

## Analysis of The Potential of Volcanic Aquifers in Supporting The Development of Groundwater Resources in Bogor District, West Java

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**Abstract:** Hydrogeological research on volcanic deposition, is essential for sustainable air management. This research is crucial for understanding the aquifer potential of volcanic deposits as a sustainable groundwater source, especially in regions experiencing rapid urbanization and agricultural expansion. It aims to analyze the aquifer potential of volcanic deposits in Bogor Regency, focusing on the Bogor Groundwater Basin, the upper Cisadane watershed, the eastern slopes of Mount Salak, and the western slopes of Mount Pangrango. The methods used include secondary data collection from regional geological maps and primary data collection through field surveys, geological mapping, and hydrogeological mapping. The results show that the volcanic rock units in this area, consisting of stony tuff, tuff breccia, lava, and andesite lava, have unique characteristics with significant potential as aquifers. Detailed geomorphological and hydrogeological mapping revealed different types of springs and physical properties of water that support the sustainability of groundwater resources. These findings contribute significantly to the development of better groundwater management policies, effective water infrastructure development, and environmental conservation strategies in Bogor District, ensuring clean water availability for the future.

**Keywords:** Aquifer, Groundwater, Volcanic Deposits

### INTRODUCTION

Hydrogeology is a branch of geology that studies the distribution and movement of underground water in soils and rocks in the Earth's crust, with a focus on the interaction between groundwater and its geological environment (Fetter, 2018). One important aspect of hydrogeology is aquifer potential, which is a layer of rock or sediment capable of storing and delivering large amounts of water (Todd & Mays, 1980). Aquifer potential is strongly influenced by the porosity and permeability of rocks, which determine the storage and flow capacity of water (Cartwright & Weaver, 2005). Aquifers with these characteristics serve as important natural reservoirs for wells, springs, and rivers, making them vital water sources for domestic, agricultural, and industrial needs (Irawan et al., 2009). Evaluation of aquifer potential by hydrogeologists through drilling methods, geological mapping, and geophysical techniques helps in managing water resources sustainably, ensuring water availability for various needs, and protecting groundwater quality from contamination (Endyana et al., 2016).

Groundwater plays a vital role for both residents and industries, especially in areas such as Bogor Regency. For residents, groundwater is the main source of clean water used for daily needs such as drinking, cooking, bathing, and washing. In addition, groundwater also supports local agriculture by providing consistent irrigation, which is crucial for the food security and economy of local communities. For the industrial sector, groundwater provides essential raw materials for various production processes, from manufacturing to food and beverage processing. This dependence makes sustainable groundwater management a top priority, to continue supporting community life and industrial activities without damaging ecosystems and depleting existing resources (Mulyanti, 2022).

Bogor District faces many challenges in meeting its clean water needs, including increasing population, urbanization, climate change, and human activities that damage the balance of groundwater resources. Rapid population growth and urbanization significantly increase the demand

for clean water, while water management infrastructure is often unable to keep up. Climate change exacerbates the situation by causing uncertainty in rainfall patterns, which impacts aquifer recharge and surface water availability. In addition, human activities such as the overuse of groundwater for agriculture and industry, as well as deforestation and land use change, contribute to the decline in groundwater quantity and quality. The combination of these factors poses a major challenge for Bogor District in ensuring the sustainable availability of clean water for all its citizens (Sarie et al., 2023).

In recent years, the high reliance on conventional groundwater sources in Bogor District has raised serious concerns regarding the decline in clean water availability. Over-exploitation has led to a decline in groundwater discharge, which threatens the sustainability of water supply for domestic, agricultural, and industrial needs. Conventional groundwater sources, which generally originate from shallow aquifers, are increasingly unable to fulfill the growing demand (Juwono & Subagiyo, 2018). Therefore, attention is turning to groundwater sources from volcanic deposits, which are considered to have greater potential and better quality. Further investigation into these sources is expected to provide a more sustainable alternative, reduce pressure on conventional aquifers, and ensure sufficient clean water supply for all communities in the future.

The results of a volcano hydrogeological knowledge of the research mentioned above should at least make the management of natural resources more careful. Regional been developed groundwater exploitation massive in the distal area the breeding industry and other groundwater users are largely determined. Meanwhile medial region is often already a settlement. Therefore, the necessary local knowledge in conservation programs is needed to keep the water seeped in the region. However, this model needs to be taken into consideration in determining the spatial structure. Thus, sustainable natural resources in the volcanic region will give the ability and capacity of water potential which can be exploited, (Hadian et al., 2016). Volcanic aquifers are sources of groundwater for both urban and rural areas. Their occurrence in geological formations and water quality are the main issues for sustainable utilization (Fenta et al., 2020).

This research aims to analyze the potential of volcanic deposit aquifers as potential groundwater sources in Bogor District in the hope of providing new insights and important contributions to the management of groundwater resources in Bogor District. The relevance of this research is significant in the context of groundwater management policy development, water infrastructure development, and environmental conservation in Bogor District. The results of the research are expected to serve as a basis for better decision-making in groundwater resource management, supporting appropriate policy formulation, infrastructure development that is responsive to clean water needs, as well as more effective environmental conservation strategies, thus ensuring sustainable clean water availability for the future.

## RESEARCH METHOD

This research will be conducted in the Bogor Groundwater Basin, the upper Ciliwung watershed, the eastern slope of Mount Salak, and the western slope of Mount Pangrango. The research method involves secondary and primary data collection. Secondary data will mainly include surface geological data such as lithology and geological structure obtained from the 1:100,000 scale regional geological map. Furthermore, primary data collection is conducted through geological and hydrogeological surveys and mapping.

Geological mapping will include observations of geomorphology, rocks, and geological structures. Geomorphological observations will use remote sensing data such as satellite imagery through analysis of Shuttle Radar Topography Mission (SRTM) and Digital Elevation Model (DEM) data with a spatial resolution of 30 meters, as well as interpretation of Landsat imagery. The mapping involves identifying and mapping the landscape and surface characteristics of the study area.

Hydrogeological mapping will focus on observing springs in the field to determine the type of spring and the physical properties of the water. These observations include mapping spring locations, measuring elevation, determining groundwater type, and measuring physical water properties such as

pH, electrical conductivity (DHL/Ec), and total dissolved solids (TDS). In addition, chemical analysis of ions and cations will be conducted in the laboratory to complement the hydrogeological data.

The combination of geological and hydrogeological mapping will provide a comprehensive picture of the potential of volcanic sediment aquifers as groundwater sources in Bogor Regency so that it can be used as a basis for better and sustainable water resources management.

## **RESULT AND DISCUSSION**

Bogor Regency has complex and diverse geological and hydrogeological conditions, influenced by the presence of volcanoes such as Mount Salak and Mount Pangrango. The geology of the area is dominated by volcanic deposits, including lava, tuff, and breccia, which form potential aquifers for groundwater sources. The varied geological structure, with numerous faults and folds, also affects the distribution and availability of groundwater. The hydrogeology of Bogor District is characterized by groundwater flow systems that recharge aquifers from surface runoff and rainwater infiltration, especially in mountainous areas. Natural springs are found on the mountain slopes, providing a source of clean water for the local population. The combination of rich geological conditions and dynamic hydrogeological systems makes Bogor District an important area for further research to ensure the sustainability of groundwater resources.

### **Geomorphology**

Based on image analysis and its origin, geomorphology in the Cisadane Watershed can be classified into seven units according to (Mawardi et al., 2019). The following is an explanation of each geomorphological unit:

#### **Formation of Volcanic Origin**

This unit is formed from volcanic activity. Its characteristics include the presence of volcanic cones, lava flows, and pyroclastic materials. Due to volcanic deposits, this area usually has a rough topography with steep slopes and fertile soil.

