Eksakta : Berkala Ilmiah Bidang MIPA
VOLUME 27 NO 04 2026, pp 620-636
ISSN : Print 1411-3724 — Online 2549-7464
DOI : https://doi.org/10.24036/eksakta/vol27-iss04/713

Eksakta
Berkala Ilmiah Bidang MIPA
http://www.eksakta.ppj.unp.ac.id/index.php/eksakta

Article

VES-GIS Application for Groundwater Potential and Aquifer Identification in Talang Kelapa District, Banyuasin, South Sumatra

Muhammad Arif[1*], Andjarila Nurryska[1], Rizka[1]

[1]Study Program of Geophysical Engineering, Faculty of Industrial Technology, Institut Teknologi Sumatera, Lampung, Indonesia

Article Info

Article history :
Received June 23, 2026
Revised July 16, 2026
Accepted July 23, 2026
Published August 30, 2026

Keywords :
Aquifer, banyuasin,
gumai formation,
GIS – AHP,
vertical electrical sounding (VES)

Abstract. Talang Kelapa District faces serious challenges regarding a high risk of groundwater drilling failure due to extreme lithological heterogeneity in the Gumai Formation. This study aims to identify aquifer geometry characteristics and accurately map groundwater potential zones to support sustainable water resource management. The method integrates Geographic Information System-Analytical Hierarchy Process (GIS-AHP) spatial analysis using six parameters: regional geology, slope, rainfall, drainage density, land use/land cover (LULC), and soil type. Subsurface validation was conducted using Vertical Electrical Sounding (VES) geophysical surveys with the Schlumberger configuration at six observation points to determine vertical resistivity profiles. The results show that the primary hydrogeological target is an unconfined aquifer system within sandstone layers, characterized by depths of 2.4–16.8 m and thicknesses reaching 21.9 m. The integration of these two methods produced a significant positive correlation between the Groundwater Potential Index (GPI) score and the actual aquifer thickness from VES, yielding a coefficient of determination (R^2) value of 0.76. This study concludes that an integrative multi-criteria approach is an effective exploration instrument for recommending optimal drilling depths and minimizing technical exploration risks.

Corresponding Author :
Muhammad Arif
Study Program of Geophysical Engineering, Faculty of Industrial Technology,
Institut Teknologi Sumatera, Lampung, Indonesia
Email : arifgtg3343@gmail.com

1. Introduction

Access to clean water has become a global strategic issue that continues to receive significant attention within United Nations policies through the sixth goal of the Sustainable Development Goals (UNESCO & American Geophysical Union, 2023). Pressure on water resources continues to increase due to population growth, urbanization, and land use changes, which directly affect the decline in groundwater availability, particularly in developing regions [1]. This condition is also evident in Talang Kelapa District, Banyuasin Regency, which has experienced rapid growth in residential areas and industrial activities.

The increasing demand for clean water has not been balanced by adequate surface water availability, resulting in a high dependence on groundwater resources. However, groundwater exploitation in this area frequently encounters several constraints, including uncertainty regarding aquifer depth, variations in water quality, and the risk of drilling failure caused by heterogeneous lithological conditions [2]. Therefore, accurate identification of groundwater potential has become an urgent necessity in this region.

Spatial-based groundwater potential mapping using Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) has been proven regionally effective in integrating surface biophysical parameters [3-5]. These studies demonstrated that GIS and AHP constitute effective methods for spatial groundwater potential mapping because they are capable of integrating various surface spatial parameters, such as geology, topography, rainfall, soil characteristics, drainage, and land use, into a unified decision-making model. Their findings indicated that this method can generate accurate groundwater potential zonation validated through field data and provide significant benefits for water resource planning, drought mitigation, and sustainable environmental management at a regional scale.

Nevertheless, the method has limitations because its results tend to be predictive of surface conditions, as this approach has not yet been able to provide verification of aquifer conditions vertically [6]. In line with this, the integration of geophysical data is considered essential to reduce uncertainties arising from subjective spatial models [7]. On the other hand, the geophysical method Vertical Electrical Sounding (VES) with Schlumberger configuration is widely recognized as a standard method for accurately identifying aquifer geometry and rock resistivity values [8-9]. However, the VES method has limitations in terms of spatial coverage because it is point-based [10]. making it less representative when used independently to map extensive areas without interpolation using other spatial data.

This approach aims to overcome the weaknesses of each method through the integration of surface spatial data and vertical subsurface data. Previous research in the Banyuasin area identified aquifer lithology using geoelectrical methods but did not integrate it with the AHP-GIS method [8]. Conversely, another study focused on groundwater potential mapping using GIS without validation through vertical geophysical data [11]. A clear research gap remains, particularly regarding the quantitative integration between surface parameter weighting and verification of subsurface aquifer thickness, especially within the complex sedimentary environment of the Gumai Formation. This study is positioned to bridge this gap by connecting GIS (Geographic Information System) and VES (Vertical Electrical Sounding) data.

The novelty of this study lies in its integrative approach, which directly synchronizes the Groundwater Potential Index (GPI) score with the actual aquifer thickness through linear regression correlation analysis. This distinguishes the present study from previous works, as VES data are not merely used as supporting information but rather as a numerical validation parameter for the constructed spatial model. Based on this framework, the study aims to spatially map groundwater potential zones using a GIS-AHP-based Groundwater Potential Index (GPI) model, followed by the identification of groundwater aquifer characteristics through the determination of resistivity variations, depth, and thickness of groundwater-bearing layers using the Vertical Electrical Sounding

(VES) method [12]. The results from both approaches are subsequently synthesized to develop a local hydrogeological conceptual model representing the aquifer system within the study area. Therefore, this study is expected to contribute significantly to the development of more accurate and applicable exploration methods while minimizing the risk of groundwater drilling failure in regions characterized by high lithological complexity.

2. Materials and Methods

2.1. Materials Methods GIS and Analytical Hierarchy Process (AHP)

The GIS and Analytical Hierarchy Process (AHP) methods were employed to spatially map surface groundwater potential zones. These methods were selected because of their capability to integrate various environmental parameters influencing the hydrogeological system. Spatial data processing, layer reclassification, and weighted overlay analysis were carried out using ArcGIS 10.8 software.

The parameters used in this decision model included regional geology, rainfall, land cover (LULC), soil type, drainage density, and slope gradient. All parameters were processed within a GIS environment through classification and weighting standardization procedures. To maintain the structural consistency of the decision model and avoid parameter redundancy, the elevation parameter was excluded from the matrix computation.

Parameter weighting was carried out using the AHP method through a pairwise comparison matrix. Each parameter was compared with the others based on its level of influence on groundwater potential. The finalized structure and mathematical calculation of the AHP comparison matrix are presented in Table 1.

Table 1. Weight Calculation

Factors	Geology	Slope	Rainfall	Drainage	LULC	Soil Type	Weight
Geology	1	2	3	3	4	4	36.18%
Slope	1/2	1	2	2	3	3	22.74%
Rainfall	1/3	1/2	1	1	2	2	13.15%
Drainage	1/3	1/2	1	1	1	2	13.15%
LULC	1/4	1/3	1/2	1/2	1	1	7.39%
Soil Type	1/4	1/3	1/2	1/2	1	1	7.39%
SUM	2.66	4.66	8	8	13	13	100%

The parameter weights were obtained through matrix normalization and subsequently tested for consistency using:

$$CR = \frac{CI}{RI}$$

CR = *Consistency Ratio*
CI = *Consistency Index*
RI = *Random Index*

In the Analytical Hierarchy Process (AHP) analysis for determining GIS parameter weights, the Consistency Index (CI) is used to measure the degree of consistency deviation within the comparison matrix, while the Random Index (RI) represents a standard random index value determined based on the number of parameters used [13]. Both components serve as the primary basis for generating the Consistency Ratio (CR), which represents the final ratio used to assess the validity of the weighting process. If the CR value is less than 0.1 (10%), the parameter weighting is considered consistent and scientifically acceptable for further spatial model processing. The consistency test of the AHP weighting produced a Consistency Ratio (CR) value of 0.0056, which is lower than the acceptable threshold of 0.1. This indicates that the pairwise comparison matrix is highly consistent and the assigned weights are reliable for groundwater potential analysis [14].

