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Groundwater Identification Employing Electromagnetic Very Low Frequency (EM-VLF) Technology for Drought Mitigation in Keben Village, Tambakromo District, Pati Regency, Central Java Province

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Abstract Groundwater potential can be effectively assessed through geophysical surveys utilizing the Very Low Frequency (VLF) electromagnetic method. This technique employs low-frequency electromagnetic waves (15–30 Mhz) to detect subsurface conductive lithologies indicative of groundwater presence. This study, conducted in Bugel Hamlet, Keben Village, Tambakromo District, Pati Regency, Central Java, aimed to delineate the spatial distribution and depth of potential groundwater resources. The region faces intensifying drought conditions; in 2023, the affected population rose from 26,791 to 37,114. Furthermore, Tambakromo presents complex geological challenges, with lithology dominated by consolidated rocks (claystone, marl, and sandstone) of the Lidah and Mundu Formations. Consequently, existing aquifer systems exhibit low productivity and limited discharge rates (< 5 liters/second) due to the impermeability of the host rocks. VLF measurements revealed conductive anomalies at depths ranging from 26.4 to 60 meters, suggesting the presence of a potential aquifer. This layer is interpreted as coarse-grained sandstone intercalated with clay, overlying a claystone bedrock. Based on this interpretation, specific coordinates were recommended for drilling. The study concludes that the Bugel area possesses a minimum groundwater potential of 3,500 liters per hour with good water quality and a dissolved solids content of 24%. Drilling at the recommended site yielded coarse sand, confirming the existence of an unconsolidated aquifer with high porosity and sustainable reserves. Project sustainability relies on collaboration between the village administration and the local farming community. Future development plans propose storing extracted water in reservoirs for distribution via piping systems to irrigate agricultural land, thereby breaking the cycle of annual water crises and enhancing local economic resilience.

1. INTRODUCTION

The ongoing phenomenon of global climate change has exerted substantial impacts on regions worldwide, including Indonesia. Rising global temperatures have accelerated polar ice melt, driven sea-level rise, altered rainfall patterns, and intensified extreme weather events. These changes have contributed to various disasters, particularly droughts and water scarcity. Over the past decade, droughts and floods have been the most frequent natural disasters in Indonesia, surpassing earthquakes, tsunamis, landslides, and other hazards (BNPB, 2024).

Pati Regency, like many areas in Indonesia, experiences a tropical climate characterized by two distinct seasons: a dry season and a wet season. The wet season lasts longer than the dry season, with minimum and maximum

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temperatures of 23°C and 39°C, respectively. The region receives an average annual rainfall of 1,002 mm over 91 rainy days (BPBD, 2024; BPS, 2024). Hydrological conditions in a region are interconnected with surrounding areas. Situated on the southeastern slopes of Mount Muria, Pati Regency's hydrology is strongly influenced by the mountain's geological structure. Due to the decreasing slope toward the lowlands and the general eastward direction of groundwater flow, groundwater velocity is higher in the steeper northern area compared to the southern area.

Regarding the drought disaster in Pati Regency in 2023, the affected areas continued to expand. Initially, 26,791 individuals were impacted, but by September 2023 this number had risen to 37,114. As a result, tens of thousands of residents faced difficulty accessing clean water. Data from the Pati Regional Disaster Management Agency show that 37,114 people from 7,949 households were affected (BPBD, 2024), compared to 26,791 individuals from 5,206 households previously. Given these conditions, identifying specific sites within water-scarce zones is essential to determine the presence of groundwater—both shallow (unconfined aquifers) and deep (confined aquifers)—to support drilling efforts and alleviate water shortages.

The recurring drought in Pati Regency, which has led to severe water scarcity, is likely to reoccur periodically. Keben Village in Tambakromo District is among the villages that frequently suffer from water shortages during the dry season (BPBD, 2023; Peraturan Daerah Kabupaten Pati, 2011). Considering the adverse impacts of drought on community livelihoods, proactive mitigation measures are urgently needed. Most residents of Keben Village are farmers or agricultural laborers, making agriculture the backbone of the local economy. Their income depends largely on crop yields, which are directly influenced by water availability for irrigation. As agriculture in the region is predominantly rain-fed, farmland becomes unproductive during extended dry periods. This situation results in declining household income, reducing residents' purchasing power and limiting their ability to finance education and meet other essential needs.