#### **Formation of Denuded Volcanic Origin**

These areas were originally formed from volcanic material, but have undergone a significant denudation process. Denudation is the process of weathering, eroding, and transporting material by water, wind, or ice, which causes these volcanic-origin formations to become smoother and lower.

#### **Formations of Volcanic Fluvial Origin**

These are the result of the interaction between volcanic activity and fluvial (river water) processes. Here, river flow has influenced and altered volcanic deposits, resulting in river valley-like formations formed from eroded and re-deposited volcanic material.

#### **Denuded Structure Origin**

These formations originate from uplifted geological structures (e.g. folds or faults) that have undergone denudation. The result is a landscape with relief patterns influenced by the original geological structure, such as hilltops and valleys parallel to the structure.

#### **Dissolution Origin Formation**

This unit is formed by the dissolution of rocks, especially carbonate rocks such as limestone. The dissolution process creates distinctive forms such as caves, and sinkholes. These areas are usually found in areas that have a rock composition that is easily dissolved by water.

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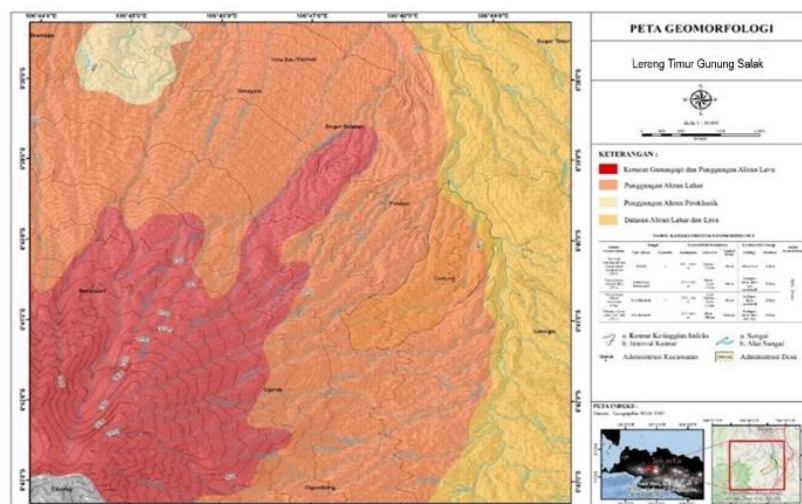
Each geomorphological unit in the Cisadane watershed exhibits a distinct geological history and natural processes, which can be seen through image analysis and field studies. These forms reflect not only past geological activity but also processes that are still ongoing today.

The shape of the landscape on both slopes is expressed by plains - too steep hills with a medium-rough texture, depicting exogenic processes that have not been intensive. The geomorphological stages of young-mature are shown by several rough slopes and some have changed due to human activities for agricultural land and housing. The height difference on the eastern slope of Mount Salak is  $\pm 2211$  meters above sea level with a flat distance of  $\pm 8500$  m to the valley, while on the western slope of Mount Pangrango  $\pm 3019$  meters above sea level, the distance is  $\pm 18,500$  m, the slope on both slopes is flat to steep or  $2^\circ$  to  $70^\circ$ , (Zuidam Van, R. A. (1985). The geomorphological units are units of plains-sloping hills with lava and pyroclastic flows (foot of the volcano), units of sloping-steep hills ridges of pyroclastic deposits - lava flows (volcano body), and units of steep hills - steep pyroclastic deposits and lava flows (slopes of volcanic peaks (**Fig. 1 and figure 2**).

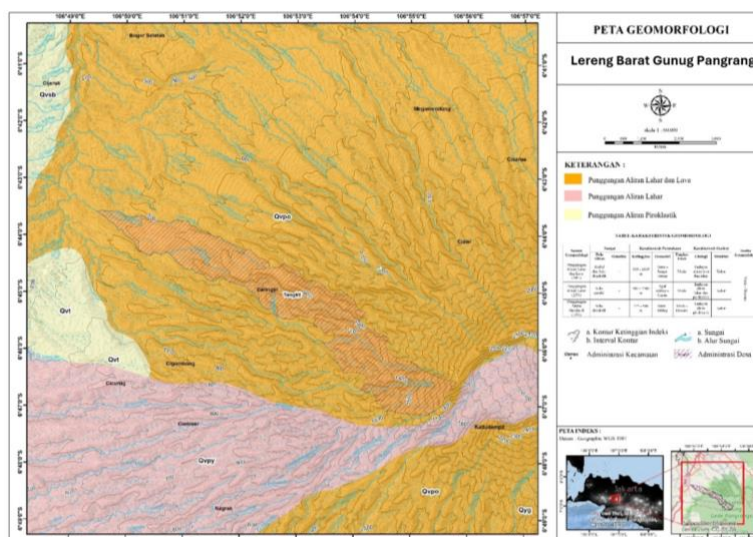
Volcano foot geomorphological unit, height ranges from 250 – 400 meters above sea level, slope  $5^\circ$  –  $20^\circ$ , parallel contour pattern, landau plains, and hills formed by lava flows. Rocks that make up Quaternary volcanic flows, tuffaceous sand breccia, sandy and fine tuff. Distribution of the extension of the S. Cisadane valley, to the body of the volcano, parallel and sub-parallel flow patterns of effluent type.

Volcanic body slope geomorphological unit, height 400–950 meters above sea level, slope  $15^\circ$ – $60^\circ$ , pyroclastic hills that are gentle to steep. Rocks that make up Quaternary volcanic products, lava flows and pyroclastic deposits, breccia, interbedded lapilli tuff, lapilli, and tuff. Parallel and sub-parallel river flow patterns, on the slopes of Mt. Salak S. Cihideng, C. Cigombing, S. Cijeruk, S. Ciparikalih, S. Ciapus, on the slopes of Mt. Pangrango S. Cisalopa, S. Ciherang, with the main river S . Cisadane, effluent flow type.

Volcano peak slope geomorphological unit, height 950 – 3019 meters above sea level, slope  $30^\circ$ – $70^\circ$ , forms a circular contour pattern and spreads parallel, in one direction from the peaks of Mt. Salak and Mt. Pangrango, forming steep hills, separated by deep valleys. The rocks that make up the results of Quaternary volcanoes, lava flows, and massive pyroclastic deposits. The flow pattern of the Radier tributaries changes parallel to form several sub-watersheds, including on the eastern slopes of Mt. Salak, Cigombong sub-watershed, Cihideung sub-watershed, Ciparikalih sub-watershed and Cijeruk sub-watershed, while on the western slopes of G. Pangrango sub-watershed, Cisalopa, the Ciherang sub-watershed, and the Caringin sub-watershed, are all part of the upstream Cisadane watershed.



**Figure 1. Geomorphological Map of the Eastern Slope of Mount Salak**



**Figure 2. Geomorphological map of the Western Slope of M. Pangrango**

The investigation area with slopes from flat to steep (about 2 to more than 30%) has a significant relationship with aquifer potential in groundwater development. Flat slopes tend to have greater groundwater accumulation due to higher water retention. On the other hand, steep slopes can drain water faster, increasing the opportunity to recharge aquifers located below. Therefore, areas with diverse slopes can provide favorable conditions for sustainable groundwater development (Akbar, 2023). An understanding of the relationship between slope and aquifer potential allows for more efficient and effective water resources management planning in utilizing groundwater potential across a range of topographic conditions.

### Stratigraphy

The rock units located in the Ciliwung watershed consist of several rock units, namely the Old Volcano Rock Unit, Pangrango Volcano Rock Unit, and Salak Volcano Rock Unit.

