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Interconnected Hydrogeological and Hydrological Systems in Volcanic Aquifer Deposits: A Conceptual Model Based on Geomorphological, Lithological Variations and Geological Structures in the Bogor Groundwater Basin, Upper Cisadane Watershed, West Java, Indonesia

Singgih Irianto T.H [1,2*], Sari Bahagiarti Kusumayudha [1], Carolus Prasetyadi [1], Yatini [1]
[1]Geological Engineering, UPN VETERAN Yogyakarta, Yogyakarta, Indonesia
[2]Geological Engineering, University of Pakuan Bogor West Java, Indonesia
singgihirianto@unpak.ic.id, saribk@gmail.com, jeng_tini@upnyk.ac.id, cprasetyadi@upnyk.ac.id
*Corresponding Author: singgihirianto@unpak.ic.id

Abstract

In volcanic aquifer deposits, understanding the interconnectedness of hydrogeological and hydrological systems is crucial for sustainable water management. This study explores the Bogor Groundwater Basin within the Upper Cisadane Watershed, West Java, Indonesia, where volcanic activities have shaped a complex geological landscape. We develop a conceptual model elucidating these interconnected systems using geomorphological, lithological variations, and geological structures. The Bogor Groundwater Basin provides critical water resources for millions, facing threats from urbanization and land-use changes. Limited knowledge of the underlying hydrogeological framework hinders effective management. To address this gap, we present a novel conceptual model integrating diverse datasets. We map lithological units, analyzing their porosity and permeability. Structural geology analysis identifies faults and fractures influencing groundwater movement. Morphometric techniques quantify the impact of topography and drainage patterns on infiltration and connectivity. Hydrochemical facies analysis, the core of our model, reveals geochemical fingerprints associated with recharge zones, flow pathways, and potential contaminant sources. This multifaceted approach yields a spatially explicit model capturing the interplay between geological controls, hydrological processes, and geochemical evolution. Our objectives are to develop a robust conceptual model of interconnected hydrogeological and hydrological systems., quantify the influence of lithology, structures, and morphometric features on groundwater flow and recharge, identify and characterize distinct hydrochemical facies, elucidating their distribution and relationship to flow pathways, and provide a framework for sustainable groundwater management in the Bogor Basin and similar volcanic settings. This study offers valuable insights into the complex interplay between hydrogeological and hydrological systems within volcanic aquifers. Our findings provide a foundation for sustainable water management strategies in the Bogor Basin and analogous volcanic environments. The findings establish a correlation between the straightness patterns of hills and valleys, morphotectonics, the overall structural pattern, and their influence on spring characteristics and distribution. Observations on 110 springs classify them into three zones; zone 1, The laharic zone, ranging from 300 to 500 meters above sea level; zone 2, Pyroclastic deposits found at an elevation of 500–700 meters above sea level, consisting of pyroclastic breccias and tuff lapilli; zone 3, At elevations spanning 700–1100 meters in pyroclastic breccias and 1100–1500 meters in andesitic lava. The developed conceptual model not only enhances our understanding of the complex subsurface processes but also offers valuable insights for sustainable water resource utilization in volcanic terrains. The findings of this research contribute to the broader field of hydrogeology and serve as a valuable reference for similar geological settings worldwide.

Keywords: Bogor groundwater basin; hydrochemical facies; morphometric analysis; volcanic aquifer deposit.

Introduction

Understanding the intricate interplay between hydrogeological and hydrological systems within volcanic aquifer deposits is crucial for sustainable water management in densely populated regions. This study delves into the Bogor Groundwater Basin, nestled within the Upper Cisadane Watershed of West Java, Indonesia, where volcanic activities have sculpted a complex tapestry of geological formations. Our aim is to develop a robust conceptual model that elucidates the interconnectedness of these systems, drawing upon a rich tapestry of data encompassing lithological variations, geological structures, morphometric analysis, and hydrochemical facies.

The Bogor Groundwater Basin serves as a critical water source for millions of inhabitants, catering to both domestic and agricultural needs. However, rapid urbanization and land-use changes pose escalating threats to its sustainability. Insufficient knowledge of the underlying hydrogeological framework impedes effective groundwater management strategies, potentially leading to depletion, contamination, and exacerbated flood risks. Darul et al. (2016) presented conceptual model of groundwater and river water interactions in Cikapundung riverbank, Bandung, West Java, and successfully replicate the previous analytical model. The calibration of the model showing appropriateness with dug wells and springs, and the identification of anomalous spots in the effluent zone indicating local changes in the groundwater-river interaction. However, the study includes reliance on a relatively small number of observation points for model calibration, potential inadequacy in capturing local variations and human activities, and the possibility of not fully capturing all dynamic processes in the hydrogeological system. Poetra et al. (2020) studied the hydrogeochemical conditions in groundwater systems with various geomorphological units in Kulonprogo Regency, Java Island, Indonesia and found that geomorphological aspects on groundwater conditions, the diverse hydrogeochemical processes in different landforms, and the involvement of specific processes like ion exchange and weathering, influence the most facies changes in different landforms in those area. Several studies related to hydrologic interconnection between the volcanic aquifer has been published for area in Bromo Tengger volcano, Lake Tana basin on the Upper Blue Nile, Kumamoto Japan and Central Kalahari Basin (Toulier et al. 2019; Nigate et al. 2016; Lekula, Lubczynski, and Shemang 2018; Hosono, Hossain, and Shimada 2020). Volcanic aquifers present unique challenges due to their complex geological makeup, often characterized by heterogeneity, anisotropy, and intricate structural controls. Understanding groundwater flow and recharge in these environments necessitates a multifaceted approach, integrating hydrogeological, hydrochemical, and geophysical methods. Raiber et al. (2015) and Shishaye et al. (2020) emphasize the importance of comprehensive aquifer characterization to discern recharge processes. The former identified preferential recharge zones in basalts, while the latter highlighted the role of upper fine-grained sediments as aquitards in Ethiopia. Kreyns, Geng, and Michael (2020) showcase the influence of connected heterogeneity on salinity distributions, stressing the importance of geological features in coastal groundwater flow. Furi et al. (2012)and Raiber et al. (2012) demonstrate the utility of multivariate statistical analysis and water isotopes in studying recharge and hydrogeochemical patterns in contrasting settings. Allocca et al. (2018) and Baiocchi, Lotti, and Piscopo (2012) reveal multi-layered aquifer systems in Italy, affected by factors like fault structures and thermal activity. Demlie, Wohnlich, and Ayenew (2008) identify distinct groundwater systems in Ethiopia, further divided into subgroups reflecting complex flow paths, lithologies, and anthropogenic influences. Charlier et al. (2011) and Vittecoq et al. (2019) utilize diverse approaches to characterize groundwater/stream interactions, preferential flow paths, and aquitard controls in different volcanic settings. Morán-Ramírez et al. (2016) develop geochemical models to assess water-rock interactions, pollution processes, and nitrate dynamics in Mexico. Aizawa, Ogawa, and Ishido (2009) present a conceptual model of a hydrothermal system based on geophysical data, highlighting the role of resistivity variations and clay layers in flow control. Bertrand et al. (2010) showcase the use of natural tracers to differentiate flow paths and chemical signatures associated with lava flow morphology in France. Izquierdo (2014) develops a conceptual model for La Gomera, Canary Islands, classifying aquifer systems and proposing four general groundwater situations for sustainable management. Liu et al. (2017) apply multivariate statistics to decipher hydrogeochemical evolution in a multi-layer aquifer system subjected to mining impacts, offering insights for groundwater quality management. The previous works, often rely on qualitative interpretations and lack quantitative validation through numerical modeling or long-term monitoring data. Integrating these approaches could strengthen model robustness and predictive power. The influence of human activities like agriculture, geothermal development, or mining on groundwater quality and flow dynamics requires further investigation.

