



Structural Control on Interpreted Subsurface River Flow Patterns in a Karst Landscape: A Case Study of the Bekah Area, Purwosari, Gunungkidul, Yogyakarta

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ABSTRACT

The Bekah karst area in Purwosari, Gunungkidul, Yogyakarta, is part of the Pegunungan Sewu karst landscape, where groundwater availability is closely related to subsurface river systems. This study investigates structural control on interpreted subsurface river-flow patterns using integrated geological, geomorphological, and Very Low Frequency Electromagnetic (VLF-EM) approaches. Field mapping was conducted to identify lithology, karst landforms, faults, joints, fractures, lineaments, and cave-related features. VLF-EM data were acquired along six west–east survey lines, with line lengths of approximately 540–800 m and a station spacing of 20 m. The data were processed into equivalent current density (ECD) sections to detect conductive subsurface anomalies. The results show that the dominant structural trend is northeast–southwest, corresponding with valley orientation, lineament patterns, and several high-conductivity anomalies. These anomalies occur mainly at approximate depths of 20–100 m, with a deeper response reaching about 140 m along Line 4. The anomalies are interpreted as potential water-bearing zones, saturated fractures, or structurally controlled subsurface drainage pathways. The findings indicate that subsurface drainage in the Bekah karst area is likely influenced by fault and fracture systems rather than lithology alone.

1. INTRODUCTION

Karst landscapes represent highly complex hydrogeological systems formed by the interaction between carbonate dissolution, secondary porosity development, and structurally controlled groundwater flow. Unlike porous aquifers, groundwater in karst terrains commonly moves through fractures, faults, bedding discontinuities, conduits, caves, and dissolution-enlarged pathways. Consequently, water movement, temporary storage, and spring discharge in these systems are spatially variable and difficult to characterize. Although karst conduits may occupy only a small proportion of total aquifer volume, they can exert a major control on groundwater hydraulics and flow organization (D’Affonseca et al., 2020; Ford & Williams, 2007; Hartmann et al., 2014). This condition creates both opportunities and challenges for groundwater exploration, particularly in regions where surface water availability is limited.

The Pegunungan Sewu Karst region in southern Java, including Gunungkidul, Yogyakarta, is one of the most prominent karst landscapes in Indonesia. This region is characterized by extensive limestone distribution, closed depressions, caves, sinkholes, dry valleys, springs, and

subsurface drainage networks. Previous studies have shown that the Pegunungan Sewu karst system consists of several hydrogeological subsystems and has long been associated with limited surface water availability, especially during the dry season (Cahyadi et al., 2021; Notosiswoyo & Kusumayudha, 1999; Riyanto, 2023). As a result, underground rivers, springs, and karst aquifers are essential water sources for local communities. However, the discontinuous and structurally influenced nature of karst groundwater flow often makes reliable groundwater-source identification difficult. Understanding the geometry, direction, and continuity of subsurface river systems is therefore crucial for supporting sustainable water-resource management in this region.

Geological structures play a fundamental role in controlling groundwater movement in karst aquifers. Faults, joints, fractures, and other discontinuities may act as preferential pathways for infiltration and subsurface flow. These structural features can enhance secondary permeability, guide conduit enlargement, and influence underground drainage direction. In deformed carbonate aquifers, groundwater flow paths and cave orientations commonly follow fracture and fault systems, although fault zones may also act as barriers or semi-barriers depending on their architecture and permeability contrast

(Adinehvand & Raeisi, 2018; Medici et al., 2021). Structural complexity may therefore produce flow deviation, branching, or separation between different groundwater pathways. For this reason, structural geological analysis is essential for interpreting subsurface river continuity in karst landscapes.

The Bekah area, located in Purwosari, Gunungkidul, represents an important karst setting where subsurface water flow is hypothesized to be influenced by fault and fracture systems. Although the presence of caves and subsurface drainage has been recognized, the relationship between geological structures and the continuity of underground flow pathways remains insufficiently understood. This limitation is important from an environmental geology perspective because karst groundwater systems are vulnerable to both scarcity and contamination. Rapid infiltration through fractures, sinkholes, dolines, and conduits may support groundwater recharge, but it may also allow pollutants to move quickly into subsurface water systems with limited natural filtration or attenuation (Campanale et al., 2022).

Because structurally controlled infiltration pathways may function both as groundwater recharge routes and potential contaminant-entry zones, subsurface investigation is required to identify their position and continuity more accurately. Geophysical methods are commonly used to support subsurface investigation in karst terrains. Among these methods, the Very Low Frequency Electromagnetic method provides a practical approach for identifying conductive subsurface zones that may be associated with saturated fractures, water-bearing conduits, fault zones, or subsurface drainage pathways. Previous studies have applied VLF-EM to groundwater exploration and underground river investigation in karst and fractured terrains (Ohwoghere-Asuma et al., 2018; Purwanto et al., 2024). However, geophysical anomalies in karst environments cannot be interpreted independently. Conductive anomalies may also be related to clay-filled fractures, weathered zones, or lithological variation. Therefore, integrating VLF-EM data with geological mapping, structural analysis, and geomorphological observation is necessary to reduce interpretation uncertainty.

Previous studies in the Gunungkidul and Pegunungan Sewu karst region have discussed groundwater characteristics, cave hydrology, hydrogeological subsystems, hydrochemical variation, water quality, and karst vulnerability (Cahyadi et al., 2021; Notosiswoyo & Kusumayudha, 1999; Riyanto, 2023). However, detailed studies that integrate structural geological mapping and VLF-EM analysis to evaluate subsurface river-flow continuity in the Bekah area remain limited. This creates a knowledge gap in understanding how fault and fracture systems influence the direction, continuity, and possible branching of underground water pathways in this local karst system.