2.2. Methods Vertical Electrical Sounding (VES)

This study was conducted in Talang Kelapa District, Banyuasin Regency, South Sumatra, during August 2025. The Vertical Electrical Sounding (VES) method was selected because of its capability to identify vertical variations in subsurface resistivity. The VES method has been proven effective in determining aquifer depth and thickness through the identification of subsurface layers based on resistivity values, and it can be applied in geological settings composed of hard rock and sedimentary formations [15].

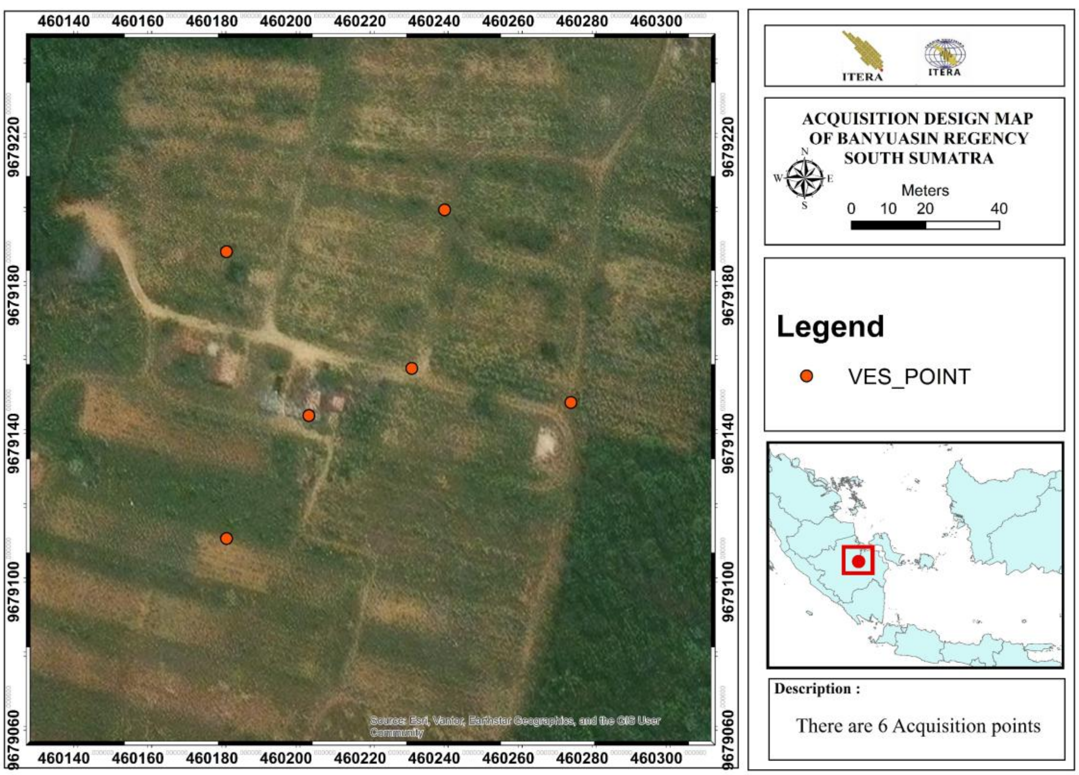

Figure 1. Survey Design Map

Figure 1 illustrates the acquisition design, in which data acquisition was carried out at six VES points distributed across the study area using a purposive sampling technique, taking into consideration geological conditions, land cover, and topography. The measurement points were subsequently arranged into VES correlation sections to generate two-dimensional subsurface profiles, with each survey line extending approximately 75–100 m.

The acquisition design employed the Schlumberger configuration, in which the current electrodes (A and B) were positioned symmetrically with respect to the midpoint, while the potential electrodes (M and N) were placed at the center with a smaller spacing interval. The initial electrode spacing was determined as a, which was then gradually increased using a specific multiplication factor to achieve greater depth penetration.

Measurements were conducted using a resistivity meter, electrodes, connecting cables, and a GPS device for coordinate determination. At each variation of electrode spacing, the electric current (I) and potential difference (ΔV) values were recorded. The acquired data were subsequently converted into apparent resistivity values using the following equation:

$$\rho_a = K \, . \, \frac{\Delta V}{I}$$

P_a = Apparent resistivity (Ω m)
ΔV = Potential difference (Volt)
I = Electric current AB (Ampere)
K = Geometric factor (m)

Subsequently, a quantitative 1D inversion process was performed using IPI2Win software to generate the true resistivity model. Interpretation was carried out by correlating the resulting true resistivity values with lithological characteristics, enabling the accurate identification of topsoil layers, unsaturated zones, aquifers, and impermeable layers within the study area.

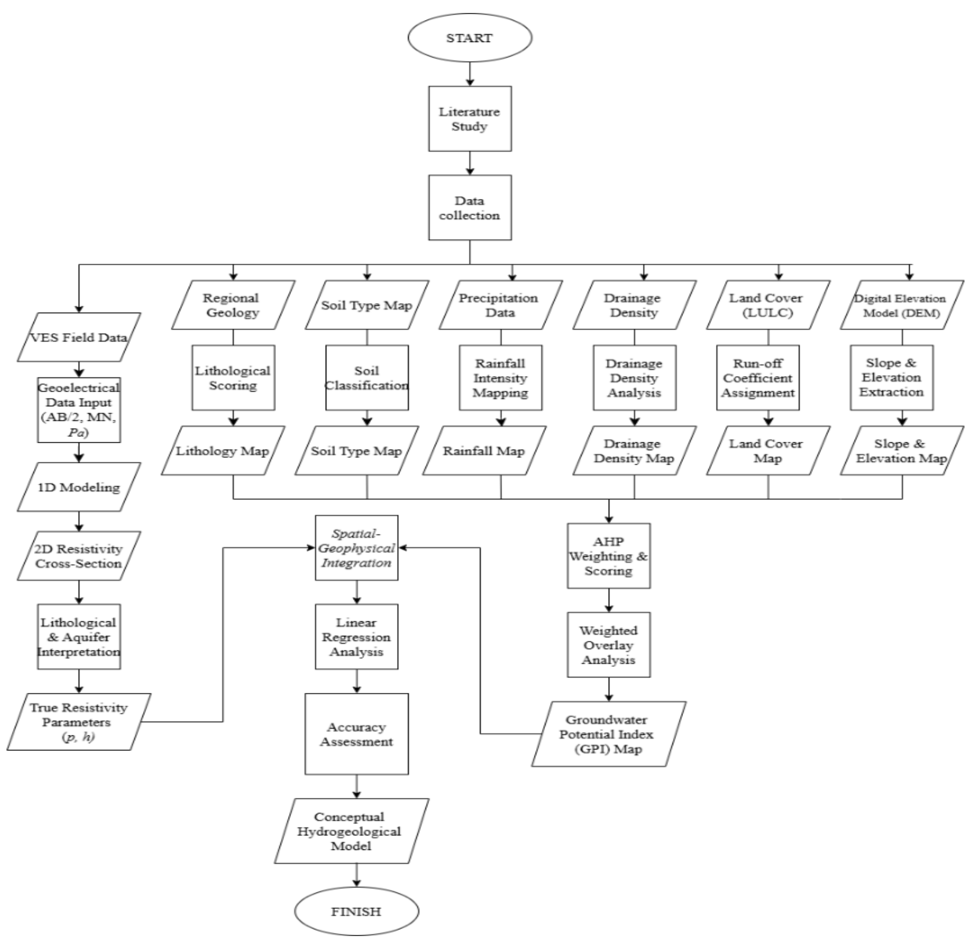

Figure 2. Flowchart Research

3. Results and Discussion

3.1 Groundwater Potential Indeks Map

Groundwater potential analysis in the study area was performed by integrating six hydrogeological conditioning factors using the Analytical Hierarchy Process (AHP).

