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MORALITY BEFORE KNOWLEDGE

Estimating groundwater availability using the electromagnetic very low frequency (EM-VLF) method

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ABSTRACT

Background: The coastal area of North Jakarta faces serious risks of groundwater table decline, seawater intrusion, and water quality degradation due to continuous groundwater extraction. Previous studies indicate that the aquifer system in North Jakarta consists of heterogeneous coastal alluvial deposits, including sand, silt, clay, and gravel. This condition causes groundwater potential to vary across locations. This study aims to analyze the potential availability of groundwater in Kalibaru Urban Village, Kampung Susun Akuarium Penjaringan, and Rusunawa Marunda. **Methods**: This study applied the Very Low Frequency Electromagnetic (EM-VLF) interpretation method to identify saturated zones beneath the surface. Field data included groundwater table depth, aquifer thickness, lithology, permeability factors, specific yield, salinity, and well measurements. **Findings:** Kalibaru Urban Village shows the highest estimated groundwater potential among the three sites, with a potential groundwater-bearing zone at 12–45 m depth and a Darcy-based relative total of 51.29 m^3/day. Rusunawa Marunda also shows potential groundwater-bearing zones at approximately 42–59 m. The variation in estimated groundwater-flow potential is associated with differences in interpreted depth, thickness, lithology, specific yield, and EM-VLF-derived salinity indicators. **Conclusion**: Groundwater bearing conditions remain locally indicated at the three study sites. However, groundwater use should be carefully limited because coastal areas are vulnerable to salinity, contamination, seawater intrusion, and groundwater-table decline. Government agencies and local communities need to strengthen groundwater-level monitoring, direct water-quality testing, pumping control, piped-water services, and rainwater harvesting. **Novelty/Originality of this article:** This study provides an EM-VLF-based assessment of groundwater potential at three coastal locations in North Jakarta. It also connects subsurface technical findings with the need for site-specific groundwater management strategies.

KEYWORDS: aquifer thickness: coastal aquifer; salinity risk**;** saturated zone; seawater intrusion.

1. Introduction

Water is a basic resource that supports human life and daily activities. It plays a central role in domestic use, agriculture, industry, sanitation, and urban development. In general, water resources can be classified into three main categories: rainwater, surface water, and groundwater (Nurayni, 2013). Each source has a different function, availability pattern, and management challenge. In coastal urban areas, these differences become more complex as freshwater systems interact with land-use change, population growth, seawater influence, and groundwater extraction. Groundwater forms when rainwater or surface water infiltrates the soil and moves through pores or fractures in subsurface layers known as

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aquifers. Compared with other water sources, groundwater often has better natural protection because soil and rock layers act as filters. Its suitability for use, however, still depends on the water's physical, chemical, and biological quality (Jangam & Pujari, 2019). Groundwater is also widely distributed, and its condition is strongly influenced by local users, pollutant sources, land-use policies, and water management practices (Foster & Ait-Kadi, 2012). When groundwater abstraction exceeds natural recharge, groundwater levels decline. In coastal aquifer systems, excessive groundwater withdrawal can reduce hydraulic heads and intensify seawater intrusion, while prolonged groundwater extraction may also contribute to land subsidence (Konikow, 2011; Prusty & Farooq, 2020; Micallef et al., 2021).

Globally, groundwater supports household water supply, irrigation, industry, and other economic activities. It is a major source of drinking water and irrigation supply worldwide (United Nations Educational, Scientific and Cultural Organization (UNESCO), 2022). In recent decades, groundwater systems in many regions have faced significant pressure from excessive extraction for domestic, agricultural, and industrial use (Konikow, 2011). Unsustainable abstraction has caused groundwater-table decline, reduced water availability, land subsidence, and seawater intrusion in many parts of the world (UNESCO, 2022). Similar conditions occur across Asia. Countries such as India, China, and Indonesia face growing pressure on groundwater resources due to rapid population growth, urban expansion, and economic development. In India, a large share of groundwater is used for agricultural irrigation, which has contributed to groundwater decline in several regions. In China, intensive groundwater extraction has also triggered land subsidence in some urban and industrial areas (Shen, 2015). These cases show that groundwater problems are not only related to water quantity. They also involve land stability, infrastructure safety, water quality, and long-term urban resilience.

In Indonesia, groundwater plays an important role as a source of clean water, particularly in large cities. Rapid population growth and urban development have increased the demand for groundwater for household and industrial use. The Ministry of Public Works and Housing reported that major urban areas, including Jakarta and Surabaya, face serious challenges related to groundwater table decline caused by intensive groundwater extraction (Ministry of Public Works and Housing, 2020). In Jakarta, groundwater use has become common because piped water services have not fully met urban demand. Around 60% of Jakarta's total water needs are reportedly supplied by groundwater (Ministry of Public Works and Housing, 2020).

Urban physical growth often creates conflicts between built-up areas and green open spaces, between building spatial planning for buildings and water, and between land-use planning and water resource management (Kodoatie & Sjarief, 2010). These conflicts can reduce infiltration areas and weaken the natural recharge process. New settlements that fail to consider environmental carrying capacity may further deplete groundwater reserves. When rainfall cannot infiltrate the soil effectively, the hydrological cycle is disrupted. This condition requires effective groundwater management strategies to maintain water availability and reduce the negative impacts of urban settlement development. Geographically, Jakarta is located on the coast, with a shoreline of approximately 35 km. The city is also the outlet for 13 rivers and two canals. Geologically, Jakarta consists of Pleistocene rock layers, while the central and southern parts contain alluvial materials. North Jakarta is dominated by coastal alluvial deposits, which generally include sand, silt, clay, and gravel. These deposits form heterogeneous aquifer systems. Because aquifers are geological formations that can store and transmit water, their potential may differ across locations depending on lithology, depth, thickness, permeability, and recharge conditions (Purnama et al., 2007).

North Jakarta is one of the urban areas experiencing rapid settlement growth. This condition increases the demand for clean water and encourages groundwater abstraction. Intensive groundwater use can cause several environmental problems, including groundwater table decline, water quality degradation, seawater intrusion, and land subsidence. Groundwater remains important for domestic, industrial, and urban needs, but its use in coastal cities requires careful control (Foster & Chilton, 2017). In North Jakarta, groundwater table decline has become a serious urban environmental problem. It is linked to excessive abstraction, land-use change, and the geological characteristics of the coastal plain. These processes increase the risk of infrastructure damage, tidal flooding, disruption of community activities, and ground instability in coastal settlements. The situation is more critical because North Jakarta is densely populated. The city has around 1.8 million residents, and groundwater still supplies a large proportion of household water demand. In Penjaringan District, population density reaches approximately 15,000 people per km^2 (Central Statistics Agency, 2024). At the same time, piped water coverage in North Jakarta remains limited, at about 40% (PAM Jaya, 2023). This gap between water demand and piped water supply has strengthened household dependence on groundwater, especially in dense settlements. Such dependence increases the risk of continued over-extraction and threatens the long-term availability of clean water.

