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SUBSURFACE INVESTIGATION OF LO AND BANGI CAVES USING THE VERY LOW FREQUENCY (VLF) METHOD FOR GEOTOURISM DEVELOPMENT

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Abstract: The existence of Lo Cave and Bangi Cave area, which are close to each other in the karst area of Kedungsalam Village, Donomulyo District, Malang Regency, has excellent potential to be developed as a geotourism destination that supports nature conservation and economic empowerment of the local community. However, until now, there is no adequate scientific data regarding the structure and direction of the cave system in the area. This study aims to determine the pattern and direction of the cave system as a basis for developing geotourism in the Lo Cave and Bangi Cave area. Data acquisition was conducted using the Very Low Frequency (VLF) geophysical method on ten measurement lines with 10 m intervals, which were adjusted to the topographic conditions and karst features in the field. The transmitter used the NWC station located in North West Cape, Australia, with a frequency of 19.800 Hz. In data processing, Baker and Myers' corrections were used to reduce the influence of topography on the data. The Fraser filter is used to make the anomaly position more visible and easier to interpret, and the Karous-Hjelt filter visualises the rock conductivity pattern against depth. VLF data processing results showed consistent conductive anomalies on all lines, indicating the presence of cavities and underground water flow paths. 3D modelling revealed that the cavity system extends from Lo Cave to the northwest, then branches at Line 3. The first branch heads southeast across Lines 6, 2, 1, and 9, while the second branch heads north until it reaches Bangi Cave. These findings provide information about the subsurface patterns and structures around Lo Cave and Bangi Cave as a scientific basis that can be used for the development of safe and sustainable geotourism.

Keywords: Cave conservation, Geotourism, Karst area, Underground cave system, Very Low Frequency (VLF)

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INTRODUCTION

Karst landscapes are one of the geological heritage sites that possess extremely high scientific, ecological, and aesthetic value (Yilmaz, 2012; Khalaf, 2022; Wang et al., 2022). Dissolving carbonate rocks such as limestone, dolomite, and gypsum by acidic water creates unique and complex landforms, such as dolines, ponors, and underground cave systems. This morphological uniqueness appeals to researchers and academics and holds great potential for developing nature-based tourism, particularly geotourism (Zhang et al., 2023; Labib et al., 2024). The presence of karst systems indicates long-term geological processes, storing important information about underground hydrology and unique biodiversity (Andreo, 2012; Susilo et al., 2018; Sahrina et al., 2022). Therefore, karst areas have great potential to be developed as educational tourism destinations supporting nature conservation and local communities' economic empowerment (Hadian et al., 2021; Khalaf, 2022).

Caves are one of the karst features that are formed naturally through the process of rock dissolution over a long period (Sánchez-Botello et al., 2018; De Waele & Gutiérrez, 2022; Rauf et al., 2023). Karst cave systems usually have underground river networks, long passages, and large rooms (chambers), making them suitable research objects in geology, ecology, and climatology (Ford & Williams, 2007; Duc & Guinea, 2014).

If the management manages the cave appropriately, the cave has the potential to be developed as a geotourism site that functions as a place for recreation and education (Sahrina et al., 2022; Hadian et al., 2025; Kusuma et al., 2025). In

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addition, cave geotourism development can provide economic and social impacts for local communities and strengthen awareness of environmental conservation (Carrillo-Hernández et al., 2024; Dousin & Aralas, 2024; Xia, 2024). One area with great potential for cave geotourism development is Kedungsalam Village, Donomulyo District, Malang Regency, Indonesia. There are two main caves in this area, Lo Cave and Bangi Cave, which, based on field observations and interviews with local communities, show indications of an active cave system developing vertically and horizontally and carrying groundwater. The existence of these two caves is visually appealing (Figure 1) and can potentially be developed as a geotourism destination. However, information regarding the internal structure of the cave, the direction of groundwater flow, and fracture patterns is still minimal. This problem is a challenge in developing geotourism, especially in designing tourist routes and reducing potential geotechnical hazards (Sunkar et al., 2022). Thus, subsurface studies are needed as a scientific basis for safe and sustainable geotourism management (Aydın & Yüceer, 2020; Zakaria et al., 2021).

