UTILIZATION OF MAGNETIC ANOMALY DATA FOR IDENTIFICATION OF FRACTURED GROUNDWATER AQUIFERS; A CASE STUDY FROM SUMBANG DISTRICT, BANYUMAS REGENCY, INDONESIA

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Abstract. This study aims to interpret the distribution of fractured groundwater aquifers in volcanic rock complexes based on local magnetic anomaly data in Sumbang District, Banyumas Regency, Central Java, Indonesia. Geologically, the study area is dominated by lahar and lava deposits originating from Slamet Volcano. The target of the study is to obtain the potential of groundwater resources for irrigation water supply, thereby contributing to food security and agro-tourism development. Magnetic data acquisition was carried out at measurement points with a spatial resolution of 100 m, and produced 256 magnetic intensity data points throughout the study area. The magnetic data were processed through a series of corrections and reductions, resulting in local magnetic anomaly values ranging from –3,089.49 – 1,502.98 nT. Reduction-to-equator (RTE) was applied to the local anomaly data to minimize dipole effects that can complicate interpretation. This procedure resulted in RTE local magnetic anomaly values ranging from –2,056.54 – 2,264.55 nT. Furthermore, horizontal gradient analysis was applied to the RTE local magnetic anomaly data to delineate the distribution pattern of fractured groundwater aquifers in the volcanic rock complexes. The calculated horizontal gradient values ranged from 0.24 – 22.72 nT/m. Maximum horizontal gradient values formed ridge-like patterns associated with suddenly changes in magnetization, which indicate lithological boundaries that may represent fractured aquifers. This interpretation is further supported by inversion modeling results, which reveal the presence of numerous fractures and cracks within the subsurface volcanic rock complexes.

Keywords: Magnetic anomaly data, fractured aquifer, reduction-to-equator, horizontal gradient, Sumbang District.

1. Introduction

Sumbang Village is an area in Banyumas Regency which occupies the northern part of the Purwokerto-Purbalingga Groundwater Basin. In this area, groundwater flows from the recharge area on the upper slopes of Slamet Volcano to the discharge area in Purwokerto City and its surroundings. A groundwater basin is an area delimited by hydrogeological boundaries, where all hydrogeological processes, such as infiltration, flow, and release of groundwater, can occur [1]. Generally, recharge areas are conservation zones; where groundwater is not intended for utilization. Meanwhile in discharge areas, groundwater can be utilized, but with environmental considerations [2]. Most of the discharge area's rock formations are alluvial with large porosity and permeability [3]. They are easily occupied and flowed by groundwater, such as Purwokerto City and its surroundings, which are composed of clay, silt, sand, and gravel [4]. The research area in the northeast of Purwokerto City and the southern part of Slamet Volcano comprises volcanic rock formations in the form of lahar deposits and andesite lava rocks, as seen on the geological map in Figure 1. In the volcanic rock environments, groundwater can fill cracks in the weathered or cracked rock complex and the transition zone between weathered rocks and fresh bedrock.

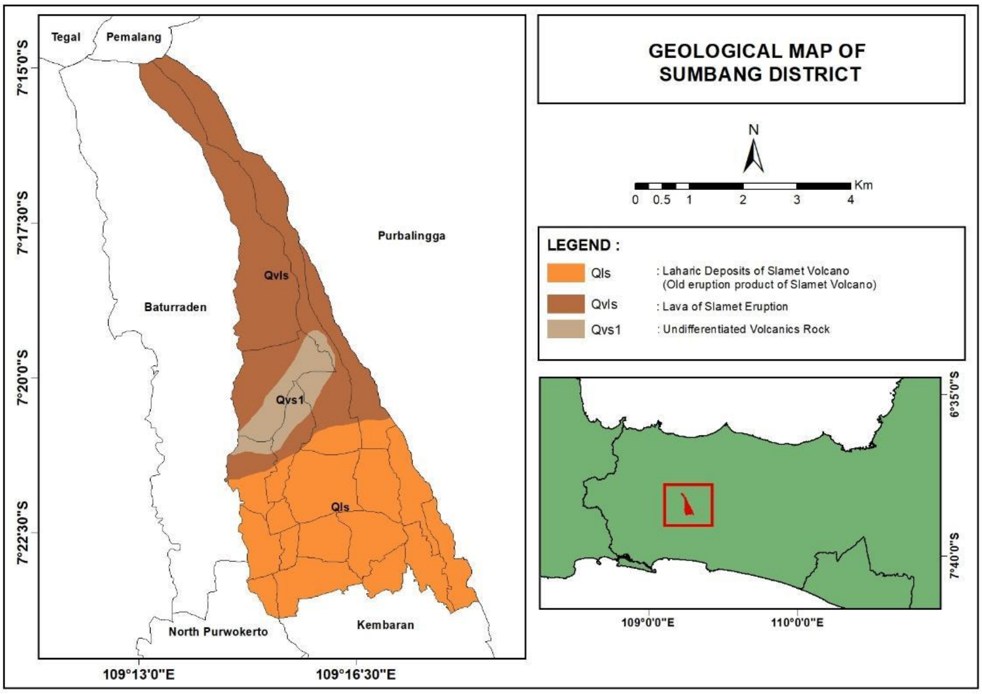

Figure 1. Geological map of the research area (source: Geological Map of Purwokerto-Tegal Sheet).