Uncontrolled groundwater use in coastal areas can also accelerate seawater intrusion. This process reduces groundwater quality and may affect public health when saline or contaminated water is used for household purposes. In Jakarta and the Thousand Islands, groundwater extraction has been associated with both seawater intrusion and land subsidence. Land subsidence has been reported as a continuing problem in Jakarta, with substantial spatial and temporal variation across locations (Abidin et al., 2011; Hasibuan et al., 2025). In North Jakarta, land subsidence can alter river flow, expand flood-prone areas, intensify seawater intrusion, reduce quality of life, disrupt economic activities, increase infrastructure-management costs, and reduce the economic value of buildings and land (Hasibuan et al., 2023). Because groundwater is stored below the surface, its condition cannot be observed directly. Therefore, groundwater assessment requires methods capable of identifying subsurface conditions. One method that can support this purpose is the Very Low Frequency Electromagnetic method, commonly known as EM-VLF. This geophysical method measures subsurface electromagnetic responses and can help interpret groundwater-bearing zones. When EM-VLF interpretation is combined with groundwater level measurements, well data, lithological information, salinity data, and groundwater use data, it can provide a stronger basis for site-specific groundwater management.

The EM-VLF method is a passive electromagnetic technique used to detect subsurface electrical properties, especially in areas with relatively high conductivity. It uses electromagnetic waves from existing VLF radio transmitters. In general, VLF electromagnetic waves operate within the frequency range of about 3 to 30 kHz, while geophysical surveys commonly use frequencies of about 15 to 30 kHz. These waves induce currents in conductive subsurface structures and produce responses that can be interpreted to identify layers, cavities, or stratigraphic conditions below the surface (Kearey et al., 2002; Purwanto et al., 2015; Alao et al., 2024a, 2024b; Berge, 2025; U.S. Environmental Protection Agency (EPA), 2025). Based on these conditions, groundwater assessment in coastal North Jakarta is important. North Jakarta faces simultaneous pressures from high population density, limited piped-water coverage, groundwater extraction, seawater intrusion, declining water quality, and land subsidence. Previous studies have discussed groundwater use, aquifer conditions, and land subsidence in Jakarta, but site-specific interpretation of groundwater potential using EM-VLF remains necessary, especially in dense coastal settlements. Therefore, this study aims to estimate groundwater potential using the EM-VLF method at selected locations in North Jakarta. The results are expected to support a more accurate understanding of local subsurface conditions and provide a technical basis for sustainable groundwater management in coastal urban areas.

2. Methods

2.1 Research sites

The study was conducted in three locations representing two types of settlements in North Jakarta, namely vertical public housing and coastal fishing settlements. These locations were selected because they differ in access to clean water and patterns of groundwater use. The three research sites were: Kampung Susun Akuarium, located in Penjaringan Subdistrict, Penjaringan District. Rusunawa Marunda Cluster B, Block B, located in Marunda Subdistrict, Cilincing District. The fishing settlement in RW 13, Kalibaru Subdistrict, Cilincing District.

2.2 Population and sampling

The study area comprised groundwater bearing zones within the three selected research sites. A total of 13 EM-VLF sampling points were selected purposively based on topographic conditions, field accessibility, and the expected presence of groundwater-bearing zones. Priority was given to low lying or valley like areas because groundwater movement is influenced by gravity, geological conditions, and topographic controls (Singhal & Gupta, 2010; Fetter, 2014). Groundwater potential was estimated through spatial analysis using Geographic Information System (GIS) software. Aquifer or saturated-zone thickness was interpreted from the EM-VLF results. Because field hydraulic-head differences were unavailable, the hydraulic gradient was not derived from EM-VLF data and was instead assumed to be 1.0 for the screening-level Darcy calculation. Interpreted thickness was used to calculate the cross-sectional flow area (A), which was combined with the hydraulic-conductivity approximation of the corresponding material. Groundwater-flow potential was then calculated using Darcy's Law (Todd & Mays, 2005), as follows:

$$Q = k.\, i.\, A \qquad \text{(Eq.1)}$$

Where Q is groundwater discharge or flow rate through rock materials (m^3/day). k is hydraulic conductivity or permeability (m/day). i is hydraulic gradient or pressure gradient, defined as the hydraulic-head difference between two points along the flow path divided by the flow-path length. A is hydrogeological cross-sectional area in the direction of groundwater flow (m^2).

Hydraulic conductivity describes the ability of soil or rock to transmit water and is commonly expressed in m/s or m/day (National Standardization Agency of Indonesia, 2005). Because field hydraulic-head differences were unavailable, a unit hydraulic gradient (i = 1.0) was applied, and the flow area was defined as aquifer thickness multiplied by a one-metre section width. Consequently, the Darcy values reported here represent relative groundwater-flow potential for comparison among points; they are not sustainable well yields and should not replace pumping-test results.

Table 1. Hydraulic conductivity values for selected materials

Rock or material type	Hydraulic conductivity (m/day)
Gravel (general)	150
Coarse gravel	270
Medium gravel	450
Fine gravel	45
Coarse sand	12
Medium sand	2.5
Fine sand	3.1
Medium sandstone	0.2
Fine sandstone	0.08
Silt	0.0002
Clay	0.0002
Limestone	0.001
Dolomite	0.2
Schist	0.00008
Slate	0.2
Tuff	0.01
Basalt	0.7
Weathered gabbro	1.4

(Todd & Mays, 2005)

The WD-3D-XYZ software also generated percentage outputs labelled as water quality, salinity, instrument-reported permeability index, and instrument-reported specific-yield index based on the recorded response. In this manuscript, these percentages are reported as instrument-derived indices for relative comparison only. The salinity index was not obtained from direct chloride, total dissolved solids, or electrical-conductivity analyses. A comparable EM-VLF application has been evaluated against field salinity measurements (Cahyadi et al., 2016), but the indices in the present study still require confirmation through laboratory water-quality testing.

2.3 Interpretation of groundwater availability using electromagnetic very low frequency method

Groundwater potential was investigated using the electromagnetic very low frequency (EM-VLF) method. The method records electromagnetic responses associated with variations in subsurface electrical conductivity. Electromagnetic waves from a VLF transmitter induce currents in conductive subsurface materials, and the resulting field response is recorded by the receiver. Conductivity contrasts may be associated with differences in lithology, saturation, dissolved-ion content, or other conductive materials; therefore, conductive anomalies are interpreted as potential groundwater-bearing zones rather than direct confirmation of groundwater. The measured responses were compared with published conductivity ranges for rock and sediment materials (Cahyadi et al., 2016; Purwanto et al., 2015).

