



Integration of geographic information system and vertical electrical sounding method for groundwater potential estimation

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ABSTRACT

Background: Suboptimal utilization of water potential may occur due to the lack of accurate mapping of potential aquifer zones to support sustainable groundwater management. Previous studies have highlighted groundwater potential using spatial analysis, but have not integrated it with geophysical analysis. This study aims to evaluate and map groundwater potential zones quantitatively through the integration of Geographic Information System (GIS) analysis and the Vertical Electrical Sounding (VES) method. **Methods:** The hydrogeological parameters processed and used as input for the weight overlay process include rainfall, slope gradient, drainage density, lithology, soil, and land use. The Analytical Hierarchy Process (AHP) was applied to assign relative weights to each parameter. Next, four VES measurement data were processed and interpreted to validate the spatial model. **Findings:** The results show that the study area is divided into five classes of groundwater potential: poor, sufficient, moderate, good, and excellent. Zones with moderate to good potential dominate the western and southeastern parts of the study area. Areas with high potential are generally associated with low slope gradients, low drainage density, and permeable volcanic rock formations such as tuffaceous sandstone with resistivity values of 36.9–41.3 Ω m. The aquifer depth in the western part is shallower (5–12 m) than in the eastern part (10–62 m). **Conclusion:** This study concludes that the integration of GIS and VES methods provides a comprehensive understanding of groundwater distribution and recharge mechanisms in complex volcanic conditions. This combined approach improves spatial accuracy and offers a new framework for sustainable groundwater resource utilization. **Novelty/Originality of this article:** The novelty of this study lies in the quantitative integration of GIS modeling with AHP validated by VES to effectively depict groundwater potential zones in heterogeneous volcanic terrain.

KEYWORDS: gis; groundwater; ves.

1. Introduction

According to data from the Central Statistics Agency (2023), rainfall in Probolinggo Regency reaches approximately 4,472 mm per year with an average of 185 rainy days. This relatively high rainfall indicates a substantial potential for water resources, both on the surface and underground. Groundwater, in particular, plays a vital role as a sustainable and strategic water resource supporting domestic, agricultural, and industrial needs. However, its utilization in the region remains limited and uneven. Field conditions reveal that most of the population still relies on surface water sources such as the main lake in the research area which is used for irrigation and household needs. One of these lakes, covering an area of about 24 hectares, functions as the main source of drinking water and irrigation for the

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surrounding communities. Nevertheless, during the dry season, several areas continue to experience drought and water scarcity, signaling an imbalance between water availability and utilization.

Hydrogeological data indicate that approximately 62.56% of Probolinggo Regency has groundwater table depths exceeding 90 m, 11.17% between 60–90 m, and only 26.27% with depths shallower than 60 m. Although perennial springs exist in certain volcanic terrains, their discharge rates tend to fluctuate seasonally, highlighting the complex relationship between rainfall, infiltration, and subsurface storage. This variability underscores the urgent need for a more accurate delineation of aquifer potential zones to support sustainable groundwater development and management. The issue is particularly critical in volcanic regions, where the heterogeneity of lithology and structural features can cause sharp contrasts in permeability and groundwater storage capacity within short distances.

Groundwater resource assessment has become an increasingly important research topic in recent decades, especially in regions facing irregular rainfall patterns and rapid land-use changes. Traditional hydrogeological surveys and well drilling methods provide detailed subsurface information but are time-consuming, costly, and spatially limited. To overcome these challenges, researchers have increasingly adopted Geographic Information Systems (GIS) and remote sensing technologies as efficient tools for spatial evaluation of groundwater potential (Arulbalaji et al., 2019; Hinton, 1996; Jha et al., 2010). These techniques allow for the integration and spatial analysis of various thematic parameters such as slope, drainage density, lithology, soil, rainfall, and land use to delineate areas suitable for groundwater recharge. However, one of the main limitations of GIS studies is their reliance on surface indicators, which often do not reflect the variability of actual subsurface hydrogeological conditions (Arulbalaji et al., 2019; Hinton, 1996). The accuracy of spatial models largely depends on the availability and quality of both spatial and subsurface data. Without direct subsurface validation, GIS models can only provide indicative interpretations rather than definitive delineations of groundwater potential. Therefore, integrating geophysical methods such as the Vertical Electrical Sounding (VES) technique is essential to improve model reliability. The VES method measures the electrical resistivity of subsurface materials, which reflects variations in lithology, porosity, permeability, and groundwater saturation (Telford et al., 1990). When combined with GIS, VES data provide quantitative subsurface constraints that enhance the interpretability of spatial groundwater potential maps.

Previous research in similar volcanic regions has demonstrated that combining spatial analysis with geophysical validation significantly improves groundwater assessment accuracy. For instance Arulbalaji et al. (2019) successfully integrated remote sensing data with VES results to map groundwater potential in southern India, while Duhita et al. (2021) highlighted the importance of slope and drainage density parameters in controlling infiltration and recharge processes. However, despite these advancements, limited studies have applied such integrated approaches in the Indonesian volcanic context, particularly in East Java. Existing works mostly focus on surface-based assessments and rarely incorporate subsurface validation. Consequently, the relationship between geomorphological conditions and aquifer properties in volcanic settings remains poorly quantified.

Unlike previous studies, this study integrates GIS-based multicriteria evaluation with subsurface validation of VES processing to quantitatively map groundwater potential zones. Six key hydrogeological parameters were analyzed using the Analytical Hierarchy Process (AHP) to assign relative weights to a weighted overlay model, depicting five classes of groundwater potential. VES data serve as a representation of subsurface resistivity values to facilitate the identification of variations in lithology, aquifer thickness, and groundwater-bearing formations, which are then compared with GIS-derived zones to validate spatial accuracy. This integrated framework of both methods provides a more comprehensive understanding of groundwater dynamics in volcanic terrain and establishes a methodological basis for sustainable groundwater management in the data limited study

area, which aligned with global initiatives such as the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation).

Despite its contributions, this study has several limitations that must be acknowledged. First, the accuracy of the findings strongly depends on the quality and resolution of secondary datasets, such as geological maps, the Digital Elevation Model (DEM), and satellite-derived rainfall data for the 2024–2025 period. Second, the absence of well log or borehole data limits direct validation of the geoelectric interpretation, resulting in a relatively qualitative rather than fully quantitative groundwater potential map. Third, limited field measurements prevent the evaluation of aquifer productivity in terms of yield or water quality. Consequently, the results presented herein should be considered indicative rather than absolute. Nevertheless, the outputs provide valuable insight into the spatial distribution of potential aquifer zones and can serve as a preliminary reference for future hydrogeological investigations, monitoring, and groundwater development planning.

Probolinggo Regency is located within the Tengger–Semeru Mountains zone, which physiographically forms part of the Quaternary volcanic belt of East Java. Geotectonically, this region lies within an active volcanic system; therefore, volcanic activity plays a major role in shaping the local morphology and lithology. Administratively, the study area is part of the Lamongan Volcanic Field (LVF) complex, which consists of approximately 61 cinder cones and 29 maars (Hinton, 1996). Mount Lamongan is an active volcano currently categorized under normal status, although it was elevated to an alert level in 2012. This volcanic activity reflects the dynamics of the Quaternary magmatic system in eastern East Java. Mount Lamongan is located between two large calderas, namely Tengger–Semeru in the west and Iyang–Argopuro in the east, which were formed by the subduction process of the Indo-Australian Plate beneath the Eurasian Plate at a rate of approximately 6 cm/year (Puspito & Shimazaki, 1995). This subduction process triggered the formation of a series of Quaternary volcanoes in East Java, including the Lamongan volcanic complex. The main volcanic body in the LVF area consists of three main craters. The Tarub cone is the oldest and is separated from the younger Lamongan cone by a northwest-southeast-oriented valley interpreted as an active fault zone (Carn, 1999).

