



Characterization of The Vadose Zone Using the Vertical Electrical Sounding (VES) Method at the ITERA Botanical Garden

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ABSTRACT

The ITERA Botanical Garden is a plant conservation center in Lampung Province that requires information on vadose zone characteristics to support water availability for its vegetation. This study used the Schlumberger configuration of the Vertical Electrical Sounding (VES) method to identify subsurface lithology, characterize the vadose zone, and estimate rock porosity based on resistivity interpretation. The results show that the subsurface lithology consists of five main layers: topsoil, tuffaceous sandstone, tuffaceous claystone, and tuff, with resistivity values ranging from 2.00 to 521.00 Ωm . The thickness of the vadose zone varies from 15 to 43 meters, with estimated porosity ranging from 11.18% to 21.82%. Thicker zones indicate a deeper groundwater table and slower infiltration processes, while thinner zones have the potential to accelerate water entry into lower layers but offer less natural protection against the risk of contamination. Differences in porosity values between layers reflect the varying capacity of rocks to store and release water, depending on their lithological type and physical properties. These findings can serve as a reference for ITERA Botanical Garden managers in identifying areas that should be prioritized for groundwater conservation, as well as areas vulnerable to contamination, thereby supporting more effective water management planning in the region.

KEYWORDS: ITERA Botanical Garden, VES, and Vadose Zone

INTRODUCTION

The Botanical Garden of the Sumatera Institute of Technology (ITERA) plays a significant role as one of the ex-situ plant conservation centers in Lampung Province. This area is home to various plant species whose survival is safeguarded outside their natural habitats (Violita et al., 2025). For this function to work effectively, two interrelated factors, water availability and soil conditions, determine whether the plants in the collection will thrive or fail to grow.

This layer is known as the vadose zone, which is the portion of soil and rock between the surface and the water table whose pores are not filled with water but are mixed with air; for this reason, it is often referred to as the unsaturated zone (Arora et al., 2019). Rainwater must pass through this zone before

reaching the underlying aquifer, and in the process, the vadose zone determines the rate of infiltration and the length of time the water is retained before seeping deeper. This means that the thickness, lithology, and porosity of this zone directly influence three factors that are crucial for the vegetation of the ITERA Botanical Garden: how quickly water reaches the roots, how long moisture is retained within the root zone, and how much water is available during the dry season.

Numerous studies have previously been conducted on subsurface conditions in the vicinity of the Sumatera Institute of Technology (ITERA) campus, particularly regarding the presence of aquifers and the potential availability of groundwater. Rizka & Satiawan (2019) conducted a geophysical study to determine the characteristics of aquifers in

the ITERA campus area and identified two water-bearing layers. The conceptual representation of the subsurface water system is illustrated in Figure 1.

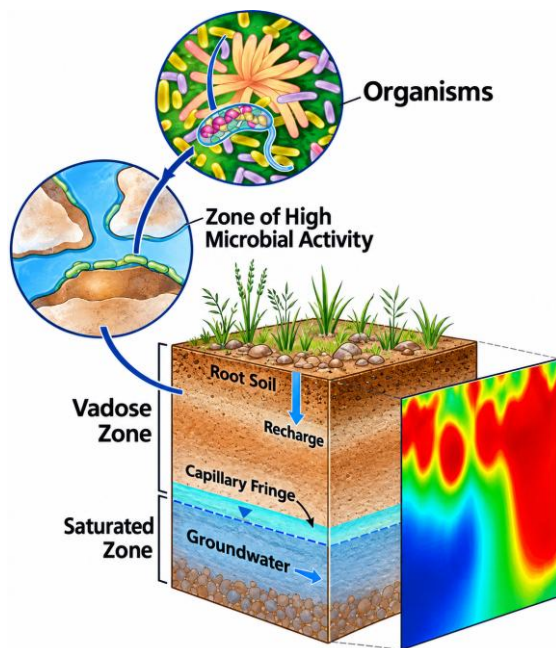


Figure 1. Illustration of the Vadose Zone (Arora et al., 2019)

The first layer is an unconfined aquifer located at a depth of less than 5 meters with a resistivity value greater than $80 \Omega \cdot m$ and is interpreted as tuff material. Meanwhile, the second layer is a confined aquifer found at a depth of more than 75 meters with a resistivity range of $220\text{--}80 \Omega \cdot m$, which is believed to consist of tuffaceous sand. Another study by Setiawan et al. (2018) also showed that water sources with significant potential in the ITERA area are generally found at depths greater than 25 meters.

Although these previous studies have provided a clear overview of the aquifer system and layer characteristics in the ITERA area, none of them has addressed the condition of the vadose zone, the subsurface layer located between the ground surface and the water table, where infiltration occurs and water is temporarily stored before reaching the saturated zone. This gap is significant because the characteristics of this zone play a crucial role in maintaining water availability for vegetation, particularly in conservation areas such as the ITERA Botanical Garden. Moreover, prior

research has been limited to identifying aquifer depth and lithology based on resistivity values alone, without examining parameters that describe the layer's water storage capacity, such as layer thickness, the Dar Zarrouk parameter, and rock porosity. Yet this information is essential for understanding the hydrogeological characteristics of shallow layers, which relate directly to the water needs of surface vegetation. Further research is therefore needed, one that goes beyond identifying aquifers and instead characterizes the unsaturated zone near the surface in greater depth.

One method suitable for obtaining this information is Vertical Electrical Sounding (VES), a non-invasive geophysical method that utilizes differences in the electrical properties of rocks to characterize subsurface conditions. The VES method works by injecting an electric current into the ground and then measuring the resulting potential difference to determine variations in resistivity with depth (de Almeida et al., 2021). This method's ability to provide vertical information on changes in resistivity makes it effective for determining layer boundaries, layer thicknesses, and subsurface material characteristics. Hussain et al. (2016) also showed that the VES method can be used to identify vadose zones based on resistivity distribution patterns.

Unlike previous studies conducted in the ITERA area, this study aims to examine the characteristics of the vadose zone at the ITERA Botanical Garden using a more in-depth interpretive approach. It not only identifies lithology based on resistivity values but also integrates the interpretation results with Dar Zarrouk parameters and estimates of rock porosity. This approach is expected to provide a more comprehensive picture of the conditions of the unsaturated zone, its water storage capacity, and the porosity of the rocks comprising the vadose zone.

This study employed the Vertical Electrical Sounding (VES) method using the Schlumberger configuration to obtain information on subsurface conditions in the ITERA Botanical Garden area. The objectives of this study include identifying subsurface

lithology based on resistivity distribution; characterizing the vadose zone based on resistivity values, layer thickness, and Dar Zarrouk parameters; and estimating rock porosity based on the interpretation of the resistivity data. The results of this study are expected to serve as foundational information for understanding shallow hydrogeological conditions and to support water resource management and vegetation sustainability in the ITERA Botanical Garden area.

RESEARCH METHOD

Locations and Data Acquisition

The research was conducted at the ITERA Botanical Garden in South Lampung. Measurements were carried out using the Vertical Electrical Sounding (VES) method with a Schlumberger configuration at five sounding points distributed throughout the study area, as shown in Figure 2. The length of the track at each VES point is 200 meters, with AB/2 not exceeding 100 meters.

The current electrode spacing (AB/2) was selected in increments ranging from 1.5 meters

to 100 meters, specifically: 1.5; 2.5; 4; 6; 8; 10; 12; 15; 20; 25; 30; 40; 50; 60; 75; and 100 meters. The potential electrode spacing (MN/2) was set at 0.5 meters when AB/2 ranged from 1.5 to 15 meters. When AB/2 was in the range of 15 to 75 meters, MN/2 was set to 5 meters. For AB/2 values of 75 and 100 meters, the MN/2 value used was 10 meters. This adjustment was made so that the measured potential difference fell within the range that the instrument could read.

Regional Geology

Based on the regional geological map (Mangga et al., 1993), the distribution of these measurement points falls within the QTI Formation. The QTI Formation consists of pumiceous tuff, rhyolitic tuff, tuff within tuffite, tuffaceous claystone, and tuffaceous sandstone (Mangga et al., 1993). The lithology indicates that this formation was formed as a result of volcanic activity from explosive eruptions that produced pyroclastic material. This pyroclastic material underwent compaction and lithification, resulting in the formation of pyroclastic rock.

