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

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

[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*
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Abstract

Over the years, Brunei has relied on surface water as the primary water source for domestic, industrial and agricultural use. Increasing population and demands for water, especially in its growing agriculture sector, has led to groundwater exploration at the Labi agricultural site for irrigation purposes driven by the Brunei Government. Electrical Resistivity Tomography (ERT) has been used extensively to delineate subsurface structures and groundwater prospects. The technique was employed in 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 resistivity model revealed groundwater zone 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. A borehole drilling encountered multiple saturated layers of sand between depths of 4 to 78 m. Pumping test showed the groundwater was able to be produced at a steady rate of 288 m^3/day. Aquifer transmissivity estimated using the unsteady Cooper Jacob analysis was 109 m^2/day indicated moderate potential for groundwater usage in the study area for irrigation purposes. The resistivity survey, combined with borehole drilling and testing, provided insights into 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.

Keywords: Agricultural Site, Electrical Resistivity Tomography, Groundwater

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 km^2 with an estimated population of 459,500 in 2019 (DEPS, 2019). 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 percent comes from groundwater resources. Groundwater abstraction is currently limited to the local bottled water industry found in the Liang area (FAO, 2011). Previous study in Brunei revealed groundwater flow system of shallow coastal aquifer in the Berakas area, Brunei-Muara District (Azhar, Abdul Latiff, Lim & Gödeke, 2019).

The Brunei Government emphasises developing agriculture and agri-food to ensure food supply security and enhance economic contribution to its GDP. Brunei's Department of Agriculture and Agrifood is currently improving irrigation, especially in relative water-scarce agricultural areas. The use of groundwater for irrigation purposes in Brunei has not been investigated before.

This study conducted groundwater exploration at the Labi agricultural site, Belait District, Brunei, for irrigation purposes.

Geophysical method using electrical resistivity tomography was first employed to investigate the subsurface lithological formations, geological structures and resistivity variations in the study area (Ashraf, Yusoh & Abidin 2018; Riwayat, Ahmad Nazri & Zainul, 2018; Kumar, Rajesh, Mondal, Warsi & Rangarajan, 2020). Resistivity results used to delineate groundwater zones and locate a suitable site for borehole drilling. A borehole lithology log was constructed and used to correlate with the study area's 2D resistivity inversion model. A pumping test of the newly drilled borehole provided a transmissivity estimate of the local aquifer.

2. Study Area

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. Groundwater exploration in the study area aims to improve the irrigation system, especially during the dry season. The area's climate is typical of 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 study area is generally flat, with no significant geological structure outcrop and features seen on the surface. Topographical elevation in the study area ranges from 7 to 30 m above mean sea level. Drainage systems are controlled by streams flowing approximately from east-southeast to west-northwest directions. Previous borehole studies conducted by Brunei's Department of Agriculture & Agrifood revealed brown and greyish soil 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 in the study area.

3. Regional Geological Setting

Brunei is located on the north coast of Borneo Island. The island's regional geology has resulted from a series of complex regional tectonic events since the Cenozoic period (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 developing many known delta systems around the island.

The study area lies within the Champion delta system. The delta developed during the Middle Miocene to Early Pliocene formed at the eastern onshore and offshore Brunei areas. Rock strata in the area are consisted of thick sand-shale sequences deposited during 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. The underlying Miri Formation is of the Middle to Late Miocene age. The lower part of the formation is argillaceous, and sandstones dominate the upper part. The Lambir Formation of Early to Middle Miocene age underlies the Lambir Hills. The northeast-southwest trending Belait anticline passes near Kampong Labi and in the Bukit Teraja areas. The predominant rock types of the Lambir Formation are sandstone and shale with minor limestone and marl intercalations.

4. Regional Geological Setting

4.1 Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) is a geophysical survey method widely used to obtain subsurface information. It is a non--destructive and susceptible method typically used for groundwater exploration (Saad, Nawawi