Lithologically, the study area is composed of rocks resulting from the eruptions of Mount Lamongan and Tarub, consisting of basaltic-andesitic lava deposits, volcanic breccias, and pyroclastic deposits. Based on the Geological Map of the Southern Mount Lamongan Area, the rock units composing the study area, from oldest to youngest, include the Argopuro Volcanic Rock Unit (Av), which is composed of andesitic-basaltic lava, volcanic breccias, and tuff; the Tarub Pyroclastic Deposit (Tp), which is pinkish-purple pyroclastic material from the eruptions of Mount Tarub; the Tarub Young Lava Deposit (Tlm), which is a combination of basaltic lava chunks and tuffaceous sand-silt bedmass; the Lamongan Pyroclastic Deposit (Lp), which consists of pyroclastic material from altered basaltic andesite and scoria basalt; the Lamongan Young Lava Deposit (Llm), which is olivine basaltic lava resulting from a young eruption of Mount Lamongan; and the Lamongan Maar Deposit (Lma), which is a product of a phreatomagmatic eruption that formed a maar crater, characterized by a circular morphology and a crater floor below the surrounding topography.

This stratigraphic sequence reflects a complex and continuous volcanic evolution since the Quaternary period. Furthermore, the study area is characterized by northwest–southeast oriented faults and fracture systems that significantly influence groundwater movement. These structures not only control hydrogeological flow but also serve as primary pathways for rainwater infiltration. They allow rainwater to percolate into weathered volcanic rocks, forming shallow aquifer zones. The combination of permeable lithology and structural fractures provides the study area with a high groundwater potential, which is widely utilized through springs and lakes. Therefore, the geological characteristics of the study area are primarily controlled by the Quaternary volcanic activity of the Lamongan–Tarub complex and the regional structural framework of eastern East Java.

Groundwater refers to water that fills pore spaces within rocks below the Earth's surface in the saturated zone. Law Number 17 of 2019 similarly defines groundwater as water stored within subsurface soil and rock layers. The availability, sustainability, and spatial distribution of groundwater are controlled by hydrogeological processes, including recharge through infiltration, subsurface flow within aquifers, and discharge to the surface. Groundwater availability is influenced by several controlling factors such as lithology, soil texture, slope, rainfall, land cover, and vegetation density (Indaryani et al., 2025). Subsurface materials are classified based on their permeability into aquifers, aquitards, aquicludes, and aquifuges (Todd, 1980). Furthermore, based on water table position, aquifers can be categorized into unconfined, confined, and semi-confined aquifers (USBR, 1977; Wali et al., 2024).

Hydrogeologically, the dominance of young volcanic rocks and the presence of active fracture systems enhance water storage capacity and infiltration, thereby providing favorable conditions for the development of shallow aquifers in this region. This combination of permeable volcanic products and fracture-controlled secondary porosity promotes effective rainwater infiltration and influences the spatial distribution of groundwater potential. Consequently, quaternary volcanism and regional structural controls play a major role in shaping the hydrogeological framework and groundwater availability in the study area. Probolinggo Regency is characterized by young volcanic sequences with secondary porosity resulting from fracturing and weathering. Water-bearing units (aquifers) are primarily developed within tuff, breccia, and lava units with relatively high permeability. According to Todd (1980), an aquifer is a water-saturated geological layer capable of transmitting significant volumes of water. Based on their hydrogeological properties (Hastuti et al., 2016), subsurface materials are classified into four principal groups: aquifers (able to store and transmit water), aquitards (able to store but only partially transmit water), aquicludes (able to store but not transmit water), and aquifuges (neither store nor transmit water).

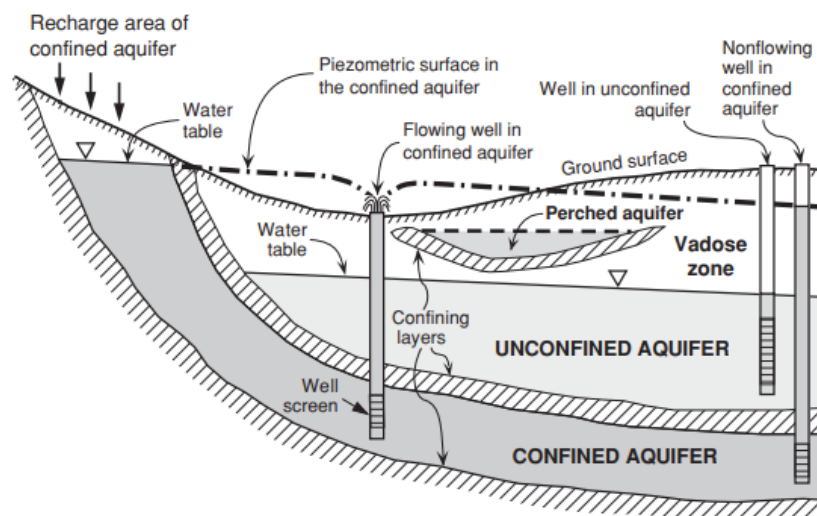


Fig. 1. Aquifer types based on groundwater level position (USBR, 1977)

The depth to the groundwater table in most central and northern areas ranges from 60 to 90 meters (Central Statistics Agency, 2023). Based on water table position, aquifers are classified into unconfined, confined, and semi-confined aquifers bounded by semipermeable layers, as shown in figure 1 (Wali et al., 2024). Overall, the geological and hydrogeological characteristics of the study area are controlled by Quaternary volcanic activity associated with the Lamongan–Tarub volcanic complex and the influence of regional tectonic structures in eastern East Java, which collectively determine the characteristics, potential, and distribution of subsurface groundwater.

2. Methods

2.1 Study area and GIS-based groundwater potential analysis

This research was conducted in Probolinggo Regency, East Java Province, which physiographically lies within the Quaternary Volcanic Zone of the Lamongan Volcanic Field (LVF). The area exhibits complex geomorphological and lithological characteristics that strongly influence groundwater occurrence. Despite having a high potential for groundwater resources, the spatial distribution and productivity of its aquifers remain poorly characterized. To address this, the study integrates spatial analysis and geophysical methods to improve the quantitative understanding of groundwater potential across the region. This research utilized secondary datasets collected between January 2024 and March 2025 from multiple international and national sources. These include the Digital Elevation Model (DEM) from the United States Geological Survey (USGS) for deriving slope gradient and drainage density parameters, Land Use and Land Cover (LULC) data from Esri Land Cover, soil maps from the Food and Agriculture Organization (FAO), regional geological maps from the Geological Agency of Indonesia, and rainfall data obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). All datasets were standardized to the UTM Zone 49S coordinate system with a uniform spatial resolution of 10×10 meters to ensure consistency during analysis.

The spatial analysis workflow was implemented using the Analytical Hierarchy Process (AHP), as proposed by Saaty (1980) to assign relative importance among parameters based on their influence on groundwater recharge potential. A pairwise comparison matrix was established to evaluate the influence of each parameter slope gradient, drainage density, land use, soil type, lithology, and rainfall on groundwater occurrence. Each factor was then normalized and assigned a weight derived from the consistency ratio (CR), which must remain below 0.10 to ensure logical coherence in expert judgment. The final weights were integrated in a Weighted Overlay Analysis using ArcGIS Pro to produce a composite map representing groundwater potential zones.