The Old Volcanic Rock Unit consists of stony tuff and volcanic rocks found in the Cigombong and Cikereteg areas. These rocks are grey, brown, and black, in the form of weathered tuff breccia with andesitic igneous rock components measuring 0.5 cm - 3 cm, dominantly 0.5 cm, angular to oblique, open packed, and medium sorting.

The Mount Pangrango Volcanic Rock Unit is composed of andesite-bedded lava (Qvpy) and lahar and andesite basalt lava (Qvpo) originating from Mount Pangrango. This unit is found in Pasirbuncir Village and is in the form of uncompacted sand, black-grey to black, medium to coarse-grained, and angular to rounded.

The Salak Volcano Rock Unit is composed of lava flows, lava, tuff breccia, and lapilli and stony tuff. The oldest rock is the stony tuff (Qvst) covered by lava, tuff breccia, and lapilli (Qvsb). Rock outcrops are found in Cileungsir and Cibandawa rivers, in the form of weathered volcanic breccia, brown in color, matrix-supported, with coarse to very coarse tuff matrix, angular to oblique igneous rock components, 2 cm - 3 cm in size and locally 5 cm in size, with poor sorting and open packing (Hadian et al., 2016).

Stratigraphic columns in several places show various rock facies, as found in geomorphological research and volcanic facies characteristics in the Cihideung and Ciparikalih Rivers, Cibadak Sub Watershed (Natasia et al., 2018), which identified several facies, namely lapilli facies, lapilli tuff facies, tuff breccia facies, and lava facies.

Meanwhile, the results of stratigraphic measurement observations in the study area on the eastern slope of Mount Salak in the Cihideung River track, and the Cigombong River on the western

slope of Mount Pangrango in the Cisalopa River and Ciherang River track, also identified the existence of distal facies, medial facies, and proximal facies, with a lithological arrangement that is almost the same as the results of the research by Natasia et al.

Surface lithology is obtained from mapping and stratigraphic measurements based on the elevation of each rock outcrop, trajectories are carried out at 4 priority locations to determine the aquifer layer and produce a lithological facies model (Figure 3 and Figure 4).

The slopes of the peak, the upper part is dominated by andesite lava, meanwhile, the lower part is interspersed with massive pyroclastic breccia rocks, which are estimated to be the youngest rocks from the Mt. Salak and Mt. Pangrango product, found at altitudes ranging from 750 -1450 meters above sea level. The andesite has thin sheeting joints which are quite intensive, and the fractures are in the form of scoured joints, secondary porosity in the fractures, and secondary aquifer. light gray to dark gray color, aphanitic (smooth) texture, the main constituent minerals consist of plagioclase, glass, and hornblende, grain size 0.1–1 mm, crystallinity, hypocrystalline, grain shape subhedral-anhedral, equigranular, shows the flow texture, the basic mass is glass, the phenocrysts are plagioclase, feldspar, quartz and hornblende, the aqueous layer (impermeable).

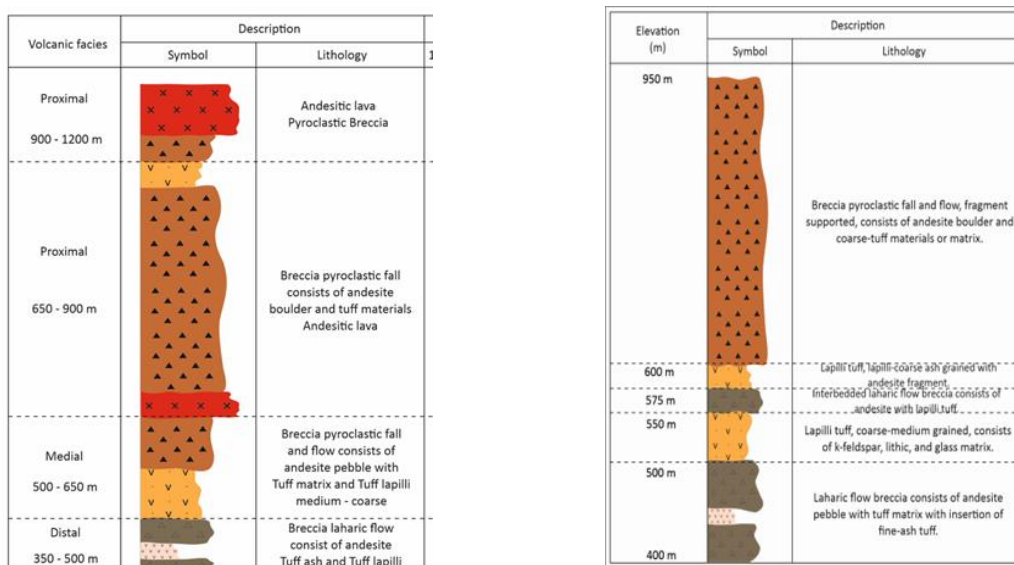
The constituent rocks on the middle slopes of the middle part (volcanic body), grain grain-supported pyroclastic breccia, matrix-supported breccia, andesite, lapilli, lapilli tuff, and tuff. Volcanic breccia is yellowish brown, components of andesitic igneous rock fragments, fine sand grain size - blocks, grain shape at an angle, matrix in the form of tuff-sand, poorly sorted, open packing, good porosity, cavity flow system between grains. Lapilli tuff breccia, supported matrix, gray color, supported matrix of andesitic igneous rock fragments, size 2 -10 cm, and pumice, oblique grain shape, tuff-sand matrix, poorly sorted, open packed, poor porosity.

The rocks that make up the slopes at the foot of the volcano, at an altitude of 330 – 530 meters above sea level, consist of laharic breccia, fine tuff, and sandy tuff. Breccia is a blackish gray and brown, component of andesitic igneous rock fragments, angular shape, size 1 cm – 10 cm, tuff matrix, brownish cream color, fine size - sand, poorly sorted, open packed, good porosity, pore flow media, aquifer layer. Tuff is yellowish gray, clay grain size - fine sand, grain shape is angular to medium round, massive, open packed, poorly sorted, soft to slightly hard, aquiclude layer.

Elevation (m)	Lithology	
	Symbol	Description
950 m		Lapilli tuff, coarse-medium ash grained, consists of k-feldspar, lithic, and glass matrix.
850 m		Pyroclastic fall and flow breccia consists of andesite boulder-pebble with matrix of coarse-medium lapilli tuff.
700 m		Lapilli tuff, coarse-ash grained, consists of k-feldspar, lithic, and glass matrix.
600 m		Pyroclastic flow breccia consists of andesite pebble with coarse tuff matrix.
550 m		Tuff, medium-fine ash grained with insertion of fine-ash tuff.
450 m		

Volcanic facies	Description	
	Symbol	Lithology
1875 m		Volcanic product Andesitic lava
750 - 1450 m		Breccia pyroclastic fall consists of andesite boulder and tuff materials Andesitic lava
550 - 750 m		Breccia pyroclastic fall and flow consists of andesite pebble with Tuff matrix and Tuff lapilli medium - coarse
350 - 550 m		Breccia laharic flow consist of andesite Tuff ash and Tuff lapilli

**Figure 3. Stratigraphic column of eastern slope of M. Salak R. Cihideung and R. Cigombong**



**Figure 4. Stratigraphic column of M. Pangrango Slope R. Cisalopa and R. Ciherang**

The Old Volcano, Mount Pangrango, and Mount Salak Rock Units reflect geological formations rich in volcanic materials, including stony tuffs, tuff breccias, lavas, and lahars. The potential of aquifers in groundwater development is closely related to the se formations' physical and hydrogeological properties. Pumiceous tuff rocks tend to have high porosity and the ability to store groundwater in cracks and pores. Tuffaceous and lapillary breccias can also contribute to the formation of good aquifers, especially if they have a weathered and permeable structure. Lava and lava flows, although perhaps less porous, can provide an overburden that restricts groundwater flow, allowing the accumulation of water underneath (Irma Lusi & Annisa Salsabilla, 2020).