The novelty of this study lies in the integration of field-based structural geological analysis with VLF-EM-derived equivalent current density (ECD) interpretation to evaluate potential subsurface drainage pathways in the Bekah karst area. Unlike previous karst groundwater studies in the Pegunungan Sewu region that mainly focused on hydrogeological characterization, water quality, or general groundwater vulnerability, this study specifically examines how fault and fracture systems may influence the spatial distribution of conductive anomalies and the interpreted subsurface river-flow pattern. This integrated structural–

geophysical approach provides a more site-specific interpretation of potential groundwater pathways and highlights zones that require further hydrogeological verification.

Therefore, this study aims to investigate the structural control on subsurface river-flow patterns and continuity in the Bekah karst area, Purwosari, Gunungkidul, Yogyakarta. Specifically, this research aims to: (1) identify the dominant geological structures controlling the study area; (2) detect subsurface conductive anomalies using VLF-EM data; (3) integrate structural, geomorphological, and geophysical evidence to interpret potential groundwater flow pathways; and (4) evaluate the environmental geological implications for karst groundwater exploration and protection. By integrating geological mapping, structural analysis, and VLF-EM interpretation, this study provides a more comprehensive understanding of subsurface river continuity in the Bekah karst area. The results are expected to contribute to groundwater exploration, karst aquifer protection, and sustainable water-resource management in water-scarce karst environments.

2. METHOD

2.1. Research Design

This study employed an integrated geological, geomorphological, and geophysical approach to investigate the structural control on subsurface groundwater flow in the Bekah karst area, Purwosari, Gunungkidul, Yogyakarta. The research was designed to evaluate the relationship between surface geological structures, karst geomorphology, and subsurface conductive anomalies interpreted as potential groundwater-bearing zones or subsurface drainage pathways. Such an integrated approach is important in karst hydrogeological studies because groundwater flow in carbonate terrains is commonly controlled by a combination of lithology, dissolution processes, fractures, faults, bedding discontinuities, and conduit networks (D’Affonseca et al., 2020; Ford & Williams, 2007; Hartmann et al., 2014; Medici et al., 2021).

The research workflow consisted of four main stages: preliminary data compilation, field geological and geomorphological mapping, VLF-EM data acquisition, and integrated interpretation of structural and geophysical data. Secondary data, including regional geological maps, topographic data, previous hydrogeological studies, and cave-location information, were used to support survey planning and interpretation. Primary data were obtained through direct field observations, structural measurements, geomorphological documentation, and VLF-EM measurements across selected transects in the Bekah area.

2.2. Geological and Geomorphological Mapping

Geological and geomorphological mapping was conducted to identify lithological characteristics, structural features, and karst landforms that may influence groundwater movement. Field observations focused on limestone outcrops, fracture zones, fault-related structures, cave entrances, sinkholes, closed depressions, dry valleys, valley alignments, and other karst morphological features. These features were documented because they may indicate surface manifestations of hidden

drainage networks, focused recharge zones, or fracture-guided groundwater movement.

Lithological observations were used to characterize the dominant carbonate units and their relationship with karst development. Attention was given to limestone units that may develop secondary porosity through dissolution, jointing, and fracturing. Geomorphological observations were carried out to identify surface drainage patterns, valley orientations, slope morphology, and possible structural lineaments. These observations were then compared with the orientation of geological structures and VLF-EM anomalies to evaluate whether the interpreted subsurface flow pathways are structurally controlled. Similar integrated interpretations are commonly applied in karst studies because conduit orientation and groundwater flow are often influenced by geological structures and surface karst morphology (Cahyadi et al., 2021; D’Affonseca et al., 2020; Hartmann et al., 2014).

2.3. Structural Data Collection and Analysis

Structural geological data were collected from exposed outcrops, including joints, fractures, fault planes, slickensides, and gash fractures. Measurements included strike, dip, rake, and fracture orientation where observable. These data were used to determine the dominant structural trends and to evaluate their possible influence on subsurface groundwater flow direction.

Joint and fracture orientations were plotted using rose diagrams to identify dominant directional patterns. Fault-slip analysis was conducted where sufficient kinematic indicators were available. The structural interpretation was used to distinguish between major fault zones, fracture-controlled pathways, and secondary discontinuities. These structural features were then integrated with geomorphological lineaments and VLF-EM anomalies to assess their influence on subsurface drainage continuity. This approach is consistent with previous studies showing that fractures and fault zones can strongly influence karst conduit orientation, groundwater flow direction, and hydraulic connectivity in carbonate aquifers (Adinehvand & Raeisi, 2018; Medici et al., 2021).

2.4. Very Low Frequency Electromagnetic Survey

The Very Low Frequency Electromagnetic method was applied to detect subsurface conductive zones that may be associated with water-bearing conduits, saturated fractures, fault zones, or subsurface drainage pathways. The VLF-EM method uses electromagnetic signals generated by distant radio transmitters operating in the very low frequency range, commonly around 15–30 kHz for geophysical applications alongside high-powered radio wave transmitters with a power output of around 100-1000 kW (Bayrak, 2002; McNeill & Labson, 1991; Ohwoghere-Asuma et al., 2018). Conductive subsurface bodies, such as water-bearing fracture zones or saturated discontinuities, can generate secondary electromagnetic responses that are detected by the receiver.