To address this knowledge gap, we present a novel conceptual model that integrates diverse datasets to unravel the intricate relationships governing groundwater flow and recharge within the basin. We begin by meticulously mapping the spatial distribution of lithological units, paying particular attention to the porosity and permeability characteristics of volcanic deposits. Subsequently, we employ structural geology analysis to identify faults, fractures, and other geological features that may influence groundwater movement. Morphometric techniques are then harnessed to quantify the influence of topography and drainage patterns on surface water infiltration and subsurface connectivity. The cornerstone of our conceptual model lies in the rigorous analysis of hydrochemical facies. By unraveling the chemical signatures of groundwater samples across the basin, we can discern distinct geochemical fingerprints associated with specific recharge zones, flow pathways, and potential contaminant sources. This multifaceted approach allows us to construct a spatially explicit model that captures the dynamic interplay between geological controls, hydrological processes, and geochemical evolution. It will quantify the impact of rocks, structures, and landscape on groundwater flow and recharge. By identifying distinct water signatures, the study will reveal flow paths and potential contamination sources. This will provide a valuable framework for sustainable water management in the basin and similar volcanic settings. The ensuing sections of this manuscript will delve deeper into each of these objectives, presenting our detailed methodology, insightful findings, and their broader implications for the future of water resource management in the region.

Materials and Methods

This study employs a multi-method approach to investigate the controls on spring distribution within the Bogor area, Indonesia. The research location is located in the upper Cisadane watershed and hydrogeological, the location is located in Bogor ground water basin on the eastern slopes of Mt. Salak and the west-ern slopes of Mt. Pangrango as can be seen from Figure 1.

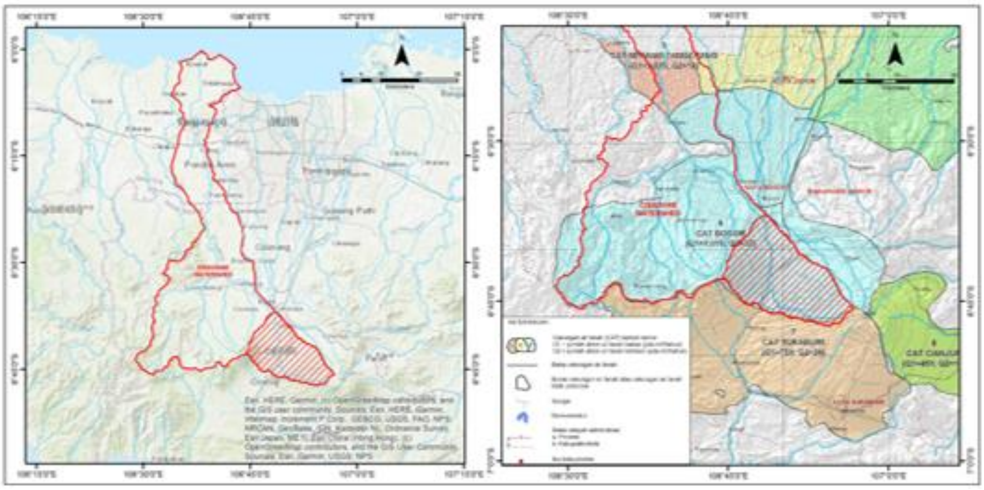

Figure 1. Map of research location in the upper Cisadane watershed (a) and Bogor ground water basin on the eastern slopes of Mt. Salak and the western slopes of Mt. Pangrango (b).

The researchers selected the four sub-catchments and the Cisadane River as priority locations for their study because they believed that these locations would provide the most comprehensive data about the hydrogeological system between the two volcanoes (Figure 2). The four sub-catchments were selected because they flow through a variety of volcanic lithologies, which is important for understanding how geology influences groundwater flow and recharge. The Cisadane River was selected because it is the largest river in the study area and it flows through the valley between the two volcanoes. The researchers believe that the river can represent the possible lithologies that originate from each volcano and that it can provide information about the interconnectivity between the groundwater and river systems.

To determine the influence of morphometry, lithological variations and geological structure (lineament) on 2 volcanic slopes, on the hydrogeological and hydrological system model of the upstream Cisadane river, it is necessary to collect various data using certain methods. The methods used include remote sensing, GIS analysis, secondary data analysis, correlative methods comparing with previous researchers, stratigraphic correlation, descriptive methods: making observations in the field, stratigraphic measurements, hydrogeological observations, structural analysis, taking documentation (photo data), and secondary data processing of the upstream Cisadane watershed hydrological system. The researchers hope that the data collected from these priority locations will help them to develop a better understanding of the hydrogeological system between the two volcanoes. This information could be used to improve the management of water resources in the area. The research integrates various data sources and analytical techniques as mentioned below.