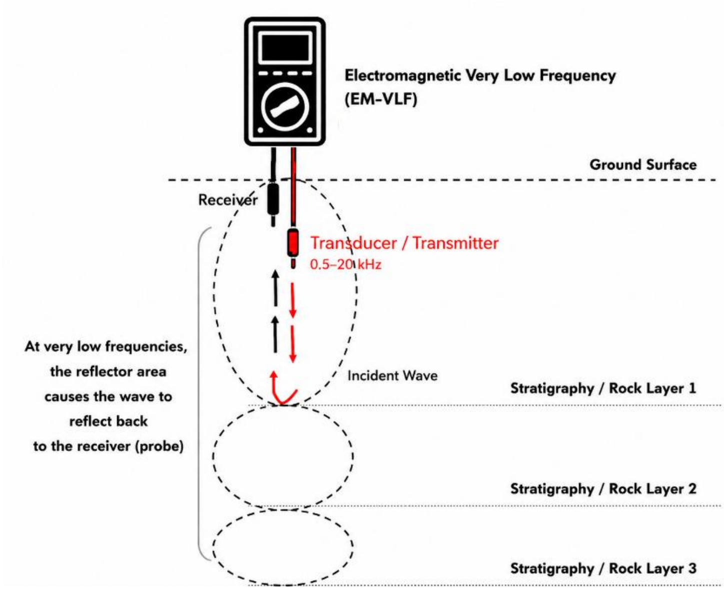

Fig. 1. Reflected electromagnetic very low frequency waves in layered rock formations (Febriarta & Purnama, 2020)

The propagation of electromagnetic waves in this method follows Maxwell's equations. Interpretation was guided by the frequency, resistivity, and conductivity ranges summarized in Table 2, adapted from published EM-VLF and applied-geophysics sources (Reynolds, 2011; Febriarta & Purnama, 2020; Cahyadi et al., 2016; Khakhim et al., 2025). The measured values were then interpolated and mapped using Geographic Information System software to support spatial comparison.

The instruments and materials used for groundwater availability measurements: EM-VLF water detector. Measuring tape. Geological maps covering the research locations. The operation and output of the EM-VLF instrument can be described as follows: The VLF transmitter is configured to generate low-frequency electromagnetic signals, commonly within the range of 3–30 kHz; A sensitive receiver is then used to detect the electromagnetic field generated by the transmitter. This receiver may consist of a magnetic loop or a specially designed antenna capable of measuring electromagnetic fields at VLF frequencies; The transmitter emits electromagnetic signals into the subsurface, where they propagate through groundwater and underlying rock; During field measurements, a measuring tape is stretched across the survey area, while the coordinates and measurement results are documented at each observation point; The receiver positioned on the ground surface detects the electromagnetic field produced by the transmitter; The receiver positioned on the ground surface detects the electromagnetic field produced by the transmitter; The measured electromagnetic-field data are subsequently analyzed, as variations in the electromagnetic field may indicate changes in subsurface conductivity caused by differences in material type or groundwater moisture conditions; The recorded data describe the distribution of subsurface conductivity, which is then interpreted to identify groundwater characteristics, groundwater depth, and potential saturated zones beneath the surface.

Table 2. Correlation between conductivity values and the electrical properties of rock materials

Rock or material composition	EM-VLF Frequency (kHz)	Resistivity (Ω m)	Conductivity (S/m)
Igneous and metamorphic rocks			
Material Type			
Granite	10-50	$5x10^3$-10^6	10^{-6}-$2x10^{-4}$
Basalt	5-25	10^3 – 10^6	10^{-6}-10^{-3}
Marble	10-27	$6x10^2$-$4x10^7$	$2.5x10^{-8}$ – $1.7x10^{-3}$
Quartz	5-25	$6x10^2$-$4x10^7$	$2.5x10^{-8}$ – $1.7x10^{-3}$
Andesite	10-50	10^2-$2x10^8$	$5x10^{-9}$ – 10^{-2}
Sedimentary rocks		-	-
Material Type			
Sandstone	15-25	$8^{-4}x10^3$	$2.5x10^{-4}$ – 0.125
Shale	5-25	$20^{-2}x10^3$	$5x10^{-4}$ – 0.05
Limestone	5-50	$50^{-4}x10^2$	$2.5x10^{-3}$ – 0.02
Soil and water			
Material Type			
Clay	0.2 – 20	1-100	0.01-1
Clayey soil	5-25	1-10	0.1-1
Sandy soil	10-50	100-1000	$10x10^{-3}$-$10x10^{-2}$
Gravelly soil	10-50	1000-10000	$10x10^{-4}$-$10x10^{-3}$
Alluvium	5-50	10-800	$1.25x10^{-3}$-0.1
Fresh groundwater	5-20	10-100	0.01-0.1
Saline seawater	0.002-0.005	< 0.2	5
Groundwater-saturated materials			
Material Type			
Sand	10-50	10-100	0.01-0.1
Fine to medium sand	5-25	1000-10000	$10x10^{-4}$-$10x10^{-3}$
Clayey sand	5-25	1-10	0,1-1
Gravelly sand	10-50	100-1000	$10x10^{-4}$-$10x10^{-3}$
Mud	5-25	0.1-1	1-10
Silt	5-25	0.01-0.1	10-100
Karst rock	*10-50*	*<1*	*>1*

(Sheriff & Geldart, 1995; Reynolds, 2011; Cahyadi et al., 2016; Febriarta & Purnama, 2020)

Groundwater potential was subsequently calculated using Darcy's Law (Eq. 1). Measurements covered 13 points distributed across Kampung Susun Akuarium, Rusunawa Marunda, and Kalibaru Subdistrict. This workflow produced screening-level estimates based on conductivity interpretation, inferred lithology, aquifer thickness, and standardized hydraulic assumptions.

3. Results and Discussion

3.1 Interpretation of groundwater estimation results using EM-VLF

3.1.1 EM-VLF measurements in Kampung Susun Akuarium

Very Low Frequency Electromagnetic (EM-VLF) measurements in Kampung Susun Akuarium were conducted at three observation points, as detailed in Table 3. At each location, the EM-VLF instrument was oriented toward the four cardinal directions—north, east, south, and west—to ensure a comprehensive interpretation of subsurface conditions. The subsequent figures and tables present the field measurement conditions and interpretation results.

Table 3. EM-VLF measurement locations in Kampung Susun Akuarium

No.	Coordinate		Location
	X	Y	
1.	700095	9322615	Northern part of Kampung Susun Akuarium
2.	700113	9322631	Rear Terrace area of Kampung Susun Akuarium
3.	700141	9322531	Outer area of Hexagon Fish Market

The hydrogeological conditions in Kampung Susun Akuarium, Penjaringan, reflect a complex coastal aquifer system. EM-VLF interpretation identified conductive zones potentially associated with water-saturated materials at depths of approximately 36–71 m. These zones may represent lenses or intercalations of coarser-grained materials within finer sediments such as clay and silt, but their groundwater-bearing character requires independent validation. This pattern is compatible with the general heterogeneity of the Jakarta Groundwater Basin, which comprises multiple hydrostratigraphic units with varying hydraulic properties (Nugraha et al., 2024). At the northern measurement point, a conductive zone occurs at approximately 48–56 m, with an interpreted thickness of about 8 m and fine-sand lithology. Instrument-derived indices report water quality of 67%, salinity of 23%, and permeability of 55%; these values are used for relative comparison and require direct field or laboratory confirmation.

At the Rear Terrace measurement point in Kampung Susun Akuarium, the interpreted water-saturated zone is found at depths of approximately 48–67 m, with a thickness of about 19 m. The dominant lithology is clay. The indicative groundwater quality is 64%, salinity is 36%, and the permeability factor is 70%. These results show that the saturated zone here is thicker than that in the northern part. Although clay can store water, its ability to transmit water is limited. The EM-VLF response may also be affected by pore-water content, clay minerals, and dissolved salt concentration. According to the Environmental Protection Agency, the EM-VLF method can detect conductive anomalies, but its interpretation has limitations and should be corroborated with geological, well, or water-quality data (U.S. Environmental Protection Agency, 2025).