Direct exploration methods, such as geological surveys and speleological exploration, do provide important information regarding the physical conditions of caves, but they still have limitations in reaching the entire subsurface structure (Suranyi et al., 2010; Gama et al., 2019), especially at depths and in areas that are difficult to access. Some structural indications can be observed on the surface. Still, this information is insufficient to determine the direction, depth, and distribution of cavities or fractures, which are critical in karst systems. To address this, geophysical approaches offer a practical solution, as they can reveal subsurface structures without damaging the environment or requiring drilling (Wang, 2017; Hussain et al., 2020). In complex and varied karst environments, the geophysical methods must have high resolution at shallow depths and efficiently cover large areas (Goldscheider, 2015). Therefore, integrating geophysical and local geological data is essential in supporting conservation efforts and the development of geotourism based on scientific data.

One promising geophysical method for studying karst areas is the Very Low Frequency (VLF) method. Based on the study by Telford et al. (1990). This method effectively detects conductive zones such as fractures, cavities, and underground rivers using electromagnetic waves from low-frequency transmitter stations. Santos et al. (2006) researched Santiago Island, Cape Verde, and successfully identified groundwater flow zones in volcanic-karst formations. De Giorgi & Leucci (2014) used the VLF method in Italy to find cavities that could cause land subsidence. A survey by Bahri et al. (2024) also successfully detected an underground river located at a depth of 30 m in the Donorojo District, Pacitan, Yogyakarta. The results of previous studies using the VLF method show that this approach is reasonably practical in identifying subsurface structures. Meanwhile, Faizal et al. (2017) mapped conductive anomalies related to dissolution zones and groundwater potential using the VLF method in Hargosari Village, Gunungkidul. The advantages of VLF lie in time and cost efficiency and its ability to identify subsurface anomalies with adequate resolution, especially in complex karst environments (Sharma et al., 2014; Eppelbaum, 2021). Based on this, this study was conducted to determine the patterns and subsurface structures of Lo Cave and Bangi Cave using the VLF method. The results of geophysical data interpretation can provide a strong scientific basis for designing safe, educational, attractive, and sustainable geotourism development, while promoting the wise and responsible utilization of karst potential.

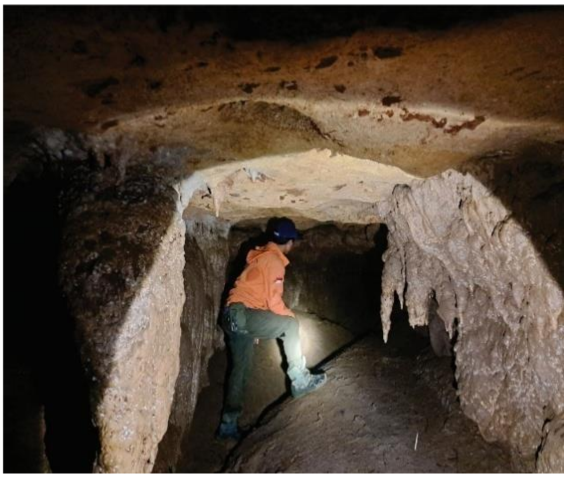
(a)   (b)

Figure 1. (a) Internal view of Bangi Cave with active stalactites; (b) Internal condition of Lo Cave showing horizontal passage (Source: Authors field survey, Kedungsalam Village, November 18-21, 2024)

MATERIALS AND METHODS

1. Study Area

The stratigraphy of South Malang Karst consists of sedimentary rocks from the Wonosari Formation, Campurdarat Formation, and Nampol Formation (Figure 2Figure). The Wonosari Formation consists of coral limestone, mudstone limestone, tuff limestone, sandstone limestone, napal, black peat mudstone, and calcirudite. The Campurdarat Formation consists of Hablur limestone and mudstone. The Nampol Formation consists of tuffaceous sandstone, claystone, sandy napal, sandy limestone, and black claystone. The age of the Wonosari Formation rock unit is concluded to be Late Miocene, and the Nampol Formation rock unit is Middle Miocene. In contrast, the Campurdarat Formation rock unit is Early Miocene. Based on the Geological Map (Figure 2), the research location is in the Wonosari Formation, which is dominated by limestone, sandy napal, and claystone intercalations (Boimau et al., 2018). The dissolution process (karstification) that has been ongoing for thousands of years has formed various distinctive features, such as dolines, ponors, underground rivers, and natural caves. These conditions make Southern Malang one of the areas rich in geological potential and highly suitable for the development of geotourism based on karst landscapes.