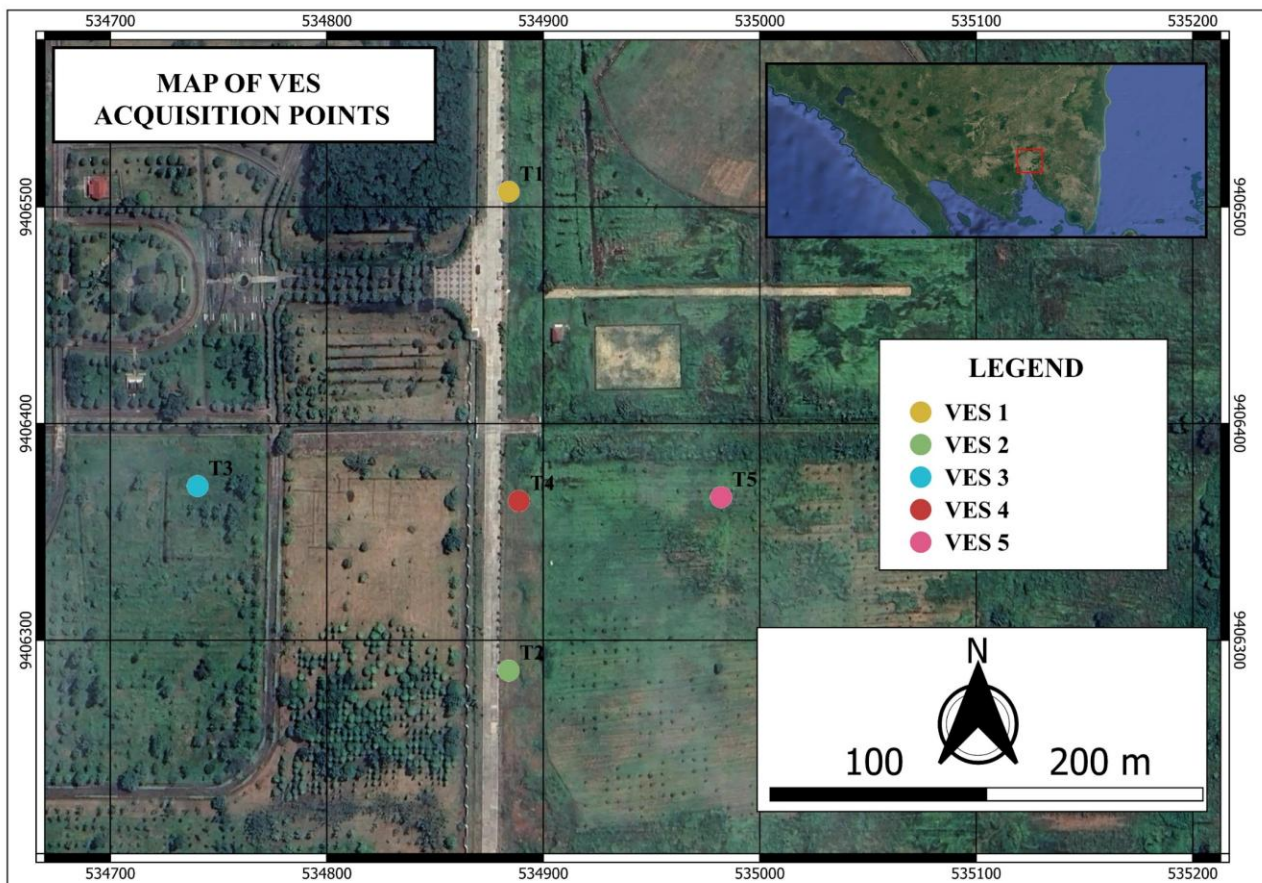


Figure 2. Design Map Based on VES Data Acquisition

Vertical Electrical Sounding (VES) Method

The VES method is one of the methods used in electrical geophysics to observe variations in subsurface resistivity with depth along a single azimuth (Ogunbo et al., 2018). This study used the Schlumberger configuration, an electrode arrangement in which the current electrodes (A and B) are spaced much farther apart than the potential electrodes (M and N). Thus, as the distance AB/2 increases, the depth of penetration increases, allowing variations in subsurface resistivity to be depicted (El Makrini et al., 2022).

The Schlumberger configuration is one of the electrode configurations used in the geoelectric method, in which the current electrodes are spaced farther apart than the potential electrodes, thereby allowing for the investigation of vertical variations in subsurface resistivity through changes in the spacing between the current electrodes (Ogunbo et al., 2018).

In Figure 3a, current flows through electrodes A and B, while the potential difference is measured between electrodes M and N. The principle behind this configuration is that the distance between the potential electrodes (M and N) is kept constant, while the distance between the current electrodes (A and B) is varied. When the distance between the current electrodes changes significantly, the distance between the potential electrodes is also changed, but by no more than 1/5 of the distance between the current electrodes. The calculation of apparent resistivity is expressed as follows (Rofifah et al., 2023):

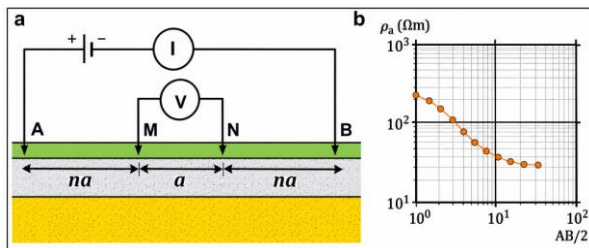


Figure 3. (a) Geophysical Electrode Configuration (b) Modified Sounding Curve Results (El Makrini et al., 2022).

$$\rho_a = K \frac{\Delta V}{I} \quad (1)$$

Where ρ_a is the apparent resistivity Ωm , and K is a geometric factor that depends on the type of configuration, specifically the distances AB/2 and MN/2. ΔV is the measured potential difference (V), and I is the current (A). The value of K, also known as the geometric factor, can be calculated using the following formula (Marín-Lechado et al., 2026):

$$K = \pi \left[\frac{(AB/2)^2 - (MN/2)^2}{MN/2} \right] \quad (2)$$

Figure 3b shows the sounding curve, which plots ρ_a on the y-axis and AB/2 on the x-axis. This sounding curve is used to determine the true resistivity values from the apparent resistivity values using forward modelling.

Vadose Zone Vulnerability Analysis

The geoelectric cross sections obtained from the VES results provide values for resistivity, depth, and thickness at each point. These parameters are then used to calculate the longitudinal conductance (S) and the resistivity of the unsaturated zone. The Dar Zarrouk parameter (DZ), or longitudinal conductance (S), is a layer parameter obtained from 1D resistivity curve modelling (Udosen et al., 2024). The following equation is used to calculate the Dar Zarrouk parameter:

$$S = \frac{h_i}{\rho_i} \quad (3)$$

Where S is the longitudinal conductance, h_i is the thickness of the unsaturated layer, and ρ_i is the resistivity of the unsaturated layer. The Dar Zarrouk parameter is used to assess the protective capacity of a layer to infiltration originating from the surface.

Porosity Calculation

Porosity is a fundamental petrophysical property of rock, defined as the ratio of the volume of voids (pores) to the total volume of the rock. These pores can be filled with air, water, hydrocarbons, or other fluids. Density is the mass of rock per unit volume (Marín-Lechado et al., 2026). These two parameters have an inverse relationship: the lower the porosity of a rock, the higher its density; conversely, the higher the porosity, the lower

the density of the rock. Resistivity difference ($\Delta\rho$) is defined as follows (Peter, 2026):

$$\Delta\rho = \rho_{max} - \rho_{min} \quad (4)$$

Where ρ_{min} is the minimum resistivity of the stratum's lithology and ρ_{max} is the maximum resistivity of the stratum. Next, calculate the resistivity percentage using the following equation (Han et al., 2011):

$$\rho = \frac{\rho_{result}}{\Delta\rho} \times 100\% \quad (5)$$

Where ρ is the resistivity, ρ_{result} is the interpreted resistivity, and $\Delta\rho$ is the difference in the resistivity range. Next, calculate the difference in the density range using the following equation (Peter, 2026):

$$\Delta d_b = d_{bmax} - d_{bmin} \quad (6)$$

Where Δd_b is the difference in the lithological density range, d_{bmax} is the maximum lithological density, and d_{bmin} is the minimum lithological density. The change in density (d) is then calculated using the equation:

$$d = \frac{P}{100} \times \Delta d_b \quad (7)$$

The relative density d_r is calculated using the following equation:

$$d_r = d_{bmax} - d \quad (8)$$

To determine the porosity value, the following formula is used, which expresses the relationship between porosity and bulk density (Fanchi, 2010):

$$\phi = \frac{d_{ma} - d_b}{d_{ma} - d_f} \times 100\% \quad (9)$$

Where ϕ is the porosity (%), d_{ma} is the rock matrix density, d_b is the calculated bulk density or relative density, and d_f is the fluid density (for freshwater, $d_f = 1.0$).