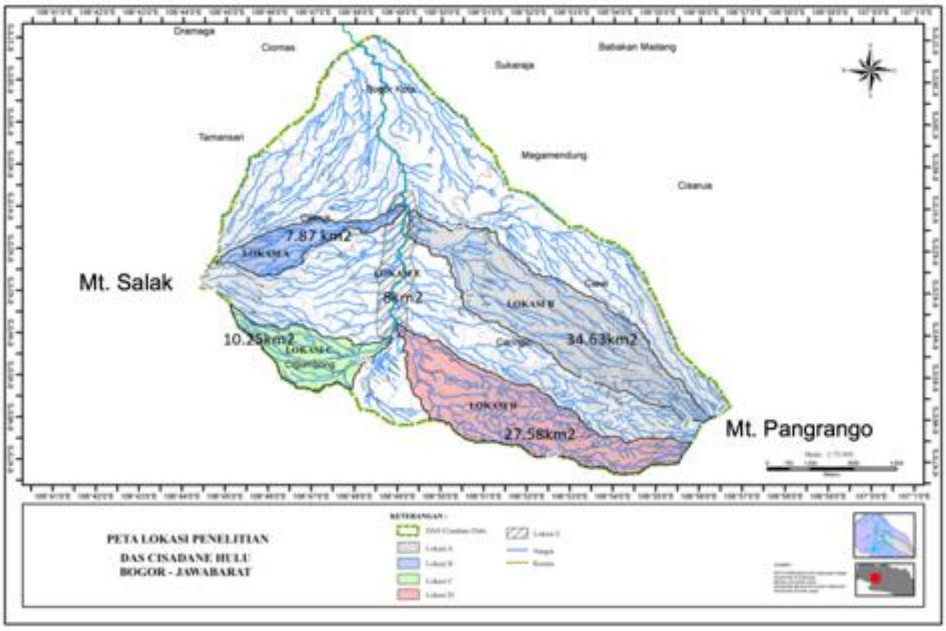

Figure 2. Map of the area for data collection

Geological Mapping

This involved collecting and analyzing data from regional geological maps (Bogor Geological Map Sheet with resolution 1:100,000), field observations, and satellite imagery (DEM ASTM – SRTM Imaging) to map the lithology, geomorphology, and geological structures of the study area. The collected data will be processed and completed using ArcGIS image data processing software, in order to be able to delineate structural parameters in the form of lineament. Lithological units, geomorphological features (e.g., valleys, hillslopes, ridges), and geological structures (e.g., faults, fractures) were mapped and digitized. Spatial relationships between these features were analyzed. The structural parameters obtained from image processing as preliminary data will be overlaid with data from field verification results and analyzed spatially.

Morphometric Analysis

This method utilized Shuttle Radar Topography Mission (SRTM) DEM data and Landsat imagery to identify and characterize lineaments and other morphotectonic features potentially influencing groundwater flow (software used: ENVI and Erdas Imagine). Lineaments and other morphotectonic features were identified and characterized using visual interpretation and automated lineament detection techniques. Their strike, length, density, and spatial relationships with geological structures were analyzed. Calculation of morphometric variables, straightness using the help of images to obtain values that show the relationship between river morphology and structure, then the data is validated with statistical tests, such as distribution normality testing (for structure and river straightness azimuth data), correlation tests (for river segment azimuth and sturdy). Morphotectonics is a landform characteristic related to tectonic activity. Identification of geomorphic cues for tectonic studies can be used to evaluate large areas quickly, and the necessary data are easily obtained from topographic maps and aerial or satellite images. The following are the equations used to determine the morphometric and morphotectonic values:

The sinuosity of the mountain face (*Smf*) is the result of a comparison of the length of the mountain face (*Lmf*) to the straight length of the mountain face (*Ls*) is calculated based on the equation developed by Bull & McFadden(1977) (Bull and McFadden 2020).

$$Smf = \frac{Lmf}{Ls} \tag{1}$$

The ratio of the width and height of the valley (*Vf*) is obtained by comparing the width of the valley (*Vfw*) with the height of the right (*Erd*) and left (*Eld*) valleys, as well as the elevation of the valley floor (*Esc*) was determined by the equation below (Bull and McFadden 2020).

$$\boldsymbol{Vf = \frac{2Vfw}{[(Eld - Esc) + (Erd - Esc)]}} \tag{2}$$

The river asymmetry value (*AF*) is obtained from a ratio of the river basin area (*Ar*) with the total area of the river basin area (At) was calculated using the equation developed by Keller and Pinter (2002).

$$\boldsymbol{AF = 100\ x\ \frac{Ar}{At}} \tag{3}$$

The springs data in the field took to get the spring type and physical characteristics like pH, electric conductivity, TDS, and discharge quantity. Springs discharge has been measured using formula developed by Todd (1980).

$$Q = V/t \tag{4}$$

where Q is the water discharge (l/s), V is the volume (l) and t is time (s)

Whereas the medium-big spring has been measured by a stream that waters out from the spring,

$$Q = v\ x\ A \tag{5}$$

where v is velocity of water stream flow (m/s) and A is area of stream section (m^2).

Subsurface Mapping

Subsurface data is known by measuring 1D and 2D geoelectric resistivity methods. The resistivity method is a geophysical method that studies the resistivity properties of rock layers in the earth. The principle of the resistivity method is to flow an electric current into the earth through the contact of two current electrodes, then measure the resulting potential distribution. The resistivity of subsurface rocks can be calculated by knowing the amount of current emitted through the electrode and the potential generated. Mathematically, the resistance value of a medium can be formulated by assuming a homogeneous medium, resistivity (Niwas & Singhal, 1981):

$$\rho = k \,.\frac{V}{I}$$

(where: ρ(rho): resistivity, k: geometric factor, V: potential difference, I: current strength)

Spring Inventory and Characterization

Systematic field surveys were conducted to locate and map springs, measure their physical properties (pH, conductivity, discharge), and collect water samples for further analysis. Field. GPS coordinates, elevation, and morphological characteristics were recorded for each spring. Physical parameters (pH, electrical conductivity, total dissolved solids (TDS), temperature) were measured in situ using portable instruments. Water samples were collected for further laboratory analysis (e.g., major ions, stable isotopes).