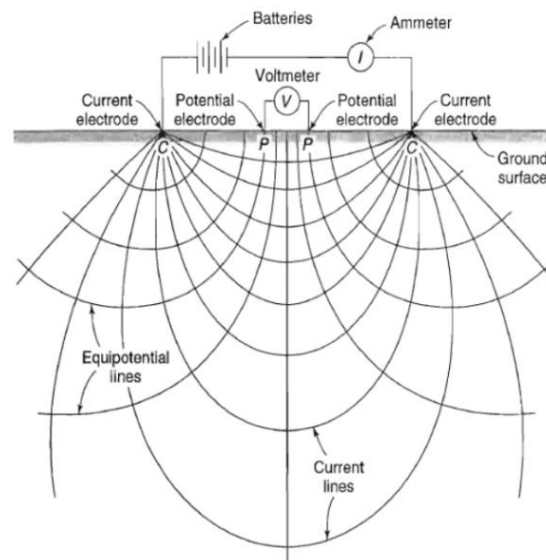


Fig. 2. Geoelectric measurement principle (Telford et al., 1990)

Each thematic layer was reclassified into five suitability categories (very low, low, moderate, high, and very high) according to its relative contribution to groundwater recharge. The classification criteria were based on published hydrogeological literature and field correlations from similar volcanic terrains (Jha et al., 2010; Arulbalaji et al., 2019). All

raster layers were resampled to an identical grid size and normalized to a 0–1 scale to maintain comparability during overlay operations. This standardization minimizes scale related errors and enhances the reliability of spatial correlations. The overlay process followed a hierarchical integration model, where hydrological, geological, and geomorphological factors were combined sequentially. The resulting spatial model delineated zones with varying groundwater potential levels, which were then validated through geophysical measurements.

2.2 Geophysical validation using VES and IDW interpolation

The validation process employed the Vertical Electrical Sounding (VES) method, a widely used resistivity-based technique for subsurface characterization. Figure 2 illustrates the principle of the VES configuration used in this study. The method involves injecting direct current (DC) into the ground via two current electrodes (A and B) and measuring the resulting potential difference between two potential electrodes (M and N). As the spacing between current electrodes (AB) increases, the electrical current penetrates deeper into the subsurface, allowing the estimation of resistivity variations with depth (Telford, 1976; Telford et al., 1990). The apparent resistivity (ρ_a) is calculated using Equation (1):

$$\rho_a = K \frac{V}{I} \quad (\text{Eq. 1})$$

where K is the geometric factor that depends on the electrode configuration and spacing. It is defined by Equation (2):

$$K = 2\pi \left(\frac{1}{C_1 + P_1} - \frac{1}{C_2 + P_1} - \frac{1}{C_1 + P_2} + \frac{1}{C_2 + P_2} \right)^{-1} \quad (\text{Eq. 2})$$

The flow of electric current in the subsurface is controlled by the electrical properties of rocks. These electrical properties reflect the response of rocks when an electric current is applied. The mechanism of electric current flow in rocks can be classified into three types: electronic conduction, electrolytic conduction, and dielectric conduction (Telford et al., 1990). Electronic conduction is primarily governed by the intrinsic properties of the solid material. Electrolytic conduction occurs in porous rocks saturated with electrolytic fluids. Meanwhile, dielectric conduction is associated with rocks that contain very few or no free electrons. The resistivity of rocks is influenced by several factors including water content, rock texture, lithology, porosity and permeability, clay mineral content, and salinity (Schon, 2011; Fajrina & Lestari, 2016). The resistivity values of several common materials are presented as follows:

Table 1. Conversion of resistivity values

Number	Material	Resistivity meter (Ohm-meter)
1	Water	-
2	Andesite	1,700 – 450,000
3	Basalt	200 – 100,000
4	Shales	20 – 2,000
5	Clay	1 – 100
6	Groundwater	0.5 – 300
7	Dry Gravel	600 – 10,000
8	Alluvium and Sand	10 – 800
9	Gravel	100 – 600
10	Tuffs	2,000- 200,000

(Telford et al., 1990)

The primary advantage of this method lies in its high vertical resolution, enabling precise identification of the boundaries between water-bearing (aquifer), impermeable, and transitional layers. The VES technique is considered particularly relevant for young volcanic

terrains, as it effectively detects resistivity variations that other surface geophysical methods may overlook. The measured resistivity data were processed using IPI2Win software to produce a one-dimensional (1D) resistivity model and estimate the thickness of each subsurface layer. Subsequently, the inversion results from the VES measurements were analyzed spatially using the Inverse Distance Weighted (IDW) interpolation method (Burrough & McDonnell, 1998). This method assigns weights based on the distance between observation points, with closer points exerting a greater influence. The general IDW interpolation formula is expressed as:

$$W_i = \frac{h_j^p}{\sum_{j=0}^n h_j^p} \quad (\text{Eq. 3})$$

where W_i is the interpolated value at point i , h_j is the distance from the sample point to the interpolated point, and p is the power parameter (commonly set to 2). The IDW technique was chosen because it produces smooth and reliable estimates even with limited or irregularly spaced observation points, a common constraint in field-based geophysical surveys.

IDW method was selected because it can generate smooth spatial estimates despite the non-uniform distribution of data points. The interpolation results were subsequently used to identify the vertical and horizontal distribution of aquifer zones, which were then compared with the GIS-based analysis. Through the integration of GIS spatial modeling and VES geophysical measurements, this study aims to produce an accurate and representative groundwater potential map. Figure 3 illustrates the study area, where the brown box indicates the area of interest that will serve as the focus for further research.

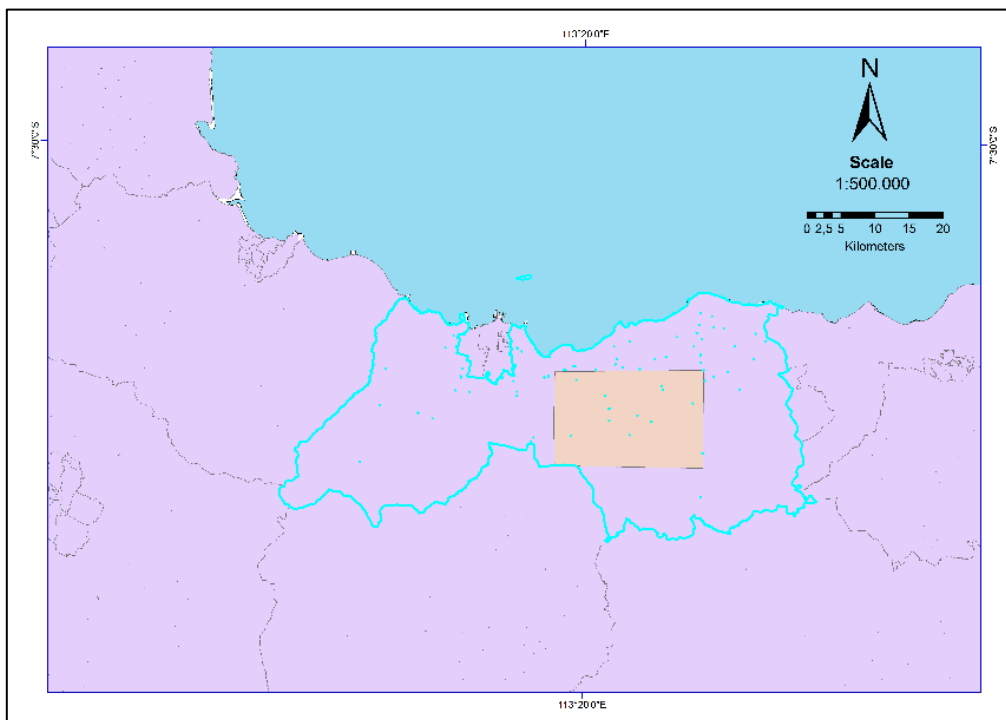


Fig. 3. Research area

3. Results and Discussion

3.1 GIS analysis

These layers were integrated through a multi-criteria GIS evaluation using the Analytical Hierarchy Process (AHP). Each thematic map represents hydrogeological factors

that influence groundwater occurrence and recharge dynamics. The integration of all spatial layers using a weighted overlay approach enables a quantitative delineation of groundwater potential zones. This multiparameter framework ensures the proportional contribution of each variable to the model, resulting in a spatially representative output that supports groundwater assessment, development, and utilization.