The EM-VLF interpretation at Hexagon Fish Market reveals the thickest water-saturated zone, extending from approximately 36 m to 71 m below the ground surface. The lithology is identified as silty clay. The indicative water quality is 70%, salinity is 59%, and the permeability factor is 68%. This location exhibits the highest indicative groundwater quantity potential among the three measurement points in Kampung Susun Akuarium. However, the high salinity value indicates that greater groundwater quantity does not guarantee suitability for domestic use. Coastal areas such as Penjaringan District are susceptible to saline water intrusion, brackish water, and elevated dissolved solids in aquifer systems. Seawater intrusion in the Jakarta Groundwater Basin can be detected using hydrochemical and hydroisotope indicators, and previous studies have documented seawater mixing in parts of the confined aquifer system in Jakarta (Setiawan et al., 2017).

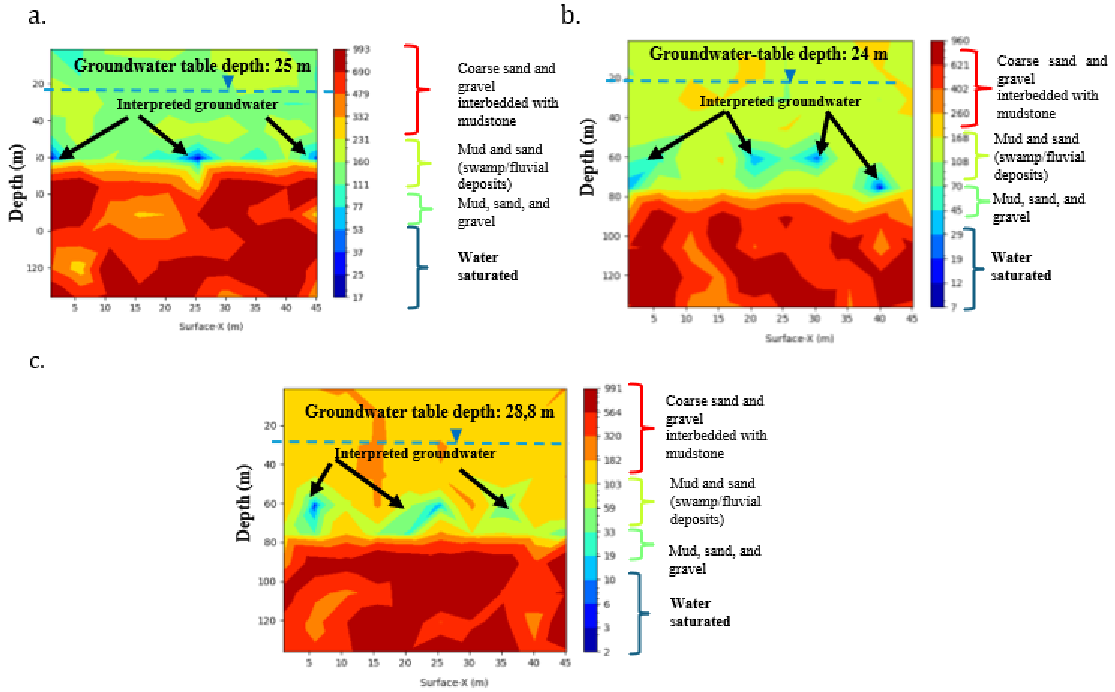

Fig. 2. Em-VLF Interpretation results at Kampung Susun Akuarium (a) Northern part of Kampung Susun Akuarium; (b) Rear Terrace area; (c) Outer area of Hexagon Fish Market

Field measurements from wells in the vicinity of Kampung Susun Akuarium indicate a shallow groundwater table at approximately 0.5 m below ground surface, whereas EM-VLF identified deeper conductive zones at approximately 36–71 m. These observations likely represent different hydrogeological levels. The well measurements characterize shallow groundwater, while the EM-VLF anomalies may reflect intermediate groundwater-bearing materials, saturated clay, or zones with elevated dissolved-ion content. The two datasets should therefore not be interpreted as direct confirmation of the same aquifer.

The hydrogeological conditions in Kampung Susun Akuarium can be interpreted as a layered coastal aquifer system. The shallow layer contains a groundwater table located near the surface, while the intermediate layer exhibits water-saturated zones at depths of several tens of meters. This configuration is consistent with the general characteristics of the Jakarta Groundwater Basin, which comprises aquifers and aquitards formed from various sedimentary materials, including sand, silt, clay, and coarser-grained intercalations. Groundwater modeling in Jakarta remains challenging due to the complexity of its aquifer system, limited field data, and hydrodynamic conditions influenced by geological variability and groundwater extraction pressures (Nugraha et al., 2024).

The fine sand lithology identified at the northern measurement point in Kampung Susun Akuarium suggests a favorable aquifer material for groundwater storage and flow. In contrast, the clay-dominatedlithology at the rear terrace indicates a more aquitard-like layer due to its limited water-transmitting capacity. The silty clay lithology at Hexagon Fish Market represents a transitional material between fine-grained sediments and layers capable of storing groundwater. Although Hexagon Fish Market exhibits the highest indicative groundwater quantity, it also has the highest indicative salinity value. This suggests that groundwater at this location may be unsuitable for drinking or cooking without further treatment or quality assessment.

3.1.2 EM-VLF Measurements in Rusunawa Marunda Block B

EM-VLF measurements in Rusunawa Marunda were conducted at Block B10, Block B9, and the central field (Table 4; Figs. 15–20). The interpreted water-saturated zones occur at approximately 42–59 m below the ground surface, while nearby shallow wells indicate groundwater at approximately 0.35–2 m. These observations represent different hydrogeological levels and should not be treated as direct confirmation of the same aquifer.

Table 4. EM-VLF measurement locations in Rusunawa Marunda Block B

No.	Coordinate		Location
	X	Y	
1.	717321	9325907	Rusunawa Marunda Block B 10
2.	717332	9325953	Rusunawa Marunda Block B 9
3.	717379	9325836	Central field of Rusunawa Marunda

Hydrogeologically, Rusunawa Marunda is part of the northern section of the Jakarta Groundwater Basin. Based on the Geological Map of the Jakarta and Kepulauan Seribu Sheet, North Jakarta is located within a coastal alluvial plain composed of clay, mud, sand, gravel, fluvial deposits, swamp deposits, and coastal deposits. This alluvial lithology indicates that aquifers in the Marunda area are not homogeneous. Sand-rich layers tend to have greater capacity to transmit groundwater, whereas silt and clay layers generally store water but have limited permeability. The northern part of the Jakarta Groundwater Basin is a coastal alluvial plain with increased risk of salinity and seawater intrusion, particularly in areas located close to the shoreline (Asih et al., 2024).

The EM-VLF interpretation at Rusunawa Marunda Block B10 indicates that groundwater occurs at depths of approximately 48–59 m. The aquifer thickness at this point is about 11 m, with a lithology dominated by silt. This material can store water, but its relatively fine pore size results in lower transmissivity than sand. The permeability factor is 65%, indicating a relatively good capacity to retain water, whereas the specific yield is 7.8%, reflecting a limited ability to release groundwater. The salinity value at this location is 52%. These results suggest that although the site has moderate groundwater availability in terms of quantity, its utilization should take into account water-quality factors, particularly the potential for salinity related to seawater intrusion.