The urgency of implementing a water supply program is reinforced by several critical factors. First, economic vulnerability is a primary concern; crop failure during droughts not only eliminates income for an entire season but also threatens food security and heightens poverty risk.

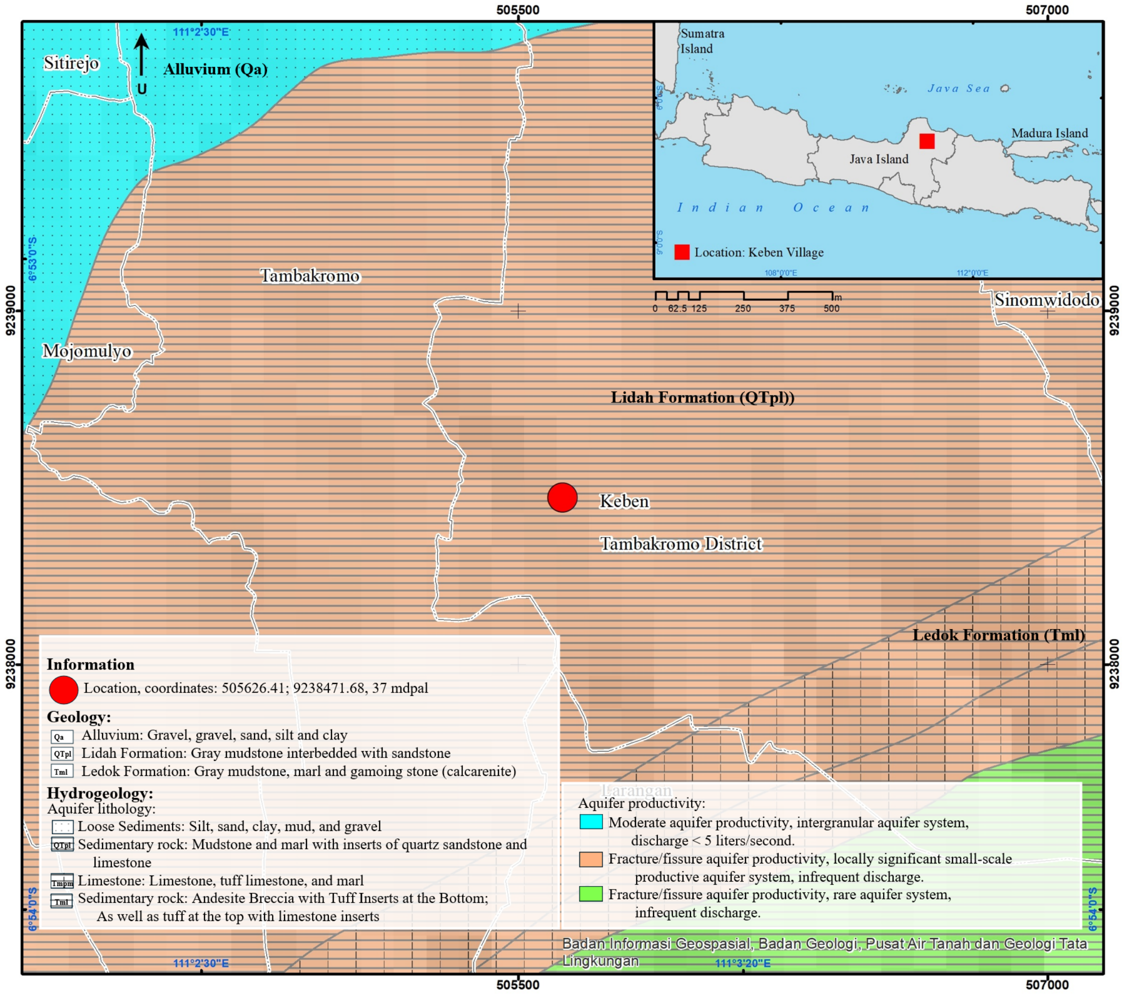

Figure 1 . The hydrogeological conditions of Tambakromo Subdistrict are dominated by consolidated rocks, namely shale and marl, with a fracture aquifer system, indicating low local productivity and scarce discharge