Regarding structural geology, South Malang is influenced by regional tectonic activity, which forms faults and cracks, and affects the cave formation process (Labib et al., 2019; Syahputra et al., 2019). This geological structure is one of the primary considerations in implementing geophysical surveys to identify the distribution patterns of subsurface cavities and detect anomalies that are not visually visible. The study locations include Lo Cave and Bangi Cave, which are suspected of having subsurface linkages that may be explored with the VLF approach. This area has a strong ecotourism potential because of its biodiversity, unusual morphology, and geological educational value, which can be used in geotourism development.. Therefore, understanding the internal structure of the two caves is an essential initial step in designing conservation strategies and sustainable utilisation of the area. This study provides an initial overview of the characteristics of the karst cave system in South Malang, which has rarely been studied in depth using a geophysical approach.

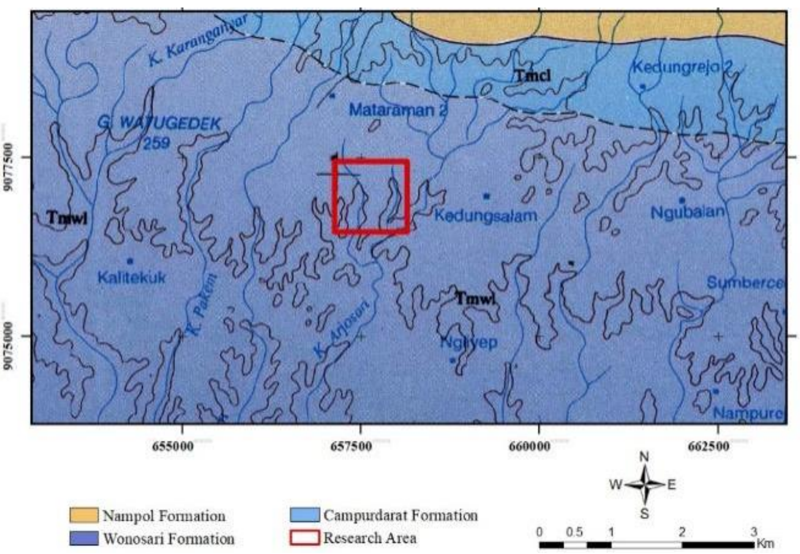


Figure 2. Geological map of the research location (Source: Developed by the authors, 2025)