**Hydrogeology  
Aquifer system**

The aquifer system of the study area was identified through surface geological mapping of the study area which covers most of S. Cihideng, the eastern part of the slope of G. Salak, and S. Ciherang on the slope of G. Pangrango.

The results of geoelectrical data acquisition and lithological interpretation based on VES (vertical electrical sounding) data, on the Western slope of Mount Pangrango consist of four lithological layers and their hydrogeological properties are as follows (Figure 5)

**First layer:** 1 – 2 meters deep, with  $\rho$  values ranging from 38  $\Omega$  to 179  $\Omega$ , interpreted as a soil layer. Low to medium resistivity values are caused by several factors, namely soil texture, soil moisture, and the soil's parent rock. This soil layer has low – high porosity, with moderate infiltration capacity.

**Second layer:** 2 – 15 meters deep, from the local surface, at an elevation of 475-511 meters above sea level, with  $\rho$  values ranging from 43  $\Omega$  to 116  $\Omega$ . This layer is interpreted as an intercalation of lapilli and pyroclastic breccia which has quite large cavities between grains (fragments). It is an unconfined aquifer layer, and the flow of voids between grains is productive.

**Third layer:** 18–38m deep, below the local ground surface, at an altitude of 475 - 516 meters above sea level, part of the foot of the volcano, with  $\rho$  values ranging from 9  $\Omega$  to 18 $\Omega$ . This layer is interpreted as compact fine tuff, which is an aquiclude or impermeable layer, an insulating layer that forms a confined aquifer.

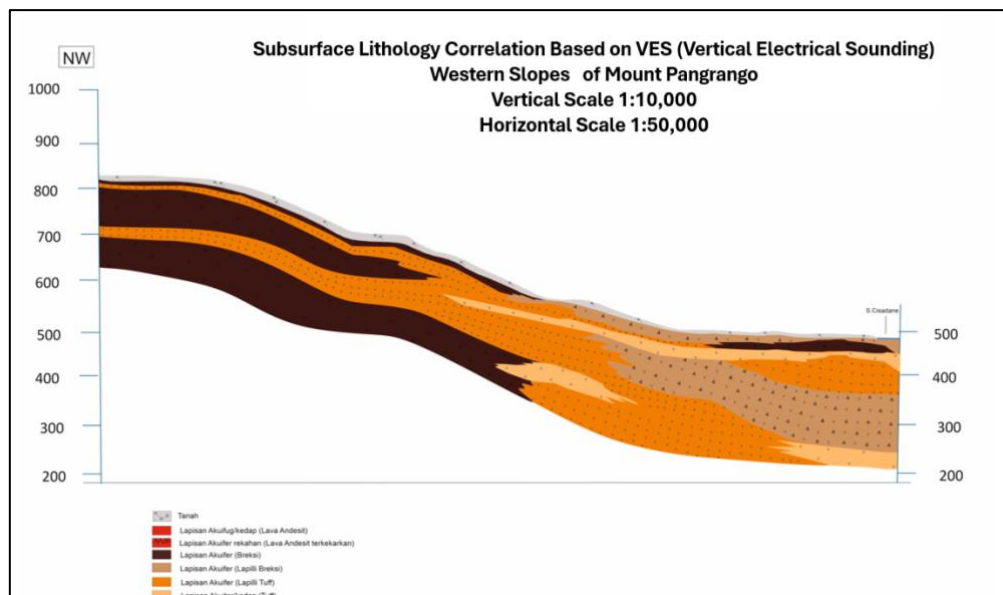
**Fourth layer:** Depth of 38 – 65 m below the local ground surface, at an elevation of 475-511 meters above sea level, part of the foot of the volcano, with  $\rho$  values ranging from 32  $\Omega$  to 56  $\Omega$ . This layer is interpreted as lapilli, with a thickness of between 25-65 meters. It is an intergranular cavity aquifer layer, with medium productivity.

**Fifth layer:** Depth of 65–120 m below the local land surface, at an elevation of 475 - 516 meters above sea level, part of the foot of the volcano, with  $\rho$  values ranging from 63  $\Omega$  to 80 $\Omega$ . Interpreted as lapilli breccia, which has quite large intergranular voids. This layer is a productive intergranular cavity aquifer.

**Sixth layer:** Depth of 120 – 150 m, below the local ground surface, at an altitude of 475 – 516 meters above sea level, part of the foot of the volcano, with a  $\rho$  value ranging from 11  $\Omega$  to 26 $\Omega$ . This layer is interpreted as compact fine tuff, which is an aquiclude or impermeable layer, as an insulating layer that forms a confined aquifer.

Cross section of aquifer layers resulting from correlation of outcrop data, rock layers

- Unconfined aquifer: Pyroclastic breccia layer with a thickness of 10 - 50 meters, inter-grain cavity aquifer system, and some fracture systems.
- Impermeable layer: Andesitic lava aquifer layer, and secondary aquifers, fracture system.
- Unconfined and semi-confined aquifers: Layers of tuff, lapilli, and breccia are found in the sloping areas at the body of the volcano, 12 - 45m thick.
- Confined aquifer Layers of tuff, lapilli, and breccia are found in the sloping areas at the foot of the volcano.



**Figure 5. Cross-section of aquifer-forming lithological layers on the western slope of M. Pangrango**

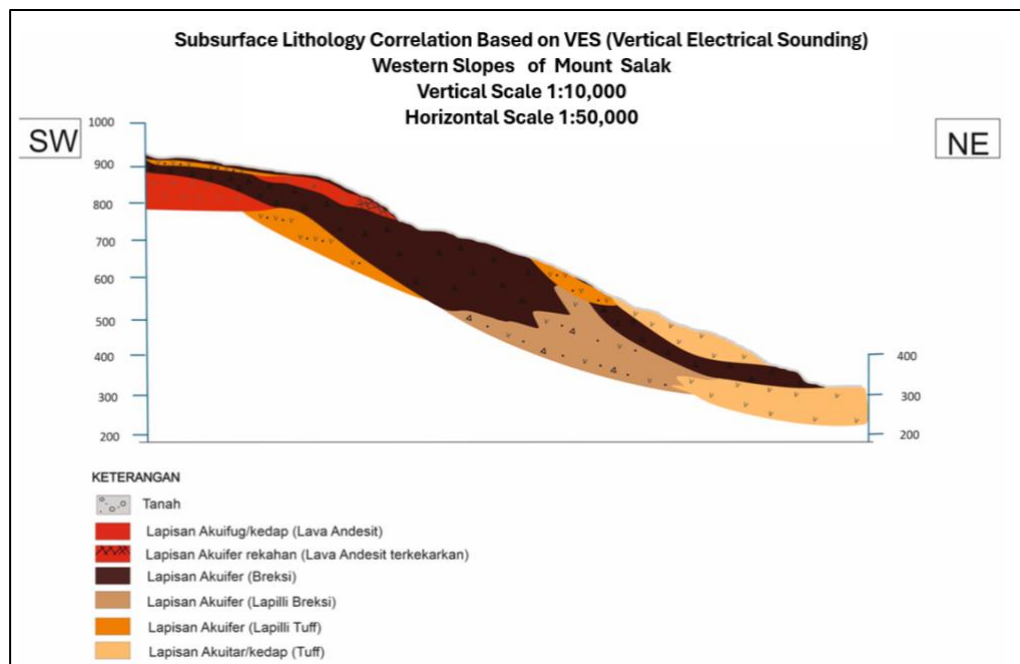
The results of geoelectrical data acquisition and lithological interpretation based on VES (vertical electrical sounding) data, on the eastern slope of Mount Salak consist of four lithological layers and their hydrogeological properties are as follows, (Figure 6)

**First layer:** 1 – 3 meters deep, with  $\rho$  values ranging from 41  $\Omega$  to 931  $\Omega$ , interpreted as soil. Variability or large intervals of resistivity values are caused by several factors, namely soil texture, soil moisture, and the soil's parent rock. This soil layer has low – high porosity, with a large infiltration capacity for groundwater replenishment.