Second, the community faces a clean water crisis. Beyond agricultural needs, residents struggle to obtain potable water for daily use—such as drinking, cooking, and sanitation—thereby increasing the risk of waterborne diseases. Third, extreme water scarcity raises the potential for social conflict, as competition for limited water sources may escalate tensions among residents. Finally, repeated droughts without long-term solutions have severe impacts, hindering economic progress and reducing overall quality of life. Therefore, identifying and utilizing deep groundwater resources offers a strategic solution to disrupt the annual cycle of water crisis in Keben Village.

Geological conditions, particularly the water-storage capacity of rocks, contribute to drought occurrence (Rey, 2017; Singhal & Gupta, 2010). The regional geology of Tambakromo Subdistrict (Figure 1) comprises Alluvium (Qa): gravel, pebbles, sand, silt, and clay; the Lidah Formation (QTpl), consisting of gray mudstone with sandstone interbeds; the Selorejo Formation (QTps), an alternation of limestone and sandstone with foraminifera; the Mundu Formation (Tmpm), a massive whitish-gray marl rich in foraminifera; the Ledok Formation (Tml), composed of gray mudstone, marl, and calcarenite; and the Wonocolo Formation (Tmw), consisting of mudstone with limestone intercalations (Kadar & Sudijono, 1993; PSG, 2018).

From a hydrogeological perspective, aquifer lithology consists of unconsolidated deposits such as clay, sand, mud, silt, and gravel; consolidated rocks including mudstone and marl (Lidah and Mundu Formations); and localized intercalations of quartz sandstone and limestone. In the southern part, aquifer lithology comprises consolidated rocks such as andesitic breccia with tuff interlayers at the base and tuff with limestone interbeds at the top (Kadar & Sudijono, 1993; PATGTL, 2015a; PSG, 2018).

Figure 2 . The research site was situated in Keben Village, Tambakromo District

Hydrogeological conditions based on aquifer productivity (Figure 1) include moderate productivity within intergranular aquifer systems, with discharge rates of < 5 liters/second. The central region contains fracture and cavity aquifers with locally small-scale productivity and limited discharge, while the southern region consists of fracture and cavity aquifers with low productivity and rare discharge (PATGTL, 2015a,b; PSG, 2018).

Based on the hydrogeological assessment (Figure 1), the area exhibits a highly localized aquifer system with very limited productivity. The minimal discharge indicates that Keben Tambakboyo Village, Tambakromo District, is a water-scarce region characterized by clay-rich aquifers (Febriarta & Purnama, 2020; Singhal & Gupta, 2010; Todd & Mays, 2005). The proposed approach involves identifying potential sites containing deep groundwater aquifers capable of sustaining sufficient discharge for long-term, continuous water supply through drilling. Geophysical surveys can be utilized to detect groundwater presence, and deep electromagnetic methods are particularly effective for estimating groundwater potential at greater depths (McNeill, 1990; Ohwoghere-Asuma et al., 2020; Yilmaz, 2001). Electromagnetic techniques can aid in interpreting water-filled fractures associated with deep aquifers Reynolds (2011). The application of very low-frequency electromagnetic waves offers improved accuracy in clay-rich formations under conditions of limited discharge (Cahyadi et al., 2017; Febriarta & Purnama, 2020; Shofyan et al., 2016; Purwanto et al., 2015). The hydrogeological setting of the Tambakromo region, dominated by consolidated rock with a fracture aquifer system, results in low aquifer productivity and minimal water availability. These conditions intensify drought impacts and hinder clean water provision efforts. The substantial rise in drought-affected residents (from 26,791 to 37,114 people) reflects high social vulnerability. In addition to drought-related risks, agricultural production may face further threats, potentially destabilizing the local food supply. Limited access to clean water increases susceptibility to waterborne diseases, while scarcity can also generate social tensions linked to competition for water resources. Moreover, drought impedes local economic development by disrupting water-dependent sectors. Following this methodological framework, the present study aims to characterize the spatial variability of groundwater occurrence and determine groundwater depths. The study area is located in Keben Village, Tambakromo District, as illustrated in Figure 2.