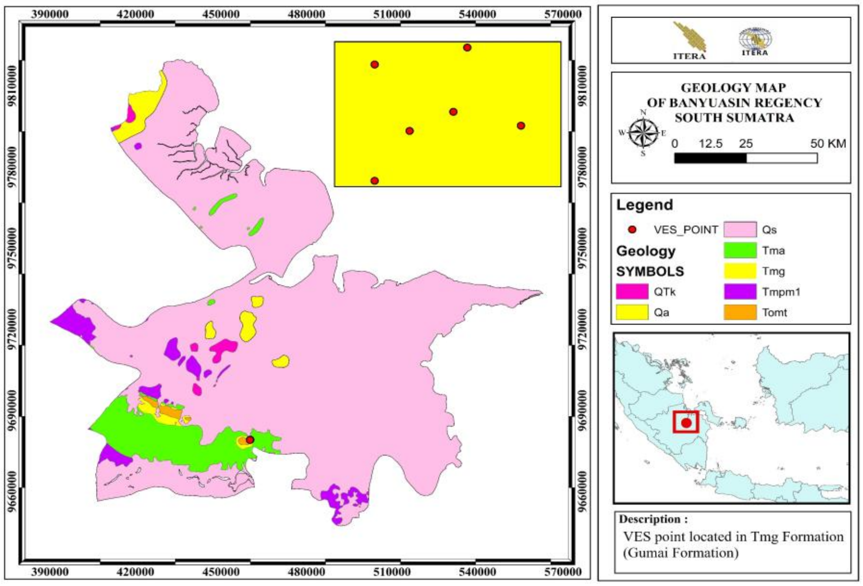

Figure 3. Regional Geology Map.

The weighting results indicate that geology is the dominant controlling factor, contributing 36.18% of the total weight, followed by slope gradient (22.74%) (Table 1). The predominance of geology is consistent with the hydrogeological characteristics of the Gumai Formation, where lithological variations control groundwater occurrence and storage [16].

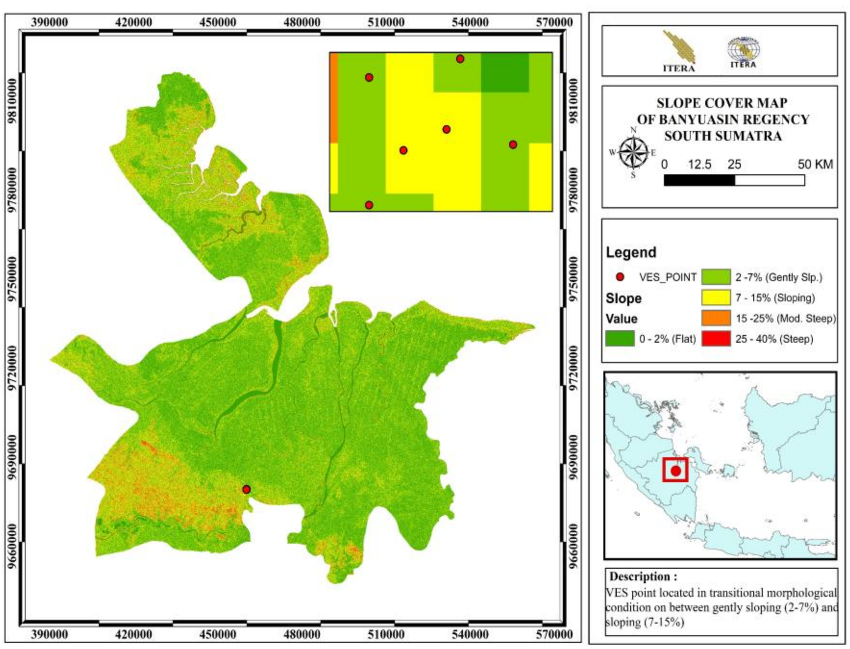

Figure 4. Slope Map

In contrast, slope primarily influences groundwater recharge by regulating infiltration and surface runoff. The weighting procedure was validated by a Consistency Ratio (CR) of 0.0056 (CR < 0.1), indicating that the pairwise comparison matrix is mathematically consistent and scientifically reliable. From a morphological perspective, Figure 4 (Slope Map) illustrates that the region is predominantly characterized by slopes ranging from 0–2% (flat) to 2–7% (gentle). Gentle topography serves as a supporting parameter because it minimizes surface runoff and increases the opportunity for water percolation into the soil.

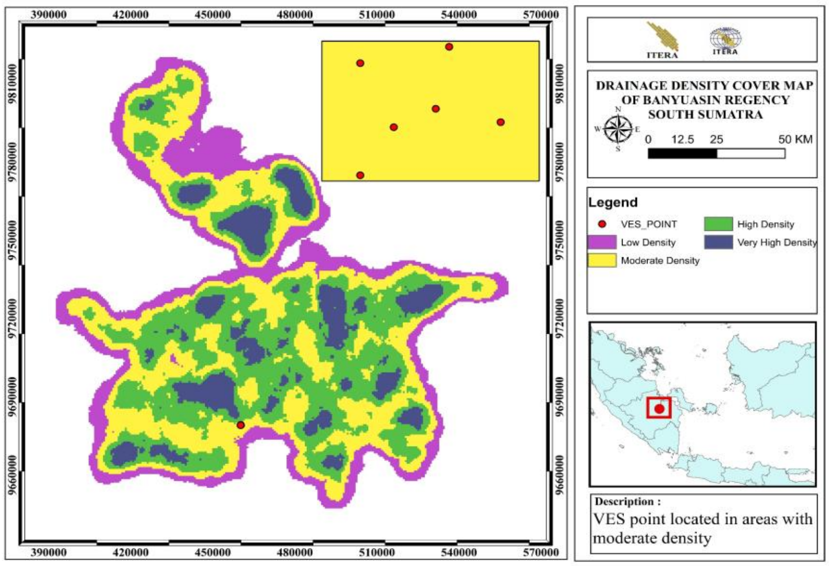

Figure 5. Drainage Map

However, this infiltration potential is spatially constrained in zones with high drainage density. Based on Figure 5 (Drainage Density Map), areas categorized as Very High hydrologically accelerate water flow toward river networks, thereby reducing the duration of water infiltration into the subsurface [17].