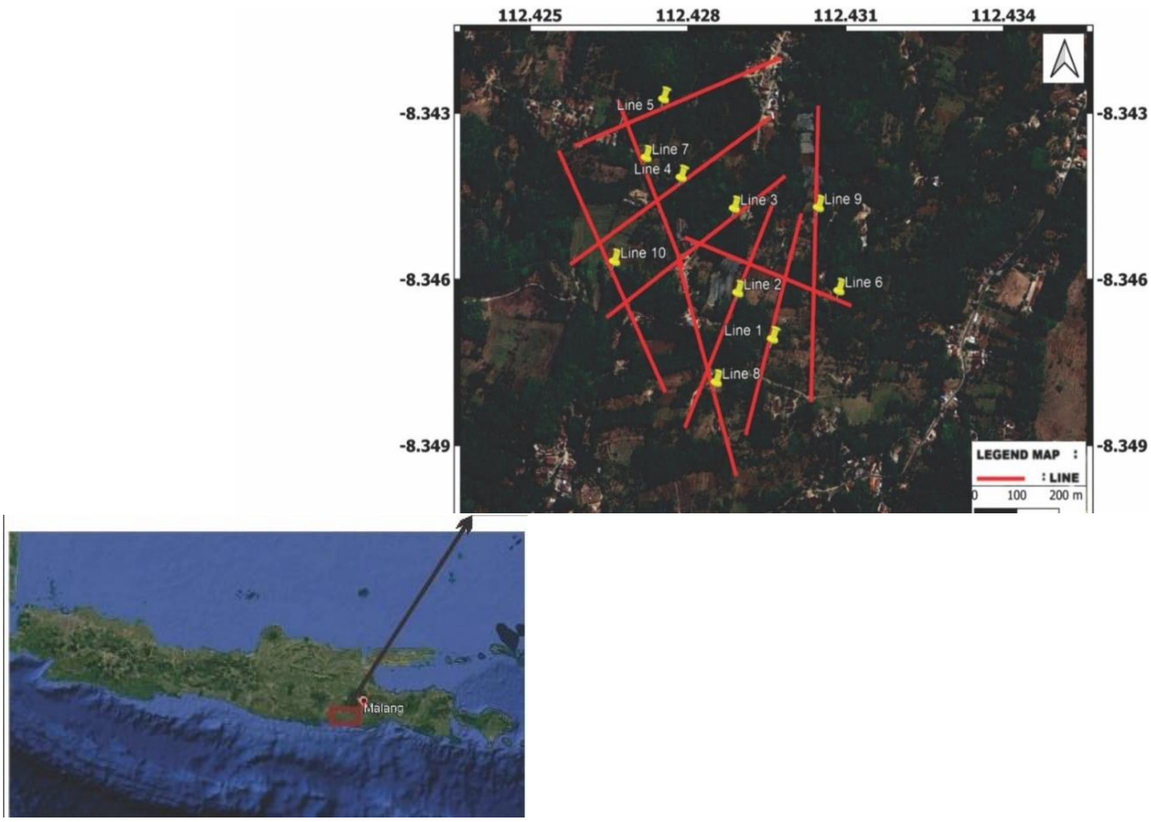


Figure 3. Research location map and VLF survey design (Source: Developed by the authors, 2024)

2. Research methodology

The VLF method is an electromagnetic (EM) method that utilizes electric and magnetic fields sourced from low-frequency radio transmitters in the frequency range of 5-30 kHz, which can provide differences in the conductivity values of subsurface rocks (Jeng et al., 2004; Sharma et al., 2014). The presence of cracks that are getting bigger and forming caves filled with water causes the conductivity value to be different from the value of the surrounding rocks. So it is easy to detect using the VLF method (Hussain et al., 2020; Iswahyudi et al., 2021; Purwanto et al., 2024; Zhang et al., 2024). VLF measurements consist of 10 lines with a distance between lines of 150-250 meters, adjusted to the topography in the field with an interval of 10 m per line (Figure 3).

The transmitter used is the NWC station located in North West Cape, Australia, with a frequency of 19,800 Hz. This station was chosen because the transmitted frequency is stronger and more stable than other VLF frequencies at the research location. Topographic correction uses the Baker and Myers method to reduce the influence of topography on the data based on the slope angle between two trajectory points, with positive correction values for ascending trajectories and negative values for descending trajectories (Baker & Myers, 1980). A moving average filter was used to separate low-frequency data from high-frequency data, ensuring that the measured signal better represented the presence of the cave. This moving average method is performed by averaging the anomaly values divided by the length of the smoothing interval used. Then, the Fraser filter is used to make the anomaly position more visible and easier to interpret (peak) (Djeddi et al., 1998; Alao et al., 2024). The Karous-Hjelt filter and Surfer software visualize the rock conductivity pattern against depth (Khalil & Santos, 2014; Sharma et al., 2014; Shirzaditabar & Karimi, 2020). Three-dimensional (3D) visualization is used to identify cave patterns, making it easier to detect the presence of cave paths or systems.

RESULTS AND DISCUSSION

The results of Very Low Frequency (VLF) data processing on ten profiles, aimed at identifying underground cave systems, are presented as conductivity pseudosections. Red colors represent high-conductivity anomalies (materials that are more conductive than their surroundings), which may indicate the presence of cavities, fractures, or underground water paths. The blue color indicates low conductivity (more resistive materials), which is typically associated with rocks with poor electrical conductivity (Sharma et al., 2014; Purwanto et al., 2024).