Isoresistivity Mapping

The lateral distribution of resistivity at various depths is illustrated using isoresistivity maps. Resistivity values at depths of 2, 10, 20, and 30 meters were derived by interpolating each VES point based on its depth, and then spatially interpolated using the Inverse Distance Weighting (IDW) method. The IDW

method works on the principle of assigning greater weight to measurement points that are closer to the estimated location, such that the relationship between data points and estimated values is inversely proportional to their distance (Liu et al., 2021). This method is used because, in spatial modelling of data obtained from a limited number of measurement points, it produces a representative lateral visualization of the subsurface without requiring complex statistical assumptions. The selection of depths of 2, 10, 20, and 30 meters is intended to represent changes in resistivity distribution at several depth levels considered representative of the progression of subsurface conditions from shallow to deeper layers.

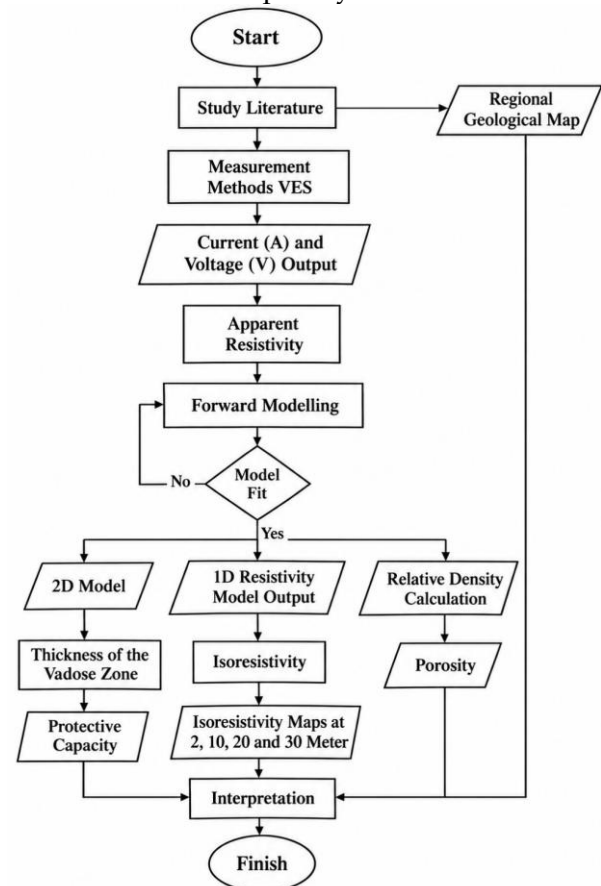


Figure 4. Research Flowchart

The resulting map was then used to identify horizontal resistivity distribution patterns and to delineate the lateral boundaries of the vadose zone throughout the study area. Variations in resistivity values at each depth were interpreted as a response to differences in lithology, water content, saturation level, and

porosity of the subsurface materials. These changes also serve as a basis for identifying the development of the vadose zone, its lateral boundaries, and the relationship among subsurface layers. This information then forms the basis for evaluating the conditions of the study area, particularly regarding the potential of the infiltration zone, the direction of development of the unsaturated zone, and its relationship to the underlying aquifer.

Research Flowchart

The overall research workflow is summarized in Figure 4. It begins with a literature review and proceeds to the development of a two-dimensional model and an iso-resistivity map.

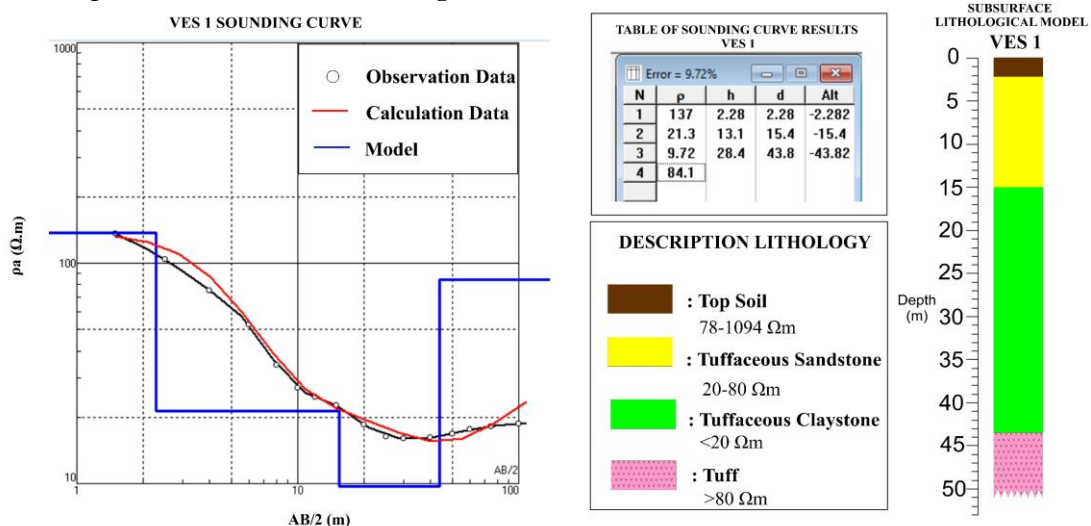
RESULTS AND DISCUSSION

Interpretation of Sounding Curves

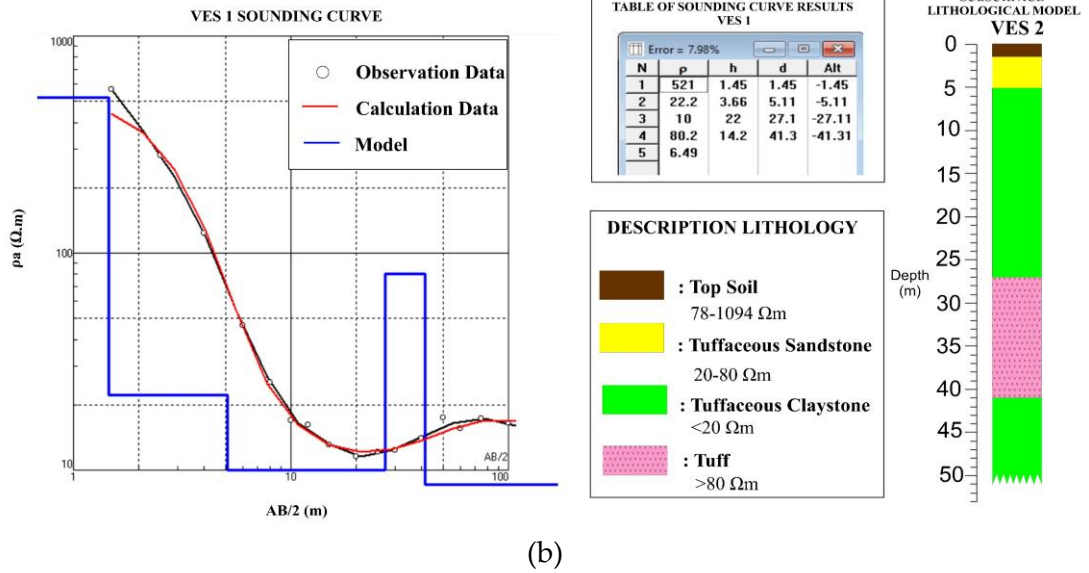
Measurements using the VES method yield apparent resistivity calculated from the geometric factor (K), current (A), and voltage (V) (Christopher et al., 2023). Apparent resistivity cannot yet be interpreted, so forward modelling is required to determine the true resistivity values. This forward modelling compares the plot of the $AB/2$ function against

apparent resistivity values (ρ_a) on the y-axis. The results of this forward modelling not only yield resistivity values but also determine the thickness (h) and depth (d). Therefore, forward modelling is necessary to determine the true resistivity values, as presented in Figure 5.