The Purwokerto-Purbalingga Groundwater Basin has a recharge area on the upper slopes of Slamet Volcano, Central Java [5]. The characteristics of this area need to be understood as an effort to maintain the sustainability or conservation of groundwater. Excessive groundwater use in recharge areas can disrupt groundwater availability in the discharge areas. Knowledge of the characteristics of rocks in the recharge areas, including their connecting areas can help evaluate the groundwater potential in the study area. Geological information indicates that the study area comprises lava formations from Slamet Volcano and vesicular andesite lava with numerous fractures, cracks, and cavities [6]. Fractures, cracks, and cavities in the volcanic rock complexes can act as productive and potential groundwater aquifers. Factors influencing fractures are rock characteristics such as bulk density, porosity, mineralogy types, and rock strength [7]. Rock fractures are usually caused through geological and natural processes such as cooling, folding, faulting, and weather changes, most of which occur in environments near the surface [8].

Groundwater exploration in alluvial areas is generally conducted using the resistivity method [9]; however, this survey method is often insensitive and experiences current injection problems when applied to hard, thick, and massive volcanic rock complexes. Therefore, other geophysical methods must be considered to replace the resistivity method. One such method is the magnetic method [10]. Using magnetic data with high spatial resolution can be a solution for groundwater exploration in volcanic rock complexes. This complex is located in an area that connects the recharge and discharge areas of the Purwokerto-Purbalingga Groundwater Basin. The results of this study are expected to help support food security (especially in Banyumas Regency) by providing irrigation groundwater for agricultural land [11], as can be seen in Figure 2, and for developing agrotourism in the Sumbang District area. Agrotourism is a tourism activity that utilizes agrarian potential as a tourist attraction. The existence of agro-tourism in Sumbang District is expected to increase community income, expand employment opportunities, and strengthen the area's image as a sustainable agriculture-based tourism area.

Figure 2. Agricultural land for rice crops in the research area (personal documentation).

2. Methods

2.1. Location and Time

Magnetic intensity data acquisition was conducted in Sumbang Village and its surrounding areas, which administratively fall within Sumbang District, Banyumas Regency, Central Java. Furthermore, the study area map is shown in Figure 3. Magnetic data processing, modeling, and interpretation were carried out at the Geophysical Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Jenderal Soedirman, Purwokerto. This study was conducted for 8 months, from March – October 2025.

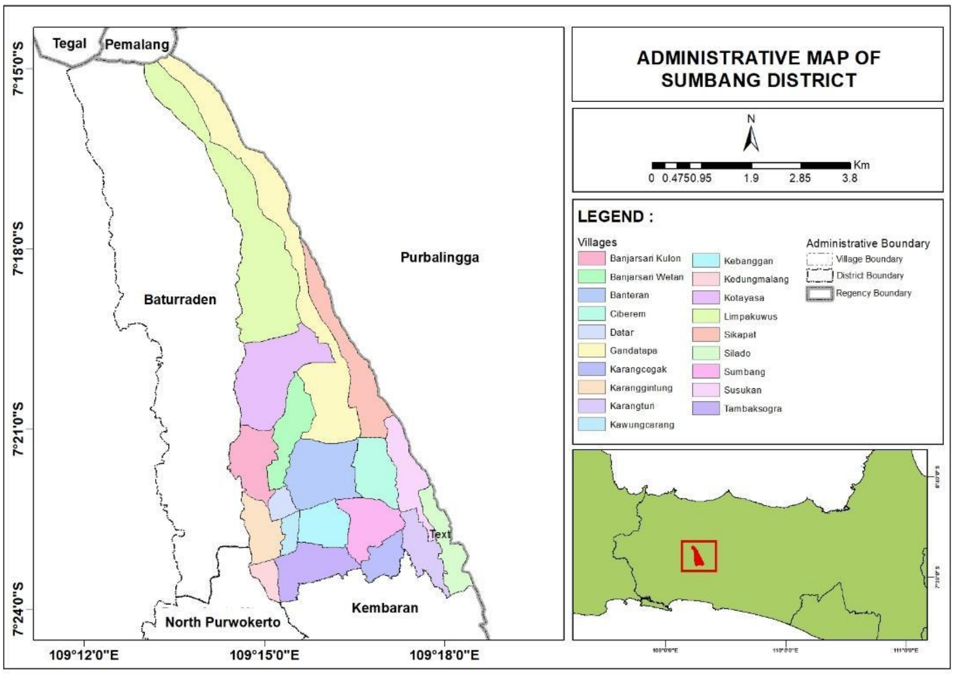

Figure 3. The administrative map of the study area (created using ArcGis).

2.2. Research Equipments

The leading equipment in this study is Proton Precession Magnetometers (PPM) type GSM-19T with an accuracy of 0.05 nT, used for total magnetic intensity data acquisition in the field. Meanwhile the supporting equipment consists of a Global Positioning System (GPS) to measure the geographical position of data points, a laptop, a compass to indicate the north direction of the earth's magnetic field during data acquisition using a PPM sensor, Google Earth to create survey design, Arc-GIS to create location and geological maps, Oasis Montaj 8.4 for creating contour maps, ZondGM2D for inverse modeling of magnetic anomaly data, digital geological maps to support interpretation, and several other application programs.