The field equipment consisted of a T-VLF receiver, compass, and GPS. Survey lines were designed based on topographic conditions, accessibility, cave positions, and the expected orientation of geological structures. Six VLF-EM survey lines were acquired, each oriented approximately west–east, with line lengths ranging from approximately 540 to 800

m and station spacing of 20 m. The survey geometry was selected to intersect the dominant NE–SW structural trend and to detect possible conductive anomalies related to subsurface groundwater pathways (Figure 1). The effective investigation depth was treated as approximate because VLF-EM penetration depends on transmitter frequency, subsurface conductivity, skin depth, topography, and local geological conditions (Alabi et al., 2021; Ohwoghere-Asuma et al., 2018).



Figure 1. VLF-EM survey-line configuration in the Bekah karst area, Gunungkidul, showing six west–east measurement lines designed to intersect the dominant NE–SW structural trend.

The propagation of electromagnetic fields in the subsurface is governed by Maxwell’s equations (McNeill & Labson, 1991; Singh & Sharma, 2015; Telford et al., 1990). For geophysical applications, the relationship between electric and magnetic fields can be expressed as:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1)$$

and

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (2)$$

where $\mathbf{E}$ is the electric field intensity, $\mathbf{H}$ is the magnetic field intensity, $\mathbf{B}$ is the magnetic flux density, $\mathbf{D}$ is the electric displacement field, and $\mathbf{J}$ is the current density. The current density can be expressed as:

$$\mathbf{J} = \sigma \mathbf{E} \quad (3)$$

where σ is the electrical conductivity in S/m. The magnetic flux density and electric displacement are related to the magnetic and electric fields through:

$$\mathbf{B} = \mu \mathbf{H} \quad (4)$$

and

$$\mathbf{D} = \epsilon \mathbf{E} \quad (5)$$

where μ is magnetic permeability in H/m and ϵ is dielectric permittivity in F/m.

In karst environments, subsurface zones containing groundwater, clay-filled fractures, or weathered conductive materials may produce higher electromagnetic responses than compact and dry limestone. Therefore, VLF-EM anomalies must be interpreted carefully by integrating them with geological and geomorphological evidence. In VLF-EM surveys, primary electromagnetic fields from distant transmitters induce secondary electromagnetic responses in

conductive subsurface bodies. The basic principle of electromagnetic induction is illustrated in Figure 2.

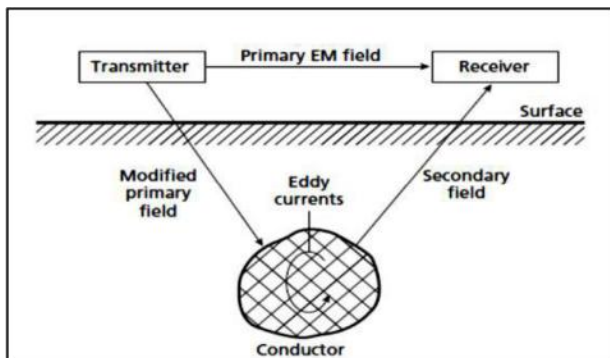


Figure 2. Schematic illustration of electromagnetic induction in the subsurface, showing the interaction between primary electromagnetic fields, conductive bodies, induced eddy currents, and secondary electromagnetic fields (Kearey et al., 2013).

2.5. VLF-EM Data Processing

The VLF-EM data were processed using both manual calculation and KHFilt software to obtain ECD sections. The processing aimed to enhance conductive anomalies and estimate their lateral and vertical continuity beneath the survey lines. The real or in-phase component was emphasized because it is commonly used to identify conductive subsurface features in VLF-EM interpretation. Fraser filtering and Karous–Hjelt filtering are commonly applied to VLF-EM data to enhance anomaly patterns and convert measured electromagnetic responses into current-density pseudo-sections (Ohwoghere-Asuma et al., 2018).

To improve the reliability of the interpretation, the VLF-EM data processing was conducted through several steps. First, the raw in-phase component was inspected to identify anomalous responses and possible noise. Second, Fraser filtering was applied to enhance crossover anomalies and convert them into positive peaks that indicate possible conductive zones. Third, Karous–Hjelt filtering was used to generate ECD pseudo-sections, allowing the lateral and vertical distribution of conductive anomalies to be visualized. The ECD sections were then compared with manually calculated results to evaluate consistency between processing approaches. Because VLF-EM interpretation is non-unique, uncertainty was assessed qualitatively by considering anomaly continuity, consistency between manual and KHFilt processing, spatial agreement with mapped structures, and correspondence with cave positions, valley alignments, and karst morphological indicators. Anomalies without clear geological or geomorphological support were treated as uncertain conductive zones rather than confirmed groundwater pathways.

Topographic correction was applied to reduce the influence of surface elevation variation on the interpreted anomaly geometry. The resulting ECD sections were examined to identify zones of relatively high conductivity. In this study, high ECD values were interpreted as conductive anomalies that may represent water-bearing zones, fracture-controlled conduits, saturated discontinuities, or subsurface drainage pathways. However, these anomalies were not interpreted

independently as definitive underground rivers. Their geological meaning was evaluated by comparing them with field-observed structures, cave positions, valley orientations, and karst geomorphological features. This cautious interpretation is necessary because VLF-EM anomalies may also be caused by clay-filled fractures, weathered zones, or other conductive geological materials (Alabi et al., 2021; Hussain et al., 2020).