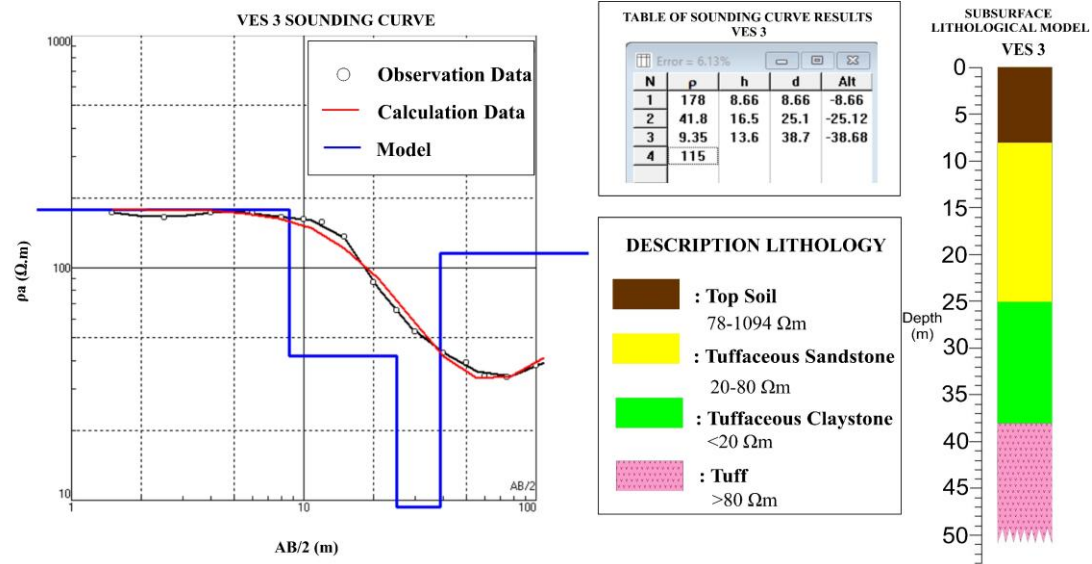
The sounding curve results and resistivity interpretations shown in Figure 5(a) through 5(e) indicate variations in resistivity values that reflect differences in lithological characteristics at the five VES points in the ITERA Botanical Garden study area. The results of the five-point sounding curves show five layers consisting of topsoil, tuffaceous sandstone, tuffaceous claystone, tuff, and tuffaceous claystone at the very bottom. Each point has a different error value. For the VES 1 sounding curve, the error value was 9.72%; for the VES 2 sounding curve, the error value was 7.98%; for the VES 3 sounding curve, the error value was 6.13%; for the VES 4 sounding curve, the error value was 11.9%; and for the VES 5 sounding curve, the error value was 9.85%. This error value indicates the difference between the observed data and the calculated data. The results of the VES curves for points 1 through 5 show small error values, indicating that the resulting model is accurate.



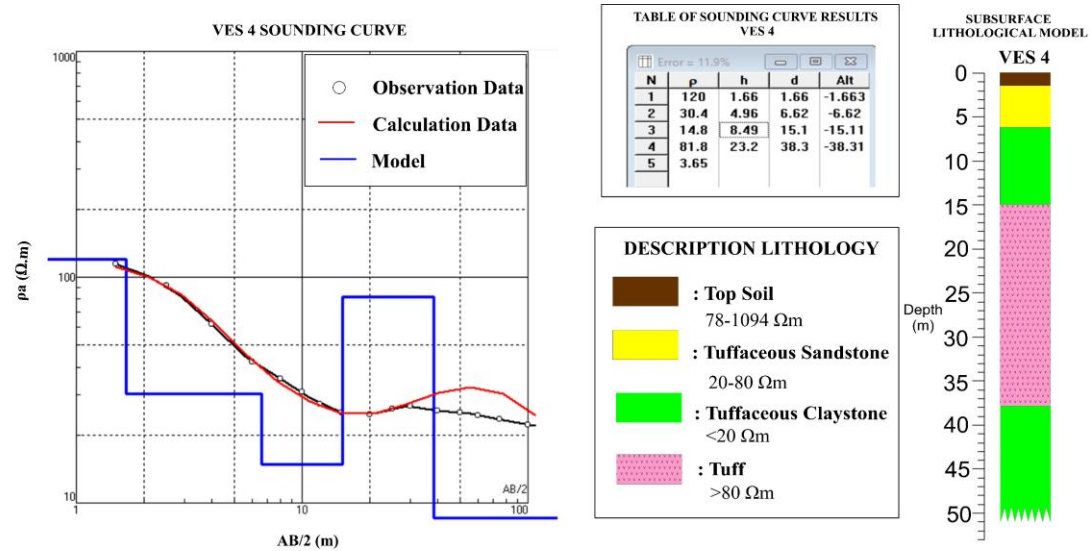
(a)



(b)



(c)



(d)

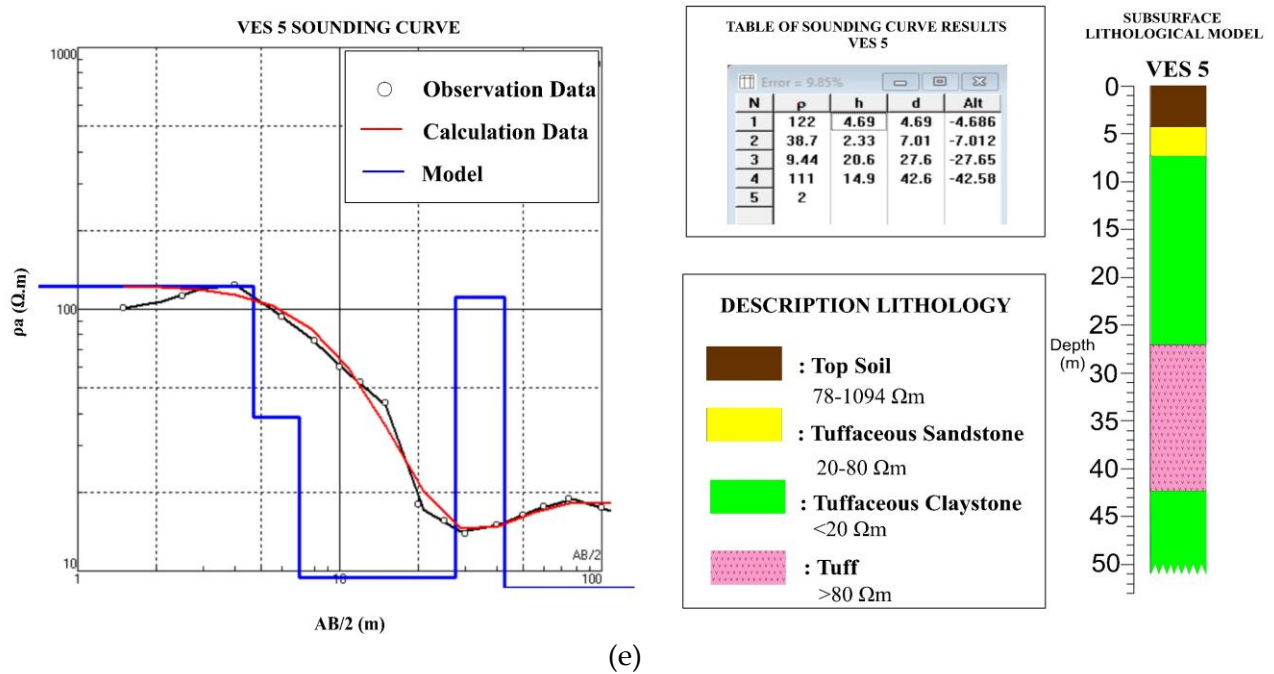
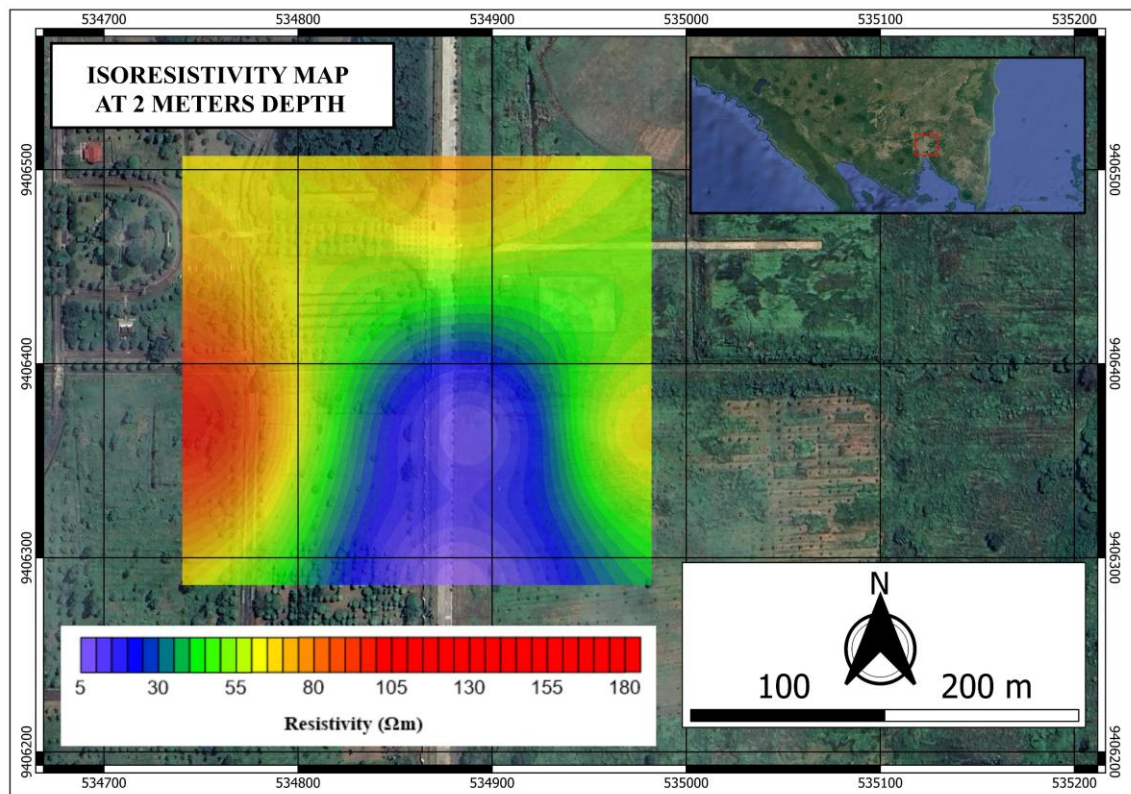