2.3. Research Procedure

The research began with magnetic data acquisition in the field, where measurements were taken at previously plotted data points in the survey design using Google Earth. The total data points were 256, distributed regularly with a distance of approximately 100 m between points. The total magnetic intensity data obtained was then corrected, including daily correction and IGRF correction. The diurnal correction aims to reduce the external magnetic effects of solar radiation during one day, while IGRF correction aims to eliminate the influence of the Earth's main magnetic field, also known as the International Geomagnetic Reference Field (IGRF), from the total magnetic intensity data. Furthermore, this corrected total magnetic intensity data is referred to as total magnetic anomaly data [12].

The total magnetic field anomaly data is still distributed on the topographical surface, which is mathematically can be expressed as $U(x,y,z)$. To enable the data to be processed in the next stage (i.e., the separation stage for local and regional anomaly data), a reduction to a horizontal surface (at the average topographical elevation of the study area) is performed. This process produces total magnetic anomaly data distributed at a height of z_0, which can be expressed as $U(x,y,z_0)$. This anomaly data reduction process to a horizontal surface uses the Taylor Series approximation with Equation (1) [13]. Equation (1) has been developed in the form of iteration, where the desired value of $U(x,y,z_0)$ can be estimated through a good approach, i.e. the value of $U(x,y,z_0)$ obtained from the i-th iteration can be used to obtain the value of $U(x,y,z_0)$ at the (i+1) iteration. The iteration process must be carried out sufficiently, so the magnetic anomaly value obtained shows convergence [13].

$$U(x,y,z_0)^{[i+1]} = U(x,y,z) - \sum_{n=0}^{\infty} \frac{(z-z_0)^n}{n!} \frac{\partial^n}{\partial z^n} U(x,y,z_0)^{[i]} \tag{1}$$

In many cases, the magnetic anomaly data targeted in this study are always superposed with other magnetic anomaly data originating from intense and broad sources, which are referred to as regional anomalies. To interpret the targeted magnetic anomalies, regional effect correction is carried out, which aims to reduce the influence of regional magnetic anomalies from the measured magnetic anomaly data. One method used to obtain regional magnetic anomaly data is through upward continuation to a certain height, where the resulting anomaly contour pattern has tended to remain constant with tiny variations. Upward continuation is a transformation process to bring potential field data (magnetic field) from a horizontal surface to another surface above it, using Equation (2) [13]. The obtained regional magnetic anomaly data is corrected to the total magnetic anomaly data distributed on a horizontal surface. The correction results are in the form of local magnetic anomaly data, distributed on a horizontal surface. The obtained local magnetic anomaly data is magnetic anomalies that have been cleared of various non-target magnetic effects, allowing them to be modeled and interpreted [12].

$$U(x,y,z_0)^{[i+1]} = U(x,y,z) - \sum_{n=0}^{\infty} \frac{(z-z_0)^n}{n!} \frac{\partial^n}{\partial z^n} U(x,y,z_0)^{[i]} \tag{2}$$

The magnetic dipole nature of local magnetic anomaly data results in multiple interpretations of magnetic anomaly contour maps, making data interpretation sometimes tricky, especially for research areas located in low magnetic latitudes such as Indonesia. Therefore, advanced data processing methods are needed to reduce the dipole effect of the Earth's magnetic field, thus simplifying the interpretation of magnetic anomaly data. One method often applied for this purpose is the reduction-to-the equator (RTE) of magnetic anomaly data [14]. Furthermore, the differential relationship for reduction to the equator can be written as Equation (3), where ΔTe is the RTE magnetic anomaly.

$$\frac{\partial^2 \Delta T_e}{\partial_\lambda \partial_v = \frac{\partial^2 \Delta T_{\lambda v}}{\partial x^2}} \quad (3)$$

Although the RTE local magnetic anomaly map is relatively straightforward in showing the location of the subsurface anomaly sources in order to clarify the lithological boundaries of the anomaly source, such as fractures and fissures, horizontal gradient analysis or first horizontal derivative (FHD) can be performed on the magnetic anomaly data. The maximum FHD value of the RTE local magnetic anomaly data sourced from anomalous objects in the form of plates (e.g. rock layers) tends to be found at the edges or boundaries of the object. Thus, the FHD with the most significant value will be localized directly at the edge or boundary of the object. The working principle of the maximum FHD is to localize the maximum change in the magnetic susceptibility value of the object in the direct lateral direction based on measured magnetic data. The results of the FHD analysis strongly support the process of qualitative interpretation of magnetic anomaly data, namely understanding the subsurface distribution based on the FHD contour pattern. Interpretation focuses on visual analysis to identify and interpret the location of groundwater fractures in the research area. The FHD value of magnetic anomaly data can be expressed as Equation (4) [13].

$$h(x,y) = \left[\left(\frac{\partial B(x,y)}{\partial x}\right)^2 + \left(\frac{\partial B(x,y)}{\partial y}\right)^2\right] \quad (4)$$

3. Results And Discussion

3.1. Magnetic Data Acquisition and Processing Results

The results of magnetic data acquisition in the research area are total magnetic intensity data supplemented by geographic position and elevation data. Data acquisition was carried out in accordance with the plotting of data points in the research design with a spatial resolution of 100 m. Furthermore, daily corrections and IGRF corrections were performed on the magnetic data as described in the Research Methods section. The final results obtained are total magnetic anomaly data with values ranging from -2271.95 – 2337.87 nT. The elevation of the research area has values ranging from 129.05 – 188.26 m. Visually, the elevation contour map and the total magnetic anomaly contour map of the research area can be seen in Figure 4. This total magnetic anomaly data is still distributed on the topographic surface, so it needs to be reduced to a horizontal surface [13]. This is related to further data processing, that requires the anomaly data to be distributed on a horizontal surface. Data reduction has been carried out at the average topographic height of the research area, which is 104.54 m, so that the iteration process in the Taylor Series can quickly reach convergence [13]. The result of this iteration process is total magnetic anomaly data that has been spread at the average topographic elevation.