**Second layer:** 3 – 50 meters deep, from the local surface, at an altitude of 750-920 meters above sea level, part of the peak slope, with a  $\rho$  value ranging from 150 – 250  $\Omega$ . This layer is interpreted as pyroclastic breccia which has quite large cavities between grains (fragments) so that it has a high resistivity value. It is a layer of intergranular cavity aquifer that is productive for supplying springs and groundwater on the slopes of the body and foot of the volcano.

**Third layer:** Depth of 9 – 30 m and 25-70 m, below the local ground surface, at an altitude of 754-920 meters above sea level, with  $\rho$  values ranging from 903 to 4768  $\Omega$ . This layer is interpreted as igneous rock, the varying resistivity values are influenced by differences in porosity, and low values have secondary porosity in the form of fractures. This layer is a low productivity fractured aquifer layer, as a medium for filling groundwater through fractures, and an aquifer or impermeable layer in parts where there are no fractures, especially at a depth of 30 – 70 m.

**Fourth layer:** 8 – 75m deep and 100-150m deep, below the local ground surface, at an elevation of 494 meters above sea level, part of the foot of the volcano, with a  $\rho$  value ranging from 11  $\Omega$  to 16 $\Omega$ . This layer is interpreted as a layer of fine and dense tuff, with a thickness of up to 45 meters. It is an aquiclude or impermeable layer, functioning as an insulating layer that forms a semi-confined aquifer.



**Figure 6. Cross-section of aquifer-forming lithological layers on the eastern slope of M. Salak**

The cross-section of aquifer layers resulting from the correlation of outcrop data, geoelectric data, and drill logs shows the layers:

- Unconfined aquifer (0-20/30 meters): pyroclastic rock (volcanic breccia).
- Impermeable layer (20 - 30 meters): dense very fine tuff, aquitard layer
- Semi-confined and confined aquifers (30 - 120 meters): lapilli, lapilli tuff, pyroclastic breccia and laharic. impermeable layer of igneous rocks.

Surface, and subsurface geological data (geoelectric and drilling log data), can provide an overview of geological and hydrogeological conditions ranging from the upper slopes to the foot of the volcano. On the upper slope: surface mapping results at elevations of 750 m to 1250 m, igneous rocks as aquifer layer and fracture-type secondary aquifer, massive pyroclastic breccia, primary aquifer layer of intergranular cavity type and fracture type, and unconfined aquifer type.

The results of surface mapping show an elevation of 550 m above sea level to 750 m above sea level on the slopes of the volcano body. Pyroclastic rocks are in the form of breccias and lapilli breccias, layers of lapilli and lapilli tuffs, tuffs, aquifer layers, aquitards, and a small portion of fracture-type secondary aquifers in breccias. The tuff layer is dense, forming an aquiclude layer as an insulating layer.

All rock layers in this zone form a multilayered aquifer with an unconfined aquifer system and a semi-confined aquifer. Changes in aquifer layers occur laterally which will affect hydraulic changes to form anisotropic aquifers.

On the lower slope (the foot of the volcano) at an altitude of 300-550m above sea level, drill log data, depth 70-120mbmt, vertical sequence shows a mixture of volcanic rocks (lava flow) in the form of breccia, tuff, lapilli tuff. From the drill data, lapilli tuff, tuff and breccia are found. The intersection between layers of lapilli tuff, lapilli, and breccia is the rock forming the aquifer layer. The tuff layer forms an impermeable layer so that the lithological variations at the foot of the two volcanoes at a depth of > 80 m form an aquifer system, free, semi-confined, and confined.

From the results of surface mapping and drilling data, it can be illustrated that the two slopes of the volcano form a free aquifer layer on the slopes of the peak, on the body of the volcano consists of free and semi-suppressed aquifers. At the foot of the volcano/valley between the two volcanoes, from geo-electrical data and drill logs, it can be seen that the lithological variation is increasing, in the form of intersections, laharic breccia, pyroclastic breccia, lapilli, and tuff, forming unconfined aquifer system at the top and confined aquifer at the bottom.

## Physical and Chemical Properties of Groundwater

### Physical properties parameter

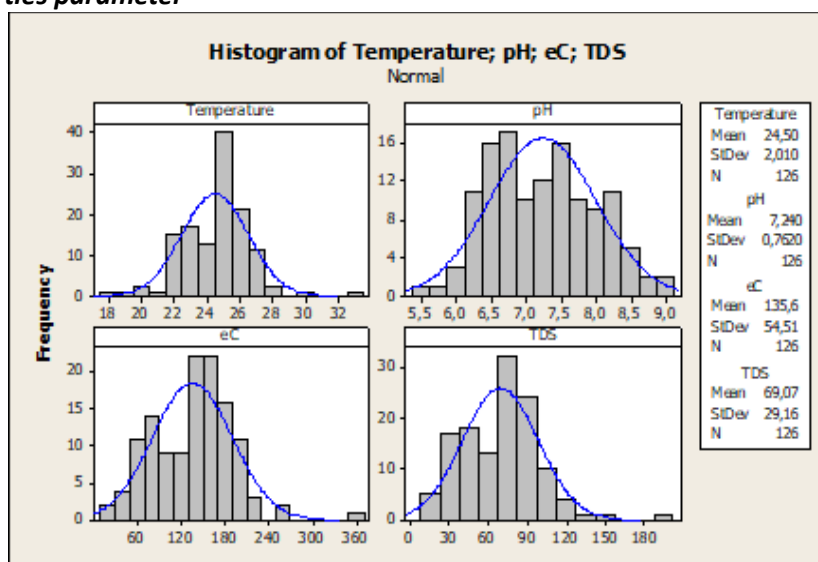
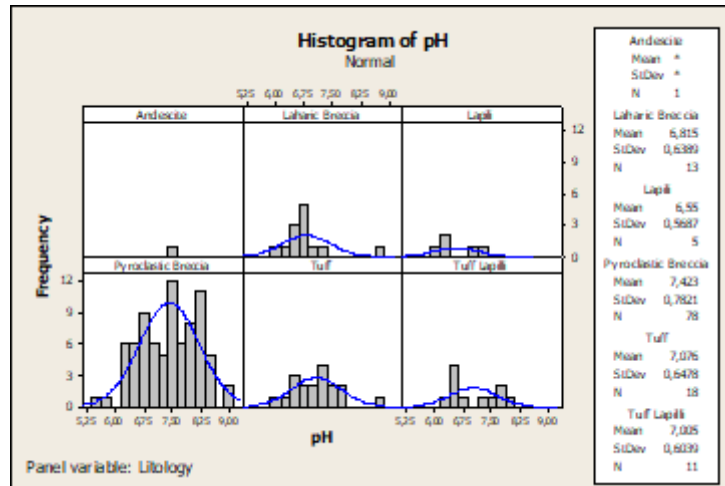


Figure 9. Frequency histogram of physical properties parameters, temperature, pH, EC, and TDS/ZPT.