3.1.1 Slope

Slope plays a critical role in controlling the infiltration runoff balance and consequently governs groundwater recharge potential (Zeng et al., 2022). Areas with steep slopes tend to experience higher surface runoff, while flatter areas promote infiltration (Duhita et al., 2021). In this study, slope data were derived from DEM analysis using ArcGIS Pro. Figure 4 presents the slope classification map of the study area, which was divided into five classes: 0–8°, 9–15°, 16–25°, 26–45°, and 46–100°. Spatial analysis shows that the western and southeastern regions are dominated by steep slopes (>25°), whereas the central region is characterized by gentle slopes (<8°).

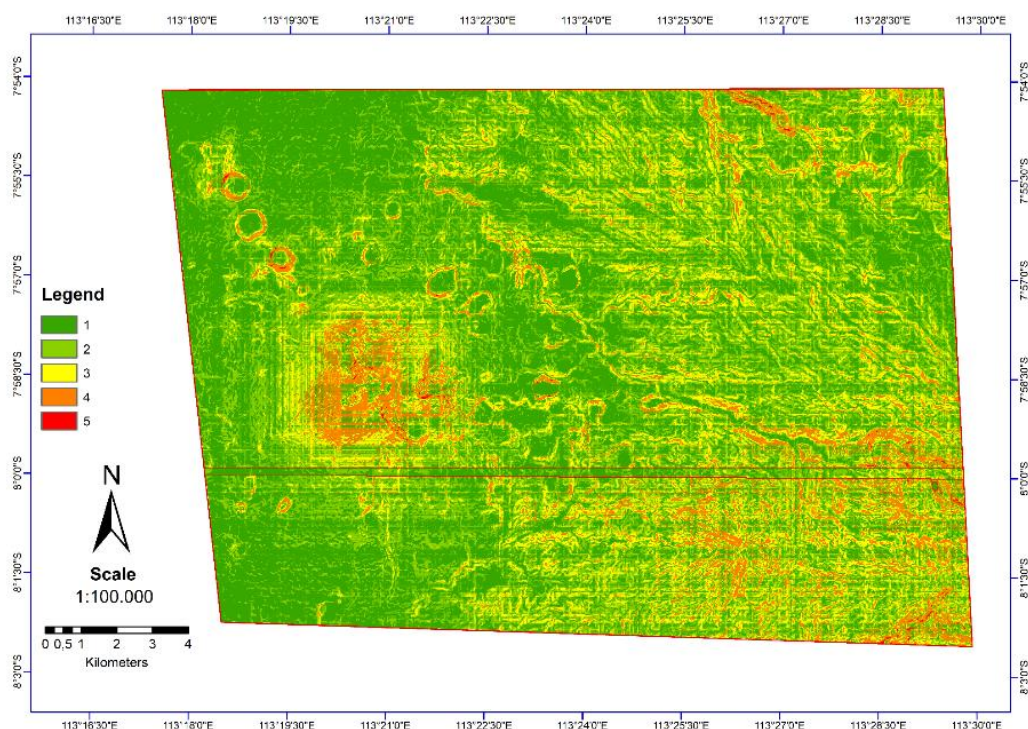


Fig. 4. Slope map of the research area

From a hydrogeological perspective, the gentle slopes in the central area increase infiltration and groundwater recharge to form a potential recharge zone. Conversely, steep slopes enhance runoff and surface evaporation, thereby restricting recharge and often leading to erosional processes. This spatial differentiation reflects the influence of local relief on subsurface hydrology. These results corroborate the findings of Kawara et al. (2024), who reported that steep volcanic terrains exhibit limited recharge capacity due to short surface residence times and increased flow velocity. Therefore, topographic gradients not only control the hydrodynamic behavior of surface water but also regulate the vertical infiltration processes that sustain shallow aquifers.

3.1.2 Drainage density

Drainage density, defined as the total length of streams per unit area, reflects the interaction between surface hydrology, soil permeability, and lithologic control (Arulbalaji

et al., 2019). The drainage density map shows spatial variation ranging from approximately 2.8 km/km² (low density) to 9.6 km/km² (high density). Regions with high drainage density typically correspond to impermeable lithologies, resulting in increased surface runoff, whereas areas with low density indicate permeable materials conducive to infiltration.