In order to obtain local magnetic anomaly data as the research target, regional and residual magnetic anomaly data were separated. Regional magnetic anomaly is a component of magnetic anomaly data originating from large-scale variations in the Earth's magnetic field, usually it is related to deep geological structures or older bedrock. This magnetic anomaly has a relatively long wavelength and its variation value is smoother compared to local magnetic anomalies. In this research, regional anomaly data was obtained through an upward continuation process to a height of 850 m, where the anomaly contour pattern has shown a smooth pattern and a small value interval [12] ranging from 800.52 – 836.52 nT. Furthermore, local magnetic anomaly data was obtained after the regional anomaly data was cleaned from the total magnetic anomaly data, with values ranging from -3089.49 – 1502.98 nT. The regional and local anomaly contour maps of the study area can be seen in Figure 5.

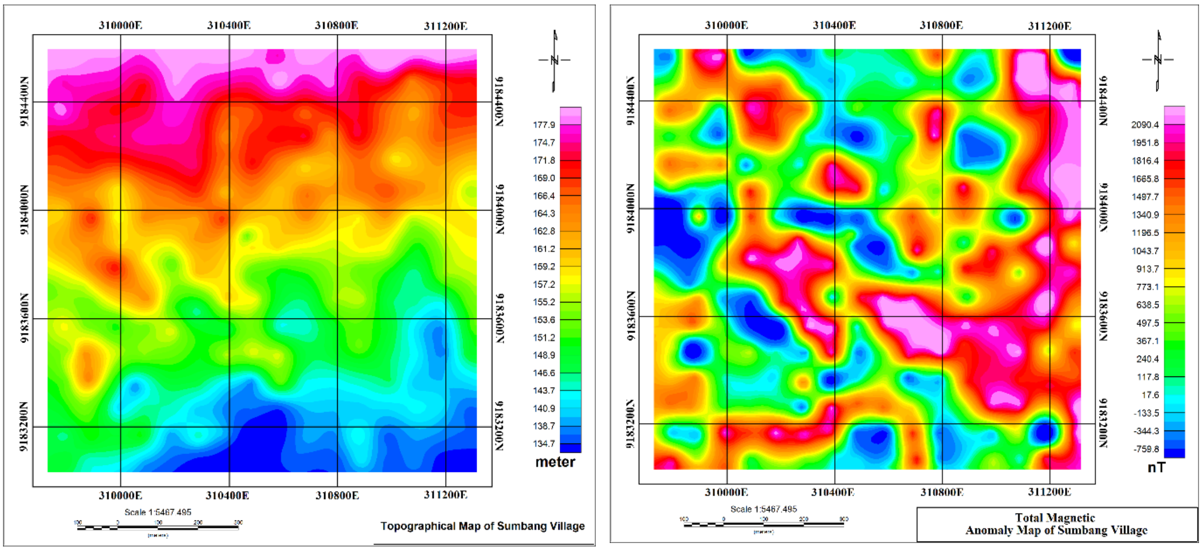

Figure 4. Topographic contour map (left) and total magnetic anomaly contour map (right) of the research area.

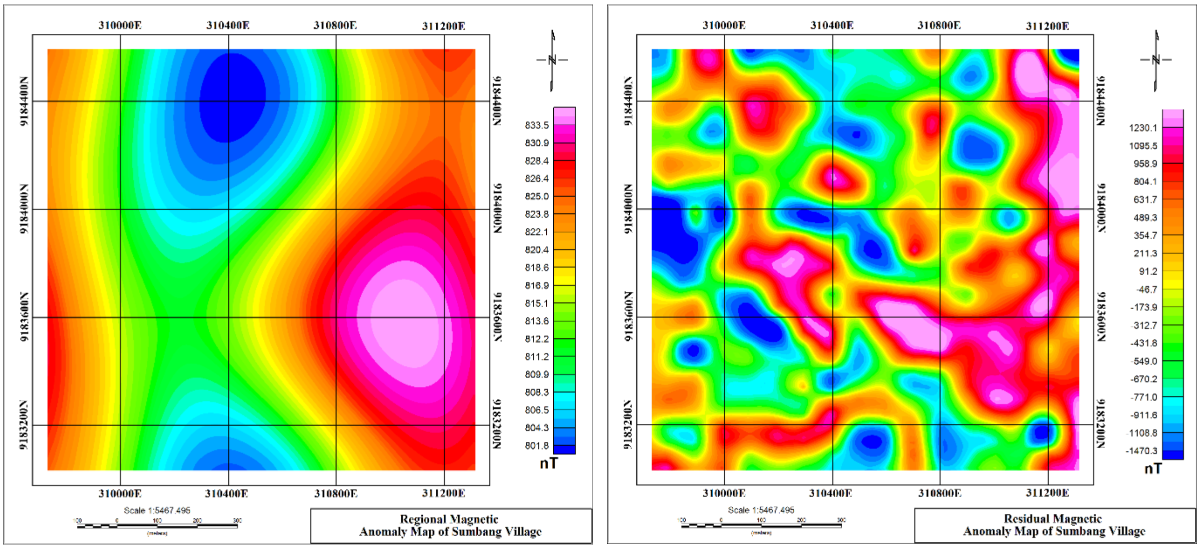

Figure 5. Regional magnetic anomaly contour map (left) and local magnetic anomaly contour map (right) of the research area.