The EM-VLF section at Rusunawa Marunda Block B9 indicates a deeper conductive zone at approximately 43–54 m, while nearby wells show a shallow groundwater table of approximately 0.35–2 m. These observations represent different hydrogeological levels. Under the assumed hydraulic conditions used in this study, the Darcy-based estimate for Block B9 is 6.82 m^3/day, equivalent to approximately 284.17 L/hour (0.079 L/s). This value is a screening estimate of relative groundwater-flow potential and should not be interpreted as a sustainable well yield.

The measurement point at the central field of Rusunawa Marunda shows a water-saturated zone at depths of approximately 42–59 m. The aquifer thickness at this point is 17 m, making it the thickest of the three measurement points in Rusunawa Marunda. However, aquifer thickness is not always directly proportional to groundwater productivity. The lithology is dominated by clay, which has fine pores and strong water-retention capacity, making groundwater difficult to release and transmit. The specific yield at this point is only 3.5%, the lowest among the three locations. The permeability factor is 70%. From a hydrogeological perspective, clay-dominated layers function more as aquitards, as they can store water but are less productive for groundwater extraction.

Field measurements from wells show that the shallow groundwater table around Rusunawa Marunda ranges from approximately 0.35–2 m. This indicates that the unconfined aquifer around the settlement is very shallow. Such a shallow groundwater table is common in low-elevation coastal alluvial plains influenced by tidal processes. Shallow groundwater is easily recharged by rainfall and surface runoff, but it is also highly vulnerable to contamination from domestic wastewater and other sources of water-quality degradation. A shallow groundwater table does not automatically indicate that groundwater is suitable for consumption. Water quality still needs to be tested. In the Jakarta Groundwater Basin, a large proportion of groundwater does not meet drinking-water standards, and coastal areas commonly show high concentrations of TDS, electrical conductivity, sodium, chloride, and iron (Asih et al., 2024).

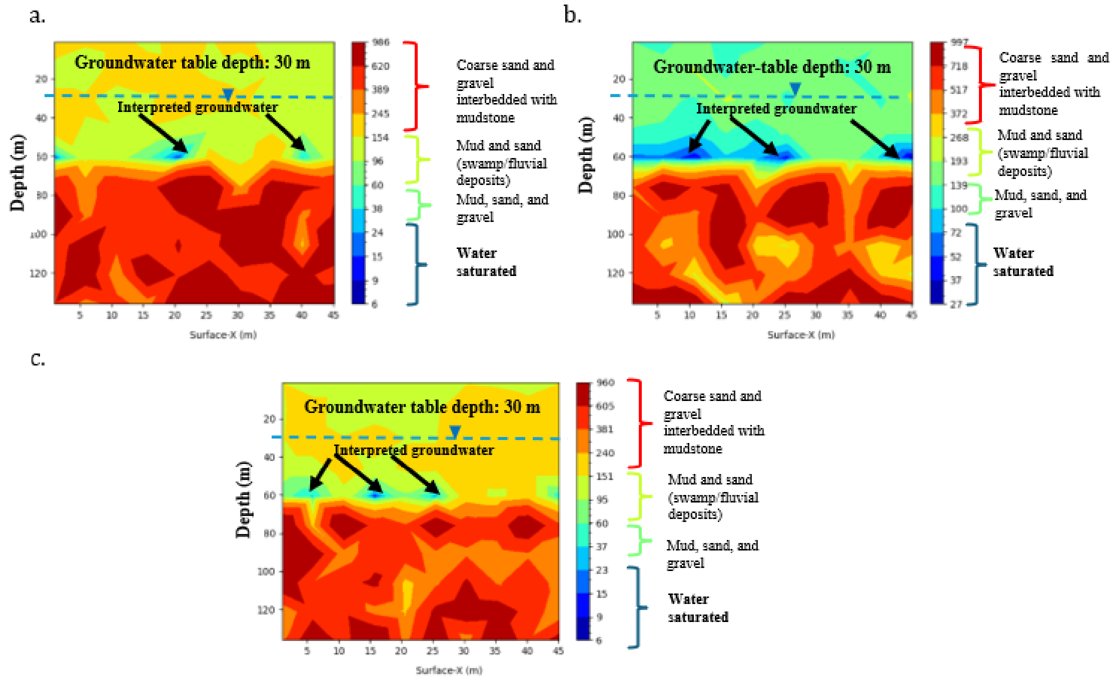

Fig. 3. Em-VLF Interpretation results at Rusunawa Marunda (a) Block B10; (b) Block B 9; (c) Central field of Rusunawa Marunda

Based on the Hydrogeological Map of Indonesia for the Jakarta Sheet and the Jakarta Groundwater Basin, the Rusunawa Marunda area belongs to an aquifer system characterized by intergranular flow within unconsolidated Quaternary deposits. This system generally has aquifers that vary both laterally and vertically because they are composed of sand lenses, silt, and clay. This condition corresponds to the EM-VLF interpretation, which shows lithological variation from silt to sandy layers and clay over relatively short distances.

Overall, the EM-VLF interpretation in Rusunawa Marunda indicates potential groundwater-bearing or saturated zones at approximately 42–59 m. Their characteristics vary among measurement points according to interpreted lithology, thickness, and instrument-derived indices. Because EM-VLF primarily detects electrical-conductivity contrasts, these zones require confirmation through borehole information, pumping tests, and direct water-quality measurements before groundwater development.

3.1.3 EM-VLF Measurements in Kalibaru Subdistrict

EM-VLF measurements in the fishing settlement of Kalibaru were conducted at seven points, as presented in Table 5. The results indicate that zones interpreted as water-saturated layers are distributed from shallow to intermediate depths. Based on the seven EM-VLF sections, the groundwater table is estimated to occur at depths of approximately 1–2 m, whereas aquifer zonation occurs at depths of approximately 12–45 m. These findings show that the hydrogeological conditions of Kalibaru Subdistrict are associated with coastal and alluvial sedimentary deposits composed of sand, silt, clay, and gravel. The EM-VLF method detects subsurface conductivity; therefore, more conductive zones may be associated with water-saturated layers, clay-rich materials, salinity, or a combination of these factors (EPA, 2025). The EM-VLF section at the Kalibaru Subdistrict Office indicates the presence of a groundwater zone at an intermediate depth. The interpretation shows that the aquifer layer occurs at depths of approximately 31-44 m, with a thickness of about 14 m. The aquifer lithology is interpreted as sandy silt, a mixture of silt and sand fractions. This lithological characteristic still allows aquifer development because the sand fraction increases effective pore space and supports groundwater transmission. The permeability factor is 63%, indicating a moderately good water-transmitting capacity, while the specific yield is 9.5%, suggesting a moderate capacity to release groundwater. The salinity value is

41%. This point has relatively good groundwater potential because of the combination of aquifer thickness and supportive lithology, although the salinity value reflects the general characteristics of a coastal aquifer.