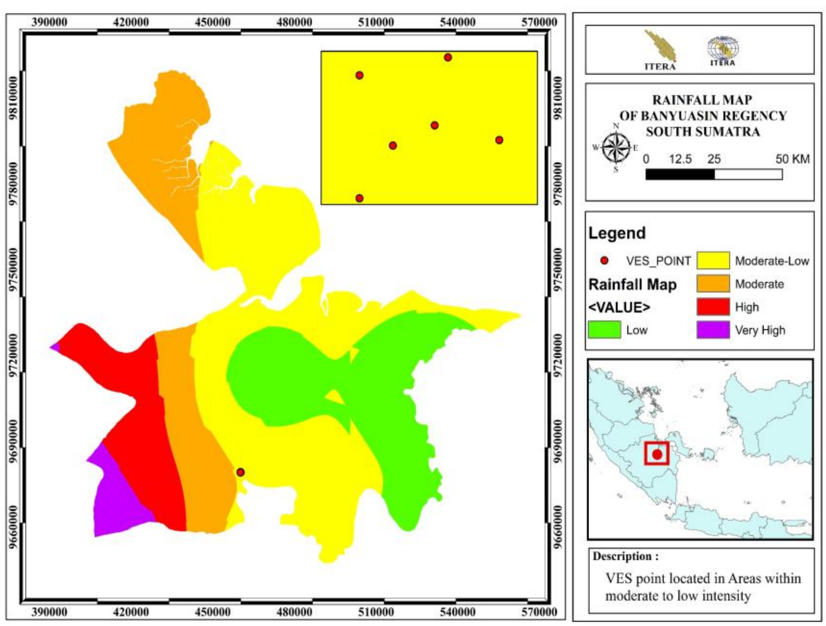

Figure 6. Rainfall Map

The interaction between rainfall and land-use conditions plays an important role in controlling groundwater recharge within the study area. As shown in Figure 6, rainfall intensity is generally classified as moderate to low, indicating that groundwater recharge largely depends on the efficiency of infiltration rather than on rainfall quantity alone.

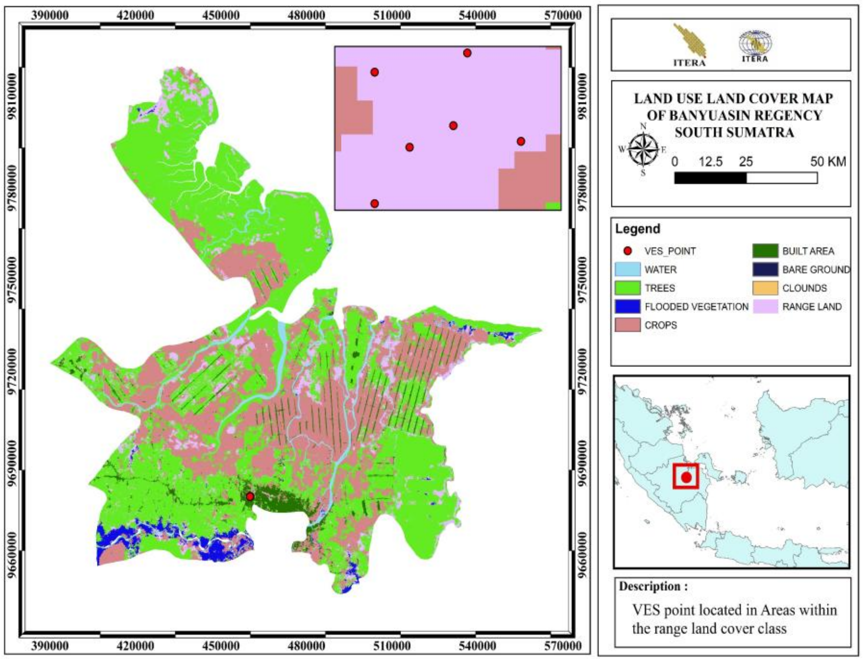

Figure 7. Land Use Land Cover Map

This condition is further influenced by land cover characteristics presented in Figure 7, where areas dominated by trees and rangeland provide greater infiltration capacity than built-up areas with relatively impermeable surfaces [18]. Consequently, the spatial distribution of groundwater potential is governed not only by rainfall availability but also by the ability of the land surface to facilitate infiltration and reduce surface runoff, consistent with the findings of [19].

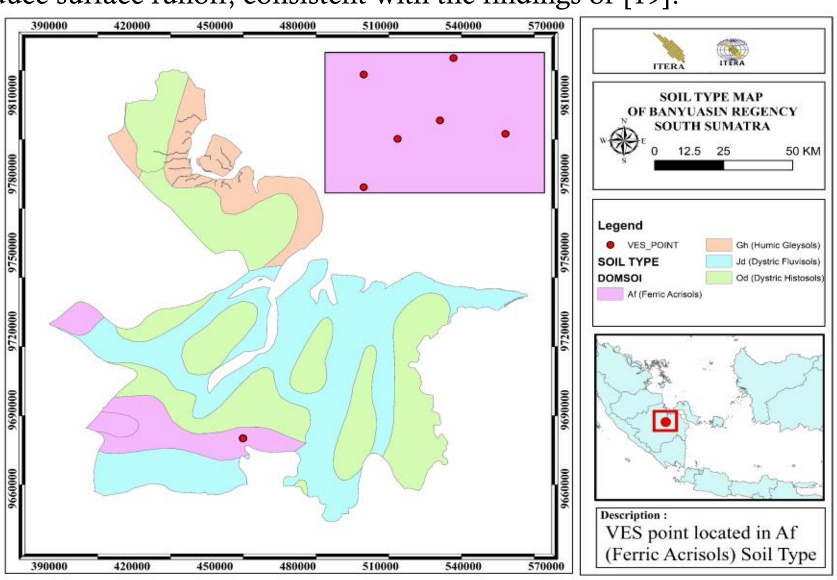

Figure 8. Soil Type Map

The spatial distribution of soil types in the study area, as presented in Figure 8 (Soil Type Map), represents an important parameter in determining groundwater potential. Soil characteristics influence the infiltration and percolation of rainfall into the subsurface, thereby affecting groundwater recharge. Areas with soils that have relatively higher permeability provide more favorable conditions for water infiltration, while soils with lower permeability tend to increase surface runoff and limit downward water movement. Therefore, the spatial variation of soil types contributes to differences in groundwater recharge potential across the study area. In the GIS-AHP analysis, soil type was assigned a weight of 7.39%, indicating that it provides a supporting contribution to the overall groundwater potential assessment alongside geology, slope, rainfall, drainage density, and land use/land cover.

The integration of all conditioning factors produced the Groundwater Potential Index (GPI) map of Talang Kelapa District. The results indicate that most of the study area is classified as having moderate groundwater potential**,** suggesting that groundwater occurrence is moderately favorable under the existing hydrogeological conditions. High-potential zones are limited to localized areas where favorable geological conditions coincide with gentle slopes and relatively well-preserved vegetation cover, creating conditions that enhance groundwater recharge despite the generally low permeability of the Gumai Formation [17]. This spatial pattern demonstrates that groundwater potential is controlled by the combined interaction of lithological and surface environmental factors rather than by a single parameter alone.

The overlay of all parameters generated the Groundwater Potential Index (GPI) Map of Banyuasin Regency. Based on the distribution of index values, most areas fall into the Moderate Potential classification [20]. High-potential zones are clustered in regions characterized by more porous sedimentary lithology, flat slopes, and well-preserved vegetation cover.