2.6. Integrated Interpretation of Subsurface Flow Pathways

The final interpretation was carried out by integrating structural geological data, geomorphological observations, and VLF-EM anomaly patterns. Conductive anomalies that showed lateral continuity across adjacent survey lines and were spatially associated with faults, fractures, cave passages, valley alignments, or karst depressions were interpreted as potential subsurface groundwater pathways. Conversely, isolated anomalies without clear structural or geomorphological support were treated as uncertain conductive zones.

The direction and continuity of the interpreted subsurface flow system were evaluated based on the spatial relationship between ECD anomalies and the dominant structural trends. Attention was given to whether the anomalies followed the NE–SW structural orientation observed in the field. This integrated approach allows a more reliable interpretation of subsurface drainage continuity and reduces uncertainty that may arise from using geophysical data alone. Previous studies have shown that the complexity of karst systems requires multiple lines of evidence, including structural, geomorphological, geophysical, hydrochemical, and tracer data, to construct a reliable conceptual model of subsurface water circulation (Chen et al., 2023; D’Affonseca et al., 2020; Hartmann et al., 2014).

From an environmental geology perspective, the interpreted subsurface flow pathways provide important information for groundwater exploration and water-resource management in the Bekah karst area. The identification of structurally controlled conductive zones may help determine potential groundwater pathways, alternative water sources, and areas that require protection from contamination due to rapid infiltration in karst terrain. This is particularly important in Pegunungan Sewu karst, where surface water is limited and local communities often depend on springs, caves, and underground rivers for water supply (Cahyadi et al., 2021; Notosiswoyo & Kusumayudha, 1999; Riyanto, 2023).

3. RESULTS AND DISCUSSION

3.1. Structural Geological Framework of the Bekah Karst Area

The Bekah area forms part of the Pegunungan Sewu karst landscape, a well-known tropical karst system in southern Java characterized by limited surface drainage, intensive subsurface flow, dolines, caves, springs, and underground river systems. Previous studies have shown that the hydrogeological behavior of the Pegunungan Sewu karst is strongly controlled by the interaction between carbonate lithology, dissolution processes, epikarst development, and

structural discontinuities such as fractures and faults (Cahyadi et al., 2021; Notosiswoyo & Kusumayudha, 1999; Riyanto, 2023). In carbonate aquifers, lithology provides the soluble medium for karstification, whereas joints, fractures, bedding planes, and fault zones commonly function as secondary permeability pathways that regulate infiltration, storage, and groundwater movement (Ford & Williams, 2007; Hartmann et al., 2014; Medici et al., 2021). Therefore, understanding the structural framework is essential for interpreting the continuity, orientation, and possible connectivity of subsurface river systems (Figure 3).

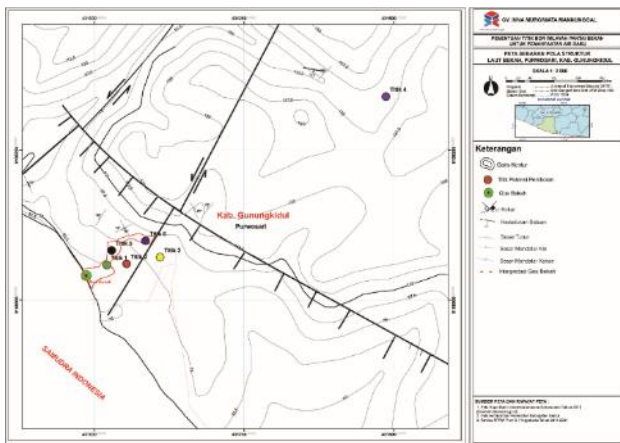


Figure 3. Structural pattern map of the Bekah karst area showing interpreted lineaments, fault traces, cave position, and the dominant NE–SW structural orientation.

Field observations indicate that the Bekah area is characterized by well-developed fractures, joints, and fault-related structures. The structural pattern is generally dominated by northeast–southwest-oriented lineaments, which are also reflected in the orientation of valleys and karst morphological features. This directional consistency suggests that the development of surface morphology and subsurface drainage pathways is not random but is at least partly controlled by the regional structural fabric. Similar relationships between lineament orientation, fracture systems, and karst groundwater potential have been reported in other karst aquifers, where structurally controlled discontinuities promote preferential infiltration and dissolution-enhanced conduit development (D’Affonseca et al., 2020; Magnabosco et al., 2020).

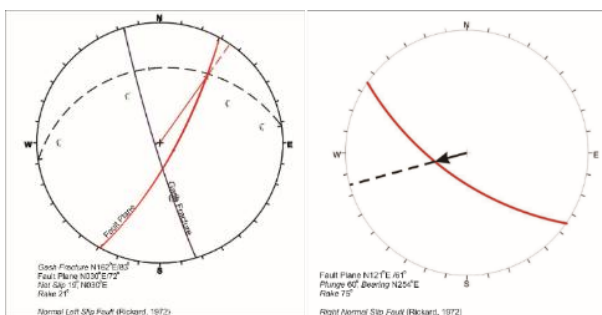


Figure 4. Fault-slip analysis of the Bekah area: (A) strike-slip fault system and (B) normal fault system.

Two primary fault types were identified in Bekah: a strike-slip fault and a normal fault (Figure 4). The strike-slip fault, positioned with a fault plane at N030°E/72° and gash fractures

oriented at N162°E/83°, and the normal fault, defined by a fault plane at N121°E/61° with a plunge of 60°, bearing N254°E, and rake of 75°, were both recognized as major factors in directing subsurface river flow.