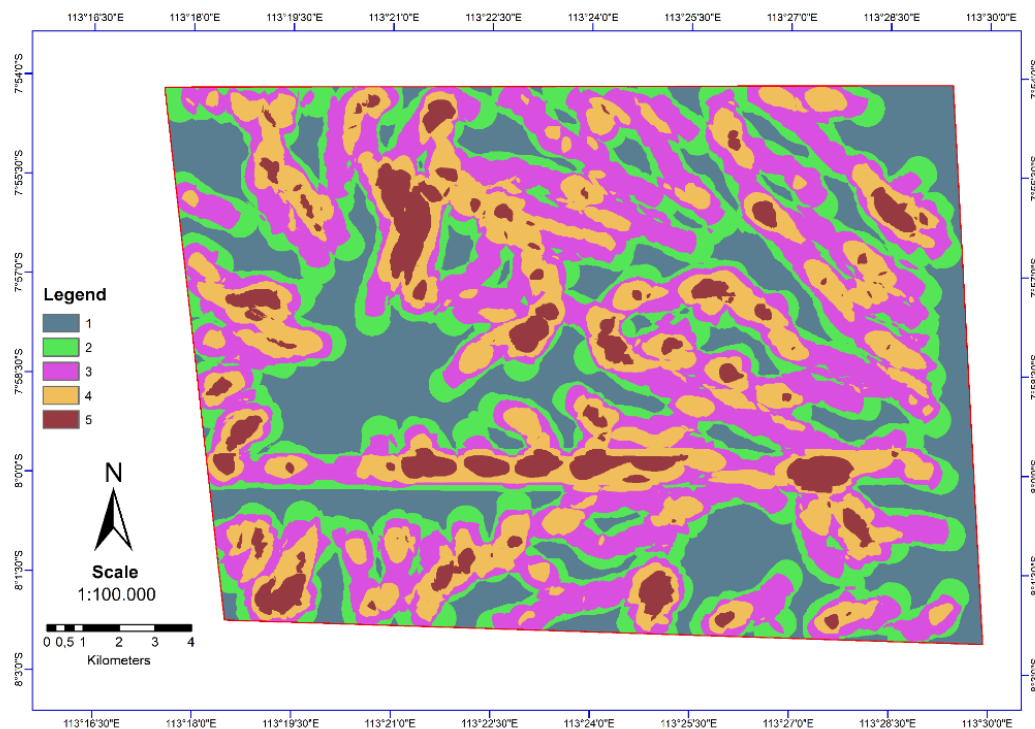


Fig. 5. Drainage density map of the research area

In the study area, drainage networks are structurally aligned along NW–SE trends, suggesting control by regional tectonic features shown in figure 5. The western and southern catchments exhibit lower drainage density, indicating higher infiltration potential. In contrast, the northern and eastern zones show dense drainage networks, implying reduced recharge capacity. Hydraulic connectivity between surface water (rivers and lakes) and groundwater is clearly visible in the central lowland areas, where river levels correspond closely with the estimated water table elevation. This relationship supports the interpretation that surface and subsurface interaction contributes significantly to aquifer recharge. Similar results were reported by Babu & Maury (2025) and Luijendijk (2022), who emphasized that lineament controlled drainage often defines preferential recharge corridors in volcanic terrains. Overall, the spatial variation in drainage density indicates that the central and western sectors serve as natural recharge zones, whereas the eastern highlands and northern ridges function as runoff zones. This reinforces the hydrogeomorphological pattern derived from the slope analysis.

3.1.3 Rainfall

Rainfall serves as the primary source of groundwater recharge, influencing both the magnitude and temporal variability of subsurface storage (Pazola et al., 2024). In this study, rainfall data from the CHIRPS satellite product were interpolated at 1 km spatial resolution to generate a continuous rainfall distribution map (figure 6). The results show a distinct west–east gradient, with higher rainfall (>3,400 mm/year) occurring in the western and eastern sectors, and lower rainfall (<2,900 mm/year) in the northern and southwestern sectors.

Figure 6 shows that spatial pattern is controlled by topographic influence and monsoonal wind regimes that enhance orographic precipitation over the Lamongan

Volcanic Field. From a hydrogeological perspective, regions with higher rainfall coincide with gentle slopes and permeable lithologies, reinforcing recharge potential. The mean annual rainfall of 3,455 mm/year classifies the area as high rainfall tropical terrain, conducive to sustained groundwater replenishment. Similar findings were reported by (Varghese et al., 2024), who demonstrated that recharge efficiency in humid volcanic terrains increases when high rainfall overlaps with permeable lithologic formations. Therefore, rainfall distribution not only governs the spatial pattern of recharge but also interacts synergistically with other parameters such as slope, drainage density, and soil permeability. This integrated effect underscores the need for multiparameter evaluation to accurately delineate groundwater potential zones.

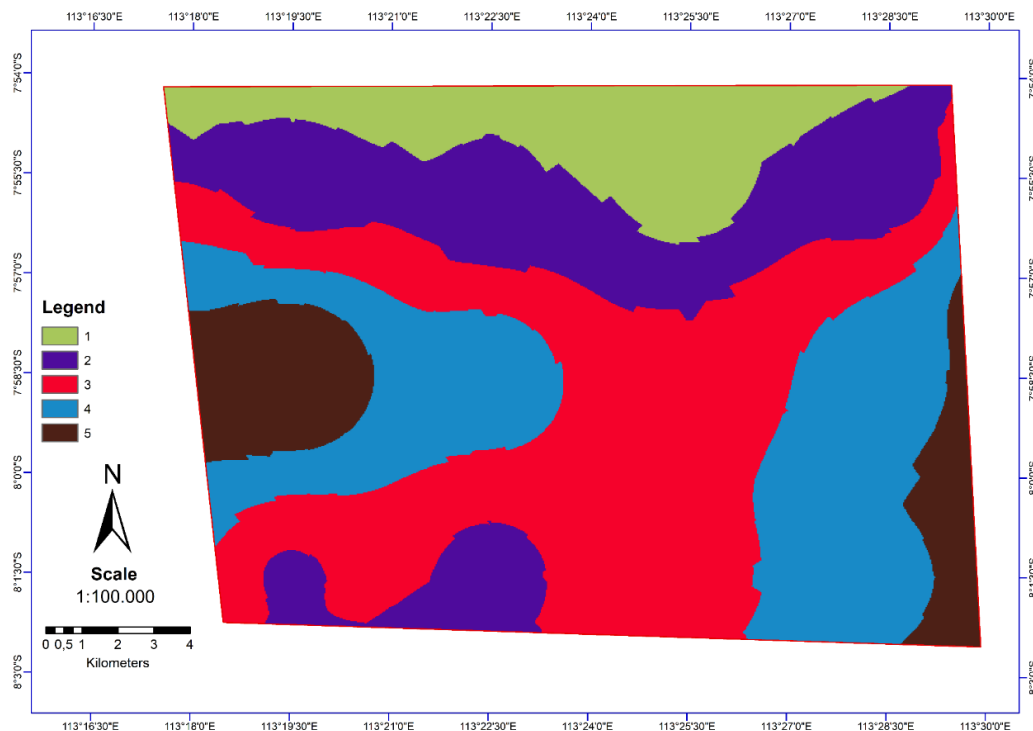


Fig. 6. Rainfall map of the research area

3.1.4 Soil and geology

Figure 7 shows a soil type map consisting of two main units, namely Eutric Regosol (Re) and To, which extend relatively west to east of the study area. Spatially, Eutric Regosol (Re) soils dominate the western to central parts of the study area, while To soils are more common in the eastern part. Eutric Regosols are young soils typically derived from volcanic materials or loose sediments. They possess a sandy to loamy texture, high porosity, and high permeability (FAO, 2015; Opoku et al., 2024), which together facilitate rapid infiltration and efficient groundwater recharge. In contrast, the To soil unit is characterized by finer-grained materials (silt and clay) that exhibit low permeability, rendering them relatively impermeable and functioning as aquitards. The contrasting physical properties of these two soil types have direct implications for groundwater dynamics. Coarse-textured soils such as Regosols promote infiltration and percolation, while fine-textured soils impede subsurface flow and increase the potential for surface ponding (Neukum et al., 2023). Accordingly, the western part of the study area, which is dominated by Eutric Regosols, is interpreted as a potential groundwater recharge zone, whereas the eastern region, characterized by finer To soils, likely represents a discharge or flow accumulation zone. Overall, the soil distribution pattern in figure 7 demonstrates a clear relationship between soil texture, permeability, and groundwater potential within the study area.