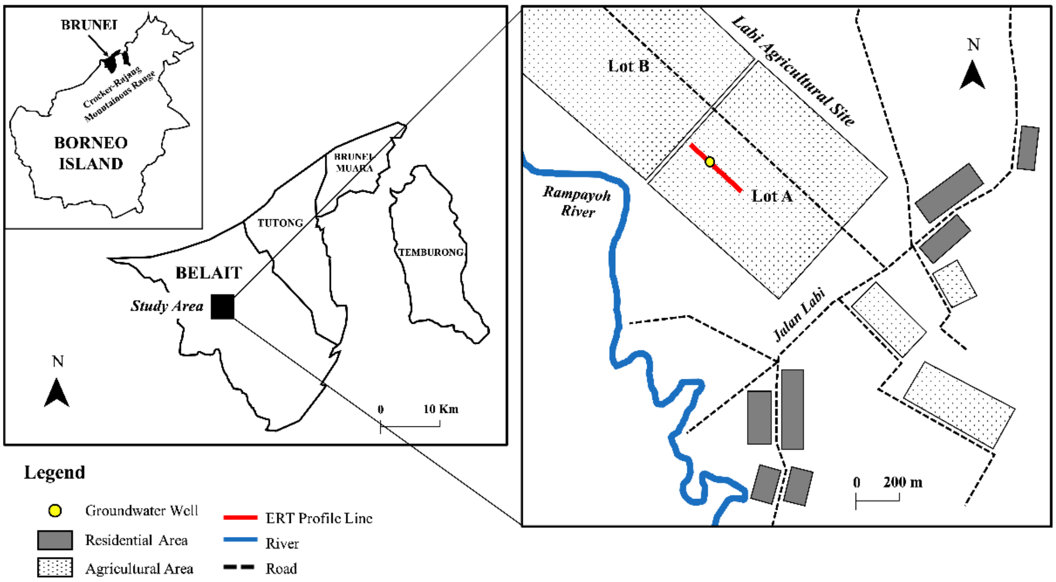

Fig. 1: Map of Brunei Darussalam showing the location of the study area.

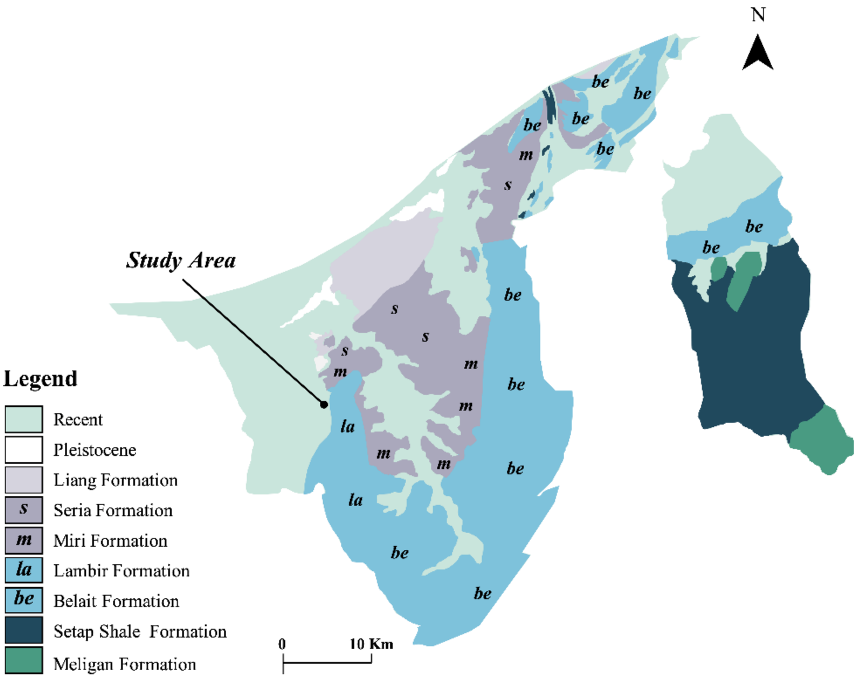

Fig. 2: Stratigraphic map of Brunei Darussalam showing the location of the study area (modified after Sandal, 1996).

& Mohamad, 2012; Annuar & Nordiana, 2018; Ashraf et al., 2018; Aziman et al., 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).

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 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). The complete set of the observed apparent resistivity data were analysed to produce a two-dimensional (2D) resistivity model through an inversion process. The ZONDRES2D software was used for the 2D inversion.

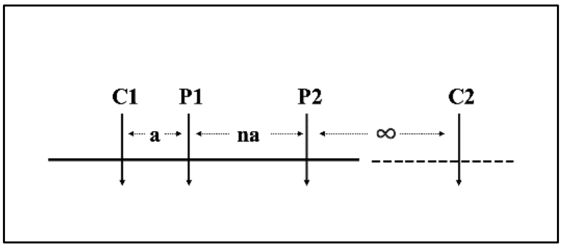

Fig. 3: The arrangement of electrodes for 2D electrical resistivity survey using the Pole-Dipole array configuration (Loke, 2012).