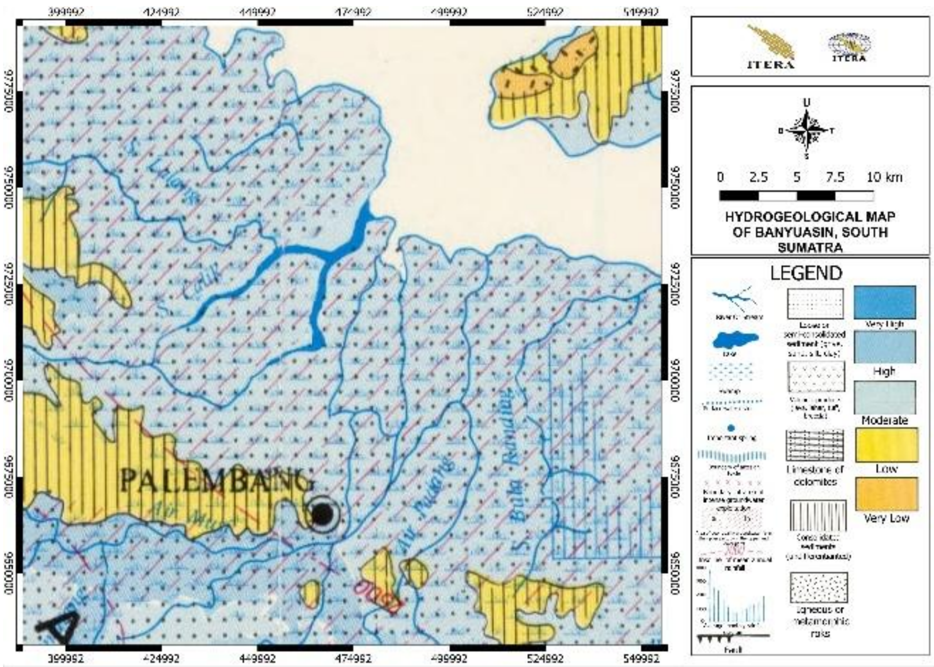

Figure 9. Hydrogeology of Indonesia [21]

According to the Indonesian Hydrogeological Map, Banyuasin Regency is situated within the eastern lowland region of Sumatra dominated by alluvial deposits, swamp environments, and Quaternary sediments, which hydrogeologically function as productive aquifers with moderate to locally high productivity. These conditions are consistent with the GPI map results, which classify most areas of Banyuasin as having moderate groundwater potential, with several high-potential zones distributed primarily in the southwestern, northern, and several specific corridor areas.

In addition, the distribution of high-potential classes on the GPI map, which tend to occur near the southern–southwestern part of Banyuasin, may be interpreted as zones with more favorable aquifer conditions, likely influenced by the fluvial system of the Musi River and more permeable sandy deposits. This interpretation is also consistent with the regional hydrogeological concept indicating that large river alluvial areas possess higher groundwater storage potential compared to clay-dominated swamp regions in coastal zones.

It can therefore be concluded that the resulting GPI map demonstrates a strong level of conformity with the national hydrogeological map, both in terms of distribution patterns and subsurface geological characteristics. Differences in detail between the two maps are considered reasonable because the Indonesian Hydrogeological Map is compiled at a regional scale of 1:2,500,000, whereas the GPI map was developed at a local scale using parameters that are more detailed and specifically adapted to the conditions of Banyuasin Regency

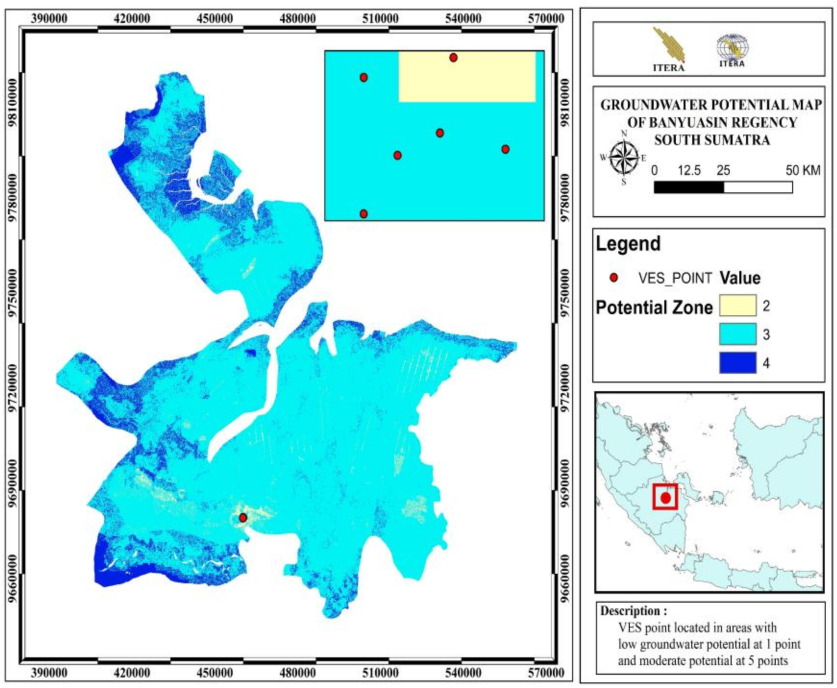

Figure 10. Groundwater Potential Map of Banyuasin, South Sumatera

3.2. Aquifer Identification Based on VES Survey Results

Based on the results of the 1D inversion modeling from six Vertical Electrical Sounding (VES) survey points, the subsurface characteristics within the study area are generally divided into three main lithological groups, namely topsoil, sandstone, and shale. The Root Mean Square error (RMSe) values obtained from the modeling range from 10.4% to 19.7%, indicating a reliable level of modeling accuracy considering the complexity of heterogeneous sedimentary lithological conditions [22-23].

The uppermost layer at all VES locations was interpreted as topsoil, with resistivity values ranging from 148 Ωm to 1129 Ωm. This relatively wide resistivity range reflects variations in soil moisture, weathering intensity, and near-surface lithological composition across the study area. Higher resistivity values are interpreted as relatively dry or unsaturated sandstone-rich materials, whereas comparatively lower resistivity values may indicate zones influenced by shallow water infiltration or increased soil moisture. These characteristics are consistent with the predominance of semi-open plantation land, where infiltration occurs through permeable surface materials but remains strongly affected by seasonal moisture conditions. Consequently, the topsoil layer mainly functions as the initial infiltration zone supplying groundwater recharge rather than as the principal groundwater-bearing unit [24].

The principal groundwater-bearing layer was interpreted within the second subsurface layer, with resistivity values ranging from 46.7 Ωm to 369 Ωm. These resistivity values are consistent with fine- to medium-grained sandstone that is likely saturated with groundwater and characterized by well-developed intergranular porosity. Such lithological characteristics provide favorable conditions for groundwater storage and movement. This interpretation agrees with the findings of [8], who reported that sandstone layers with resistivity values between 41 and 450 Ωm represent the primary groundwater-bearing zones within the Gumai Formation.

The interpreted aquifer thickness varies considerably among the VES locations, indicating that groundwater storage is not uniformly distributed throughout the study area. Thicker sandstone aquifers are expected to provide greater groundwater storage capacity and are therefore more favorable for groundwater development, whereas thinner aquifer sections may yield lower groundwater potential because of their limited saturated thickness. These variations likely reflect lateral changes in sandstone deposition and the heterogeneous stratigraphic characteristics of the Gumai Formation. Consequently, aquifer thickness represents an important consideration for identifying suitable groundwater exploration and drilling locations [25].

Geometrically, the interpreted aquifer thickness ranges from 13.76 m to 21.9 m, with the thickest groundwater-bearing zones identified at VES 3 and VES 5. At both locations, a shale layer exhibiting resistivity values between 38.1 Ωm and 38.7 Ωm was encountered at depths of approximately 16.8 m and 19.9 m, respectively, extending beyond the maximum investigation depth. This shale layer is interpreted as a relatively low-permeability unit that forms the lower boundary of the aquifer system, consistent with the regional stratigraphy of the Gumai Formation [8]. Overall, the VES interpretation indicates that groundwater is primarily stored within unconfined sandstone aquifers of variable thickness, reflecting lateral lithological heterogeneity across the study area. These field-based observations provide independent support for the groundwater potential distribution predicted by the GIS-AHP model and establish the basis for the quantitative correlation analysis presented in the following section.