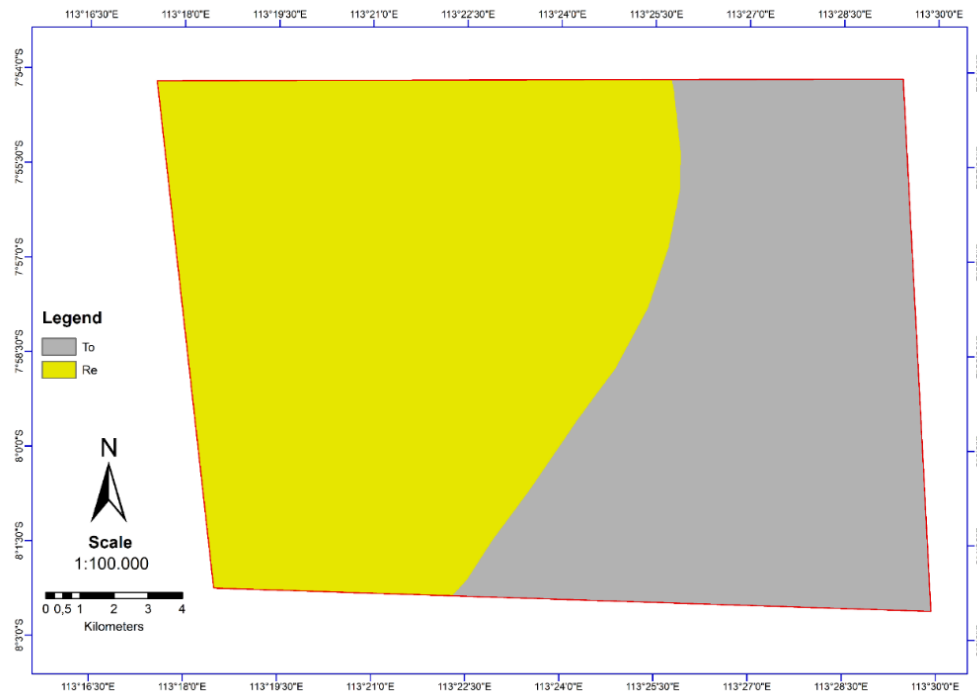


Fig. 7. Soil map of the research area

Figure 8 illustrates the lithological distribution within the study area, which consists of two main rock units: the Argopuro Volcanic Rock and the Lamongan Volcanic Rock. Spatially, the Lamongan Volcanic Rock dominates the western portion of the area, while the Argopuro Volcanic Rock occupies the eastern part. These two units exhibit contrasting petrological and physical characteristics that strongly influence the region’s groundwater potential. In contrast, the Lamongan Volcanic Rock consists of younger volcanic deposits, including olivine basalt lava, tuff, and maar deposits formed by phreatomagmatic eruptions. These deposits are generally loose, fractured, and more porous due to their young volcanic origin, which enhances both primary and secondary permeability. As a result, this rock unit exhibits favorable hydrogeological characteristics and serves as a potential aquifer zone, capable of storing and transmitting groundwater effectively.

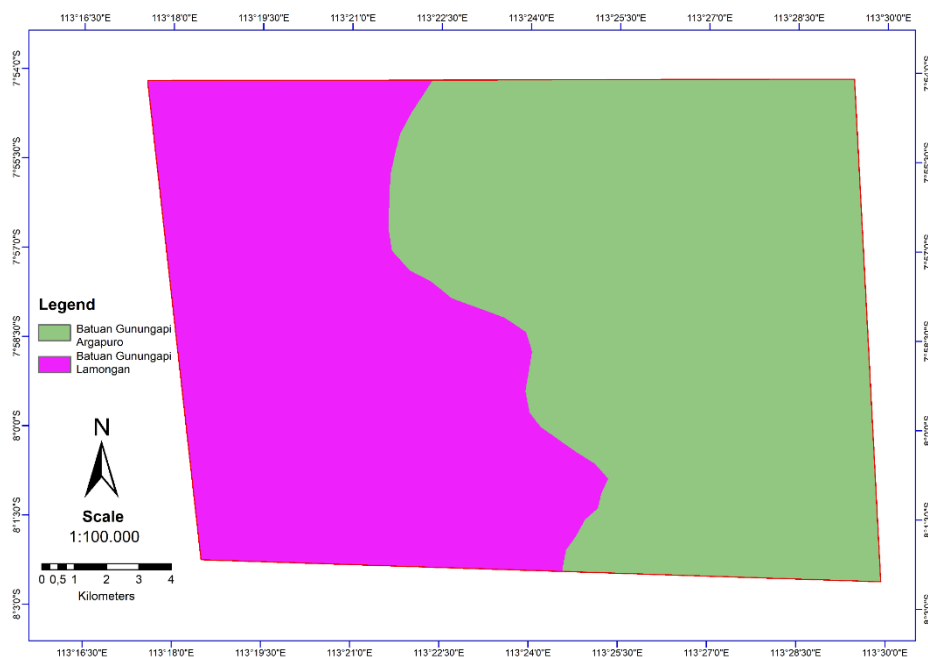


Fig. 8. Geology map of the research area

The differences in lithological composition directly affect groundwater dynamics in the region. Rocks with high porosity facilitate greater rainfall infiltration, while high permeability enables subsurface water flow and storage (Todd & Mays, 2005). Conversely, compact rocks with low permeability, such as the massive Argopuro lava, tend to impede water flow and act as natural barriers to groundwater movement. In general, areas underlain by Lamongan Volcanic Rocks are interpreted as primary recharge zones owing to their permeable and porous nature, whereas regions dominated by Argopuro Volcanic Rocks function as impermeable or low-permeability zones that restrict groundwater circulation. These interpretations are consistent with hydrogeological principles emphasizing that lithological porosity and permeability are the principal factors controlling groundwater potential and flow direction (Dumont et al., 2021; Millett et al., 2023; Todd & Mays, 2005).

3.1.5 LULC

Figure 9 presents the land use and land cover (LULC) distribution in the study area, derived from Esri Land Cover imagery at a scale of 1:100,000. The dominant land cover is vegetation (green), which extends across most of the central to southern portions of the area. Agricultural land (yellow) and bare land (dark brown) occur in smaller patches, primarily in the northern and southwestern regions. Settlement areas (red) are scattered in the western and eastern parts, while water bodies (light blue) appear locally, particularly in the central portion of the study area.

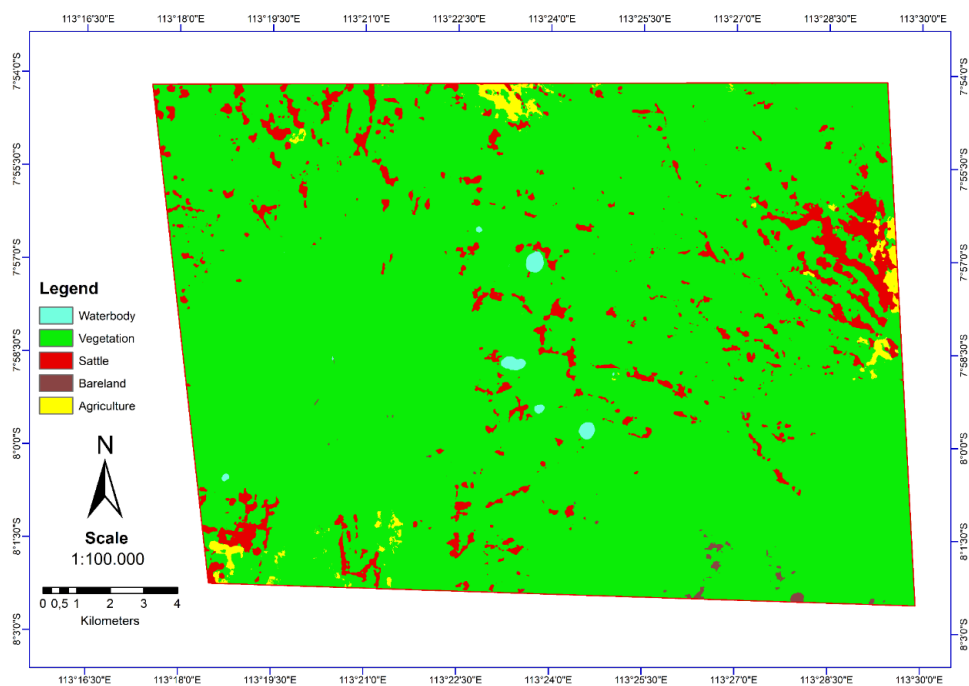


Fig. 9. LULC map of the research area

The spatial distribution pattern in figure 9 indicates that the study area is predominantly characterized by natural land cover, consisting mainly of vegetation and agricultural land. Both types of cover play crucial roles in promoting groundwater infiltration and recharge (Mengistu et al., 2022). Areas with vegetation cover and water bodies have high groundwater potential because both types of cover facilitate the infiltration of rainwater into the underlying soil and rock layers. Conversely, residential areas and open land tend to have low infiltration capacity due to surfaces covered by impermeable materials such as buildings or compacted soil, increasing surface runoff and reducing groundwater potential.