2. METHOD

The research employed a direct field survey supported by a complete set of measurement instruments. Measurement points were selected based on the Geological Map, with consideration of fracture orientation and length, as well as community-sourced information regarding areas experiencing water scarcity and locations of existing shallow wells. These considerations were used to improve measurement efficiency and optimize data collection.

The primary instrument used was an EM-VLF device, which records magnetic fields using a coil and electric fields using an electrode dipole (Stewart, 2008). The instrument is compact, portable, and easily transported in the field. It requires only one operator to conduct measurements, assisted by an additional operator who records positional information or logs offline data. Data acquisition using the VLF method is relatively straightforward and can be conducted effectively by one or two individuals.

Groundwater identification can be conducted using the electromagnetic method, specifically through the application of Very Low Frequency (VLF) techniques (Ward & Hohmann, 1988). Jamal & Singh (2018), VLF-EM is a passive geophysical method that utilizes naturally available EM waves generated by ground-based military radio transmitters used primarily for navigation. These transmitters operate at approximately 42 global locations (Loudet, 2023). EM-VLF waves, typically operating at frequencies between 15–30 kHz, function as a primary electromagnetic field capable of identifying conductive and water-saturated rocks beneath the Earth's surface (Ohwoghere-Asuma et al., 2020). In this process, the primary EM wave induces electrical currents in conductive rock layers, which then become the primary target for measurement (Gnaneshwar et al., 2011).

The Very Low Frequency (VLF) technique relies on radio transmitter signals with extremely long wavelengths. These transmitters, positioned globally, primarily support marine navigation and communication systems. Operating within a frequency range of 15–25 kHz and a transmission power of 100 to 1,000 kW (Dentith & Mudge, 2014; Kirsch, 2006), they emit electromagnetic waves consisting of electric field components Ex and Ez and a magnetic field component Hy. The electric field component Ex induces subsurface currents, particularly within elongated conductive structures such as fractures oriented toward the transmitter (Sheriff & Geldart, 1995). These induced currents generate an additional magnetic field component Hz, producing a tilted magnetic field vector in regions containing good conductors (Ward & Hohmann, 1988). The intersection of this tilted vector marks the center of the conductive structure. A radio receiver equipped with a tilted antenna—aligned to maximize signal strength—measures this tilt angle (McDowell et al., 2002). Interpretation of EM-VLF data, correlated with resistivity values and associated lithologies, is summarized in Table 1.

3. RESULT AND DISCUSSION

The measurement point was georeferenced to UTM Zone 49S at coordinates x = 505626.41 and y = 9238471, with an elevation of 37 meters above mean sea level. The measurement locations are shown in Figure 3.

Table 1 . Variability of conductivity values (mS/m) and electrical conductivity across different rock formations

Rock Composing Materials	Frequency EM-VLF (kHz)	Resistivity (Ω m)	Conductivity (Siemens/m)
Igneous & Metamorphic Rocks	-	-	-
Granite	10–50	5×10^3–10^6	10^{-6}–2×10^{-4}
Basalt	5–25	10^3–10^6	10^{-6}–10^{-3}
Marble	10–27	6×10^2–4×10^7	2.5×10^{-8}–1.7×10^{-3}
Quartz	5–25	6×10^2–4×10^7	2.5×10^{-8}–1.7×10^{-3}
Andesite	10–50	10^2–2×10^8	5×10^{-9}–10^{-2}
Sedimentary Rocks	-	-	-
Sandstone	15–25	8–4×10^3	2.5×10^{-4}–0.125
Shale	5–25	20–2×10^3	5×10^{-4}–0.05
Limestone	5–50	50–4×10^2	2.5×10^{-3}–0.02
Soil and Water	-	-	-
Clay	0.2–20	1–100	0.01–1
Clayey soil	5–25	1–10	0.1–1
Sandy soil	10–50	100–1,000	10×10^{-3}–10×10^{-2}
Gravelly soil	10–50	1,000–10,000	10×10^{-4}–10×10^{-3}
Alluvium	5–50	10–800	1.25×10^{-3}–0.1
Groundwater (freshwater)	5–20	10–100	0.01–0.1
Seawater (saltwater)	0.002–0.005	< 0.2	5
Water-Saturated Rocks	-	-	-
Sand	10–50	10–100	0.01–0.1
Fine-to-medium sand	5–25	1,000–10,000	10×10^{-4}–10×10^{-3}
Silty sand	5–25	1–10	0.1–1
Gravelly sand	10–50	100–1,000	10×10^{-4}–10×10^{-3}
Mud	5–25	0.1–1	1–10
Silt	5–25	0.01–0.1	10–100
Karst rock	10–50	< 1	> 1