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

Borehole testing was performed immediately after the completion of the borehole drilling. 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 tube well at 45 m depth and continuously pumping water out from the well through a 2-inch riser pipe. The tube 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 below ground level, before allowing the well to recover naturally. The time-drawdown data in both trials were interpreted for aquifer transmissivity and hydraulic conductivity.

4.3 Aquifer Transmissivity and Hydraulic Conductivity

In this study, the Cooper-Jacob straight-line time-drawdown method was used to analyse the

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

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 thegeneral assumption for determining aquifer parameters from time-drawdown data assumes that the pumping well is screened throughout the entire thickness of the aquifer being tested (Fetter, 2001).

Transmissivity is defined as the rate at which water passes through a unit width of the aquifer under a hydraulic gradient unit. 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):

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

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

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

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

5. Results and Discussion

5.1 2D Resistivity Model and Groundwater Zone

An electrical resistivity study was carried out at the Labi agricultural site to delineate subsurface geological formations, structures and groundwater potential. 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 ranges from 5 to 700 ohm-m. Two zones were interpreted; the topsoil and the groundwater zone. The topsoil is distinctive of resistivity values from 100 to 700 ohm-m, with a depth of 10 m to 40 m from the ground surface. In the study area, the topsoil overlies the potential groundwater zone. The groundwater zone is distinctive of resistivities ranging from 5 to 100 ohm-m. Resistivity values of less than 100 ohm-m are typical of soils below the water

Table 3: Aquifer classification based on Transmissivity values.

Transmissivity (m^2/day)	Aquifer Classification
<5	Negligible
5 – 50	Weak
50 – 500	Moderate
>500	High

table due to groundwater effects (Keller & Frischknecht, 1996). In contrast, resistivity values of soils above the water table are typically higher as they tend to be much drier (Riwayat et al., 2018). A Borehole drilling target was identified at the horizontal distance of 100 mof the survey line, considering the favourable and well-defined resistivity contrast to the surrounding geological formations at a depth of about 20 m to 80 m.

5.2 Borehole Lithology and Resistivity Correlation

A new borehole was drilled to 80 m below the ground surface to investigate the geological formation in the study area. 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 and resistivity correlations are shown in Fig. 5. With careful correlation with lithology differences, resistivity surveys can be helpful to detect anomalous bodies or potential groundwater zones (Saad et al., 2012; Annuar & Nordiana, 2018; Ashraf et al., 2018; Aziman et al., 2018; Kumar et al., 2020). The saturated sandy layers found from the borehole drilling was characterised as the groundwater zone, inferred from the resistivity model. 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 groundwater test wells to further determine the soil properties.

5.3 Borehole Pumping Tests and Aquifer Characterisation

Borehole pumping tests are vital for understanding the aquifer performance in various hydrogeological settings. The pumping test was conducted to investigate water table responses and groundwater availability in the study area. The time-drawdown and recovery curves 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 at 4 hours after the stop of the pumping up. Based on the pumping test results, the groundwater was produced at a steady rate of 288 m^3/day (12 m^3/hr), suggesting the well has sufficient groundwater for withdrawal and distribution for irrigation purposes.

The pumping test provided an estimate of 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 m^2/day, showing moderate potentiality for groundwater usage in the study area for irrigation purposes (Table 3). Aquifer parameters in this study suggest that the hydraulic conductivity is 2.75 m/day, typically associated with unconsolidated deposits of alluvial and fine sand (Spitz & Moreno, 1996).

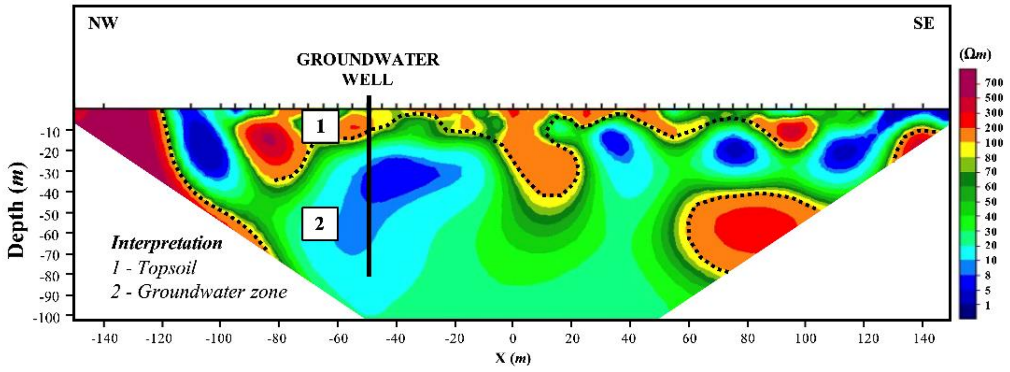

Fig. 4: The 2D resistivity model of the survey line.