Geostatistical Analysis

Spatial distribution of spring characteristics was analyzed using geostatistical techniques to identify relationships with geological structures and lithology (software used: ArcGIS Geostatistical Analyst). Spatial distribution of spring characteristics and geochemical parameters were analyzed using geostatistical techniques (e.g., kriging, spatial autocorrelation analysis) to identify relationships with geological structures, lithology, and morphotectonic features.

Results and Discussion

Geological Mapping of The Bogor Groundwater Basin, Upper Cisadane Watershed, West Java, Indonesia

The results of the morphological analysis of satellite imagery and DEM data using GIS software revealed a variety of geomorphological units and slope breaks in the study area showed in Figure 3. The variation in the morphology and slope breaks is influenced by the variation in lithology and tectonics as summarized in the Table 1. The steep slopes and lithology influence the hydraulic gradient, which increases the pressure that controls groundwater flow and the emergence of springs. The results of the analysis suggest that the four sub-catchments and the Cisadane River are located in different geomorphological units. The first sub-catchment is located in the valley unit of the foot of the volcano, where the slopes are relatively gentle. The second and third sub-catchments are located in the body of the volcano, where the slopes are more varied. The fourth sub-catchment is located in the summit to the body of the volcano, where the slopes are very steep. The variation in geomorphological units is likely to influence the groundwater flow and recharge patterns in the study area. The gentle slopes in the valley unit of the foot of the volcano are likely to promote infiltration and recharge of groundwater. The more varied slopes in the body of the volcano are likely to create a more complex groundwater flow system. The very steep slopes in the summit to the body of the volcano are likely to limit infiltration and recharge of groundwater.

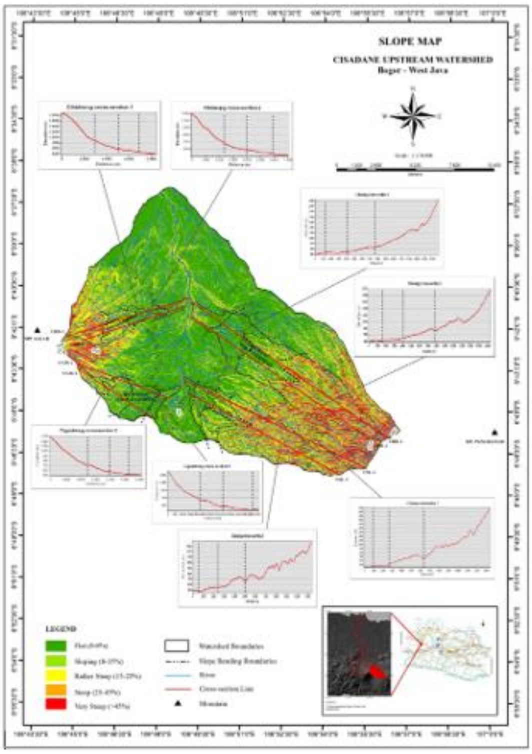

Figure 3. Geological Mapping of The Bogor Groundwater Basin, Upper Cisadane Watershed, West Java

The study identified three distinct volcanic deposit facies on the eastern slope of Mount Salak and the western slope of Mount Pangrango, aligning with the model by Bogie and Mackenzie (1998). These facies varied in topography, rock type, and water availability, as illustrated in Figure 5. The proximal facies in the study area cover the upper summit to the middle slope of the volcanic edifice, characterized by rough to very rough topography, featuring steep cliffs and extremely steep ravines. The slope appearance in the proximal facies exhibits concentric patterns and partial terracing formed by lava flows. The dominant rock types in this facies are andesitic and basaltic lavas, along with massive pyroclastic breccias, distributed within the elevation range of 700-1500 meters above sea level (masl). Proximal 1: At elevations between 900 and 1500 masl, this sub-facies is composed of lava flows experiencing fractures and very coarse pyroclastic fall deposits in the form of massive breccias. Proximal 2: Ranging from 700 to 900 masl, this sub-facies is characterized by predominantly massive breccias and lapilli tuff, forming permeable layers. Numerous springs, both contact-type and fracture-induced, are observed in this zone.

Table 1. The variation in lithology and tectonics by elevation.

Elevation (mbsl)	Slope Break	Geomorphological Unit
300 - 500	Slope break 1	Valley unit of the foot of the volcano
600 - 700	Slope break 2	Undulating to steep slope unit of the body of the volcano
700 - 1100	Slope break 3	Steep to very steep slope unit of the body of the volcano
1100 - 1500	Slope break 4	Very steep slope unit of the summit to the body of the volcano

The medial facies in the study area cover the lower slope of the volcanic edifice, exhibiting rough to moderately rough topography with somewhat steep slopes. The landscape consists of hills formed by pyroclastic deposits. The rock composition in this facies includes interlayered pyroclastic breccias with fragments of igneous rocks ranging from blocks to pebbles, accompanied by thick layers of coarse to very coarse lapilli composed of fractured igneous rocks and glass. The rocks in this facies are permeable. Abundant water sources are observed, with variable discharge rates ranging from 0.1 liters/second to 40 liters/second. The distal facies extend from the slope and base of the volcanic edifice to the valleys between mountains, such as the Cisadane River headwaters. The landscape consists of gentle slopes and, in some areas, plains, exhibiting smooth relief and gentle cliffs indicating the presence of flow. The rock composition in this facies includes lahars, lapilli tuffs, and fine ash deposits. Some of these rocks are permeable, while others are impermeable. In this facies, water sources are comparatively less abundant, with discharge rates ranging from 1 liter/second to 130 liters/second.