The rose diagram of joint orientations shows a dominant NE–SW trend, indicating that the principal fracture system is aligned with the regional structural grain (Figure 5). This orientation is important because open fractures and tension joints may enhance vertical infiltration and lateral conduit enlargement, particularly where they intersect with bedding planes or pre-existing dissolution zones. However, the hydraulic role of fault zones may vary depending on fault architecture. Fault damage zones may increase permeability and act as preferential flow corridors, whereas clay-rich or cataclastic fault cores may locally reduce permeability and behave as barriers or semi-barriers to groundwater flow (Adinehvand & Raeisi, 2018; Medici et al., 2021).

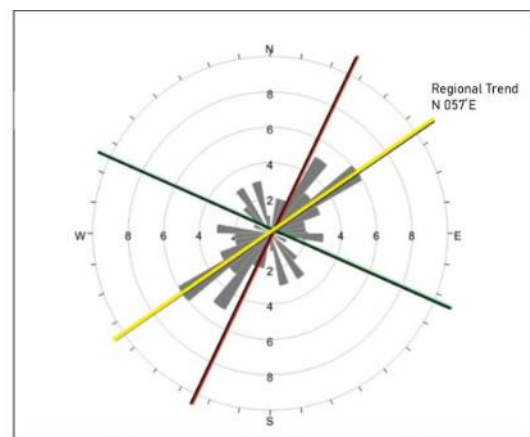


Figure 5. Rose diagram of joint orientations in the Bekah area, showing the dominant NE–SW fracture trend.

Fault analysis identified two main fault systems in the study area. The first fault system is interpreted to have a strike-slip component, whereas the second fault system shows a normal-slip component (Figure 6). The presence of fault planes, gash fractures, and systematic joint orientations indicates that the Bekah karst system has been affected by tectonic deformation, producing zones of structural weakness that may influence the geometry and continuity of underground drainage. In karst terrains, such tectonically generated discontinuities commonly guide dissolution processes and may evolve into enlarged fissures, caves, or subsurface conduits when they are connected to active recharge and discharge systems (D’Affonseca et al., 2020).

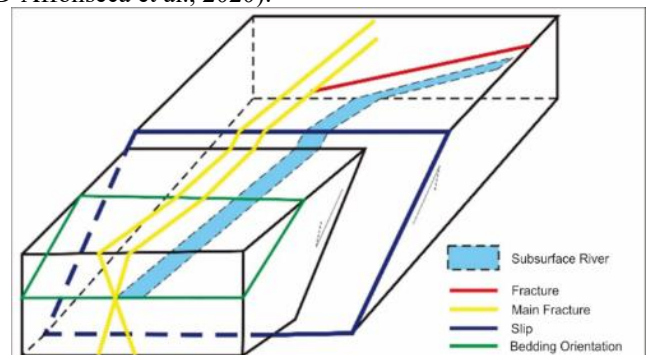


Figure 6. Conceptual model illustrating the influence of faults, fractures, and bedding orientation on interpreted

subsurface river-flow pathways in the Bekah karst area. The blue zone represents the interpreted groundwater-bearing pathway, yellow lines indicate main fractures, red line indicated secondary or minor fracture, green lines show bedding plane orientation, and blue planes represent faults or structural discontinuities.

From a hydrogeological perspective, the NE–SW structural trend is particularly significant because it is consistent with the interpreted direction of subsurface flow obtained from the VLF-EM data. VLF-EM has been widely applied in karst terrains to detect conductive subsurface zones associated with water-filled fractures, cavities, or underground river pathways (Hussain et al., 2020; Purwanto et al., 2024). The agreement between structural measurements, lineament orientation, karst morphology, and VLF-EM anomalies supports the interpretation that groundwater movement in the Bekah area is structurally guided. Consequently, faults and fractures in this area should not only be regarded as tectonic features, but also as environmental geological controls on groundwater availability, subsurface flow connectivity, and potential groundwater vulnerability in the karst system.

3.2. VLF-EM Response and ECD Anomalies

The VLF-EM survey was conducted along six measurement lines oriented approximately west–east, with line lengths ranging from about 540 to 800 m and a station spacing of 20 m. This survey configuration was designed to intersect the dominant NE–SW structural trend identified from field structural measurements and lineament analysis. Because VLF-EM is sensitive to lateral conductivity contrasts, such a configuration is useful for detecting conductive subsurface features that may be associated with groundwater-bearing fractures, fault zones, weathered zones, or subsurface karst conduits. Similar applications of VLF-EM have been reported in karst and groundwater studies, particularly for detecting conductive zones related to underground rivers, fractures, and saturated discontinuities (Ohwoghere-Asuma et al., 2018; Purwanto et al., 2024).

The processed ECD sections show several zones of relatively high conductivity beneath the survey lines. In this study, these high-ECD zones are interpreted as conductive anomalies. The Karous–Hjelt filtering approach is commonly used to transform VLF-EM in-phase data into apparent current-density pseudo-sections, allowing conductive bodies to be visualized in two dimensions (Alabi et al., 2021; Karous & Hjelt, 1983; Ohwoghere-Asuma et al., 2018). However, these sections should be regarded as interpretive pseudo-sections rather than exact representations of subsurface geology. Therefore, high-ECD anomalies should not automatically be interpreted as underground river pathways. They may also represent saturated fracture zones, clay-filled discontinuities, weathered materials, or other conductive bodies. This ambiguity is a common limitation of VLF-EM interpretation and requires geological control for reliable interpretation (Alabi et al., 2021; Hussain et al., 2020).