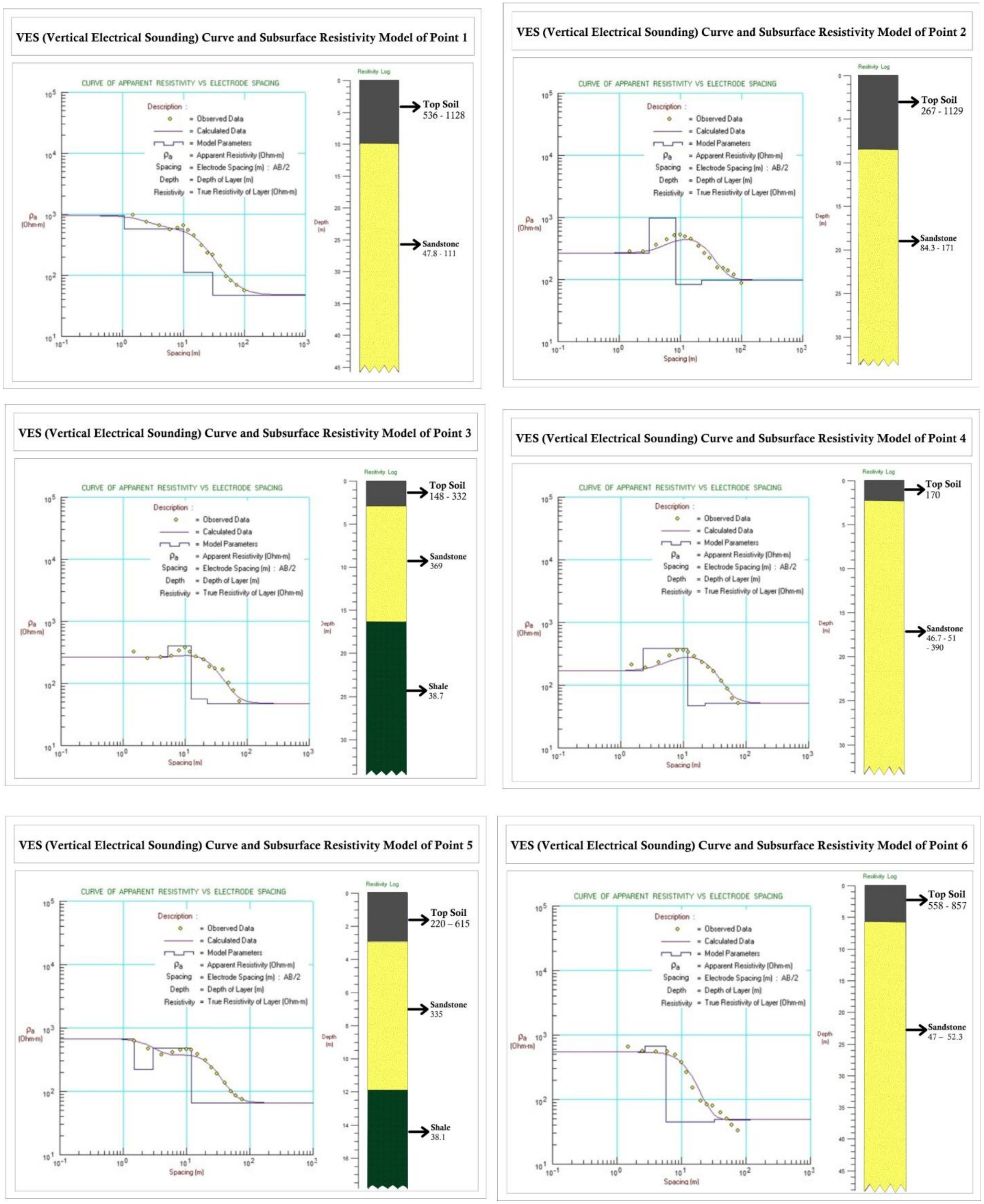

Figure 11. VES Curve an Sybsurface Resistivity Model of Point 1-6

3.3 Correlation Between GIS-Derived Groundwater Potential Index and VES Aquifer Thickness

To evaluate the reliability of the GIS-AHP model, the Groundwater Potential Index (GPI) obtained from spatial analysis was quantitatively compared with aquifer thickness interpreted from the six VES survey locations. A simple linear regression analysis was performed to examine the relationship between both variables [26]. The regression results indicate a positive linear relationship with a coefficient of determination (R^2) of 0.76, demonstrating that 76% of the variation in aquifer thickness can be explained by the GPI values generated from the GIS-AHP model.

The positive correlation suggests that locations with higher GPI values generally correspond to thicker aquifer zones. This finding confirms that the selected environmental parameters, including geology, slope, rainfall, drainage density, land use, and soil type, successfully represent the hydrogeological conditions controlling groundwater occurrence in the study area. Although several local deviations remain, the overall trend indicates that the spatial model provides reliable predictions for groundwater exploration.

Similar relationships between GIS-derived groundwater potential indices and field observations have been reported in previous studies using integrated GIS-AHP approaches. However, unlike previous studies where VES data were used only for qualitative verification, this study quantitatively validates the spatial model using measured aquifer thickness. This approach provides stronger evidence regarding the predictive capability of the GIS-AHP model.

Therefore, the obtained regression coefficient demonstrates that the integration between GIS-AHP and VES is suitable for groundwater exploration in lithologically heterogeneous areas such as the Gumai Formation [27]. The proposed workflow reduces exploration uncertainty while improving the accuracy of drilling target selection [28].

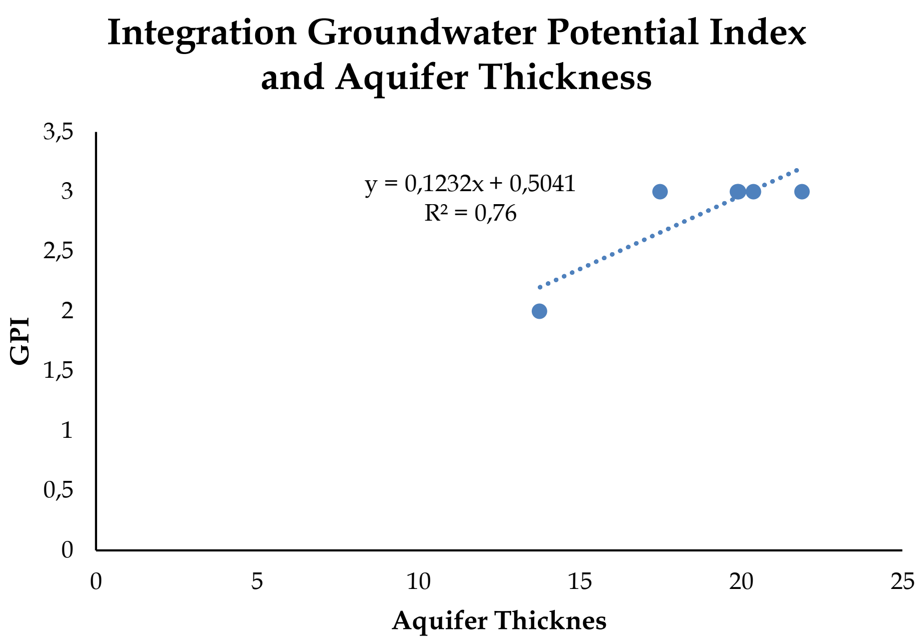

Figure 12. Integration Groundwater Potential Index and Aquifer Thinckness

3.4 Conceptual Hydrogeological Model

The developed hydrogeological conceptual model represents the final synthesis integrating surface spatial parameters with vertical subsurface characteristics, as illustrated in Figures 13 and 14. Based on the conceptual models of the VES 6-5-3 and VES 4-1-2 correlation profiles, the hydrogeological system within the study area is defined as an unconfined aquifer system stored within sandstone lithology. Groundwater recharge occurs through the vertical infiltration of rainwater passing through porous topsoil layers, where zones with high GPI values reflect areas with low percolation resistance. The groundwater table generally follows surface morphology, with groundwater flow moving toward thicker sandstone basins that serve as the primary accumulation zones [29]. This indicates the development of a local flow system in which infiltrated water directly enters shallow aquifers and flows through intergranular pore spaces over annual timescales.