Table 5. EM-VLF measurement locations in Kalibaru Subdistrict

No.	Coordinate		Location
	X	Y	
1.	713481	9325088	Kalibaru Subdistrict Office
2.	713827	9325522	Nur Arrahman Mosque RW 13
3.	713983	9325681	Al Mubarokah Prayer Room RW 4
4.	713419	9324869	Jami Al Ikhlas Mosque RW 1
5.	714020	9325347	Alfamart Kalibaru Timur IV RW13
6.	713430	9325209	Indomaret Kalibaru Timur RW 3
7.	713700	9325325	Darussalam Al Amin Mosque RW 2

The EM-VLF interpretation at Nur Arrahman Mosque indicates that the groundwater table is approximately 1 m deep. The zone interpreted as a water-saturated layer occurs at depths of approximately 29-45 m, with an aquifer thickness of about 16 m. The lithology at this point is dominated by clay. Clay has very small pore spaces and can retain water, but it is less effective at releasing water. This condition is consistent with the specific yield value of 3.5%, which is relatively low. The permeability factor is 70%, and the salinity value is 35%. Hydrogeologically, this point is interpreted as a saturated zone with moderate potential, but groundwater quality and clay-dominated lithology may be limiting factors. Specific yield is an important parameter because it indicates the proportion of water that can be released from saturated material by gravity, rather than merely the total amount of water stored within rock or sediment pores (Johnson, 1967).

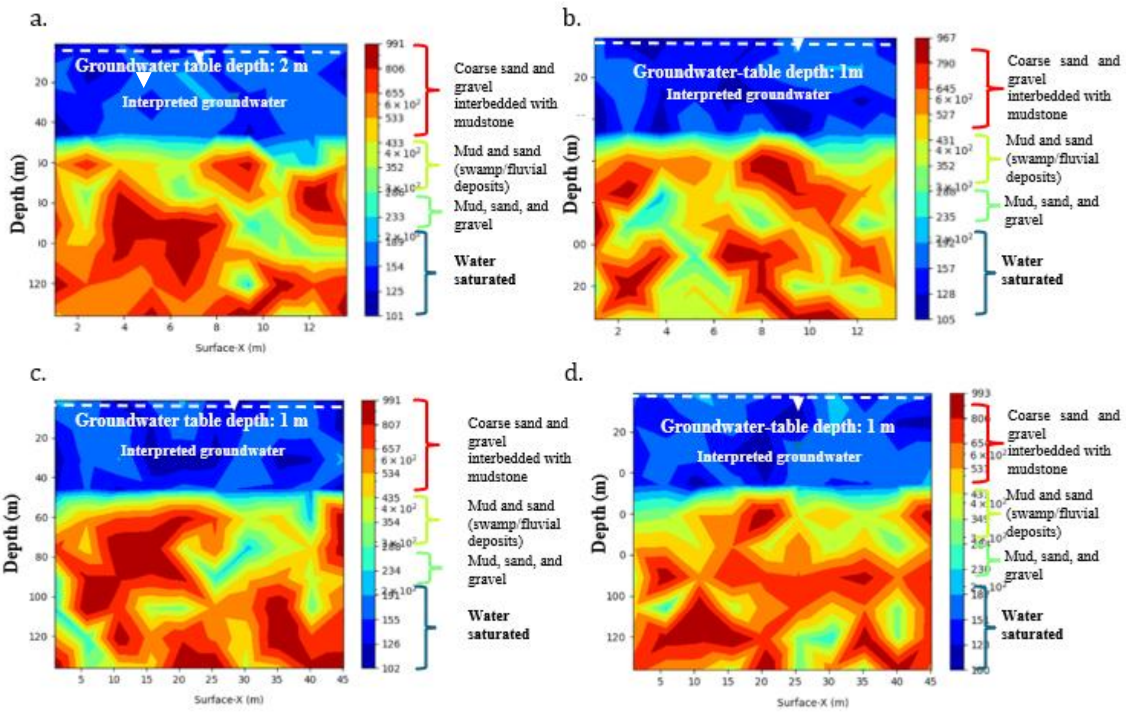

Fig. 4. Em-VLF Interpretation results in Kalibaru Subdistrict (a) Kalibaru Subdistrict Office; (b) Nur Arrahman Mosque, RW 13; (c) Al Mubarokah Prayer Room; (d) Jami Al Ikhlas Mosque

The Al Mubarokah Mushola point indicates a relatively shallow conductive zone. The interpretation suggests that a potential groundwater-bearing zone begins at approximately 23 m depth, with an interpreted thickness of about 10 m; the exact lower boundary should be verified against the original EM-VLF section. The lithology is interpreted as coarse sand, which is hydrogeologically favorable because of its effective pore space and groundwater-

 https://doi.org/10.61511/eam.v4i1.2026.3794

transmission capacity. The instrument-derived specific-yield index is 26.4%, the permeability index is 44%, and the salinity index is 70%. The elevated salinity indicator suggests a potential groundwater-quality constraint and possible seawater influence, which should be verified through direct hydrochemical analysis.

The EM-VLF interpretation at Jami Al Ikhlas Mosque indicates that the aquifer zone occurs at depths of approximately 12-29 m, with a thickness of about 17 m. This aquifer is among the shallowest and thickest of the seven measurement points. The lithology at this point consists of coarse sand or gravel, indicating highly favorable materials for groundwater storage and transmission. Coarse-grained materials such as sand and gravel generally have higher hydraulic conductivity than silt and clay, particularly when their intergranular pores are well connected. The specific yield reaches 27.9%, the highest value in the Kalibaru fishing-settlement area, indicating that this point has a greater capacity to release groundwater. However, the salinity value is 67%. Therefore, although this point has strong potential based on lithology and aquifer thickness, its high salinity remains a major limiting factor for groundwater utilization.

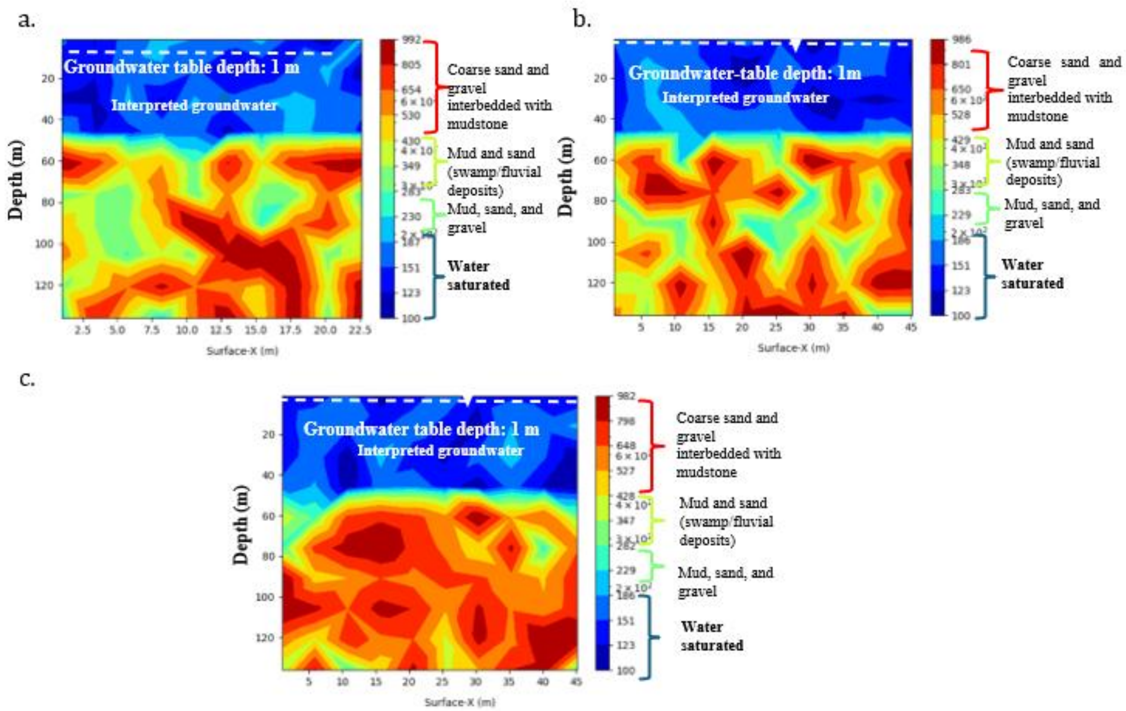

Fig. 5. Em-VLF Interpretation results in Kalibaru Subdistrict (a) Alfamart Kalibaru Timur IV; (b) Indomaret Kalibaru Timur; (c) Darussalam Al Amin Mosque