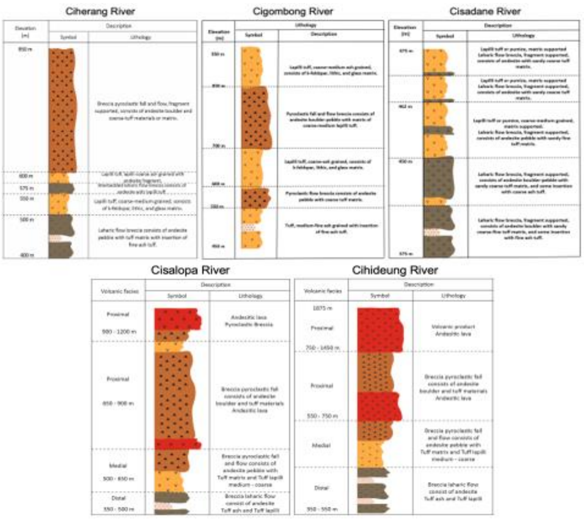

Figure 4. Lithology/surface rocks from mapping results on river trajectories through stratigraphic measurements of the elevation approach for each rock outcrop.

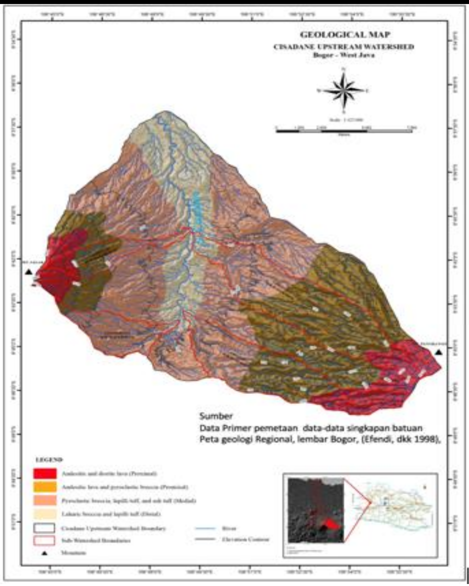

Figure 5. Geological map of Cisadane upstream watershed

The observed facies in the volcanic deposits of the eastern slope of Mount Salak and the western slope of Mount Pangrangi align with the facies model proposed by Bogie and M.K Mackenzie (1998). The distinct characteristics of the proximal facies, featuring rough relief and steep cliffs formed by lava flows, contrast with the medial facies, which exhibit hills formed by pyroclastic deposits with permeable rocks and abundant water sources. The distal facies, extending to valleys and river basins, display smoother relief with a mix of permeable and impermeable rocks, resulting in less abundant water sources. These findings contribute to a better understanding of the geological features and hydrogeological implications of volcanic deposits in the studied area. The variations in rock types, topography, and water availability among the different facies highlight the importance of considering such heterogeneity in geological and hydrogeological assessments of volcanic terrains. Further studies could explore the implications of these findings for land use planning, natural resource management, and hazard mitigation in volcanic regions.

Volcanic facies	Description		Slope	Springs		Physical Hydraulic Properties
	Symbol	Lithology	10° 15° 20° 30° >45°	Number	Zone / Type	
1875 m Proximal 750 - 1450 m		Volcanic product Andesitic lava		5	1 Fracture spring	Impermeable rock Secondary permeability Sheeting joint & shear joint Non-symetrical pattern
Proximal 550 - 750 m		Breccia pyroclastic fall consists of andesite boulder and tuff materials Andesitic lava		18	2 - Contact spring - Depression spring - Fracture spring	Permeable rock Primary permeability & secondary permeability Impermeable andesite
Medial		Breccia pyroclastic fall and flow consists of andesite pebble with Tuff matrix and Tuff lapilli medium - coarse		10	3 - Contact spring - Depression spring	Permeable rock Primary permeability
Distal 350 - 550 m		Breccia laharic flow consist of andesite Tuff ash and Tuff lapilli		3	4 - Contact spring - Depression spring	Permeable rock Primary permeability Impermeable

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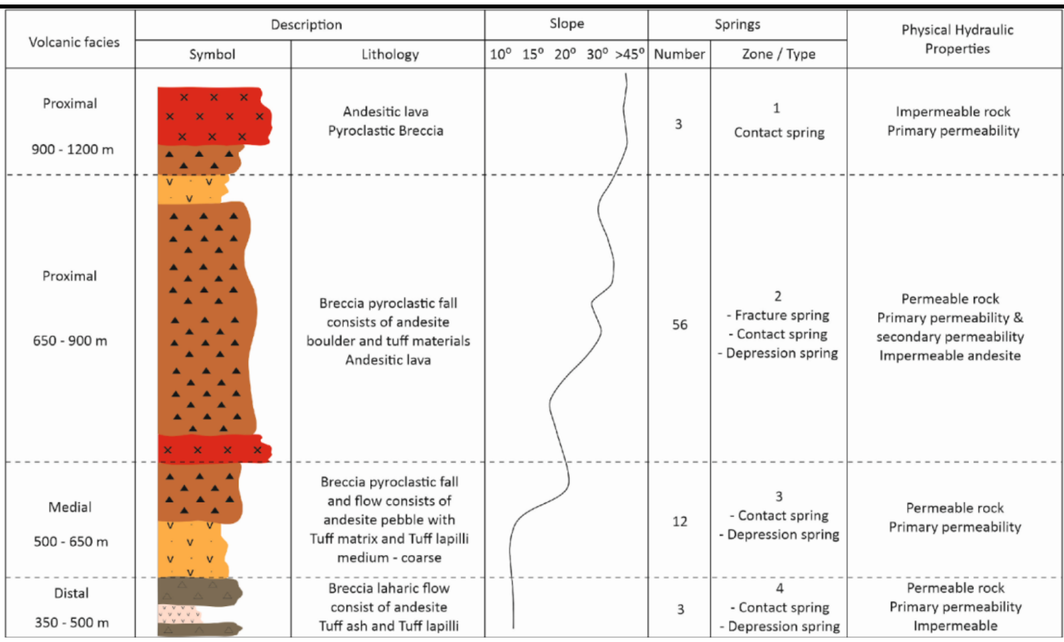

Figure 6. Correlation of lithological facies, morphology and distribution of springs and hydrogeological systems on the slopes of Mount Salak and Mount Pangrango.