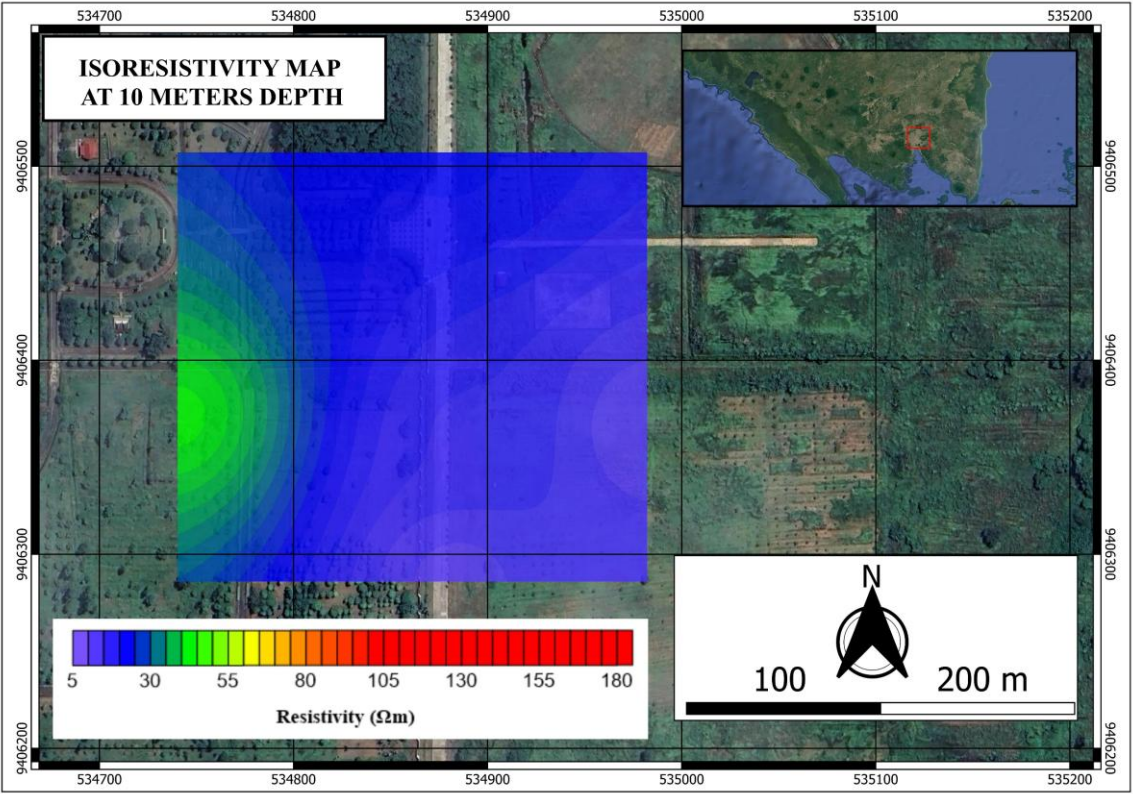
Figure 5. Sounding Curves: (a) VES 1, (b) VES 2, (c) VES 3, (d) VES 4, and (e) VES 5

Isoresistivity

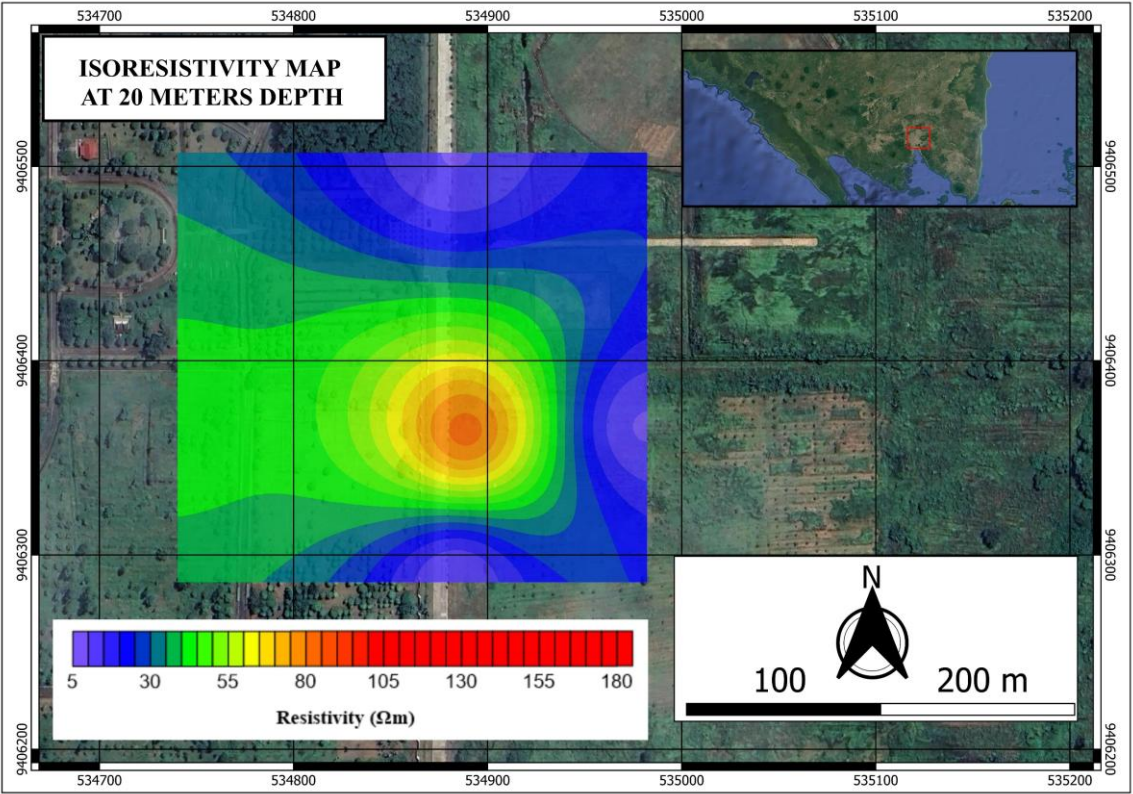
Resistivity values vary both horizontally and vertically. These variations depend on the type of lithology and are related to the porosity and water content of the rock (Archie, 1942).

Therefore, it is necessary to map the distribution of resistivity with respect to depth. Such mapping helps identify differences in material characteristics. The results of this mapping are shown on the isoresistivity map in Figure 6 .