Sources: Adji et al. (2024); Cahyadi et al. (2017); Dentith & Mudge (2014); Febriarta & Purnama (2020); McDowell et al. (2002); Reynolds (2011); Stewart (2008); Telford et al. (1990); Yilmaz (2001).

Figure 3 . The measurement location is in Bugel, Keben Village with the measurement direction south southwest

This method employs low-frequency electromagnetic waves to assess the electrical conductivity of subsurface rocks, which is closely related to their water content. Figure 4 presents the results of the Very Low Frequency Electromagnetic (VLF-EM) survey, illustrating the relationship between resistivity—defined as a material's ability to oppose electric current flow—and depth (Cahyadi et al., 2017). The red-shaded section in Figure 4 represents the saturated zone or aquifer, characterized by lower resistivity due to the presence of water. The graph provides information on groundwater depth, potential discharge, water quality, and EM-VLF interpretations. As shown in Figure 4, five water-bearing zones were identified at depths ranging from 26.4 m to 108.0 m. The saturated zone occurs between depths of 26.4 and 60 m, indicating the presence of aquifer layers. The total borehole depth (Total BHD) reaches 208.0 m. The measured water discharge is 3,805 LPH (liters per hour), demonstrating significant aquifer productivity (Febriarta & Purnama, 2020). Overall water quality is rated at 46%, suggesting the presence of minerals or dissolved constituents. The water salinity level is 24%, reflecting its salt content, with higher percentages indicating greater salinity. The permeability factor is 70%, indicating the rock's capacity to transmit water, where higher permeability corresponds to more efficient groundwater flow.

The EM-VLF measurement results present a subsurface profile (Figure 4), where the X-axis represents the measurement distance in meters and the Y-axis indicates depth in meters. The color scale corresponds to resistivity or conductivity values of the subsurface materials (Kirsch, 2006). Water-bearing rocks typically show higher conductivity (blue) relative to dry or impermeable rocks (red). Interpretation of the profile indicates that the highly conductive zones, shown in dark blue, likely represent aquifer layers. Light blue areas indicate zones with lower conductivity, which may correspond to the upper or lower portions of the aquifer or materials containing less water. The thickness of the aquifer can be estimated from the depth interval occupied by the conductive zone. Resistive zones, represented in red, indicate high-resistivity materials such as igneous rocks or compacted clay layers. Based on the profile, several conductive zones occur at specific depths, with the most notable aquifer potential appearing at approximately 60 meters.

Based on the interpretation of EM-VLF data, the optimal drilling points are indicated by the boxed markers on the profile, which denote the recommended locations for groundwater extraction. These points were selected based on the thickness and continuity of the conductive zones. According to the profile (Figure 5), the recommended drilling location is positioned 16 meters from the instrument. The site corresponds to coordinates 505619.6 and 9238457.2, with an elevation of 37 meters above mean sea level (masl) (Figure 6). The drilling recommendations are summarized in Table 2.