3.2. Magnetic Data Filtering Results

Magnetic surveys have drawbacks, such as complexity in interpretation due to the dipole nature of the magnetic field. The dipole nature of the magnetic field results in magnetic anomaly contour maps being subject to multiple interpretations, making modelling and interpretation of magnetic anomaly data difficult, typically for areas at low magnetic latitudes such as Indonesia (including the study area). One method that can be used to reduce the dipole effect is reduction to the equator (RTE) of the local magnetic anomaly data [15]. The equation has been explained in the Research Methods section. RTE in magnetic anomaly data is a data filtering technique that aims to eliminate the effects of the inclination and declination of the Earth's magnetic field on the magnetic data. This is conducted to make the observed magnetic anomaly data easier to interpret, especially in low-latitude areas. After reduction to the equator, data were obtained with values ranging from -2056.54 – 2264.55 nT. The magnetic anomaly pattern appears to be observed at the equator, where the magnetic field is completely horizontal [16].

Although the RTE local magnetic anomaly map is relatively straightforward, to clarify the lithological contact boundaries of the anomaly source, particularly fractures in the igneous rock complex, a first horizontal derivative or horizontal gradient analysis was performed on the local magnetic anomaly data which had been reduced to the equator as described in the Research Methods. When this filter is applied to interpret the data in two dimensions (2D), the horizontal gradient values will tend to form ridges above sudden changes in magnetization [17]. The presence of several ridges on the map can be used as an indication of the presence of lithological contact boundaries (in the form of fractures) in the volcanic rock complex. The results of the horizontal gradient calculation show magnitudes ranging from 0.238 – 22.752 nT/m. Visually, the RTE local magnetic anomaly contour map and the FHD contour map are shown in Figure 6. Based on the results of the FHD contour map analysis, the anomaly contour pattern is relatively more straightforward. The maximum FHD value of the RTE local magnetic anomaly data originating from anomalous objects tends to be localized at the boundaries or edges [13].

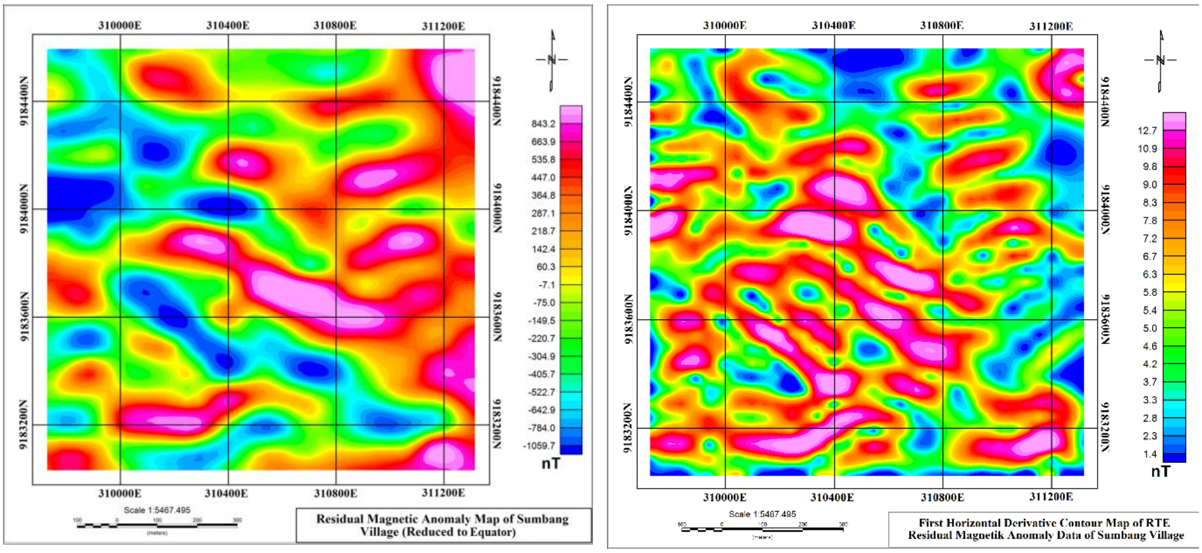

Figure 6. Local magnetic anomaly contour map reduced to the equator (left) and FHD contour map (right) of the study area. The maximum FHD patterns are indicated by red contours which are interpreted as the locations of groundwater fractures.

3.3. Magnetic Data Modeling Results

Subsurface anomaly source modeling was performed using the ZondGM2D application. Modeling was performed along selected trajectories on the RTE local magnetic anomaly contour map. Determination of the trajectory location was based on the FHD contour map overlaid with the RTE local magnetic anomaly contour map. The modeling trajectories depicted on the RTE local magnetic anomaly contour map are presented in Figure 6, while the anomaly profiles and modeling results are shown in Figures 8 and 9. In performing the modeling, several geomagnetic field parameters are required, including the Earth's main magnetic field (IGRF), declination angle, and inclination angle, as shown in Figure 7 [18].