The ECD sections produced by manual calculation and KHFilt processing show generally comparable anomaly patterns. This consistency increases confidence that the major conductive anomalies are not merely processing artifacts but likely reflect subsurface features with significant conductivity

contrast. Nevertheless, their hydrogeological significance becomes stronger only where the anomalies coincide with independent geological and geomorphological indicators, such as cave locations, fault zones, systematic fracture trends, valley alignments, dolines, and other karst morphological features. Integrated interpretation is particularly important in karst aquifers because groundwater movement is commonly controlled by a combination of lithological dissolution, fracture connectivity, and conduit development (D’Affonseca et al., 2020; Ford & Williams, 2007; Hartmann et al., 2014; Medici et al., 2021).

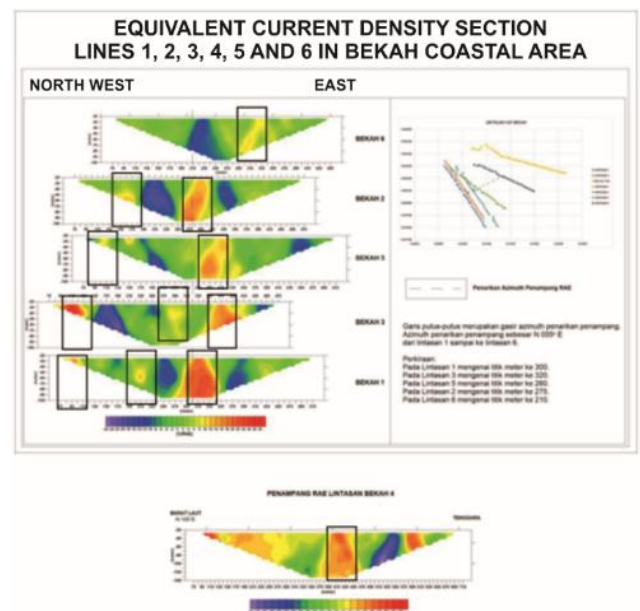


Figure 7. ECD sections of the Bekah karst area derived from VLF-EM data, showing high-conductivity anomalies interpreted as potential groundwater-bearing zones.

Several high-conductivity anomalies occur at approximate depths of 20–100 m, with deeper responses observed along Line 4, reaching about 140 m. These depth estimates should be treated cautiously because the depth shown in VLF-EM ECD sections is affected by transmitter frequency, subsurface conductivity, skin depth, filtering assumptions, and the non-unique nature of electromagnetic responses. However, the lateral continuity of anomalies across several survey lines suggests that the conductive zones may represent interconnected subsurface pathways rather than isolated water pockets. This interpretation is consistent with the general behavior of karst aquifers, where groundwater flow is commonly concentrated along fractures, dissolution-enlarged discontinuities, and conduit networks rather than being evenly distributed through the rock matrix (D’Affonseca et al., 2020; Hartmann et al., 2014).

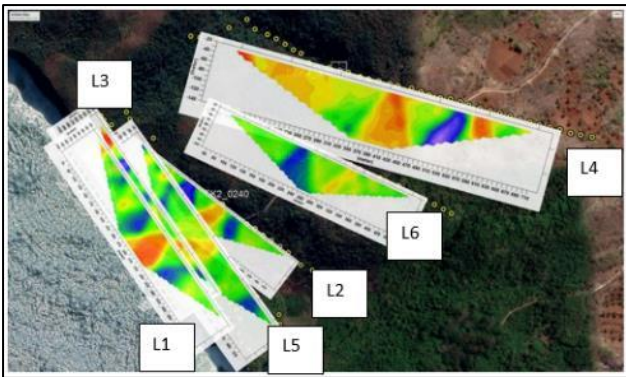


Figure 8. Spatial overlay between ECD sections and VLF-EM survey-line configuration, showing the relationship between conductive anomalies and survey-line position.

In the Bekah area, the spatial agreement between high-ECD anomalies, the dominant NE–SW structural trend, and karst geomorphological indicators supports the interpretation that subsurface groundwater flow is structurally guided. Therefore, the VLF-EM anomalies are best interpreted as potential groundwater-bearing structural corridors or subsurface drainage pathways, rather than as definitive underground rivers without further verification. Additional confirmation from cave mapping, tracer tests, resistivity surveys, borehole data, or hydrochemical correlation would improve the reliability of this interpretation.

3.3. Interpretation of Subsurface River Flow Continuity

Integrated interpretation of structural data and VLF-EM responses suggests that the main subsurface drainage trend in the Bekah area is generally oriented northeast–southwest. This trend corresponds closely with the dominant fracture and lineament orientation observed in the field. The spatial agreement between the NE–SW structural pattern and the distribution of high ECD anomalies indicates that geological structures likely exert an important control on the development and continuity of subsurface drainage. In karst aquifers, the geometry of conduits and preferential flow paths is commonly influenced by bedding planes, joints, fractures, faults, and other discontinuities, although their exact position and hydraulic behavior remain difficult to predict without supporting hydrogeological data (D’Affonseca et al., 2020; Ford & Williams, 2007; Hartmann et al., 2014; Medici et al., 2021).

