due to the inhomogeneous properties of the soil materials comprising mainly alternating sand and clay, the resistivity and chargeability values often overlap, resulting in ambiguous interpretations. Future studies should include drilling groundwater test wells to determine the soil properties and aquifer potential further.
Conclusion

Electrical resistivity tomography and induced polarization methods were successfully applied to detect groundwater at eight agricultural development areas in Brunei targeted for irrigation. Resistivity datasets showed subsurface resistivity variations ranging from about 1 to 500 ohm-m in the study area. This suggested variations in geological formations and aquifer systems. 2D inverted resistivity model helped mapped aquifer zones in all the surveyed locations, mainly at shallower depths (< 100 m). Resistivities ranging from 1 to 100 ohm-m and chargeability values of less than 1 mV/V signify favourable groundwater prospects underneath the topsoil layer and correlated with borehole lithology data and drilling results and site-5. New groundwater well drilling was conducted to 96 m depth at site-1 and 80 m depth at site-5 with groundwater yields of 4.3 and 288 m³/day, respectively. The estimated aquifer transmissivity values are 0.53 and 109.8 m²/day, while their hydraulic conductivity values are 0.05 and 2.75 m/day, respectively. Estimated parameters of the aquifer units indicate significant variation in the amount of groundwater availability for withdrawal and distribution for irrigation purposes in the study area. The combination of IP and ERT significantly helped to identify the suitable drilling for Well-L1. The study presented the resistivity and chargeability characteristics, as well as the results of two newly drilled groundwater pumping wells of the studied area, and evaluated groundwater availability for groundwater use for irrigation. Future studies are necessary to locate irrigation wells with significant groundwater potential. Future drilling is planned to install groundwater monitoring wells next to the groundwater pumping well.

Declarations

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Conflict of Interest  The authors declare no conflict of interest.

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**Figures**
Figure 1

Map of Brunei showing the four major districts, rivers and survey locations (sites 1-8); Inset map of Southeast Asia showing the location of Brunei.
Figure 2

Geological map of Brunei (after Sandal, 1996).
Figure 3

Chrono-lithostratigraphy of central onshore Brunei (after Osli, 2020).
Gradient Array Configuration

\[ k = \frac{2\pi m (n+1) a}{(n+1) + m (m+1)} \]

Pole-Dipole Array Configuration

\[ k = \text{geometric factor} \]

\[ k = 2\pi m (n+1) a \]

Figure 4

Schematic representation of gradient and pole-dipole array configurations; ‘a’ represents the distance between the electrodes (Loke, 2012).
Figure 5

Inverse model resistivity and chargeability sections of Line 12.
**Figure 6**

Inverse model resistivity and chargeability sections of Line 16.
Figure 7

Borehole lithology of groundwater Well-B1 and Well-L1 showing correlation with resistivity values and groundwater yield.

Figure 8

Drawdown of pumping and recovery curves of groundwater Well-B1 and Well-L1.