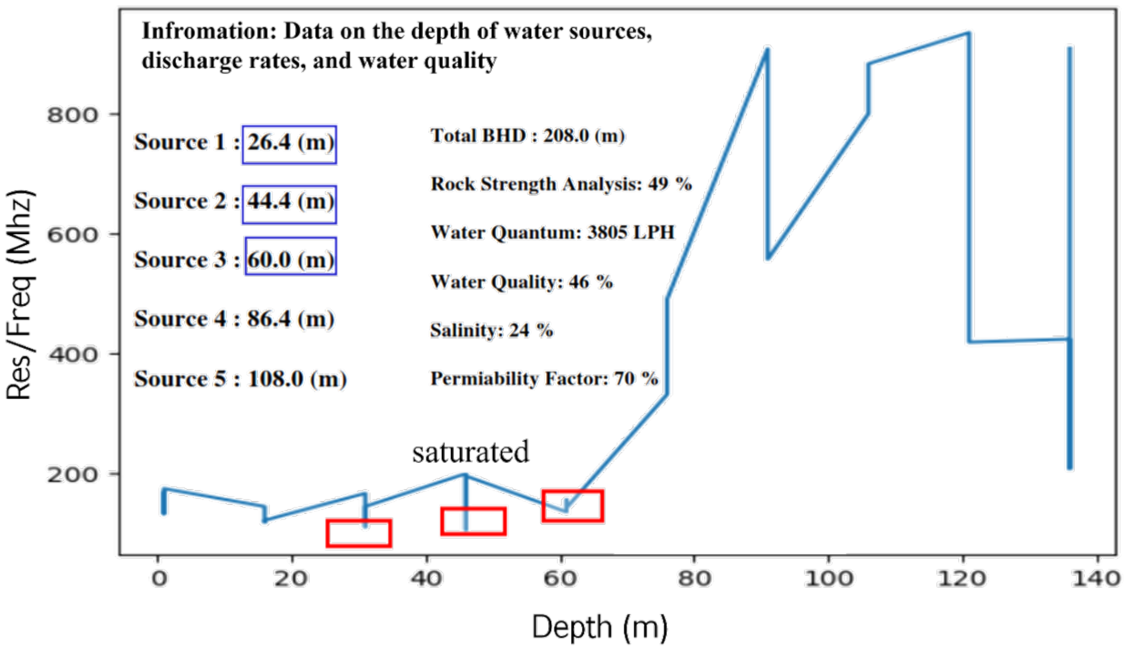

Figure 4 . EM-VLF measurement results found groundwater at a depth of 26.4 - 60 m

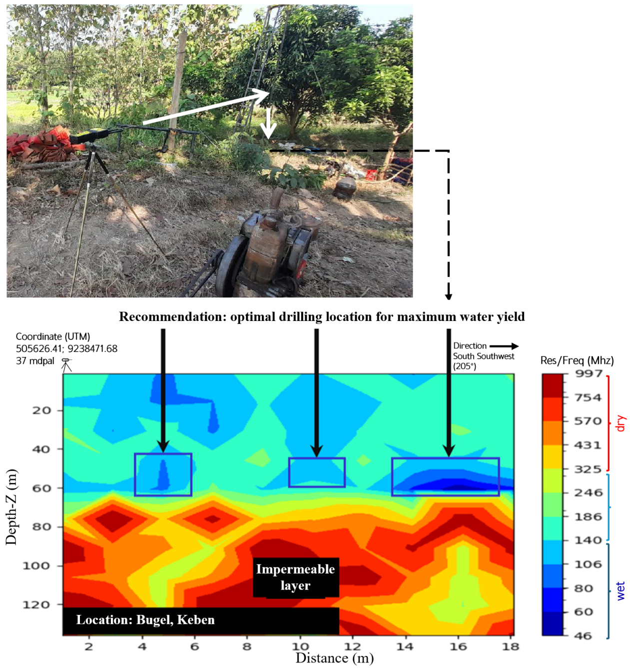

Figure 5 . Results of EM-VLF, the recommended drilling location is at a distance of 16 from the instrument

Figure 6 . Borehole was drilled at Easting 505619.6, Northing 9238457.2, and a vertical depth of 37 meters above mean sea level

Based on the interpretation and analysis of the data, drilling was carried out at coordinates (UTM Zone 49S) 505619.6 and 9238457.2, with an elevation of 37 meters above sea level, or approximately 16 meters from the instrument. A correlation was identified between a frequency value of 140 MHz and coarse sand material. This coarse sand represents an unconsolidated aquifer lithology. The characteristics of unconsolidated aquifers – high porosity and permeability – Indicate the presence of groundwater resources with good long-term sustainability.