The average groundwater temperature in Bogor District is 24.5°C, with the most frequent temperature range between 22.5 and 25°C. Groundwater pH values were almost evenly distributed from 5.5 to 9, with an average pH of 7.2 and dominance in the range of 6.5 to 7.5. Total Dissolved Solids (TDS) values ranged from 13 ppm to 305 ppm, with dominant values between 70 ppm to 80 ppm, and the highest TDS recorded at 305 ppm. The distribution pattern of TDS is very similar to the distribution of electrical conductivity (eC), as eC values are strongly influenced by TDS concentrations.

Hydrogeologically, these groundwater quality characteristics can provide an idea of the potential of aquifers in groundwater development in the Bogor District area. Water quality that has a neutral to slightly alkaline pH and moderate to low TDS content indicates the potential for relatively good groundwater development. (Hertika et al., 2022).

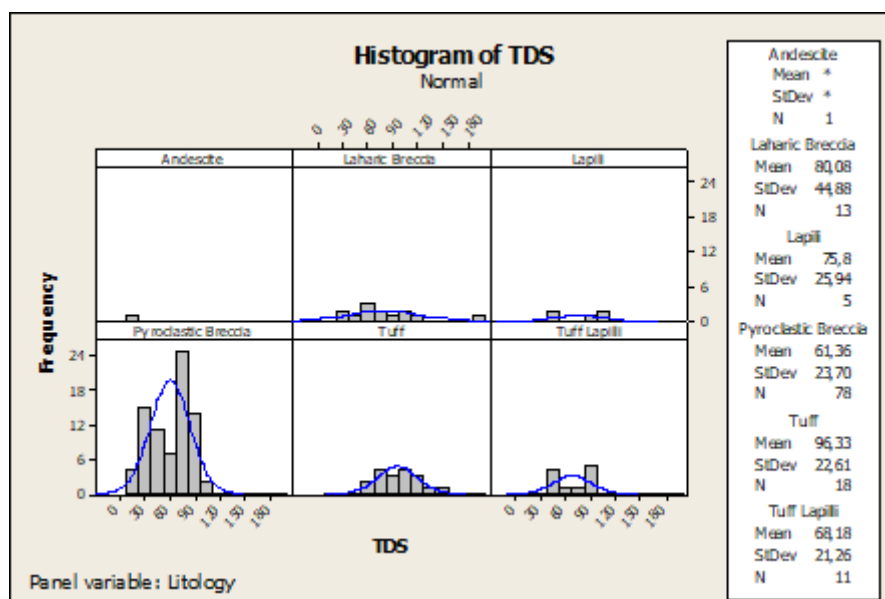
**Correlation of pH and Lithology**



**Figure 10. Histogram of pH frequencies, about lithological assemblages**

The pH values ranged from 6-9 with an average of 7.1, the most frequent values being 7 to 7.2. The figure shows that groundwater in the Breccia has the highest pH of 8.5-9, which is 6.7. Hydrogeologically, relatively neutral to slightly alkaline pH values may indicate the potential for good groundwater development. Water with a pH in this range tends to have a good ability to hold various types of chemicals required by plants and living organisms. However, particularly for high-pH waters such as those found in breccia formations, attention needs to be paid to the possibility of chemical processes affecting nutrient availability and heavy metal toxicity (Yanti, 2023).

**TDS dan Litologi**



**Figure 11. Histogram of TDS frequencies, about lithological assemblages**

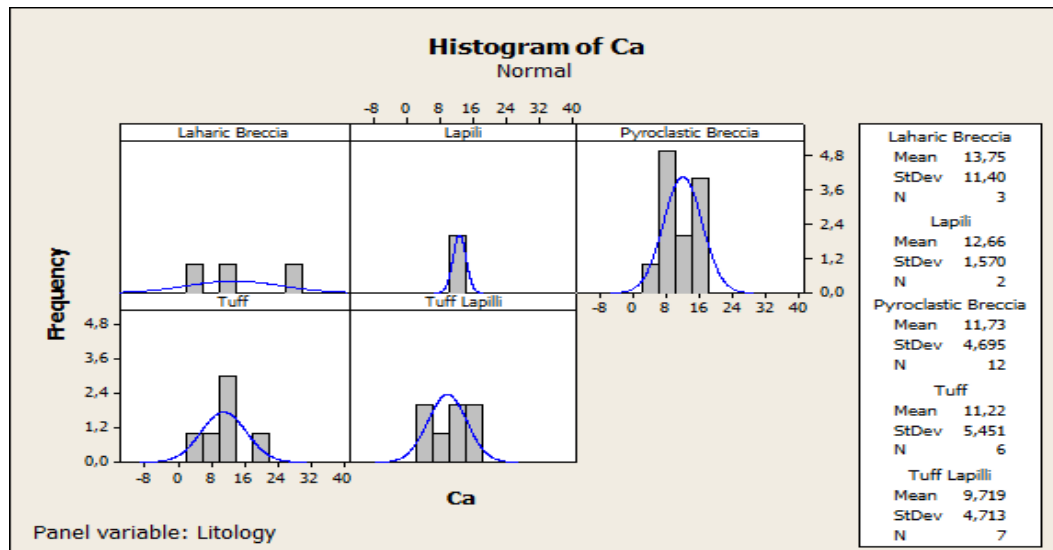
The average Total Dissolved Solids (TDS) value on the western slopes of Mount Pangrango is 78 ppm, with a range of frequent values between 13 and 305 ppm. Springs with TDS greater than 200

ppm indicate the presence of meteoric water, with the highest TDS value of 305 ppm found in deep wells in depressed aquifer systems. Meanwhile, the average TDS on the eastern slopes of Mount Salak was 101 ppm with a range of frequently occurring values between 26 and 198 ppm also indicating meteoric water types. No springs on the eastern slopes of Mount Salak have TDS values of more than 200 ppm. Hydrogeologically, the relatively low TDS values indicate the potential for quality groundwater development on both slopes of the mountain (RA, 2018).

**Chemical parameters**

**Cation Element**

**Ca Vs Lithology**



**Figure 12. Histogram of Ca cation chemistry parameters about lithological type**

The histogram of Ca<sup>2+</sup> concentration in meq/L in the aquifer system of volcanic deposits, including lahar breccia, lapilli, pyroclastic breccia, tuff, and lapilli tuff, shows the variation of calcium content in groundwater. From the analysis, the highest average calcium content was found in the Laharic breccia with a value of 13.75 meq/L, while the lowest was in the lapilli tuff with a value of 9.7 meq/L.

These variations indicate differences in aquifer characteristics in each rock formation, which may affect the potential for groundwater development in the area. For example, a higher calcium content in the Laharic breccia may indicate the potential for harder groundwater or higher mineralization, while a lower calcium content in the lapilli tuff may indicate a purer groundwater source or less affected by mineralization processes (Purnama, 2019).