A study in the volcanic deposits of the eastern slope of Mount Salak and the western slope of Mount Pangrangi, Indonesia, used resistivity measurements to interpret the types of rocks and their hydrogeological properties. The results are summarized in the table 2 and table 3 below. The results show that the volcanic deposits in the study area are composed of a variety of rock types, including tuff, lapilli, and breccia. The resistivity values of these rocks are correlated with their hydrogeological properties. For example, tuffs with low resistivity values are likely to be aquitards, while breccias with high resistivity values are likely to be aquifers.

Table 2. Correlation of resistivity values with lithological type and hydrogeological properties

Resistivity Range (Ω m)	Criteria	Lithology	Hydrostratigraphy
< 15	Very low	Compact tuff	Aquiclude
16 - 30	Low	Fine ash tuff	Aquitard
31 - 70	Medium 1	Coarse lapilli tuff	Aquifer
71 - 120	Medium 2	Lapilli breccia	Aquifer
121 - 200	Medium 3	Medium to coarse breccia	Aquifer
201 - 450	High	Coarse to boulder breccia	Aquifer
> 450		Igneous rock	Aquifuge

The study also found that the resistivity values of the rocks can be used to correlate with data from boreholes and outcrops. This information can be used to develop a better understanding of the hydrogeological system in the study area. The different colors on the map represent different rock types. The red areas are composed of tuff, the blue areas are composed of lapilli, and the brown areas are composed of breccia. The study findings have important implications for water resource management in the study area. The presence of aquifers in the volcanic deposits suggests that there is a potential for groundwater resources. However, the study also found that the aquifers are not evenly distributed throughout the study area. This information can be used to identify areas where groundwater resources are most likely to be found.

Table 3. Correlation of resistivity values with lithological type and hydrogeological properties

Line	Min. Resistivity (Ω m)	Max. Resistivity (Ω m)	Lithology
1	5	15,000	Soil, breccia, lapilli, and tuff
2	2	10,000	Soil, breccia, lapilli, and tuff
3	3	1,000	Lapilli and tuff
4	5	500	Lapilli and tuff
5	2	150	Soil and breccia
6	3	120	Breccia

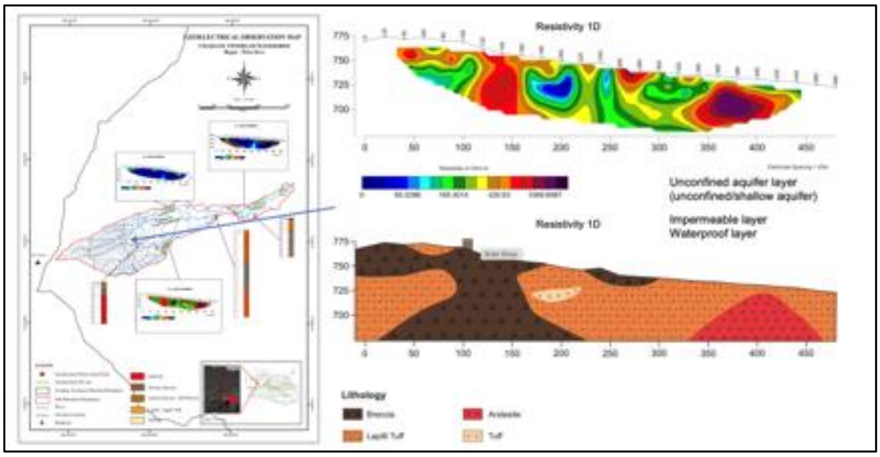

Figure 7. Geoelectric profile, at the top of the Cihideung sub-watershed

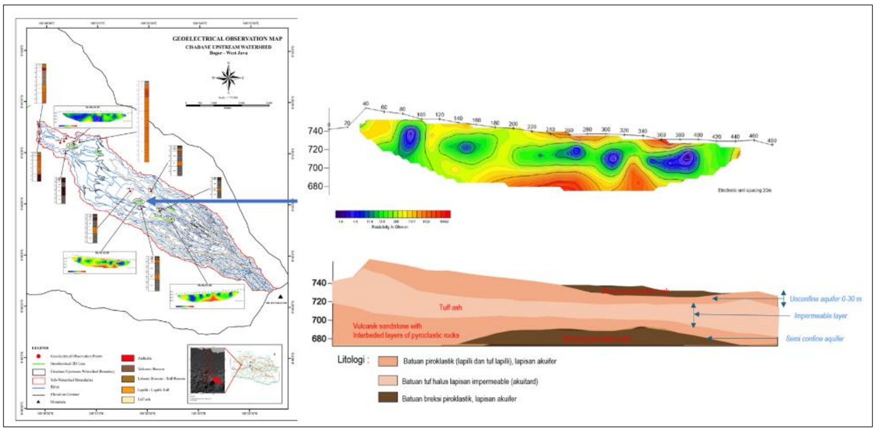

Figure 8. Lithological profile of geoelectric results in the middle section Ciherang sub-watershed

The data in table 4 and 5 shows the chemical composition of various rock types found on the slopes of Mount Salak and Mount Pangrango in Indonesia. The rocks were analyzed in a laboratory and the table lists the percentage of various chemical elements they contain, including Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), Iron Oxide (Fe_2O_3), and others. Based on the data, there appears to be a difference in the chemical composition between the rocks found on the slopes of Mount Salak and those found on Mount Pangrango. For example, the rocks from Mount Salak have a higher average percentage of SiO_2 and CaO, while the rocks from Mount Pangrango have a higher average percentage of Al_2O_3 and Fe_2O_3. This difference in chemical composition could be due to the different geological processes that formed the two volcanoes. Mount Salak is a stratovolcano, while Mount Pangrango is a shield volcano. Stratovolcanoes erupt with a mixture of lava, ash, and rock fragments, while shield volcanoes erupt primarily with fluid lava flows. This difference in eruption style could explain the different chemical compositions of the rocks found on the two volcanoes.