Model Used:	IGRF2025
Latitude:	7.3805° S
Longitude:	109.2837° E
Elevation:	0.0 km Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2025-05-17	0.7422°	-30.9554°	38,412.6 nT	38,409.4 nT	497.6 nT	-23,040.0 nT	44,792.5 nT
Change/year	0.0190°/yr	0.1042°/yr	24.9 nT/yr	24.7 nT/yr	13.1 nT/yr	80.1 nT/yr	-19.9 nT/yr

Figure 7. Earth's magnetic field parameters required in magnetic data modeling.

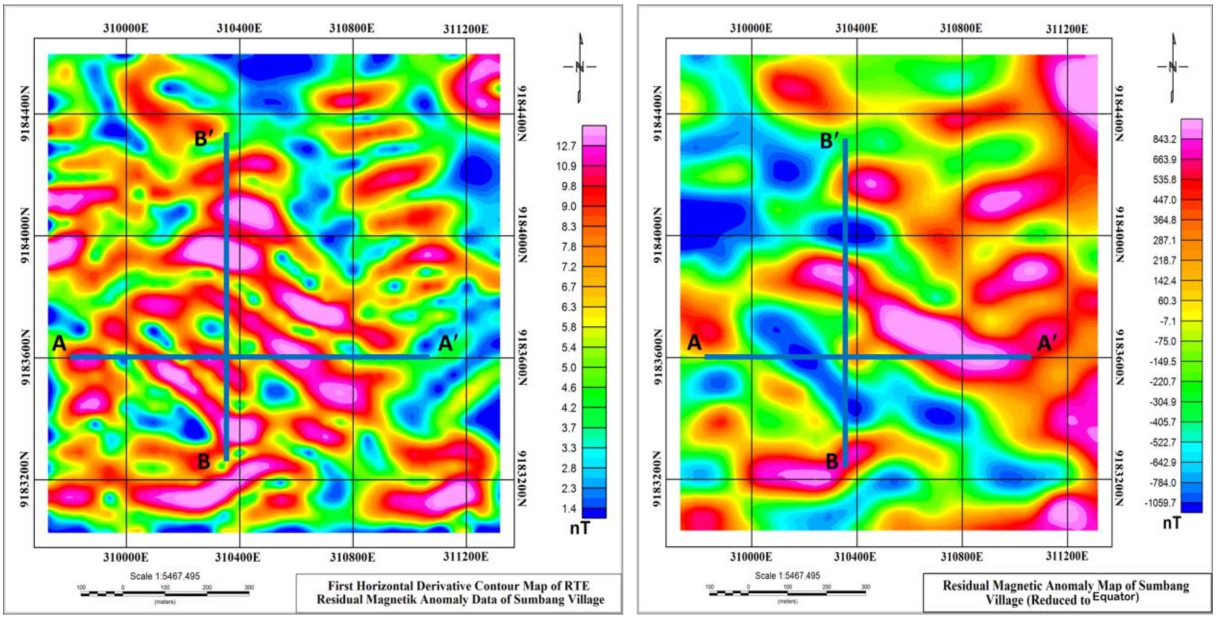

Figure 8. The positions of the inversion modeling trajectories are determined on the FHD contour map which is then adjusted to the RTE local magnetic anomaly contour map.