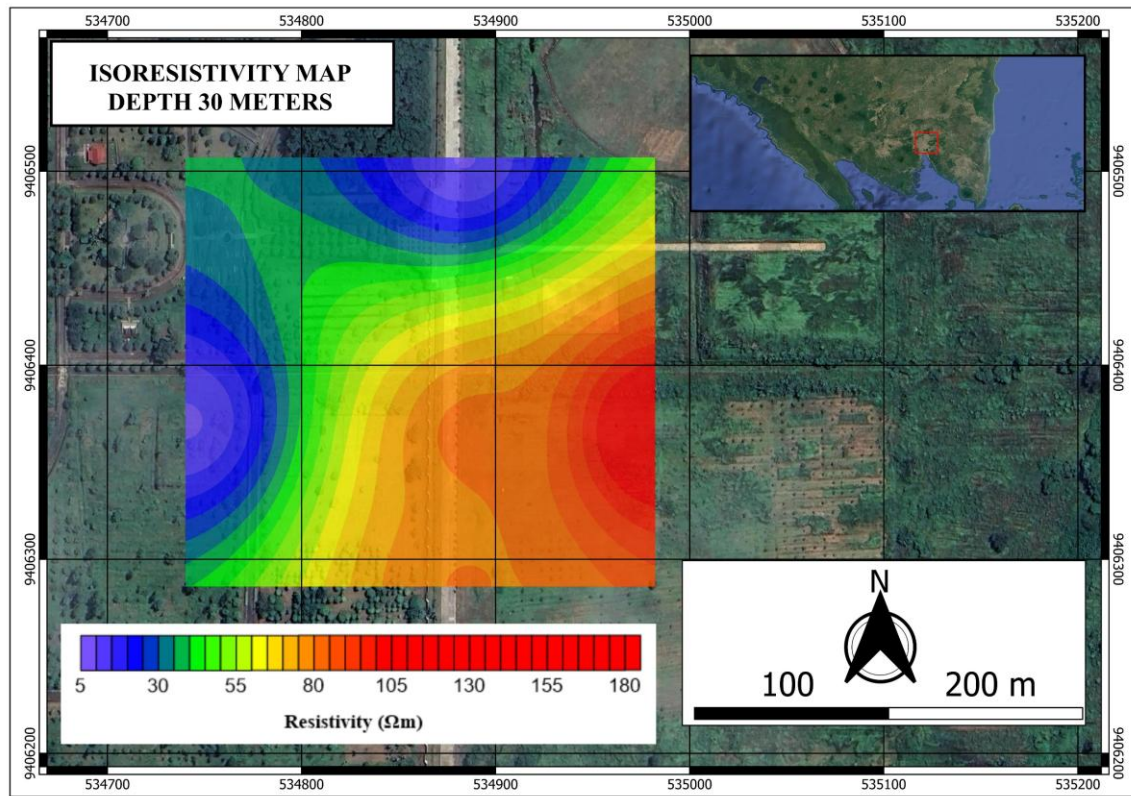




(b)



(c)



(d)

Figure 6. Isoresistivity Maps using the Inverse Distance Weighting (IDW) Method at Each Depth:

(a) 2 meters, (b) 10 meters, (c) 20 meters, (d) 30 meters

An isoresistivity map is a map that shows the distribution and horizontal variation of resistivity in the study area at different depths (Nisar et al., 2023). The isoresistivity map was interpolated using the Inverse Distance Weighting (IDW) method, resulting in the resistivity distribution shown in Figure 6. The figure shows that at a depth of 2 meters, resistivity values range from 22.2 to 178 Ωm ; at a depth of 10 meters, resistivity values range from 9.44 to 41.8 Ωm ; at a depth of 20 meters, resistivity values range from 9.44 to 81.8 Ωm ; and at a depth of 30 meters, resistivity values range from 9.72 to 111 Ωm . Low resistivity values at each depth are shown in blue, while high resistivity values are shown in red.

The results of the isoresistivity map show a pattern of resistivity values that increases with depth in the central part of the study area. This indicates differences in subsurface lithological characteristics, which are also shown in the results of the 1D VES model,

where zones with high resistivity are interpreted as more compact and dry material, while the low-resistivity zone is interpreted as softer, more conductive material. Vertically, at depths of 10 to 30 meters, a zone of low resistivity begins to appear. This correlates with the subsurface conditions at the ITERA Botanical Garden, which are dominated by volcanic deposits of the Lampung Formation, specifically tuffaceous sandstone, tuffaceous claystone, and tuff, all of which have low rock resistivity.

Thickness of the Vadose Zone

The vadose zone is the zone located between the ground surface and the water table; therefore, the thickness of the vadose zone is calculated by determining the difference in depth between the aquifer (tuff layer) and the ground surface (Jie et al., 2022). The thickness of the vadose zone is shown in Figure 7.

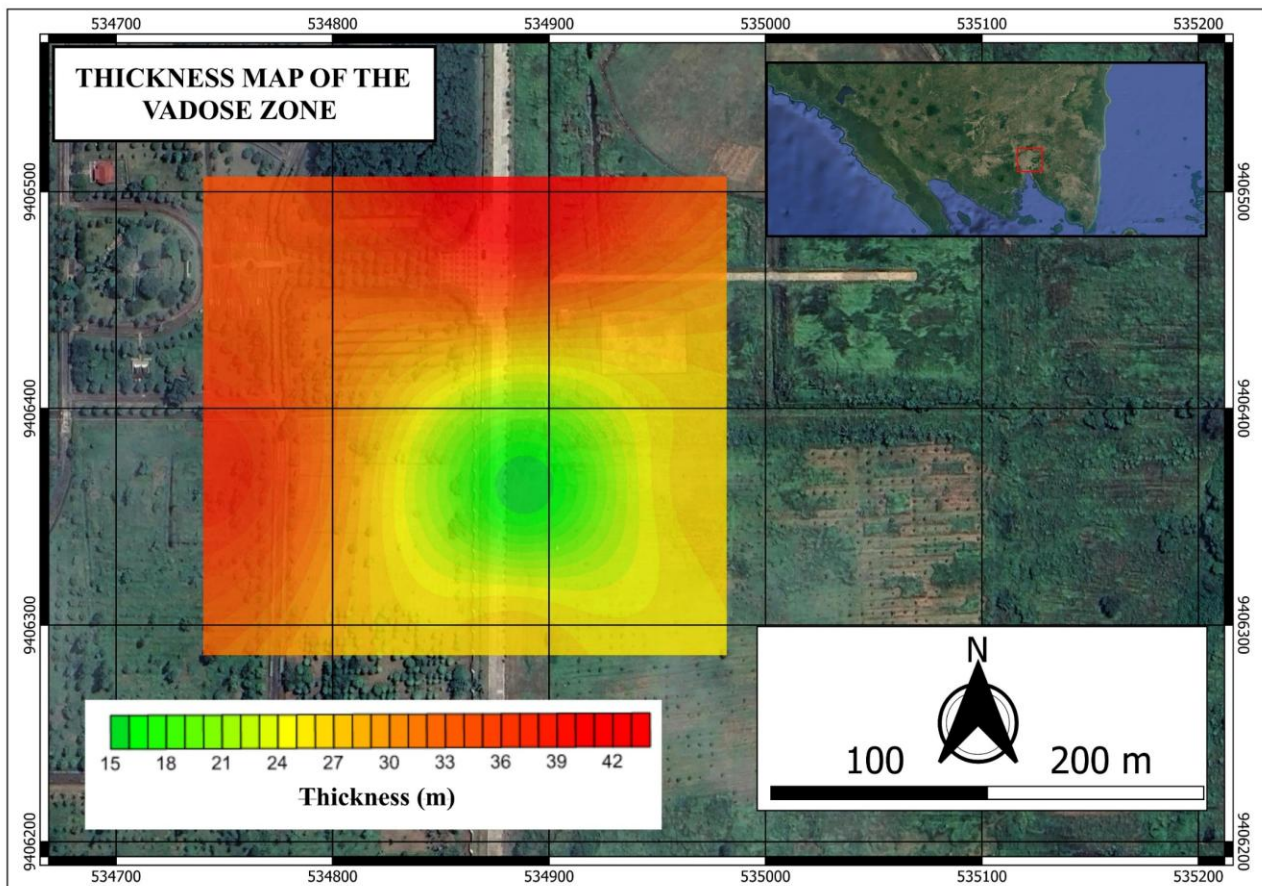


Figure 7. Map of Vadose Zone Thickness

The thickness of the vadose zone is an important factor affecting the delay in groundwater recharge. A significant delay in groundwater recharge occurs due to the large thickness of the vadose zone (Jie et al., 2022). In Figure 7, the areas with the greatest vadose zone thickness are at research points 1 and 3. The groundwater table in these zones is deeper, so it takes longer for rainwater to reach the saturated zone. This condition indicates a greater temporary water-holding capacity in the unsaturated zone. In addition to thickness, the delay in groundwater recharge is also caused by the porosity of the subsurface layer. The thicker the vadose zone, the greater the volume of the unsaturated zone that infiltrating water must pass through before reaching the groundwater table. Consequently, a thicker vadose zone results in slower groundwater recharge because the water must seep through a thicker

unsaturated zone before reaching the aquifer (Mbiimbe et al., 2020). This condition is one of the factors preventing groundwater levels in some parts of the ITERA Botanical Garden from rising immediately after rainfall.

Protective Capacity

Vertical and lateral variations in geophysical methods require several additional parameters that effectively link resistivity and hydrogeological properties, or a combination of various derived properties, namely thickness and resistivity, to accurately identify additional information and characteristics of the study area. This is known as the Dar Zarrouk parameter (Nemer et al., 2023). These parameters are divided into low, medium, and high zones, indicated by the colors blue, green, and red, respectively, as presented in Figure 8.