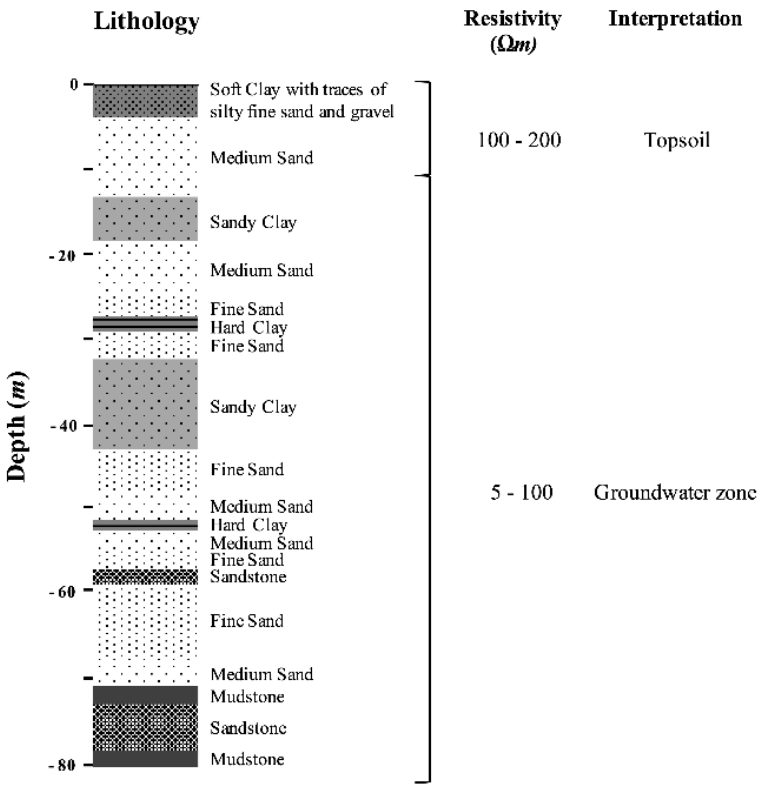

Fig. 5: Correlation of 2D resistivity model with the borehole lithology at a distance of 100 m of the survey line.

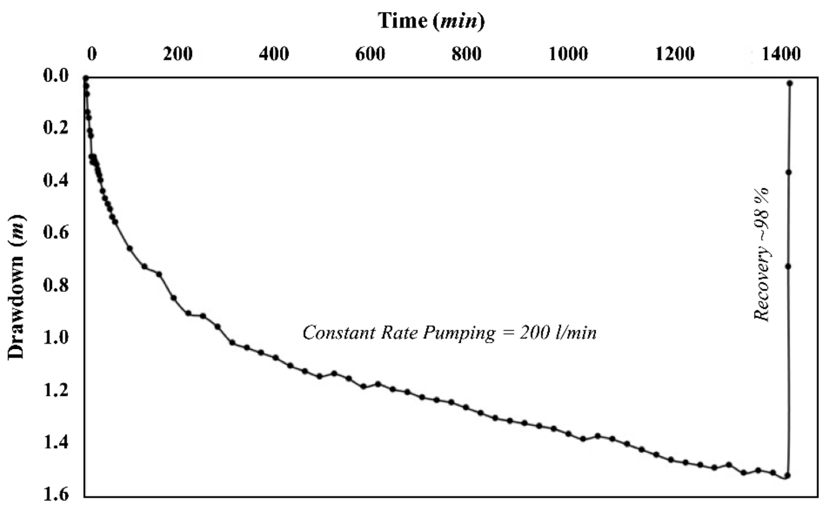

Fig. 6: Time-drawdown and recovery curves of the newly drilled borehole in the study area.

6. Conclusions

Electrical resistivity tomography conducted at the Labi agricultural site provided an understanding of the subsurface geological formations and structures through variation in resistivity. Resistivity values ranged from 5 to. 700 ohm-m in the obtained resistivity inversion model. The 2D 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 resistivity datasets, a suitable drilling target was identified.

The 2D 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. The groundwater was produced at a steady rate of 288 m^3/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 m^2/day and a hydraulic conductivity of 2.75 m/day.

The resistivity datasets and borehole lithology have immensely helped in 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.

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