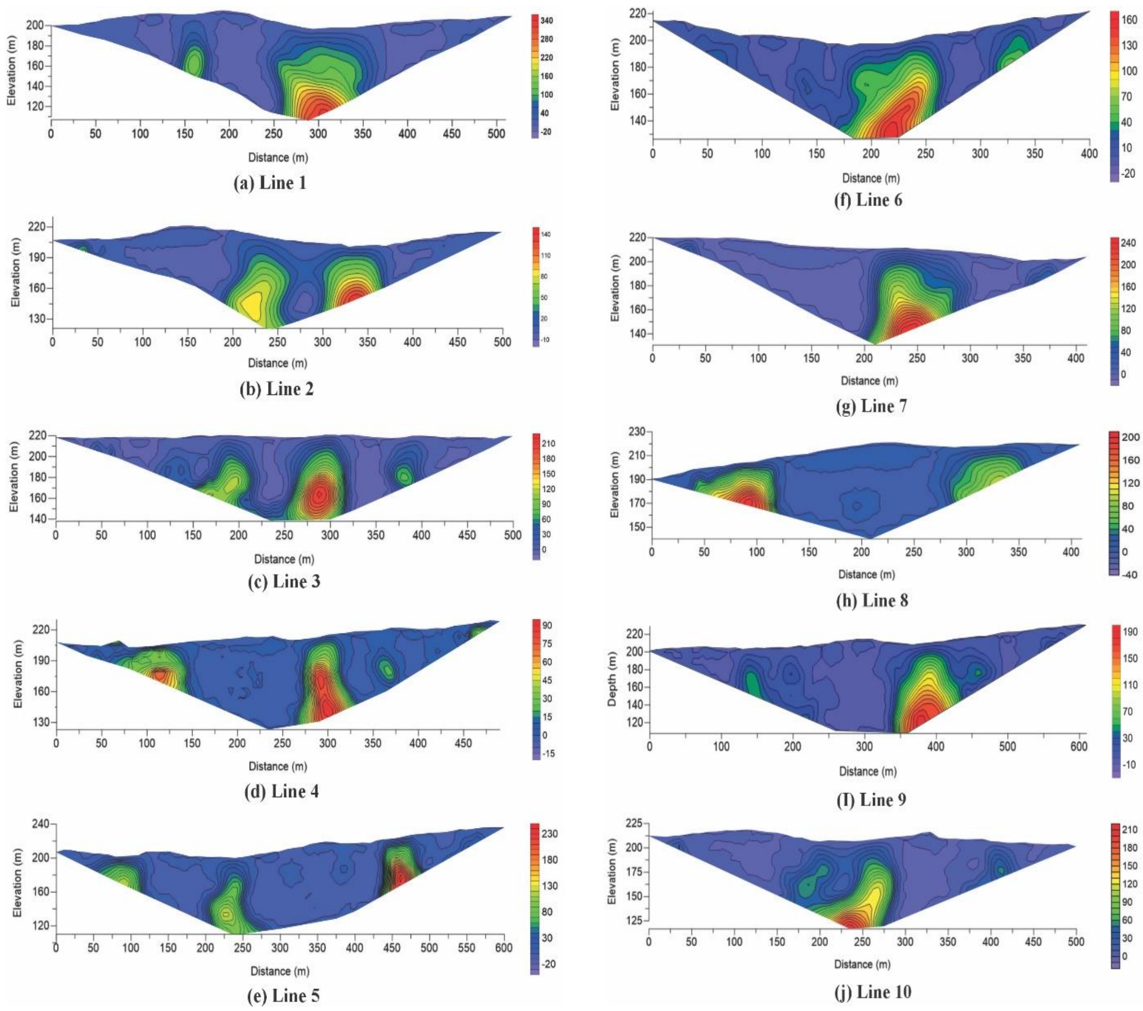


Figure 4. 2D VLF-EM subsurface conductivity image for ten measurement lines
in the karst area of Lo Cave and Bangi Cave, Kedungsalam Village (Source: Authors, 2025)

Figure 4a shows the results of Karous-Hjelt filter processing on Line 1, which shows a conductive anomaly at a distance of 150-165 meters at a depth of 15 meters, and a second anomaly at a distance of 320-360 meters at a depth of 45 meters.