Accordingly, areas dominated by vegetation and agricultural land are interpreted to have greater groundwater availability compared to residential or bareland zones that are more susceptible to runoff. According to UNESCO (1973) classification of natural and semi-natural vegetation (ISRIC, 2005), vegetation is a major factor in soil formation and regulation of the hydrological cycle due to its role as a source of organic matter and its ability to increase water infiltration. Dense vegetation helps slow surface runoff and enhances groundwater retention through root systems. Meanwhile, Hagare et al. (2022), stated that areas with natural land cover such as forests and shrubs contribute significantly to increasing groundwater recharge compared to built-up areas or intensive agriculture. Based on the LULC map and supporting literature, it can be inferred that vegetation and water body zones function as recharge areas, whereas settlement and bareland zones act as runoff areas, directly affecting the spatial distribution of groundwater potential in the study area.

The integration of six thematic layers through AHP and weighted overlay produced a composite groundwater potential map (figure 10). The study area was classified into five classes: Poor, Fair, Moderate, Good, and Excellent. Approximately 53% of the area falls into the Moderate class, predominantly distributed in the central and southeastern sectors. Good to Excellent zones represent 32% of the area and are primarily located in the western and southern regions near major drainage lines and structural intersections. Poor to Fair zones occupy around 15% of the area, concentrated in the elevated northern and northeastern regions characterized by compact lithology and steep slopes.

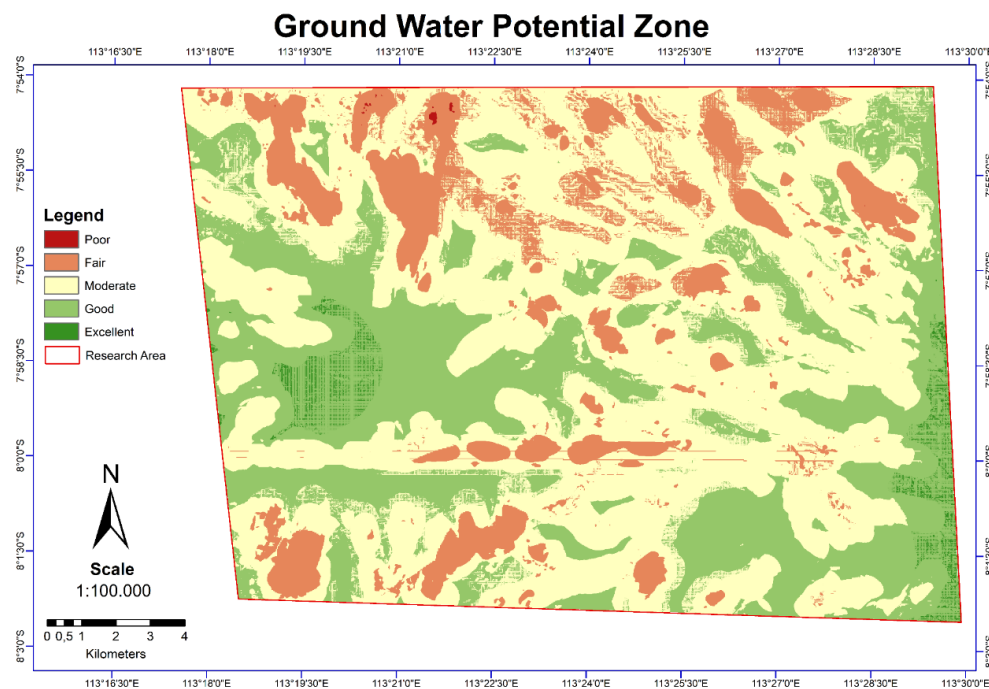


Fig. 10. Aquifer potential map

The distribution of groundwater potential zones shown in figure 10 demonstrates that geological and morphological conditions exert a strong influence on groundwater availability. Areas classified as Good to Excellent potential are typically associated with young volcanic deposits and lava flows (T_{1m}) that possess high porosity and permeability, facilitating infiltration and groundwater storage. Conversely, Fair to Poor potential areas are commonly found in older volcanic formations (A_v), composed of compact andesite-basalt lava and breccia, which act as relatively impermeable units. Geological structures such as lineaments and drainage alignments play a crucial role as the main controls of subsurface water movement and accumulation. Spatially, the Excellent and Good potential zones tend to align with structural and drainage patterns, suggesting that fractures and faults serve as preferential pathways for groundwater flow. Consequently, regions characterized by high structural density are considered promising targets for groundwater

exploration and development, whereas ridge and pediment zones with impermeable lithology generally exhibit limited groundwater potential.

According to Jha & Tripathi (2021), the GIS-based weighted overlay method is an effective tool for delineating groundwater potential zones by integrating geomorphological, drainage, and lithological parameters. They emphasized that structural alignments and hydrogeomorphological conditions are key factors influencing groundwater recharge. Similarly, Todd & Mays (2005) explain that areas with porous lithology, high permeability, and vegetative land cover are ideal locations for rainwater infiltration, which forms productive aquifers. Based on the results of the overlay analysis and supporting literature, it can be concluded that the Moderate to Excellent zones identified in this study represent areas with substantial potential for groundwater recharge and utilization. The resulting map serves as an initial hydrogeological reference for groundwater exploration planning and provides a scientific basis for sustainable water resource management in the study area.

3.2 VES analysis

The Vertical Electrical Sounding (VES) results from four locations were processed through a curve-fitting procedure, which involves matching the observed apparent resistivity curve with the calculated one while considering the associated error value. This process is largely influenced by resistivity values and layer thicknesses during the fitting stage. To achieve high-resolution results, the maximum penetration depth was set at one-third of the total current electrode spacing (Harjito, 2013). The data processing for all sites yielded error rates below 5%, indicating high data quality and accuracy. Lithological interpretation was performed by correlating the measured resistivity values with rock characteristics. The resistivity ranges were classified as follows: resistivity values $<30 \Omega\text{m}$ are interpreted as sandy silt, sandy clay, and tuffaceous claystone, and resistivity values between $30\text{--}150 \Omega\text{m}$ are interpreted as sandy breccia and tuffaceous sandstone.

At VES Point 1, the subsurface stratigraphy shows a topsoil layer with a resistivity of $46.4 \Omega\text{m}$ and a thickness of approximately 6.23 m, underlain by a tuffaceous claystone layer with a low resistivity of $23.4 \Omega\text{m}$. The third layer, composed of tuffaceous sandstone, occurs at a depth of around 10 m and exhibits a relatively high resistivity of $40.1 \Omega\text{m}$, suggesting the presence of significant groundwater. At Point 2 (elevation 531 m), the topsoil has a resistivity of $49 \Omega\text{m}$ and a thickness of 1.74 m. The tuffaceous sandstone layer has a thickness of 26–31 m with a resistivity of $40.7 \Omega\text{m}$, while the third layer, characterized by a low resistivity of $24 \Omega\text{m}$, is likely composed of tuffaceous claystone. At Point 3, the topsoil layer exhibits a resistivity of $44.1 \Omega\text{m}$ and a thickness of about 3 m, followed by a tuffaceous claystone layer with a resistivity of $20.7 \Omega\text{m}$. The third layer, consisting of tuffaceous sandstone, is found at a depth of 10–23 m and has a resistivity of $41.3 \Omega\text{m}$, again suggesting the presence of groundwater. Below this lies another tuffaceous claystone layer with a resistivity of $25 \Omega\text{m}$. At Point 4, the topsoil layer ($44.1 \Omega\text{m}$) is approximately 3 m thick, underlain by a relatively thick tuffaceous claystone layer extending to a depth of 62 m with a resistivity of $20.7 \Omega\text{m}$. Beneath it lies tuffaceous sandstone with a resistivity of $36.9 \Omega\text{m}$ extending to 100 m depth.