**Mg Vs Lithology**

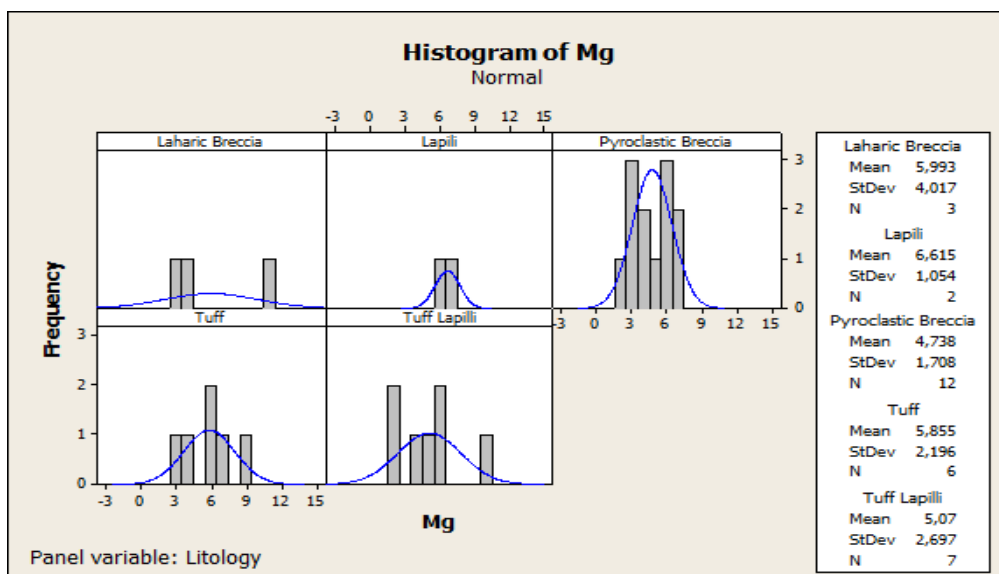


Figure 13. Histogram of Ca cation chemistry parameters about lithological type

The concentration of  $Mg^{2+}$  in meq/L in the aquifer system of volcanic deposits, including lava breccia, lapilli, pyroclastic breccia, tuff, and lapilli tuff, shows variations in magnesium composition. The average magnesium composition in the groundwater samples ranged from 4.7 to 5.9 meq/L, with the highest value of 5.9 meq/L in the lahar breccia and the lowest of 4.7 meq/L in the pyroclastic breccia lithology.

These variations indicate differences in the chemical characteristics of the aquifers in different rock formations, which may affect the potential for groundwater development in the area. For example, higher magnesium concentrations in the lahar breccia may indicate the potential for harder groundwater or higher mineralization, while lower concentrations in the pyroclastic breccia may indicate a purer groundwater source or less affected by mineralization processes (UTAM, 2021).

Na

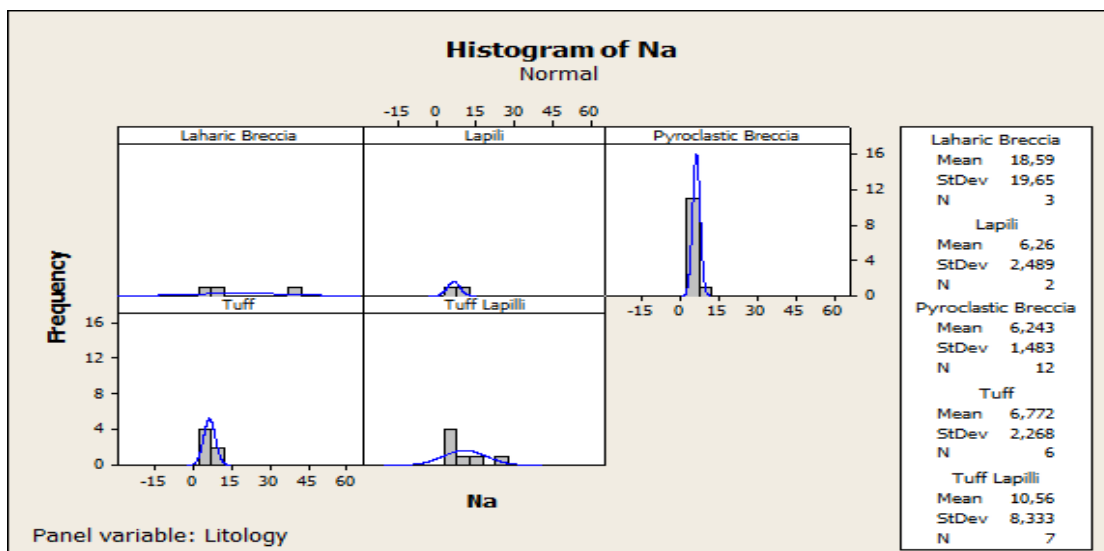
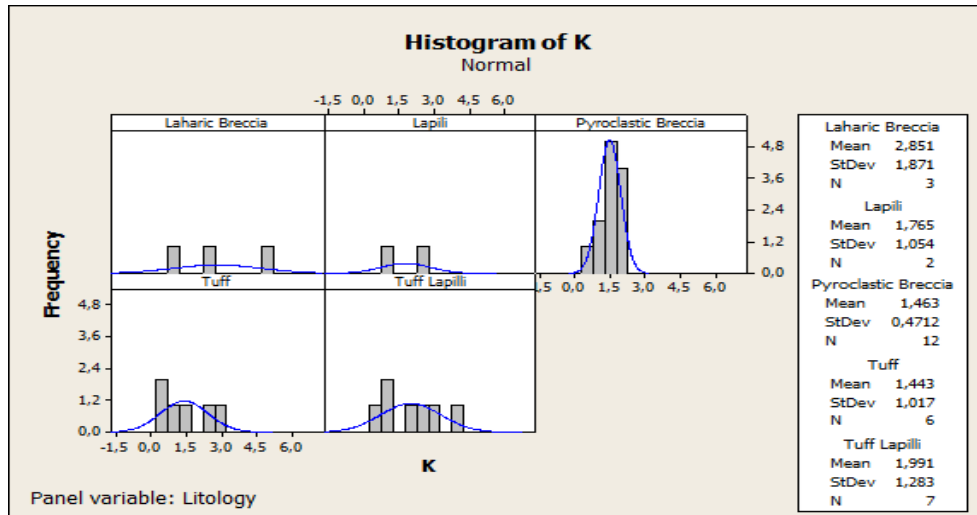


Figure 14. Histogram of  $Na^{2+}$  cation chemistry parameters about the lithological type

The concentration values of  $Na^{2+}$  in meq/L in the aquifer system in lava breccia, lapilli, pyroclastic breccia, and lapilli tuff rocks show uneven frequency of occurrence in all groundwater samples. The average sodium content in groundwater for each lithological type ranged from 6.7 to 18.59 meq/L, with the highest values found in the lahar breccia.

This variation indicates differences in the chemical characteristics of the aquifers in different rock formations, which may affect the potential for groundwater development in the area. For example, the higher sodium content in the lahar breccia may indicate the potential for groundwater to be more affected by mineralization processes or infiltration of chemicals from the surrounding environment (Purnama, 2019).