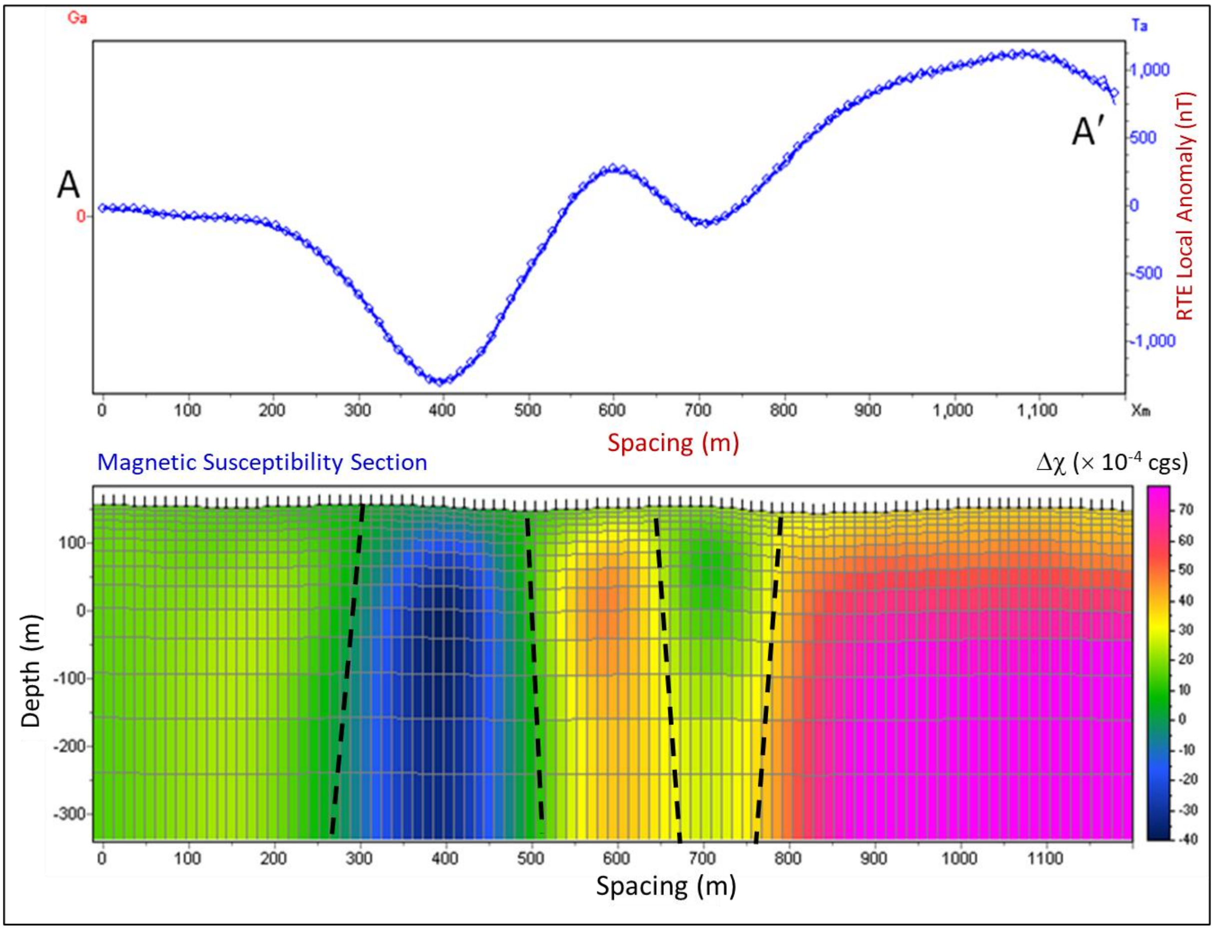

Figure 9. Results of 2D inversion modeling of RTE local magnetic anomaly data along the AA2 trajectory and estimated fracture locations (dotted lines) in the volcanic rock complexes.

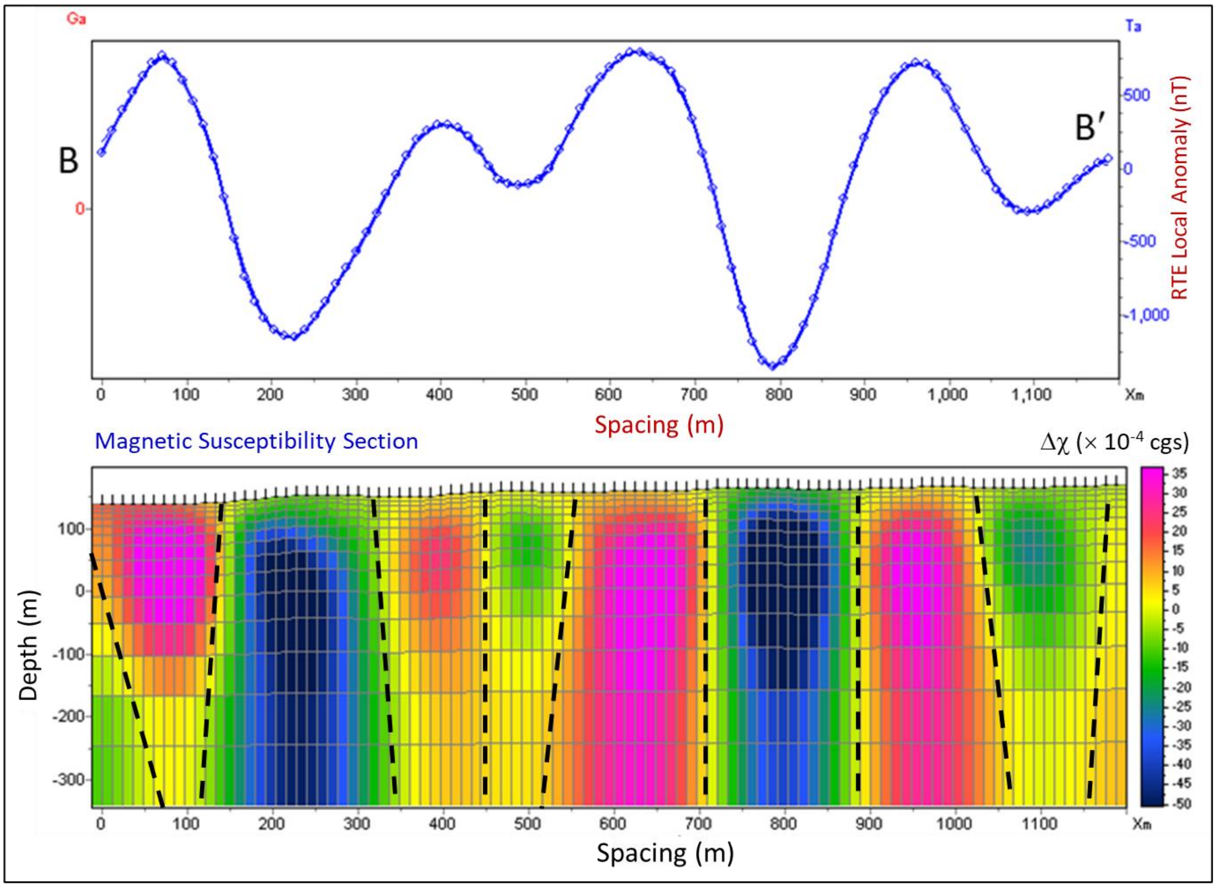

Figure10. Results of 2D inversion modeling of RTE local magnetic anomaly data along the BB2 trajectory and estimated fracture locations (dotted lines) in the volcanic rock complexes.