Community empowerment in groundwater drilling for public benefit is a complex and multidimensional process (PATGTL, 2015b). It encompasses knowledge and skill transfer, community-based water resource management, and local capacity development. Community engagement is essential for the success and long-term sustainability of the project and can be strengthened through community outreach and guidance, active participation, capacity building, and sustainability initiatives. Community outreach and guidance function as distinct yet complementary approaches. Outreach raises community awareness and understanding of the project, while guidance enhances local skills and capacity in water resource management. Implementing these approaches concurrently is critical for ensuring the success and sustainability of groundwater drilling activities (Shofyan et al., 2016).

The success of this program fundamentally relied on the active support and participation of the village government and the local community, which served as the principal pillars for implementation and long-term sustainability (Rey, 2017). This engagement manifested in several key ways.

The Keben Village government served as the primary facilitator and mediator. They supported administrative permitting, conducted community outreach to disseminate program information, and assisted in identifying initial measurement points based on local knowledge and community needs. The administrative backing and legitimacy provided by the village government were essential in ensuring smooth implementation without social constraints.

Simultaneously, the local community – particularly farmers with plantations near the project site – demonstrated strong enthusiasm and active involvement. Their contributions included providing critical information about historically drought-prone areas, assisting in the preparation of measurement transects and safeguarding equipment in the field, and supplying labor for non-technical tasks during the survey and drilling phases. This collaborative approach fostered a sense of ownership, a vital factor for sustainable management. The community recognizes that the extracted groundwater is a communal resource to be managed collectively for shared benefit.

Aligned with the program's primary objectives, the extracted water will be collected in a reservoir. A distribution system will then be designed to convey this water efficiently to community-owned agricultural lands.

Table 2 . Drilling depth recommendation

Drilling was conducted at points located 5, 11, or 16 meters from the equipment, with a recommendation for the placement of a vertical water source screen at depth	1. The aquifer was found at a depth of 26.4 m, but exhibited a restricted discharge rate 2. The aquifer exhibits a depth of 44.4 meters and provides an adequate discharge 3. Groundwater with a depth of 60-60 meters is available with a high discharge rate (minimum 3,500 liters/hour)

This subsequent phase aims to ensure a reliable supply of irrigation water during the dry season, thereby increasing agricultural productivity and farmer income while reducing economic vulnerability to drought. The reservoir and piping system will be designed collaboratively, incorporating community input to determine the most effective pipeline routes and distribution points.

Active participation includes establishing working groups comprising community members to oversee implementation. Additionally, the transfer of knowledge and skills involves providing training on sustainable water resource management, including water conservation and efficient water use. This includes forming community-based organizations responsible for the operation and maintenance of bore wells. Finally, it requires meaningful community participation in decision-making regarding water utilization and management.

4. CONCLUSION

Based on the EM-VLF measurement results, it can be concluded that several aquifer layers are present, as indicated by distinct low-resistivity zones at depths ranging from 26.4 m to 60 m. The groundwater potential is favorable, with a relatively high discharge rate (minimum 3,500 liters per hour). Given the region's vulnerability to drought, comprehensive mitigation and adaptation strategies are required, including sustainable water resource management, water conservation, and diversification of water sources. The development and implementation of an early drought warning system are also essential. To obtain a more complete understanding of groundwater conditions at the site, further water quality assessments – through laboratory analyses of chemical and microbiological parameters – are recommended.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest. All authors have read and approved the final version of this manuscript, Identification of Groundwater Existence Using Electromagnetic Wave Technology–Very Low Frequency (EM-VLF) to Overcome Drought in Tambakromo District, Pati Regency, Central Java Province.

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