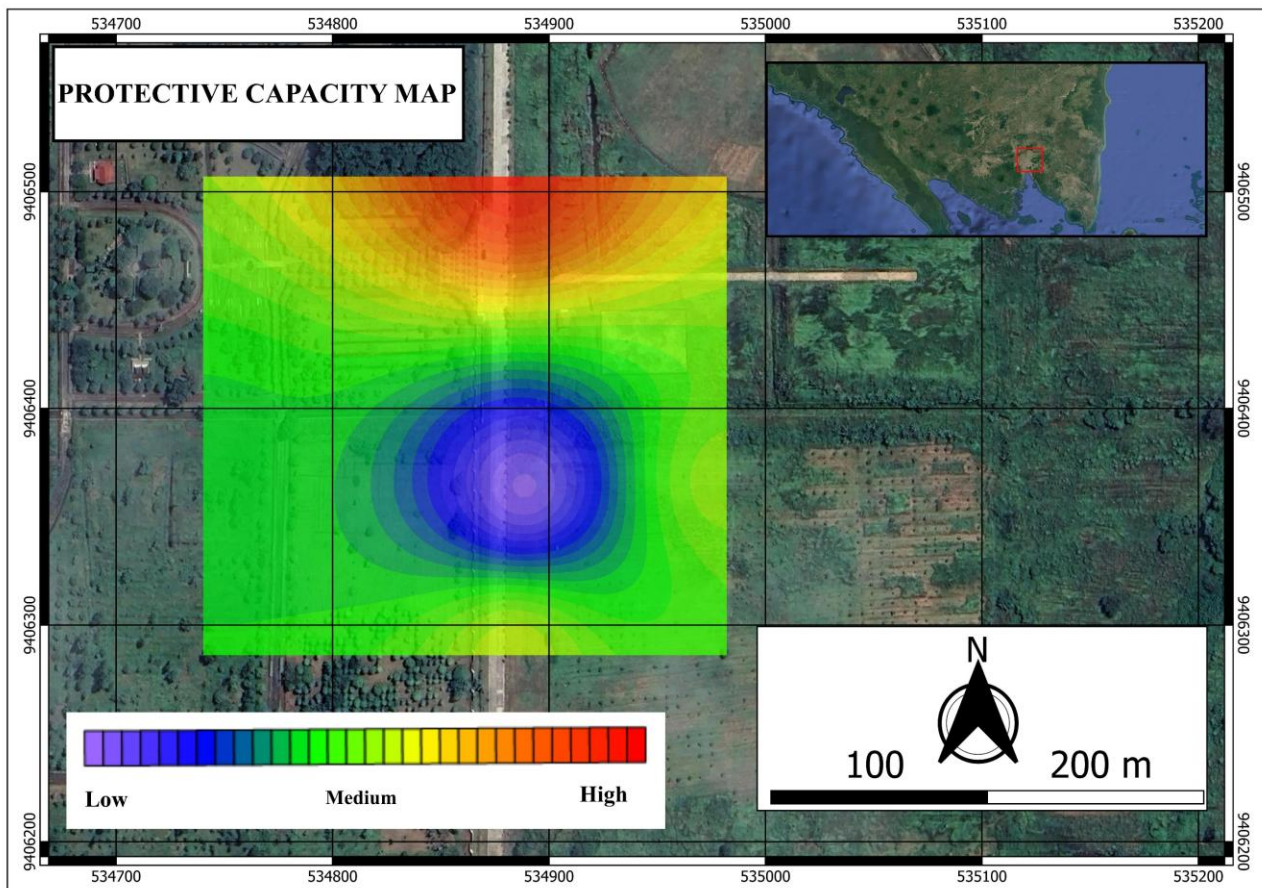


Figure 8. Protective Capacity Map

The thickness of the vadose zone is directly proportional to the aquifer's protective capacity in shielding groundwater from surface contamination (Mbiimbe et al., 2020). At Point 1, where the vadose zone is approximately 43 meters thick, the aquifer's protective capacity is relatively high because the thicker unsaturated zone can slow the movement of contaminants toward the saturated zone. Conversely, at Point 4, where the vadose zone is thinner, the likelihood of contaminants reaching the aquifer is relatively higher. Therefore, in the management of the ITERA Botanical Garden, the area around Point 4 should not be used for composting, chemical storage, or organic waste disposal to minimize the risk to groundwater, a vital resource for the area.

Porosity

Porosity is the ratio of the total pore volume of a rock to the total volume of the rock itself (Ortiz-Marqués et al., 2025). The results of vadose zone porosity for each VES

measurement, namely the lithological porosity of the vadose zone, are presented in Table 1.

Table 1. Vadose Zone Porosity Measurement Results for Each Layer at Five Observation Points

Points	Layer	Porosity (%)
T1	Topsoil	20.00
	Tuffaceous Sandstone	10.91
	Tuffaceous Claystone	11.76
T2	Topsoil	20.00
	Tuffaceous Sandstone	11.52
	Tuffaceous Claystone	12.35
T3	Topsoil	20.00
	Tuffaceous Sandstone	21.82
	Tuffaceous Claystone	11.18
T4	Topsoil	20.00
	Tuffaceous Sandstone	15.76
	Tuffaceous Claystone	18.24
T5	Topsoil	20.00
	Tuffaceous Sandstone	20.61
	Tuffaceous Claystone	11.76

The vadose zone in the study area consists of three main layers: topsoil, tuffaceous sandstone, and tuffaceous claystone. These three layers have different porosity values at each research site, as shown in Table 1. These

differences in porosity values reflect variations in the physical characteristics of the subsurface materials, such as grain size, degree of weathering, and degree of rock compaction. The topsoil layer has the highest porosity value, at around 20%, indicating that this layer has more pore space than the layers beneath it. The porosity values of tuffaceous sandstone range from 10.91% to 21.82%, indicating that this layer still has fairly good pore space. Meanwhile, tuffaceous claystone generally exhibits lower porosity values, ranging from 11.18% to 18.24%, suggesting that this layer has, on average, undergone greater compaction and therefore has relatively less pore space. These variations in porosity indicate subsurface heterogeneity in the study area of the ITERA Botanical Garden, which is composed of tuff deposits.

Conceptual Model

To determine the continuity or distribution of subsurface lithology from the VES points, a two-dimensional lithological

distribution model was created. The lithological distribution can be depicted based on the resistivity values at each VES point, which are then correlated based on their ranges. Each lithology has a different resistivity value. The results of the two-dimensional model are shown in Figure 9.

The 2-dimensional model shows the distribution of subsurface lithologies, starting with topsoil in the first layer, tuffaceous sandstone in the second layer, tuffaceous claystone in the third layer, tuff in the fourth layer, and tuffaceous claystone in the fifth layer. The results of this lithological interpretation indicate that the vadose zone is estimated to extend from the first to the third layers. In addition, a 2-dimensional lithological distribution model that intersects this two-dimensional model was created, as shown in Figure 10. The results of the 2-dimensional model show the same lithology as the previous 2-dimensional model. Thus, these overlapping 2-dimensional results can improve the accuracy of lithological interpretation.