**K**

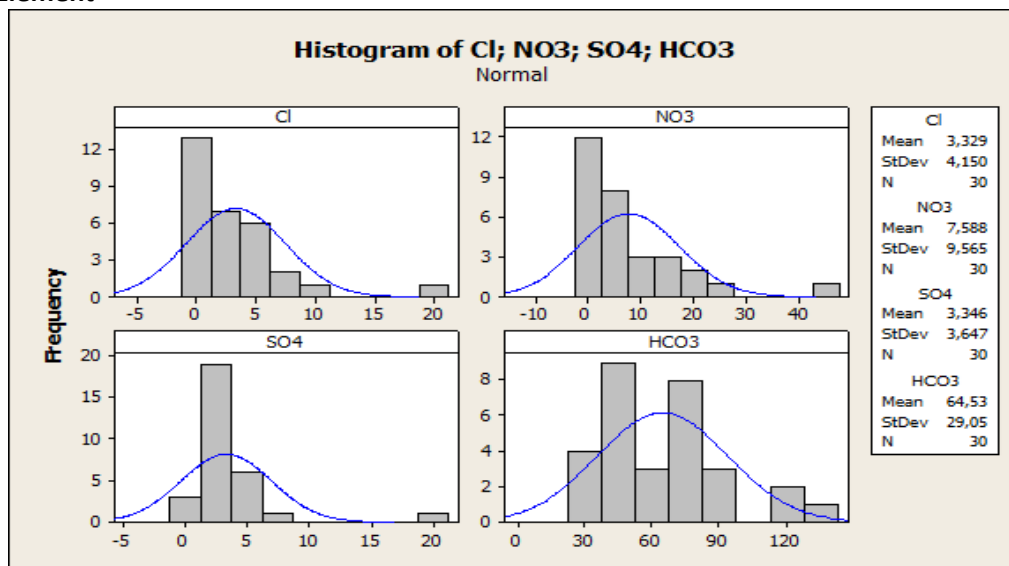


**Figure 15. Histogram of cation chemistry parameter K about lithological type**

The Na<sup>2+</sup> concentration values in meq/L in the aquifer system in lava breccia, lapilli, pyroclastic breccia, and lapilli tuff rocks show significant variations. The frequency of sodium content is considerable, with the average of each rock type ranging from 1.44 to 2.85 meq/L. The highest value was found in the lava breccia with a concentration of 2.85 meq/L.

This variation indicates differences in the chemical characteristics of the aquifers in the various rock formations, which may affect the potential for groundwater development in the area. Higher sodium concentrations, especially in the lahar breccia, may indicate the influence of geological processes or human activities that could affect groundwater quality (Purnama, 2019).

**Anion Element**



**Figure 16. Histogram of anion chemical parameters**

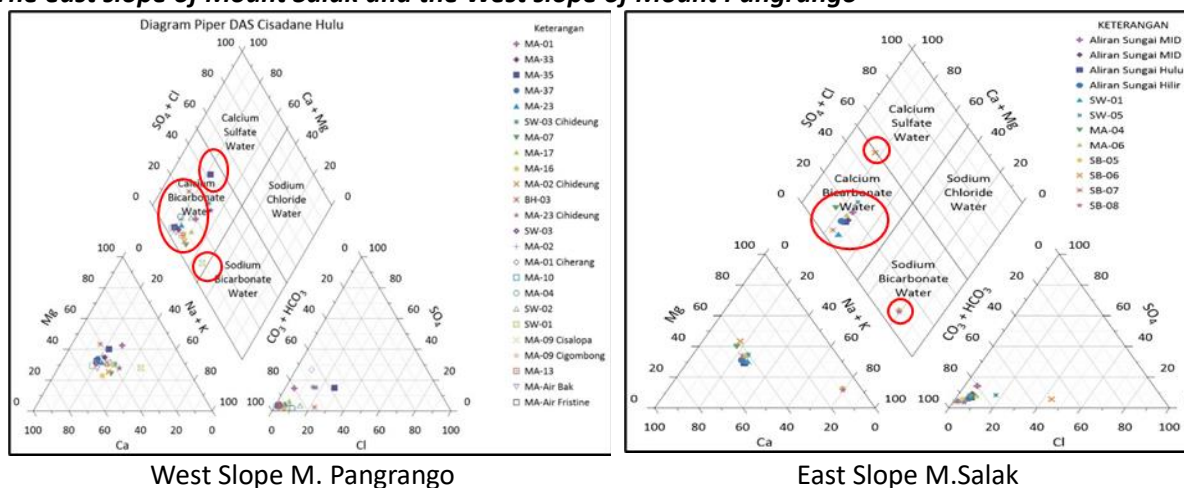
- Chloride (Cl<sup>-</sup>): Chloride averaged 3.3 meq/L, from 70 samples. The highest value was 9.26 ppm in the lapilli tuff rock, while the lowest value was 0.17 ppm in the pyroclastic breccia rock.

- (NO<sub>3</sub>): Average NO<sub>3</sub> 7.5 ppm, from 70 samples. highest value is 27.8 ppm in lapilli rock, while the lowest value is 0.5 ppm in pyroclastic breccia rock.
- Sulfate (SO<sub>4</sub><sup>2-</sup>): Average SO<sub>4</sub> 3.36 ppm, from 70 samples. the highest value of 5.8 ppm in lapilli tuff rock, while the lowest value <0.5 ppm in pyroclastic breccia rock.
- Bicarbonate (HCO<sub>3</sub><sup>-</sup>): Average SO<sub>4</sub> 64.5 ppm, from 70 samples. highest value is 138.9 ppm in laharic breccia rock, while the lowest value is 20 ppm in lapilli tuff rock.

This variation in concentration indicates differences in the chemical characteristics of groundwater in different rock formations, which may affect the potential use of groundwater for various purposes, including human consumption and agriculture (Gumilar, 2023).

## Groundwater facies

### The east slope of Mount Salak and the West slope of Mount Pangrango



West Slope M. Pangrango East Slope M. Salak  
**Figure 17. Groundwater facies of the eastern slopes of M. Salak and western slopes of M. Pangrango**

Piper Plot results of major ion concentrations resulted in 3 facies (IRIANTO, 2022):

1. Ca, Mg, HCO<sub>3</sub> (Calcium, Magnesium bicarbonate) facies.

In this facies, it is suspected that the dominant Ca content comes from rocks containing Ca Plagioclase such as andesite, the dominant HCO<sub>3</sub> is suspected of mixing with precipitation water (rainwater). This is evidenced by the low EC values of 26 to 135  $\mu$ S/cm and TDS values of 19 to 110 mg/liter, so it is estimated that this groundwater comes from local groundwater flow.

2. Na, K, Mg HCO<sub>3</sub> (Sodium, Potassium Magnesium Bicarbonate) Facies

This facies is found in samples from deep wells in depressed aquifers (artesian). The appearance of the Na element in this facies is thought to be water through rocks containing Na Plagioclase such as labradorite andesite rocks, the K (Potassium) element is thought to come from rocks containing K - Feldspar. Elemental Mg (magnesium). The water in this well comes from an old stream of water from a regional groundwater flow, characterized by a TDS value of 305 mg/liter. Springs in this facies are interpreted through rocks containing pyroxene and olivine. These springs are intermediate as evidenced by Ec values of 115 to 145  $\mu$ S/cm and TDS of 77 to 99 mg/litre and emerge through contact and compression-type springs. It is estimated that this groundwater originates from intermediate groundwater flow characterized by TDS values of 62-89 ppm.

3. Na, K, Mg HCO<sub>3</sub> (Sodium, Potassium Magnesium Bicarbonate) Facies

This facies is found in samples from deep wells in depressed aquifers (artesian). The appearance of the Na element in this facies is thought to be water through rocks containing Na Plagioclase such as labradorite andesite rocks, the K (Potassium) element is thought to come from rocks containing K - Feldspar. Elemental Mg (magnesium). The water in this well comes from an old stream of water from a regional groundwater flow, characterized by a TDS value of 305 mg/liter.

## CONCLUSION

Based on the observations, this research shows that an in-depth understanding of the geological and hydrogeological conditions in Bogor Regency, particularly regarding the aquifer potential of volcanic deposits, is essential to ensure the sustainability of groundwater resources. The old volcanic rock units, Mount Pangrango and Mount Salak, with various types of volcanic rocks, have unique characteristics that affect the distribution and quality of groundwater. Through detailed geological and hydrogeological mapping, including stratigraphic analysis, this research provides a strong scientific basis for the development of groundwater management policies, water infrastructure development,

and environmental conservation efforts in Bogor District. The results of this research are expected to guide better decision-making and more sustainable management strategies in the future.

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