The results of the 2D modeling are presented only qualitatively, without taking into account the specific lithological composition of the subsurface rocks. The modeling is focused on the identification of fractured aquifers within the volcanic rock complex. In addition to the major fractures visible in the model, numerous minor fractures, fissures, and cavities are commonly found in andesitic lava rocks [19]. Furthermore, several rock units located near the surface of the study area are likely to have undergone weathering, thereby exhibiting higher groundwater content. The weathering of volcanic rocks plays a crucial role in controlling their physical and hydrogeological properties [20]. Weathering process not only alters the mineral composition and textural characteristics but also enhances secondary porosity and permeability through the development of micro-fractures and dissolution features. In volcanic regions, particularly those dominated by lava flows such as andesite, progressive weathering leads to the breakdown of primary minerals into clay-rich assemblages, thereby increasing the capacity of the subsurface rocks in the study area to store and transmit groundwater [19].

3.4. Analysis and Discussion

Reduction-to-the Equator (RTE) is a widely recognized and highly effective technique in magnetic data processing, specifically designed to significantly enhance interpretational clarity, particularly in regions characterized by low magnetic inclination, such as the study area. The RTE method carefully corrects the lateral shifts and distinct asymmetries in anomaly patterns, which primarily result from the inclination and declination angles of the Earth's magnetic field. Consequently, magnetic anomalies can be precisely relocated above their true subsurface sources. Through the application of RTE filter, magnetic anomaly geometries become more symmetric and distinctly centered over the anomalous bodies, thereby greatly facilitating the identification of the boundaries, dimensions, and orientations of subsurface structures. This technique is critical for substantially improving the accuracy and reliability of geological interpretations, including those related to fractured groundwater studies in volcanic rocks, as well as in the broader domains of mineral and hydrocarbon exploration [15].

In this study, the application of the First Horizontal Derivative (FHD) method to the RTE-local magnetic anomaly data proved to be an effective technique for enhancing the detection of lateral variations in magnetic anomaly data, thereby assisting in the identification of fractured aquifer locations in the volcanic rock complexes. The principle of FHD lies in the computation of the first horizontal derivative of magnetic anomaly data, which accentuates the boundaries of magnetization contrasts between intact rock zones and deformation zones. Fractures are generally characterized by reduced magnetization due to weathering processes or the infilling of non-magnetic materials, which consequently appear as sharp gradient anomalies on the FHD contour maps. Thus, FHD analysis enables the delineation of fracture patterns [21], provides a more detailed understanding of structural connectivity, and reveals orientations that are highly valuable for subsurface geological interpretations, particularly in the investigation of fractured groundwater aquifers. The FHD technique is particularly useful in groundwater exploration, particularly in hard-to-reach areas or areas with relatively magnetically homogeneous bedrock. By identifying fracture locations, groundwater resource potential can be accurately evaluated, thereby ensuring the availability of groundwater for the community.

Fractures in volcanic rocks play a crucial role as the primary pathways for groundwater movement and storage. Volcanic rocks are typically hard and compact, resulting in low matrix porosity; however, fractures formed by tectonic activity or magma cooling processes generate secondary voids capable of storing and transmitting groundwater. The fracture systems enable rainfall infiltration to penetrate deeper into the subsurface, filling rock cavities and forming fractured aquifers that serve as significant potential water sources. Nevertheless, the distribution and storage capacity of groundwater are strongly dependent on the connectivity, density, and orientation of the fractures. Thus, hydrogeological and geophysical investigations, including those using magnetic methods, are essential for comprehensively assessing aquifer potential within volcanic rock complexes [22].

4. Conclusion

A geophysical survey with magnetic method was conducted in Sumbang Village, Sumbang District, Banyumas Regency, to identify the distribution of fractured aquifers in the volcanic rock complexes. Geologically, the study area is predominantly composed of lahar deposits and lava flows from Slamet Volcano. The study began with the acquisition of magnetic intensity data in the field at a spatial resolution of 100 m. Magnetic data processing has involved several stages, resulting in local magnetic anomaly values ranging from –3,089.49 – 1,502.98 nT. To minimize the influence of magnetic dipole effects that complicate interpretation, reduction-to-the equator (RTE) was applied to the local magnetic anomaly data, resulting in values between –2,056.54 – 2,264.55 nT. The identification of fractured aquifers in the volcanic rock complexes was then carried out by calculating and analyzing the first horizontal derivative (FHD) of the RTE local magnetic anomaly data. The FHD values obtained range from 0.238 – 22.752 nT/m, with the maximum values forming ridges that indicate suddenly changes in magnetization. The abundance of ridge patterns in the FHD map suggests the presence of lithological boundaries, which are interpreted the locations of fractured aquifers. This qualitative interpretation is further also supported by the results of 2D-inversion modeling, which reveal numerous fractures within the volcanic rock complexes. Thus, the findings of this study are expected to show the presence of abundant groundwater resources in the study area, which can support groundwater-based irrigation to enhance food security and promote agro-tourism development.

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