The Alfamart Kalibaru Timur point shows a potential groundwater-bearing zone at approximately 27–43 m, with an interpreted thickness of about 16 m and medium-sand lithology. The instrument-derived specific-yield index is 24%. The Darcy-based discharge estimate is 7.68 m^3/day, equivalent to approximately 320 L/hour (0.089 L/s), under the assumed hydraulic conditions. This value represents relative groundwater-flow potential rather than sustainable well yield. The salinity index is 55%, indicating that direct hydrochemical testing is required before utilization.

The Indomaret Kalibaru Timur point shows an aquifer zone at depths of approximately 31-41 m, with a thickness of about 10 m. The aquifer lithology is clay, which limits its ability to release groundwater. The specific yield is 3.5%, indicating that water in this layer is not easily released by gravity. The permeability factor is 70%, indicating a moderate water-transmitting potential, while the salinity value is 40%. This point indicates relatively better water quality and moderate salinity, but its aquifer potential is hydrogeologically less favorable than that of points dominated by medium sand, coarse sand, or gravel.

The interpretation at Darussalam Al Amin Mosque shows a potential groundwater-bearing zone at approximately 30–38 m, with an interpreted thickness of about 8 m and very fine-sand lithology. The instrument-derived specific-yield index is 12.2%, indicating moderate relative groundwater-release potential. The salinity index reaches 77%, the highest among the Kalibaru measurement points. This elevated salinity indicator suggests a potential groundwater-quality constraint; possible seawater influence should be verified through direct hydrochemical analysis because EM-VLF conductivity alone cannot confirm seawater intrusion.

Overall, the EM-VLF interpretation indicates that the aquifer system in Kalibaru Subdistrict consists of shallow to intermediate sedimentary aquifers occurring at depths of approximately 12–45 m. The lithology varies among sandy silt, clay, coarse sand, gravel, medium sand, and very fine sand. This variation demonstrates that the aquifer condition is heterogeneous and layered. Such characteristics are consistent with coastal, swamp, and fluvial depositional environments, which commonly produce lateral and vertical variations in sediment composition. Aquifers composed of medium sand, coarse sand, or gravel have better potential than clay-dominated aquifers because their larger grain sizes allow more effective intergranular pore connectivity for groundwater flow. The distribution of sand, silt, and clay sediments is important for understanding groundwater-flow characteristics because the size and arrangement of subsurface materials strongly influence groundwater storage and movement.

The hydrogeological conditions of Kalibaru Subdistrict demonstrate the relationship among a shallow groundwater table, coastal alluvial sediments, and the risk of seawater intrusion. Saline groundwater in the Jakarta Groundwater Basin occurs in the upper confined aquifer within 3 km of the coastline, while slightly saline groundwater may occur within 9 km of the coast (Setiawan et al., 2017). This condition is relevant to Kalibaru Subdistrict because the area is located in the coastal zone of North Jakarta and shows high indicative salinity values based on EM-VLF interpretation.

Kalibaru Subdistrict in Cilincing District continues to face limited access to clean water services. Many households in coastal North Jakarta rely on non-piped water sources, often incurring higher costs (Huwaina et al., 2022). This context supports the recommendation against further groundwater exploitation in Kalibaru. Instead, reducing groundwater dependency by expanding piped-water services and developing alternative sources, such as Rainwater Harvesting (RWH), is advised. Although RWH has been implemented in RW 13, Kalibaru Subdistrict, it requires more systematic and sustainable management.

3.2 Groundwater vailability

Groundwater-flow potential at the research sites was estimated using Darcy's Law. In this study, the instrument-derived permeability factor from the EM-VLF interpretation was used as an approximation of hydraulic conductivity (K) for the screening-level Darcy calculation. Because direct hydraulic-head differences were unavailable, the hydraulic gradient was assumed to be one ($i = 1.0$), and the cross-sectional flow area was calculated from interpreted saturated-zone thickness multiplied by a one-meter section width. The resulting Q values are therefore comparative estimates of relative groundwater-flow potential, not measured or sustainable well yields. The use of instrument-derived permeability as a hydraulic-conductivity approximation is a methodological limitation and should be validated through field hydraulic testing for future application. Groundwater-flow estimates for each measurement point are presented in Table 6, and the regional summary is provided in Table 7.

The Darcy-based groundwater discharge calculation for Kampung Susun Akuarium indicates moderate to relatively high local groundwater potential, with estimated discharge values ranging from 4.40–23.80 m^3/day. The highest discharge was recorded at the Hexagon Fish Market measurement point. This elevated groundwater potential is likely attributable to an aquifer thickness of 35 m and a permeability value of 0.68 m/day. EM-VLF interpretation indicates that the water-saturated zone in Kampung Susun Akuarium is located at intermediate to deep depths, approximately 36–71 m below the ground surface. Groundwater utilization in this area should be approached with caution, as portions of the aquifer material consist of clay and silty clay, and the interpretation indicates a relatively high salinity value of 59%. Although the area demonstrates favorable groundwater quantity potential, water-quality testing is essential prior to intensive domestic use.

Table 6. Estimated groundwater availability at the research sites

No	Coordinate X	Coordinate Y	Location	Lithology	Aquifer thickness (m)	Permeability (m/day)	Hydraulic gradient	Aquifer area (m^2)	Discharge (m^3/day)	Discharge (L/hour)
1.	713481	9325088	Kalibaru Subdistrict Office	Sandy silt	14	0.63	1	14	8.82	367.50
2.	713827	9325522	Nur Arrahman Mosque RW 13	Clay	16	0.70	1	16	11.20	466.67
3.	713983	9325681	Al Mubarokah Prayer Room RW 4	Coarse sand	10	0.44	1	10	4.40	183.33
4.	713419	9324869	Jami Al Ikhlas Mosque RW 1	Coarse sand/ gravel	17	0.43	1	17	7.31	304.58
5.	714020	9325347	Alfamart Kalibaru Timur IV RW 13	Medium sand	16	0.48	1	16	7.68	320.00
6.	713430	9325209	Indomaret Kalibaru Timur RW 3	Clay	10	0.70	1	10	7.00	291.67
7.	713700	9325325	Darussala m Al Amin Mosque RW 2	Very fine sand	8	0.61	1	8	4.88	203.33
8.	700095	9322615	Northern part of Kampung Susun Akuarium	Fine sand	8	0.55	1	8	4.40	183.33
9.	700113	9322631	Rear terrace of Kampung Susun Akuarium	Clay	19	0.70	1	19	13.30	554.17
10.	700141	9322531	Outer area of Hexagon Fish Market	Silty clay	35	0.68	1	35	23.80	991.67
11.	717321	9325907	Rusunawa Marunda Block B10	Silt	11	0.65	1	11	7.15	297.92
12.	717332	9325953	Rusunawa Marunda Block B9	Sandy silt	17	0.62	1	11	6.82	284.17
13.	717379	9325836	Central field of Rusunawa Marunda	Clay	14	0.70	1	17	11.90	495.83