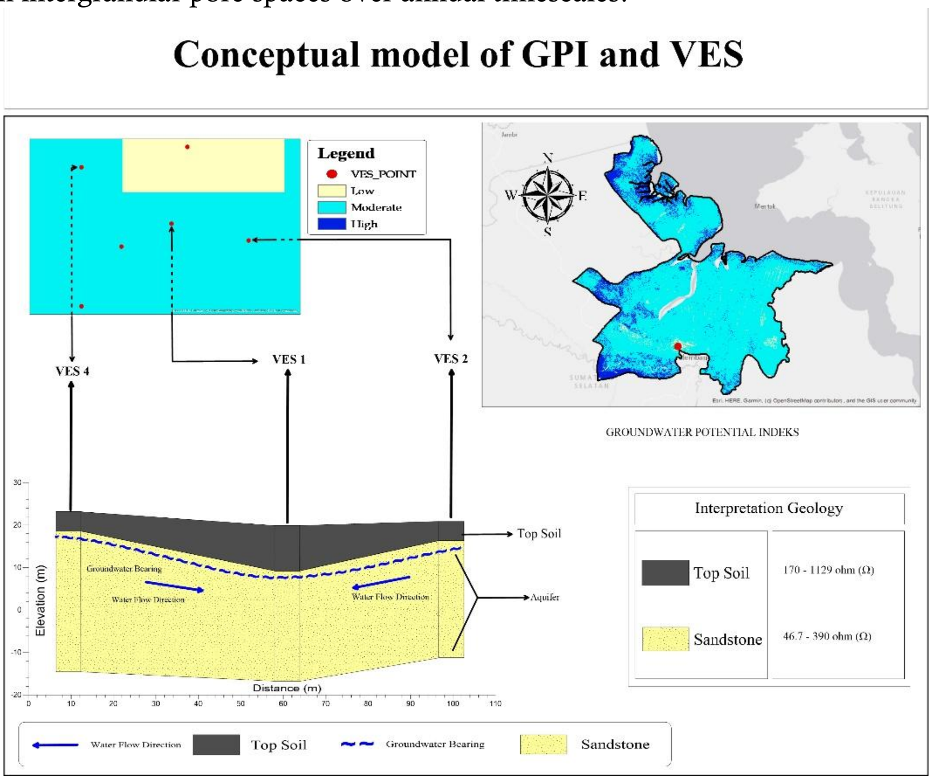

Figure 13. Conceptual model of GPI and VES L4, L1 & L2

Subsurface identification also revealed the role of shale layers with very low resistivity values (38.1–38.7 Ωm), which function as aquicludes or impermeable basal layers. The presence of these layers within the Gumai Formation acts as a barrier to downward vertical flow (base flow), thereby allowing groundwater masses to remain stored and concentrated within the overlying sandstone layers. This multidimensional integration provides a technical solution for groundwater resource development in Banyuasin Regency, where optimal drilling depths are recommended within the range of 20 to 30 meters [30]. By implementing this integrative approach, the risk of exploration failure caused by lithological heterogeneity can be significantly minimized while simultaneously ensuring cost efficiency in borewell construction for local communities.

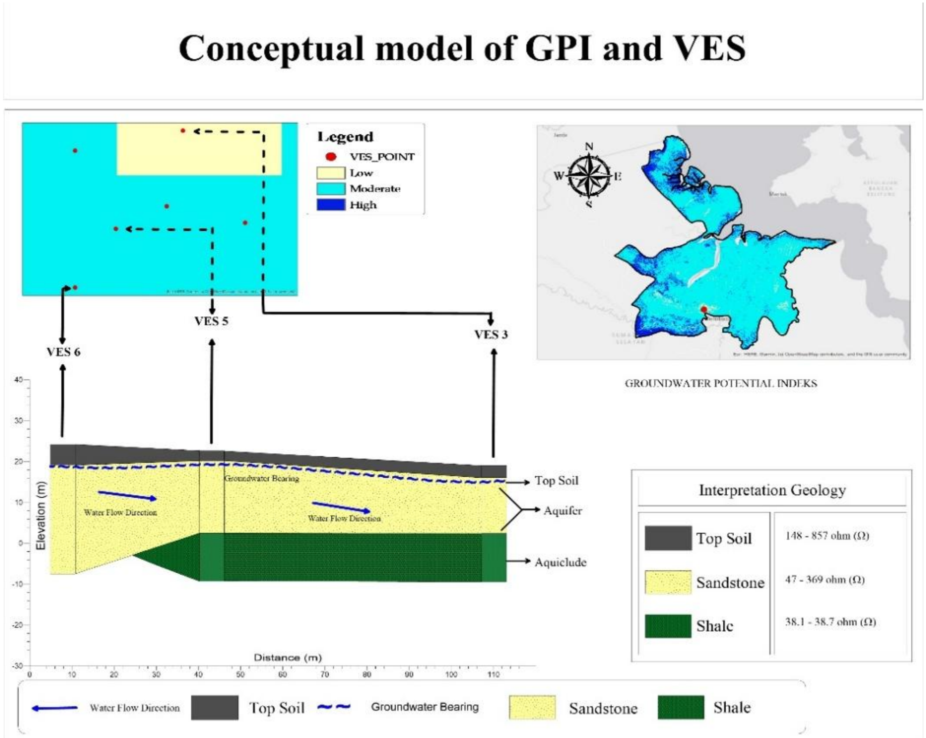

Figure 14. Conceptual Model of GPI and VES L6, L5 & L3

4. Conclusion

This study successfully demonstrates that the integration of the Vertical Electrical Sounding (VES) geophysical method and Geographic Information System–Analytical Hierarchy Process (GIS-AHP)-based spatial analysis is capable of providing high accuracy in mapping groundwater potential in Talang Kelapa District. The subsurface identification results indicate that the aquifer system within the study area is an unconfined aquifer within the Gumai Formation, occurring at depths ranging from 2.4 m to 16.8 m, with aquifer thickness varying between 13.76 m and 21.9 m. The novelty of this study is demonstrated through the strong linear correlation between the spatial model (GPI) and the actual aquifer thickness data obtained in the field, which produced a coefficient of determination value of R = 0.76. This achievement provides a significant contribution to the hydrogeological literature in the form of an integrative model capable of reducing exploration uncertainty within heterogeneous sedimentary formations, while also offering practical solutions for borewell planning through the recommendation of optimal drilling depths ranging from 20 to 30 meters.

Although the study produced accurate results, several limitations remain, particularly regarding the limited number of VES survey points, which may have restricted the detailed representation of lateral lithological variations between observation points. In addition, the parameters used in the GIS analysis did not yet incorporate long-term seasonal groundwater table fluctuation data. Therefore, future studies are recommended to employ broader and denser geophysical survey methods, such as 2D/3D Electrical Resistivity Tomography (ERT), in order to map aquifer geometry in greater detail. It is also recommended that pumping tests be conducted at borewell locations to periodically validate the hydraulic characteristics of the aquifer. Furthermore, continuous groundwater table monitoring is necessary to complement this spatial potential model with aspects of water resource sustainability in response to future climate change and dynamic land-use changes

References

[1] McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., ... & Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global environmental change*, *27*, 96-105.