The interpreted ECD sections indicate at least three possible subsurface conductive anomalies. Sections 1 and 2 show anomalies that are relatively consistent with the inferred upstream continuation from the northeast toward the southwest. These anomalies are interpreted as potential conductive zones associated with the main subsurface drainage system. Their alignment with the dominant structural trend strengthens the interpretation that subsurface flow is guided by fracture and fault systems. Previous VLF-EM applications in karst terrains have demonstrated its usefulness for delineating subsurface conductive responses associated with water-filled cavities, fracture networks, or possible underground drainage routes, particularly when supported by geological and geomorphological observations (Purwanto et al., 2024; Zakaria et al., 2021).

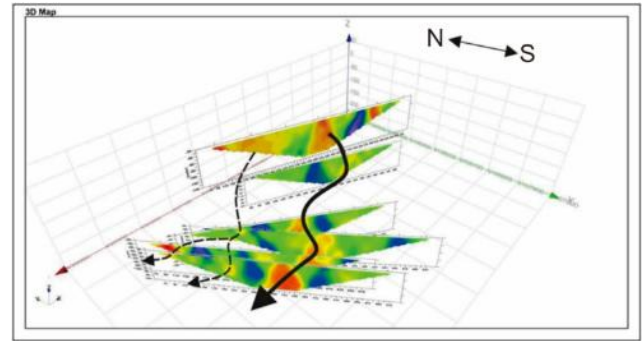


Figure 9. Interpretation of potential subsurface drainage pathways based on manual ECD processing.

In contrast, Sections 3 and 5 show anomaly patterns that differ from the expected position of the known Bekah Cave flow. This discrepancy may indicate the presence of a larger or separate subsurface flow system beyond the currently mapped cave passage. Another possibility is that the anomalies represent branching conduits, saturated fracture zones, or clay-rich/weathered structural discontinuities that are not directly connected to the main Bekah Cave outlet. Therefore, these anomalies should be interpreted as potential hydrogeological targets rather than definitive underground river segments. This caution is important because karst aquifers are characterized by high spatial heterogeneity, unmapped conduits, and structural uncertainty; different conduit configurations may produce similar geophysical or hydrological responses (D’Affonseca et al., 2020; Hartmann et al., 2014).

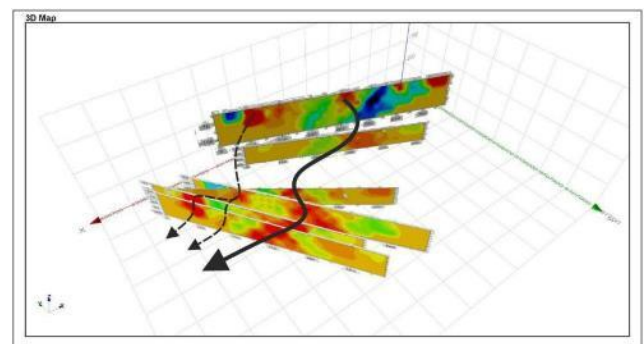


Figure 10. Interpretation of potential subsurface drainage pathways based on KHFilt processing.

The presence of significant conductive anomalies west of the Bekah Cave outlet suggests that the subsurface drainage network may be more complex than previously recognized. These anomalies may represent alternative flow pathways, branching conduits, or secondary groundwater routes controlled by fractures and fault-related discontinuities. Such branching or multi-pathway behavior is common in karst aquifers, where groundwater flow is concentrated along dissolution-enlarged fractures and conduits embedded within a lower-permeability carbonate matrix (Hartmann et al., 2014). However, because VLF-EM mainly detects conductivity contrast, additional verification through cave mapping, tracer tests, resistivity imaging, borehole data, or hydrochemical correlation is needed to confirm whether these anomalies represent active groundwater flow pathways (D’Affonseca et al., 2020).

Based on the combined evidence, the Bekah subsurface river system is interpreted as part of a structurally controlled

multi-pathway groundwater system. The dominant inferred drainage trend is NE–SW, but local deviations may occur due to the influence of faults, fracture intersections, conduit branching, and lithological or permeability contrasts. This interpretation explains why some VLF-EM anomalies correspond well with the known cave system, while others appear displaced from the expected cave position. Therefore, the Bekah karst system should not be interpreted as a single linear underground river, but rather as a complex subsurface drainage network whose continuity is strongly influenced by the structural framework.

3.4. Structural Control on Karst Groundwater Flow

The integrated structural and VLF-EM results indicate that the Bekah karst system is controlled by structural anisotropy rather than by lithology alone. The NE–SW trend observed in joints, lineaments, valley orientation, and conductive anomalies suggests that groundwater movement is preferentially organized along fracture-controlled permeability corridors. This pattern is consistent with the behavior of deformed carbonate aquifers, where faults, joints, and fracture systems commonly guide groundwater flow, conduit development, and cave orientation (Adinehvand & Raeisi, 2018; D’Affonseca et al., 2020; Medici et al., 2021). However, the Bekah system also shows local deviations from this main trend, particularly west of Bekah Cave, where conductive anomalies are displaced from the expected cave-flow position. These deviations may reflect branching conduits, secondary fracture-controlled pathways, or isolated conductive zones related to weathered or clay-filled discontinuities (Hartmann et al., 2014).

Compared with more mature and laterally continuous karst drainage systems, the Bekah area appears to represent a structurally compartmentalized drainage network. The coexistence of strike-slip and normal fault components may create intersecting fracture zones that locally enhance permeability and provide potential pathways for groundwater movement. At the same time, the possibility of fault-core barriers or low-permeability zones cannot be excluded because fault zones in carbonate aquifers may either enhance flow through fractured damage zones or impede flow through low-permeability fault cores (Adinehvand & Raeisi, 2018; Medici et al., 2021). Therefore, the interpreted flow system should be viewed as a structurally controlled multi-pathway network rather than a single continuous underground river. This interpretation is important because it explains why some VLF-EM anomalies correspond with the expected cave-flow direction, whereas others occur away from the known Bekah Cave outlet.