Table 4 Chemical composition of rocks from laboratory analysis of the slopes of the Salak volcano (Ciherang river basin area)

Rock type*	Chemical Composition (%)							
	SiO_2	AL_2O_3	Fe_2O_3	Fe	CaO	MgO	Na_2O	K_2O
TF	39.8	9.96	20.1	27.7	39	0.5	0.05	1.83
LPL	51.5	14.6	24.3	34.5	19	0.6	0.03	2.36
BRK	54	14	26.6	37.6	17.2	0.6	0.01	2.04
BRK	52.3	13.8	26.8	37.7	18.5	0.5	0.04	1.62
BRK	53.2	17.4	24.6	35.6	16.3	0.4	0.014	2.46
Average	50.16	13.952	24.48	34.62	22	0.52	0.0288	2.062

* LPL: Lapili, TF: Tuff, BRK: Breksi, LV: Lava.

Table 5. Chemical composition of rocks from laboratory analysis of the slopes of the Pangrango volcano (Cihideung river basin)

Rock type*	Chemical Composition (%)							
	SiO_2	AL_2O_3	Fe_2O_3	Fe	CaO	MgO	Na_2O	K_2O
TF	54.1	13.7	17	26	14.1	0.3	0.01	1.97
TF	45.7	17.2	36.7	46.6	14.6	0.5	0.05	0.53
LV	43.5	13.6	20.6	29	29	0.6	0	1.76
BRK	55.6	16.7	33.8	46.6	9.41	0.2	0	1.46
TF	61	21.3	16.8	27.9	2.27	0	0.04	2.45
LV	39.8	9.96	20.1	27.6	39	0.5	0.05	1.83

* LPL: Lapili, TF: Tuff, BRK: Breksi, LV: Lava.

The data which based on the weight percentage of Na_2O and K_2O and SiO_2 are plotted on a rock classification graph developed by Le Bas M and Streckeisen A (1991) and the plot of the two data falls into the intermediate basaltic and basaltic andesitic groups, showing the classification of alkaline andesite. From this mineral content, groundwater will be produced which will contain a lot of the dominant elements calcium (Ca), and magnesium (Mg), and a little sodium (Na). The rocks are classified as intermediate to basaltic andesitic, based on their Na_2O/K_2O and SiO_2 content. This classification suggests that the rocks are formed from a mixture of basaltic and granitic magmas. The chemical composition of the rocks has implications for the quality of groundwater in the study area. The high content of calcium and magnesium in the rocks suggests that groundwater in the area will be hard, with a high concentration of these minerals. The low content of sodium in the rocks suggests that groundwater in the area will be low in sodium, which is beneficial for human health.

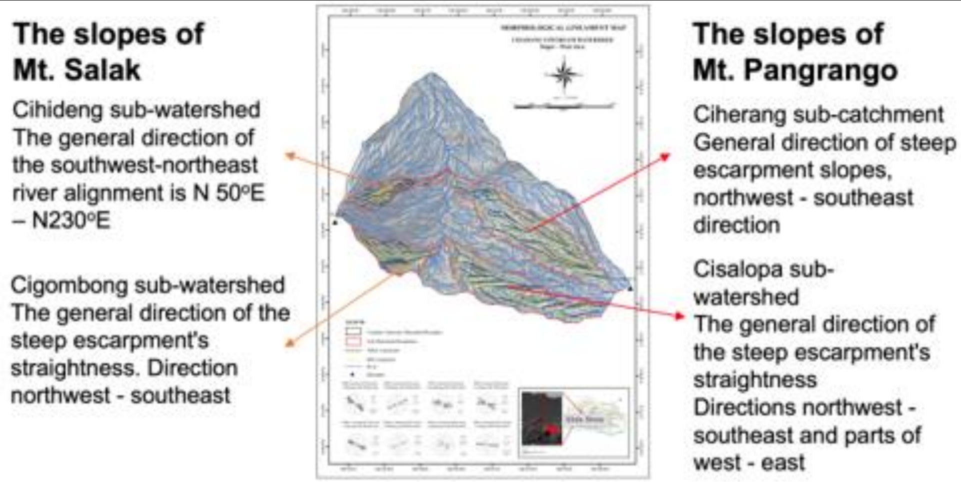

Figure 9. Geological structures identified based on lineament analysis

An analysis of lineaments in the volcanic slopes surrounding Mount Salak and Mount Pangrango in Indonesia revealed distinct structural trends as can be seen in Figure 10. On the slopes of Mount Salak, the Cihideng sub-watershed exhibits rivers predominantly aligned in a southwest-northeast direction, ranging from N 50°E to N 230°E. The Cigombong sub-watershed showcases a northwest-southeast trend in the straightness of its steep escarpments. Similarly, the Ciherang sub-catchment surrounding Mount Pangrango reveals a dominant northwest-southeast direction in its steep escarpments. Interestingly, the Cisalopa sub-watershed presents a more complex pattern, featuring both northwest-southeast and west-east orientations in its escarpment's straightness. These findings suggest contrasting structural influences shaping the landscapes in different sub-watersheds, and warrant further investigation to understand their geological implications.