The first anomaly is smaller than the second anomaly and is located very close to the mouth of Lo Cave, so it is considered a cavity connected to Lo Cave. Meanwhile, the second anomaly is thought to be influenced by the presence of a water-filled cave. On Line 2 (Figure 4b), two conductive anomalies are considered to be water-filled caves. The first anomaly is located at a distance of 260-275 meters at a depth of 20 meters, and the second anomaly is located at 340-380 meters at a depth of 24 meters. Both anomalies are linear, with the anomalies on Line 1, which are not far from the mouth of Lo Cave.

Line 3 (Figure 4c) shows the presence of two conductive anomalies. The first anomaly is located at a distance of 150-190 meters and has a depth of 25 meters, while the second is located at 260-310 meters and has a depth of 26 meters. The location and depth of these anomalies are linear with those on Lines 1 and 2, thereby reinforcing the interpretation that these anomalies are part of a cavity system connecting Lo Cave and Bangi Cave.

On Line 4 (Figure 4d), there is one conductive anomaly zone at a distance of 275-350 meters at a depth of 15 meters, which is suspected to be a cave parallel to the mouth of Bangi Cave. The anomaly zone at a distance of 75-160 meters is not believed to be part of the primary cavity connecting Lo Cave and Bangi Cave. In addition to being close to the surface and not linear with the cavity on the previous line, field data also indicates the presence of a ponor or fracture where water enters the underground system during the rainy season at this location, as shown in 5a.

Line 5 (Figure 4e) shows three conductive anomalies at distances of 60-100 meters, 210-260 meters, and 435-480 meters. Based on their positions and direct observations in the field, it is concluded that these three anomalies are not part of the Lo Cave and Bangi Cave systems. This phenomenon demonstrates that fractures or caves formed by the dissolution of carbonate rocks can create irregular patterns, indicating the complexity of the underground structure in karst areas (White, 1989; Mylroie, 2020; De Waele & Gutiérrez, 2022).

Figure 4f shows that Line 6, which intersects Lines 1, 2, 3, and 9, indicates the presence of conductive anomalies at a distance of 180-250 meters with a depth of 25 meters. It correlates with anomalies on Lines 1 and 2, which are suspected to be part of a cave system. Above the mouth of Bangi Cave, on Line 7 (Figure Figure 4g), a higher conductive anomaly is seen compared to other areas on the line. This can be seen at a distance of 220-290 meters and a depth of less than 20 meters.

A relatively high conductive value was also observed at the end of Line 8 (Figure 4h), at a distance of 60-110 meters at a depth of less than 20 meters, possibly due to the presence of a ponor, as seen in

Figure 5b, right at that point. A conductive anomaly was also observed at a distance of 310-340 meters. The existence of this anomaly is the same as the position of the anomaly on Line 3 (Figure 4c), so it is suspected to be the same cave.

Line 9 (Figure Figure 4i) shows a conductive anomaly at 370–430 meters. This anomaly corresponds to the position of the conductive anomaly on Line 6 (Figure 4f), which is considered the same cave.
Line 10 shows a conductive zone at a distance of about 215–265 meters with a depth of 30 meters. The location of this anomaly is the same as the first anomaly shown on Line 4 (Figure 4d), which Ponor causes. Interpretation of VLF data shows the presence of fractures and cavities in the soil around Lo Cave and Bangi Cave. The existence of this karst feature is marked by a conductive anomaly higher than the surrounding rocks on each measurement line.

Figure 6 shows that the anomaly is a network of interconnected cave systems between Lo Cave and Bangi Cave. The cave passage begins at Lo Cave, heads northwest, branches at Line 3, and turns southeast. Another branch extends north to Bangi Cave. Based on direct observations, water enters Bangi Cave when it rains. These water streams meet at Line 3 and flow southeastward across Lines 6, 2, 1, and 9, as shown in Figure 6.