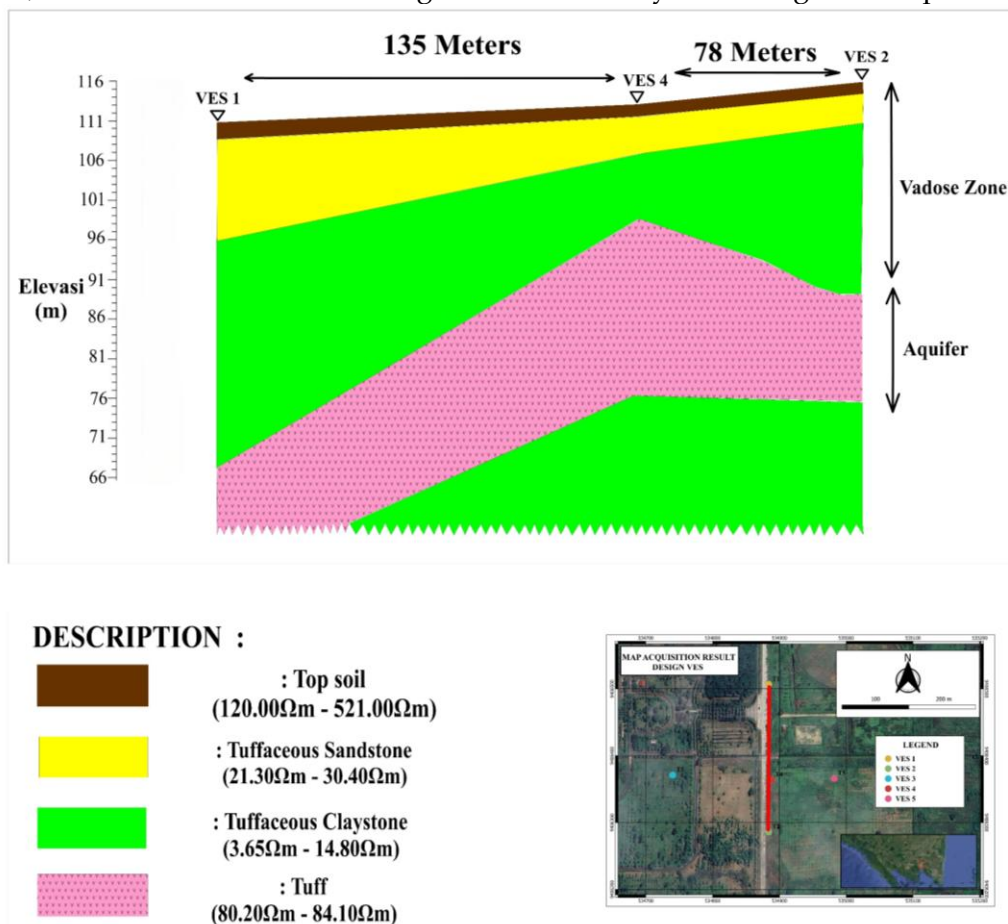


Figure 9. 2D Subsurface Lithological Model at VES 1, VES 4, and VES 2

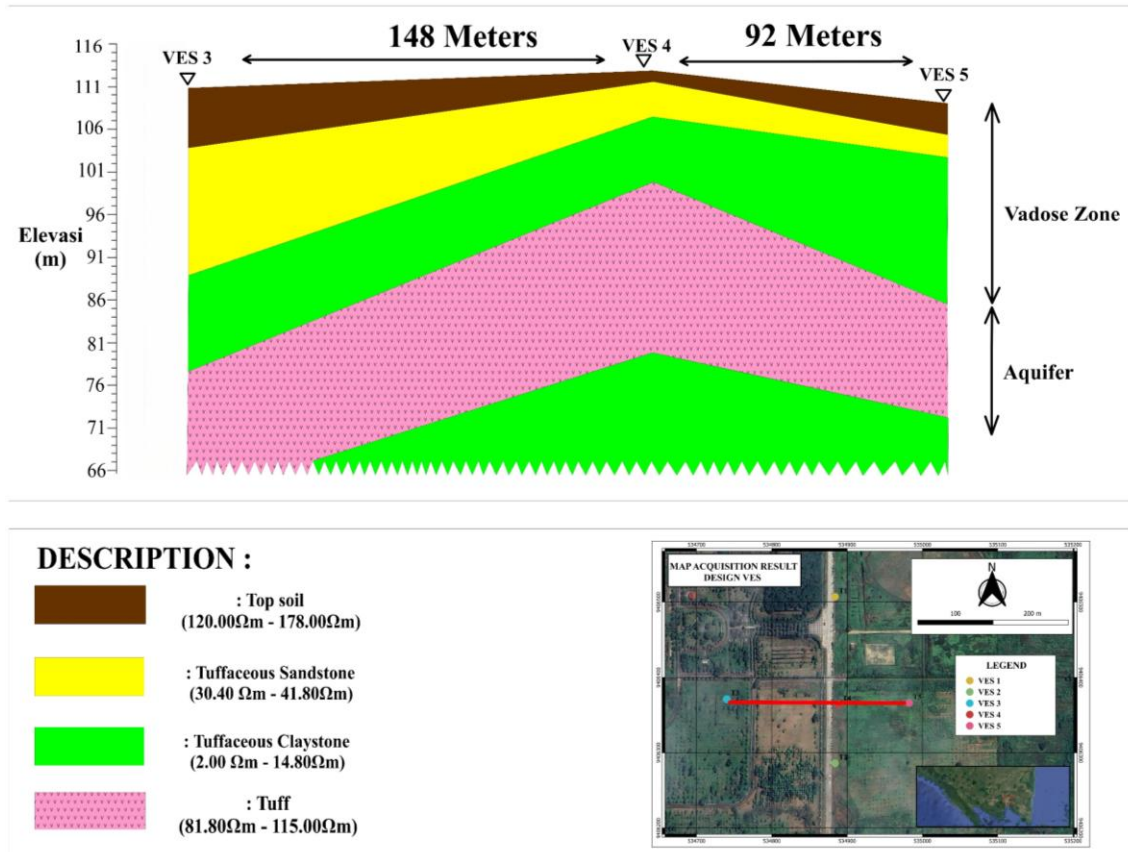


Figure 10. 2D Model of Subsurface Lithological Distribution from VES Points 3 to 5

Ecological Interpretation

The thickness of the vadose zone varies from location to location based on the results of the VES method. At Point 1, the vadose zone thickness is 43 meters; at Point 2, the vadose zone thickness is 27 meters; at Point 3, the vadose zone thickness is 38 meters; at Point 4, the vadose zone thickness is 15 meters; and at Point 5, the vadose zone thickness is 27 meters. In addition, the porosity of each layer varies, as shown in Table 1. The thickness of the vadose zone and the layers within it can affect water storage and air circulation. The higher the porosity of the layer and the thinner the vadose zone, the faster the aquifer recharges and the less effective its natural filtration becomes (Hartmann et al., 2021). These conditions affect the growth and root systems of the plants at the ITERA Botanical Garden, so this area requires attention. Point 1 has a relatively deeper vadose zone compared to the other points, so the potential for contamination of the aquifer in that area is lower, which can support the sustainability of the ITERA Botanical Garden ecosystem.

Hydrogeological and Ecological Implications of the Vadose Zone on the Function of the ITERA Botanical Garden

The thickness of the vadose zone at the ITERA Botanical Garden varies from one measurement point to another. This is clearly evident in the two-dimensional lithological cross-section that has been compiled. These variations in thickness essentially reflect the distance that rainwater must travel before it finally reaches the groundwater table. In areas with a shallow vadose zone, rainwater tends to be absorbed more quickly until it reaches the aquifer. This condition is certainly beneficial for meeting the water needs of the Botanical Garden's plants, especially during the dry season. In contrast, areas with a deeper vadose zone serve as a temporary reservoir for rainwater, as they can retain infiltrating water for a longer period of time.

Beyond its role as a pathway for infiltration, the vadose zone also functions as a natural filter that helps trap some pollutants before the water fully seeps in. However, this filtration capacity decreases in areas where the

vadose zone has high porosity and is thin, thereby increasing the likelihood of aquifer contamination by surface runoff (Ashagrie et al., 2025). This is a cause for concern, given that various activities at the ITERA Botanical Garden, such as the use of fertilizers or other chemicals on the soil surface, have the potential to be carried away and seep through the vadose zone into groundwater sources.

CONCLUSION

Based on the processing, interpretation, and analysis of Vertical Electrical Sounding (VES) geophysical data, this study concludes that the interpretation of resistivity values indicates that the subsurface lithology in the study area consists of five main layers, namely topsoil, tuffaceous sandstone, tuffaceous claystone, tuff, and tuffaceous claystone.

The vadose zone was identified based on resistivity values. The thickness of the vadose zone varies among the measurement points, ranging from 15 to 43 meters. Areas with a thicker vadose zone have a deeper groundwater table, so the infiltration time to the saturated zone is relatively longer. Conversely, areas with a thinner vadose zone have the potential for faster groundwater recharge, but their natural protection against surface contamination is relatively lower.

Porosity estimates indicate differences in pore space characteristics among the various lithologies. The topsoil layer has the highest porosity, followed by tuffaceous sandstone, while tuffaceous claystone has the lowest porosity. These variations in porosity reflect the heterogeneity of the rocks' physical properties in the vadose zone and are one of the factors influencing the subsurface layers' ability to store and release water.

This study still has some limitations that need to be taken into account. The use of a five points sounding with a Schlumberger configuration and a 200 meters line length does not sufficiently represent the subsurface conditions of the ITERA Botanical Garden as a whole, given the area's considerable size and the nature of VES interpretation, which can only depict layers vertically (one

dimensionally), meaning that lateral lithological variations are not yet fully understood; the penetration depth achieved is also limited by the length of the electrode array used. The identification of subsurface lithology, resistivity values, layer thickness, and Dar Zarrouk parameters was based on the interpretation of isoresistivity from the VES data, while the estimated rock porosity values were derived from lithological interpretation referring to these resistivity values. Given these limitations, future research is recommended to increase the number and density of sounding points. It is also recommended that measurements be taken using the 2-dimensional geoelectric method so that the distribution of resistivity can be determined both vertically and horizontally. In addition, repeat measurements during different seasons could help evaluate the effect of soil moisture content on resistivity results. Control data from wells or groundwater data are also needed to validate the interpretation of resistivity results and to ensure the sustainability of the groundwater system in this area. Given that the available data are still limited, the results of this study should be used as preliminary references that need to be supplemented by further surveys before being fully implemented in the water management planning for the ITERA Botanical Garden.

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