This structural control has important environmental implications because it affects both groundwater availability and groundwater vulnerability. Structurally controlled fractures and conduits can enhance groundwater recharge and increase the potential for water accumulation in subsurface drainage pathways. However, the same pathways may also increase vulnerability to contamination because water and pollutants can rapidly enter the aquifer through fractures, sinkholes, dolines, and dissolution conduits with limited filtration, sorption, or natural attenuation (Campanale et al., 2022; Lan et al., 2019). Therefore, identifying structurally controlled flow pathways is important not only for

groundwater exploration, but also for groundwater protection, land-use planning, and environmental management in the Bekah karst area. In this study, the coincidence between the NE–SW fracture-lineament trend, high-ECD anomalies, and the inferred subsurface drainage direction supports the interpretation that groundwater movement in the Bekah area follows structurally controlled permeability corridors.

3.5. Environmental Geology Implications

In the context of Gunungkidul, these findings are particularly relevant because seasonal drought can increase dependence on subsurface water sources, while settlement expansion, agriculture, tourism activity, and unmanaged waste disposal may increase contamination risk above structurally controlled recharge zones.

The interpretation of structurally controlled subsurface flow in the Bekah area has direct relevance to water-resource management in Gunungkidul, where seasonal drought can increase dependence on subsurface water sources. In addition, settlement expansion, agriculture, tourism activity, and unmanaged waste disposal may increase contamination risk above structurally controlled recharge zones. The Pegunungan Sewu karst region is characterized by limited surface water availability, recurring dry-season water shortages, and strong dependence on springs, caves, underground rivers, and karst aquifers as water sources for local communities (Cahyadi et al., 2021; Notosiswoyo & Kusumayudha, 1999; Riyanto, 2023). Therefore, identifying possible subsurface flow pathways, branching systems, and structurally controlled groundwater corridors is important for guiding future groundwater exploration, cave-hydrology investigations, and sustainable water-supply planning. In karst drainage basins, understanding the connection between recharge areas, underground conduits, and spring outlets is essential for evaluating groundwater potential and developing appropriate water-resource management strategies (Cahyadi et al., 2021).

The conductive anomalies located west of Bekah Cave may represent potential alternative groundwater pathways, branching conduits, or saturated fracture zones. However, these anomalies should be interpreted as priority targets for further verification rather than direct evidence of active underground river flow. Complementary methods such as electrical resistivity tomography, tracer tests, cave surveying, borehole validation, and hydrochemical analysis are needed to confirm whether these anomalies are hydraulically connected to the known Bekah Cave system or represent other conductive geological features such as clay-filled fractures or weathered zones. Integrated geophysical and hydrogeological approaches are therefore needed in karst studies because subsurface conditions are spatially complex, and reliance on a single dataset may increase interpretive uncertainty (Chen et al., 2023; Hussain et al., 2020). Tracer tests and hydrochemical monitoring are particularly useful for verifying recharge–discharge connectivity and identifying active groundwater pathways in karst systems (Chen et al., 2023).

From a land-use and environmental management perspective, areas located above interpreted flow pathways should be treated as sensitive recharge or groundwater-protection zones. Human activities at the surface, including waste disposal, intensive agriculture, settlement expansion, livestock activity, and uncontrolled land modification, may

pose risks to groundwater quality if they occur near structurally controlled infiltration pathways. Karst aquifers are particularly vulnerable to contamination because water and pollutants can rapidly enter the subsurface through fractures, sinkholes, dolines, ponors, and dissolution conduits, often with limited filtration, sorption, or natural attenuation (Campanale et al., 2022; Lan et al., 2019). Therefore, the results of this study can contribute to the development of more sustainable groundwater management strategies in the Bekah karst area, especially by identifying zones that require further investigation, protection, and careful land-use control.

4. CONCLUSION

This study demonstrates that subsurface river flow in the Bekah karst area is strongly influenced by geological structures, particularly faults, joints, and fracture systems. The dominant northeast–southwest structural trend corresponds with valley orientation, lineament patterns, and high-conductivity anomalies interpreted from VLF-EM data, suggesting that structural discontinuities act as preferential pathways for infiltration, conduit development, and groundwater movement. The ECD sections reveal several conductive anomalies interpreted as potential water-bearing zones or structurally controlled subsurface drainage pathways. The main interpreted drainage trend is northeast–southwest, with possible branching or additional pathways west of Bekah Cave. These findings suggest that the Bekah subsurface drainage system may represent a complex multi-pathway groundwater network rather than a single linear underground river.

From a practical perspective, the identified conductive anomalies, particularly those located west of Bekah Cave, should be prioritized for future groundwater exploration and verification. These zones may serve as potential targets for follow-up investigations using electrical resistivity tomography, tracer tests, cave surveying, hydrochemical analysis, or borehole validation. In terms of environmental management, areas located above the interpreted structural corridors should be considered sensitive recharge and groundwater-protection zones because contaminants may rapidly enter the karst aquifer through fractures, sinkholes, and dissolution pathways. Therefore, the results of this study can support groundwater exploration planning, karst aquifer protection, and sustainable water-resource management in the Bekah karst area.

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