(a) **(b)**

Figure 5. Ponors at the study site acting as entry points for surface water into the underground karst system:
(a) ponor observed on line 4, and (b) ponor observed on line 8 (Source: Authors field survey, Kedungsalam Village, 2024)

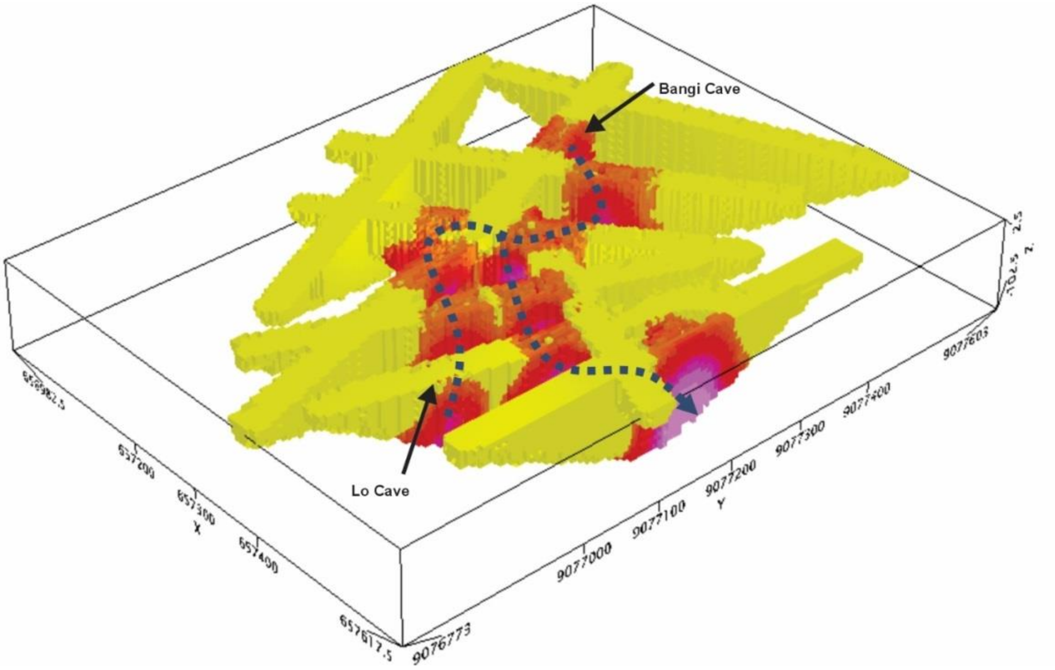


Figure 6. The Lo Cave and Bangi Cave patterns from VLF data show conductive anomalies in all lines (Source: Authors, 2025)

In addition to the presence of conductive anomalies suspected to be the Lo Cave and Bangi Cave systems, several anomalies were also identified that appeared without a clear pattern, interpreted as isolated cavities or fracture zones resulting from dissolution processes (Figure 4). These results are consistent with those reported by De Waele & Gutiérrez (2022), who stated that the emergence of cavities and fractures scattered and separated from the central cave system is caused by uneven rock dissolution processes. Several factors, such as pre-existing fractures and localized groundwater flow dynamics, influence the dissolution of carbonate rocks.

The results of VLF surveys around Lo Cave and Bangi Cave, which indicate the presence of interconnected underground cavities, provide the initial basis for developing cave geotourism in Kudungsalam Village.

To ensure that tourism in the karst area is educational and environmentally friendly, the following steps should include environmental assessment, infrastructure development based on geological stability, and community participation.

CONCLUSION

Based on the results of research in the karst areas of Lo and Bangi Caves using the Very Low Frequency (VLF) method, it is found that there are conductive anomalies that represent interconnected underground cavities, starting from Lo Cave to the northwest, then branching to the southeast and north towards Bangi Cave.

The presence of conductive anomalies forming a network of caves and ponors also indicates the potential vulnerability of the area to sinkhole hazards. Although the VLF method effectively detects conductivity laterally, it has limitations in providing a more detailed and accurate picture of the variation of the subsurface layer at the research site.

Thus, further research needs to be conducted by integrating other methods, such as Electrical Resistivity Tomography (ERT) or hydrogeological modelling, to obtain more detailed information on the karst system in Lo Cave and Bangi Cave.

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