Rusunawa Marunda exhibits moderate screening-level groundwater potential relative to the other two research areas, with estimated values ranging from 6.82–11.90 m^3/day. EM-VLF sections indicate potential groundwater-bearing zones at approximately 42–59 m. The area is hydrogeologically dominated by silt, sandy silt, and clay, which generally transmit groundwater less effectively than sand or gravel. At Block B9, the Darcy-based estimate is 6.82 m^3/day (approximately 284.17 L/hour) and the instrument-derived salinity index is 24%. These results support relative comparison among measurement points but require pumping tests and direct water-quality measurements before any groundwater-development decision.

Groundwater potential in Kalibaru Subdistrict is reflected by Darcy-based estimates ranging from 4.40–11.20 m^3/day across seven measurement points, with the highest point-scale estimate at Nur Arrahman Mosque. EM-VLF interpretation indicates potential groundwater-bearing zones at approximately 12–45 m. Considering the combined indicators of discharge, interpreted lithology, and indicative salinity, the Kalibaru Subdistrict Office and Alfamart Kalibaru Timur points show relatively favorable groundwater potential; however, their elevated salinity indices (41% and 55%, respectively) indicate that groundwater quality should be verified through direct hydrochemical testing before utilization.

Groundwater utilization at all research locations should be conducted under controlled conditions. Excessive abstraction can lower groundwater levels, reduce well performance, intensify seawater intrusion in coastal aquifers, and contribute to land subsidence (Konikow, 2011; UNESCO, 2022; Ministry of Energy and Mineral Resources, 2009). Sustainable management should include regulated pumping, groundwater-level monitoring through observation wells, periodic direct water-quality testing, expansion of piped-water services, and greater use of alternative sources such as rainwater harvesting. Recharge areas should also be protected through appropriate land-use and infiltration measures. New wells should only be developed after site-specific hydrogeological verification, including pumping tests and water-quality analysis.

Table 7. Summary of Darcy based groundwater discharge estimates by research area

No.	Location	Number of point	Total discharge (m^3/day)	Total discharge (Liter/hour)
1.	Kampung Susun Akuarium	3	41.50	1,729.17
2.	Rusunawa Marunda	3	25.87	1,077.92
3.	Fishing Settlement of Kalibaru Subdistrict	7	51.29	2,137.08

Piped-water coverage in Jakarta remains insufficient to meet demand, and excessive groundwater extraction is closely linked to land subsidence and other environmental risks. North Jakarta and West Jakarta are prioritized for piped-water development due to their combined challenges of water-supply gaps, land subsidence, and groundwater-quality issues (Taftazani et al., 2022). Coastal settlements in Jakarta continue to face limited access to clean water, with some households relying on non-piped sources. Rainwater harvesting offers an additional means to improve water access, particularly in areas not consistently served by piped-water networks (Huwaina et al., 2022). Based on the measurement results, the safest approach to groundwater utilization involves adherence to groundwater-potential zoning, discharge control, groundwater-level monitoring, and water-quality supervision. Sites with high discharge potential but elevated salinity should not be automatically prioritized, while locations with moderate discharge and lower salinity may provide more sustainable options. This strategy is critical to prevent groundwater-level decline, seawater intrusion, reduced well productivity, and increased land subsidence.

4. Conclusions

This study shows spatial variation in screening-level groundwater potential among Kalibaru Subdistrict, Kampung Susun Akuarium, and Rusunawa Marunda. EM-VLF interpretation identified conductive subsurface zones at approximately 12–45 m in Kalibaru, 36–71 m in Kampung Susun Akuarium, and 42–59 m in Rusunawa Marunda. These zones are interpreted as potential groundwater-bearing or saturated zones rather than confirmed aquifers. Darcy-based relative totals are 51.29, 41.50, and 25.87 m^3/day, respectively; however, these totals are influenced by unequal numbers of purposively selected points and do not represent regional groundwater reserves or sustainable yields. At the point scale, Nur Arrahman Mosque has the largest estimate in Kalibaru (11.20 m^3/day), the outer Hexagon Fish Market has the largest estimate in Kampung Susun Akuarium (23.80 m^3/day), and the central field has the largest estimate in Rusunawa

Marunda (11.90 m^3/day). Block B9 and Alfamart Kalibaru Timur have corrected estimates of approximately 284.17 and 320.00 L/hour, respectively. The variation in estimated groundwater-flow potential is associated with differences in interpreted lithology, saturated-zone thickness, and EM-VLF-derived salinity indicators; these associations were not tested statistically.

Nearby well observations indicate shallow groundwater that is distinct from the deeper conductivity anomalies interpreted by EM-VLF. Both shallow groundwater and deeper conductive zones may be affected by coastal processes, saline-water influence, contamination, and groundwater abstraction; however, these effects require confirmation through direct groundwater-level and hydrochemical measurements at all sites. Because EM-VLF does not directly confirm groundwater occurrence or water quality, no site should be developed solely on the basis of the present results. Future research should use denser grid-based sampling, direct water-quality measurements, borehole validation, and pumping tests to determine aquifer continuity, chemical suitability, and sustainable yield. Until these validations are completed, groundwater abstraction should be restricted, monitored, and complemented by expanded piped-water services, demand management, and rainwater harvesting.

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Author Contribution
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Ethical Review Board Statement
Ethical Review Board Statement: Not applicable. Ethical review and approval were not required for this study because the research did not involve human participants, animal subjects, clinical procedures, biological specimens, personal data, or questionnaire-based data collection. The study only used field measurements, including electromagnetic very low frequency (EM-VLF) interpretation and groundwater table depth observations, supported by relevant secondary data.

Informed Consent Statement
This study did not involve human participants, personal data, interviews, questionnaires, clinical procedures, or identifiable individual information. The research was limited to field-based geophysical measurements using electromagnetic very low frequency (EM-VLF),

groundwater table depth observations, and secondary data analysis related to groundwater availability at the study locations.

Data Availability Statement

The data generated and analyzed during this study are not publicly archived. The field measurement data, including electromagnetic very low frequency (EM-VLF) interpretation results, groundwater table depth observations, lithological interpretation, and groundwater potential calculations, are available from the corresponding author upon reasonable request. Secondary data used in this study are available from the sources cited in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. This research received no external funding. Therefore, no external funder had any role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Declaration of Generative AI Use

During the preparation of this work, the authors used ChatGPT by OpenAI to assist in improving language clarity, academic structure, grammar, and manuscript formatting. The tool was used only to support manuscript preparation and did not replace the author's scientific judment, data analysis, interpretation, or conclusions. After using this toll, the authors reviewed, verified, and edited the content as needed and took full responsibility fot the content of the publication.

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