Figure 11 illustrates the geoelectrical cross-section derived from the four VES points, revealing the hydrological relationship between the aquifer and the central lake along the profile. The lake functions as a through-flow system, facilitating water exchange between the lake body and the surrounding aquifer. In the western section (VES 1–2), the volcanic sand layer acts as a productive aquifer zone, allowing subsurface water to flow laterally toward the lake (Gahala et al., 2024; Irvine et al., 2024). Conversely, in the eastern section (VES 3–4), a tuffaceous clay layer overlying the tuffaceous sandstone acts as an aquitard, restricting eastward water movement from the lake. This configuration suggests that the lake may serve as both a recharge and discharge zone, depending on the local hydraulic gradient.

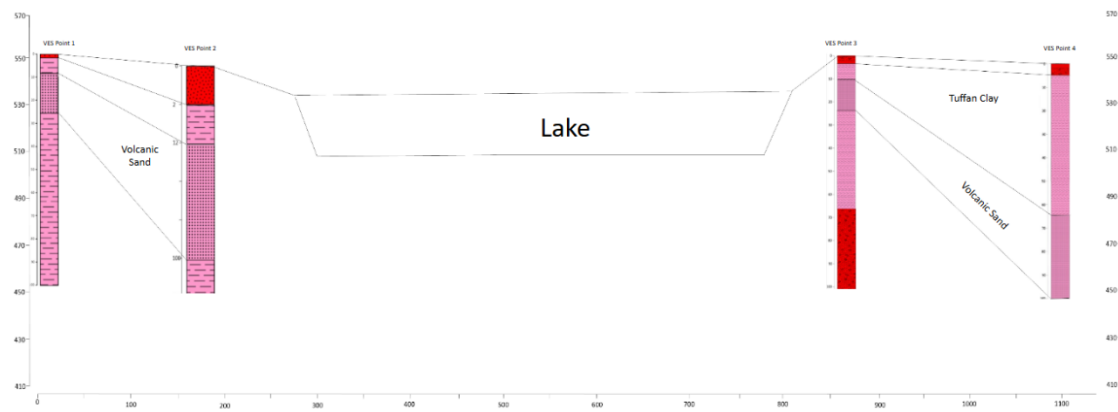


Fig. 11. Geoelectrical cross-section of the VES

The dominance of tuffaceous sandstone in the subsurface indicates favorable groundwater potential due to its porous and permeable nature, which facilitates infiltration and groundwater flow (Walraevens et al., 2025). Meanwhile, the presence of tuffaceous clay as an impermeable layer enhances water storage within the confined aquifer system. Overall, the VES results corroborate the findings from GIS-based spatial analysis, confirming that the western and southeastern parts of the study area possess moderate to high groundwater potential. The western and southeastern parts of the study area are dominated by zones with good groundwater potential. This condition is validated by VES measurement results, which indicate the presence of a layer of high-porosity volcanic sand that acts as a water storage medium in the area. Based on the interpretation, the western part has shallower groundwater potential with an aquifer layer depth of 5–12 meters, while the eastern part shows aquifer potential depths ranging from 10–62 meters.

3.3 Implications

The integration of GIS multicriteria analysis with VES validation provides a robust framework for groundwater assessment in volcanic terrains. The GIS model quantified the spatial variability of recharge related parameters, while VES verification confirmed subsurface continuity and aquifer depth. Together, these approaches ensure both horizontal and vertical representation of groundwater systems. The results show that geomorphology, lithology, and land cover collectively control groundwater potential. Gentle slopes, low drainage density, and permeable volcanic formations correlate strongly with high groundwater potential, whereas steep slopes and compact lithologies restrict recharge and storage capacity. The good agreement between the aquifer zones identified by GIS analysis and those confirmed by VES indicates this approach is suitable for semi-quantitative hydrogeological modeling.

This study shows that integrating GIS multicriteria analysis with VES effectively reduces uncertainty in groundwater exploration in data limited volcanic environments. The methodological framework aligns with recent advances in quantitative hydrogeoinformatics (Maiti et al., 2024; Nistor et al., 2015) which emphasize integrated modeling as a strategy for sustainable groundwater resource planning. The resulting groundwater potential map can guide well site selection, the development of recharge interventions, and the formulation of land use regulation to support sustainable water resource management. The methodological framework is broadly transferable and can be applied in other volcanic regions that exhibit heterogeneous lithology and geomorphology, thereby offering a scalable quantitative reference for future groundwater assessment efforts.

4. Conclusions

This study comprehensively evaluated and mapped groundwater potential zones in Probolinggo Regency by integrating Geographic Information System (GIS) based spatial analysis with the Vertical Electrical Sounding (VES) geophysical method. This integration successfully depicts five different classes of groundwater potential ranging from poor, sufficient, moderate, good, and very good across the study area. The moderate class dominates approximately 53% of the region, primarily distributed in the western and southeastern sectors. In contrast, high-potential zones are concentrated in the northern and eastern areas, whereas low-potential zones are generally located along the southwest and northeast coasts. The integration of spatial indicators and subsurface geophysical validation clearly demonstrates that groundwater occurrence in the region is strongly controlled by morphological conditions, lithology, and drainage density. Areas characterized by gentle slopes, low drainage density, and young volcanic formations with high porosity were identified as the main recharge zones. Validation of the spatial analysis using VES data revealed a consistent correlation between the weighted overlay results from the AHP-based GIS analysis and the subsurface resistivity values.

The identified aquifer layer, composed primarily of tuffaceous sandstone, exhibits resistivity values ranging from 36.9 to 41.3 Ωm . Spatially, aquifers in the western part are relatively shallow (5–12 m), while those in the eastern part occur at greater depths (10–62 m). The results show that combining GIS-based spatial analysis with VES geophysical validation provides a more accurate and comprehensive picture of the characteristics and dynamics of groundwater in volcanic areas. This integrated approach has proven effective in spatially determining groundwater potential zones and can serve as a scientific basis for sustainable water resource planning and management in areas with complex geological conditions. To strengthen the results, future studies are recommended to integrate well data and groundwater quality assessments to validate and refine the spatial model of groundwater potential, thereby improving the reliability of the analysis and its application in water resource management in volcanic areas.

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Author Contribution

Conceptualization, Methodology, Investigation, Writing Original Draft, and Visualization, A.K.

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Not available.

Informed Consent Statement

Not available.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Public datasets used in this study include:

- USGS: <https://earthexplorer.usgs.gov/>
- Esri Land Cover: <https://livingatlas.arcgis.com/landcover/>
- FAO Soils Portal: <https://www.fao.org/soils-portal/data-hub/>
- CHIRPS Rainfall Estimates: <https://www.chc.ucsb.edu/data/chirps>

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used ChatGPT and Grammarly to assist in improving grammar and clarity. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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