[2] Karandish, F., Liu, S., & de Graaf, I. (2025). Global groundwater sustainability: A critical review of strategies and future pathways. *Journal of Hydrology*, *657*, 133060.

[3] Doke, A. B., Zolekar, R. B., Patel, H., & Das, S. (2021). Geospatial mapping of groundwater potential zones using multi-criteria decision-making AHP approach in a hardrock basaltic terrain in India. *Ecological Indicators*, *127*, 107685.

[4] Melese, T., & Belay, T. (2022). Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia. *Global Challenges*, *6*(1), 2100068.

[5] Ifediegwu, S. I. (2022). Assessment of groundwater potential zones using GIS and AHP techniques: a case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, *12*(1), 10.

[6] Uc Castillo, J. L., Martínez Cruz, D. A., Ramos Leal, J. A., Tuxpan Vargas, J., Rodríguez Tapia, S. A., & Marín Celestino, A. E. (2022). Delineation of groundwater potential zones (GWPZs) in a semi-arid basin through remote sensing, GIS, and AHP approaches. *Water*, *14*(13), 2138.

[7] Neven, A., & Renard, P. (2023). A novel methodology for the stochastic integration of geophysical and hydrogeological data in geologically consistent models. *Water Resources Research*, *59*(7), e2023WR034992.

[8] Mutaqin, D. Z., Mardiana, U., Mohammad, F., Alfadli, M. K., & Csssa, B. Y. (2021). Sistem Akuifer Air Tanah Daerah Sukamoro Kabupaten Banyuasin-Sumatera Selatan. *Jurnal Ilmiah Dinamika Rekayasa*, *17*(2), 137-147.

[9] Zhao, Y., & Foong, L. K. (2022). Predicting electrical power output of combined cycle power plants using a novel artificial neural network optimized by electrostatic discharge algorithm. *Measurement*, *198*, 111405.

[10] El Makrini, S., Boualoul, M., Mamouch, Y., El Makrini, H., Allaoui, A., Randazzo, G., ... & Muzirafuti, A. (2022). Vertical Electrical sounding (VES) technique to map potential aquifers of the Guigou Plain (Middle Atlas, Morocco): hydrogeological implications. *Applied Sciences*, *12*(24), 12829.

[11] Sankar, K., Karunanidhi, D., Kalaivanan, K., Subramani, T., Shanthi, D., & Balamurugan, P. (2023). Integrated hydrogeophysical and GIS based demarcation of groundwater potential and vulnerability zones in a hard rock and sedimentary terrain of Southern India. *Chemosphere*, *316*, 137305.

[12] Tahera-Tun-Humayra, U., Islam, M. R., Hosen, M. B., Kader, Z., Sharker, R., Hasan, M., ... & Pervin, R. (2025). Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Narshingdi District, Bangladesh. *Environmental Challenges*, 101335.

[13] Garuti, C., & Mu, E. (2025). A Novel Consistency Index CI-G: Recruiting Compatibility Index G for Consistency Analysis. *Mathematics*, *13*(16), 2666.

[14] Saaty, T. L. (1991). Some mathematical concepts of the analytic hierarchy process. *Behaviormetrika*, *18*(29), 1-9.

[15] Arunbose, S., Srinivas, Y., & Rajkumar, S. (2021). Efficacy of hydrological investigation in Karumeniyar river basin, Southern Tamil Nadu, India using vertical electrical sounding technique: A case study. *MethodsX*, *8*, 101215.

[16] Zhang, B., Zeng, F., Wei, X., Khan, U., & Zou, Y. (2022). Three-dimensional hierarchical hydrogeological static modeling for groundwater resource assessment: A case study in the eastern Henan Plain, China. *Water*, *14*(10), 1651.

[17] Nazaripour, H., Sedaghat, M., Shafaie, V., & Movahedi Rad, M. (2024). Strategic assessment of groundwater potential zones: a hybrid geospatial approach. *Applied Water Science*, *14*(8), 185.

[18] Cleophas, F., Moktar, N., Zahari, N. Z., Adnan, F. A. F., Tair, R., Budin, K., ... & Bidin, K. (2024). Field evaluation of a simple infiltration test and its relationship with soil physical properties of three different types of land uses. *Science, Engineering and Health Studies*, 24020008-24020008.

[19] Bronstert, A., Niehoff, D., & Schiffler, G. R. (2023). Modelling infiltration and infiltration excess: The importance of fast and local processes. *Hydrological Processes*, *37*(4), e14875.

[20] Aslan, V., & Çelik, R. (2021). Integrated GIS-based multi-criteria analysis for groundwater potential mapping in the euphrates's sub-basin, harran basin, turkey. *Sustainability*, *13*(13), 7375.

[21] Indonesia. Direktorat Geologi Tata Lingkungan. Sub Direktorat Hidrogeologi. (1983). *Peta hidrogeologi Indonesia 1:2,500,000 / Hydrogeological map of Indonesia 1:2,500,000* [Peta]. Direktorat Geologi Tata Lingkungan.

[22] Pěgřimočová, Z., & Ritz, M. (2025). Raman spectroscopy as an alternative approach for prediction of silicate mineral content in sedimentary rocks. *Scientific Reports*, *16*(1), 2891.

[23] Trabelsi, F., Bel Hadj Ali, S., & Lee, S. (2022). Comparison of novel hybrid and benchmark machine learning algorithms to predict groundwater potentiality: case of a drought-prone region of Medjerda Basin, northern Tunisia. *Remote Sensing*, *15*(1), 152.

[24] Fauzia, Surinaidu, L., Rahman, A., & Ahmed, S. (2021). Distributed groundwater recharge potentials assessment based on GIS model and its dynamics in the crystalline rocks of South India. *Scientific Reports*, *11*(1), 11772.

[25] Hendrizan, M. (2022). Clastic Sediment Characteristics of Gumai Formation: Preliminary Study of Tertiary Rocks in South Sumatra Basin. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1047, No. 1, p. 012010). IOP Publishing.

[26] El-Rawy, M., Batelaan, O., Alshehri, F., Almadani, S., Ahmed, M. S., & Elbeltagi, A. (2023). An integrated GIS and machine-learning technique for groundwater quality assessment and prediction in Southern Saudi Arabia. *Water*, *15*(13), 2448.

[27] Sreeja, I. S., Aju, C. D., Achu, A. L., Reghunath, R., Prakash, P., & Raicy, M. C. (2025). Geospatial modelling of groundwater potential zones validated with well discharge and electrical resistivity in a tropical catchment. *Evolving Earth*, 100094.

[28] Yousefi, M., Lindsay, M. D., & Kreuzer, O. (2024). Mitigating uncertainties in mineral exploration targeting: Majority voting and confidence index approaches in the context of an exploration information system (EIS). *Ore Geology Reviews*, *165*, 105930.

[29] Benton, J. R., McGuire, K. J., & Schreiber, M. E. (2022). Subsurface permeability contrasts control shallow groundwater flow dynamics in the critical zone of a glaciated, headwater catchment. *Hydrological Processes*, *36*(9), e14672.

[30] Mohammed, S. H., Mohammed, M. A., Karim, H. A., Al-Manmi, D. A. M., Aziz, B. Q., Mustafa, A. I., & Szűcs, P. (2025). Integrating geospatial, hydrogeological, and geophysical data to identify groundwater recharge potential zones in the Sulaymaniyah basin, NE of Iraq. *Scientific Reports*, *15*(1), 9920.