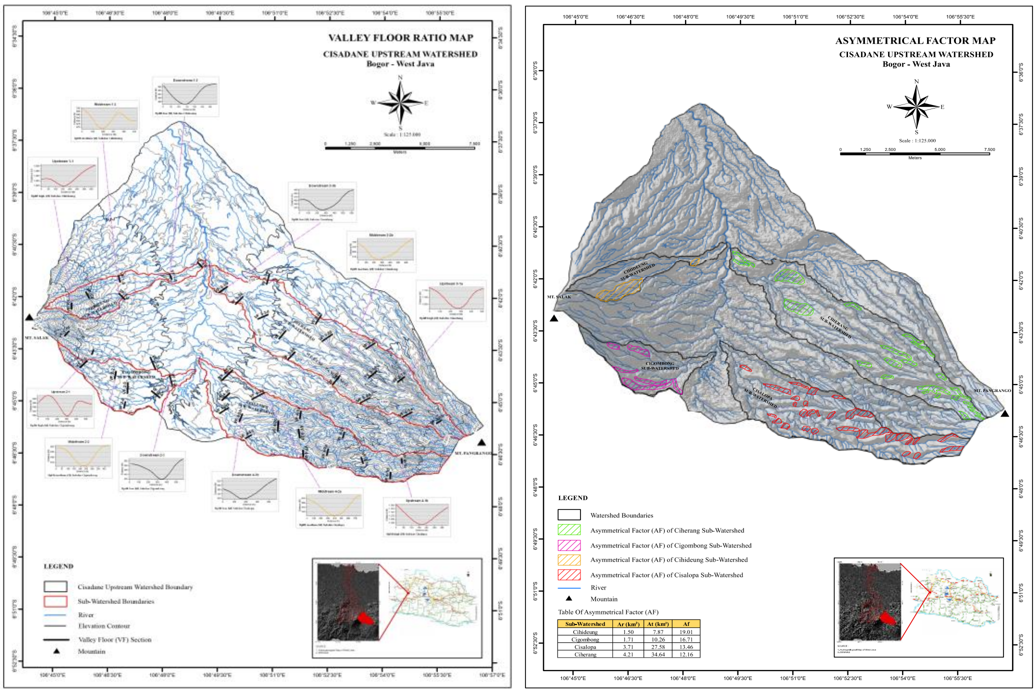

Figure 10. Morphotectonic analysis, Sinuosity Mountain Front SMF, Vally Floor VF and Asymmetry Factor AF

A morphotectonic analysis of the slopes of Mount Salak and Mount Pangrango in Indonesia was conducted to assess the impact of tectonic activity on the landscape. The analysis focused on three indicators: the sinuosity of the mountain front (SMF), the valley floor ratio (VF), and the asymmetry factor (AF). The results of the SMF analysis showed that the slopes of the two volcanoes are dominated by class 1 sinuosity, which indicates active tectonics. The VF analysis showed that the slopes are predominantly class 2 or 3, which indicates moderate active tectonics. The AF analysis showed that the slopes are all class 1, which also indicates active tectonics. Based on these results, it is concluded that the slopes of Mount Salak and Mount Pangrango are all affected by active tectonics. The combination of high SMF and AF values suggests that the tectonic activity is causing the mountains to rise and fall, creating steep slopes and narrow valleys. The moderate VF values suggest that the tectonic activity is also causing the valleys to be widened and deepened. These findings have implications for the management of natural resources in the study area. The active tectonics could pose a hazard to infrastructure and communities and could also affect the quality of groundwater. Further research is needed to understand the specific impacts of tectonic activity in the area.

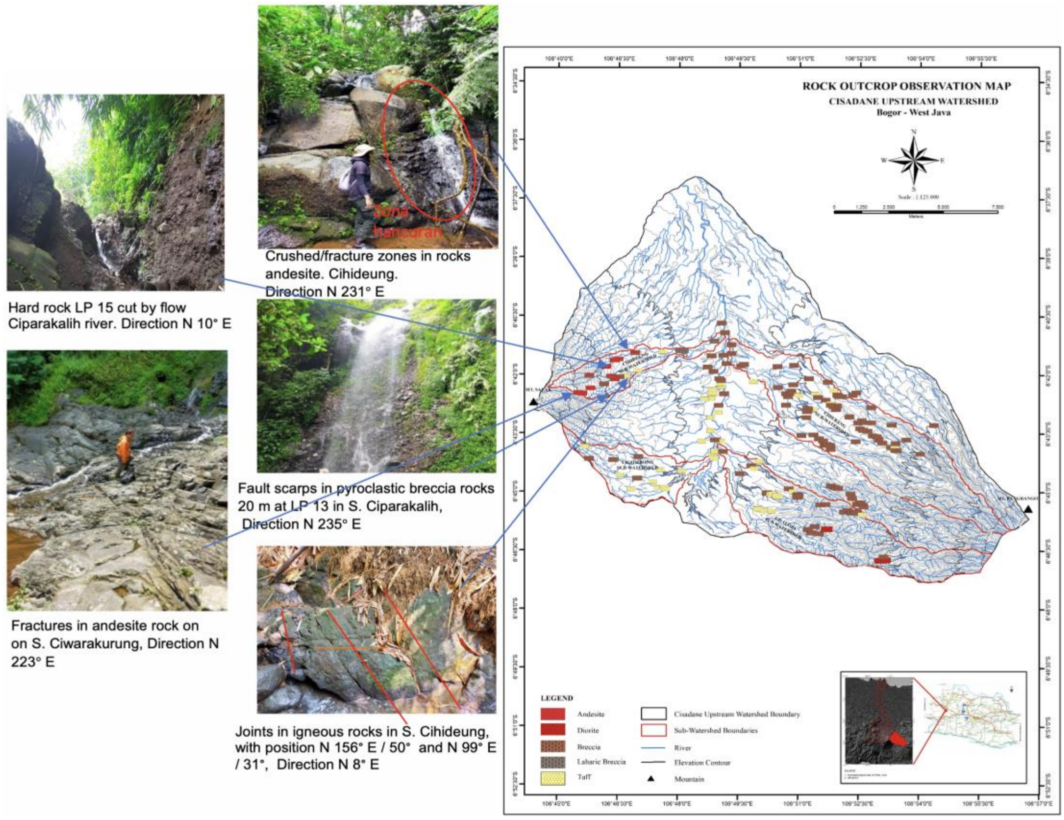

Figure 11. Field observations on the slopes of Mount Salak and Mount Pangrango

Field observations on the slopes of Mount Salak and Mount Pangrango in Indonesia identified several indicators of past tectonic activity. Evidence of crushed and fractured zones within andesite rocks was found in the Cihideung sub-watershed, aligned approximately N 231° E. Additionally, distinct fault scarps were observed in pyroclastic breccia formations at two locations: a 20-meter scarp at LP 13 in Sungai Ciparakalih trending N 235° E, and another scarp in the same location and direction. Furthermore, a hard rock exposure at LP 15, exposed by the Ciparakalih river flow, showed signs of deformation with a N 10° E direction. Finally, fractures within andesite rocks were identified on Sungai Ciwarakurung, trending N 223° E. These combined observations suggest a complex network of structural features across the study area, potentially influenced by tectonic forces. Further investigation is needed to fully understand the nature and implications of these structures for the landscape and potential hazards.

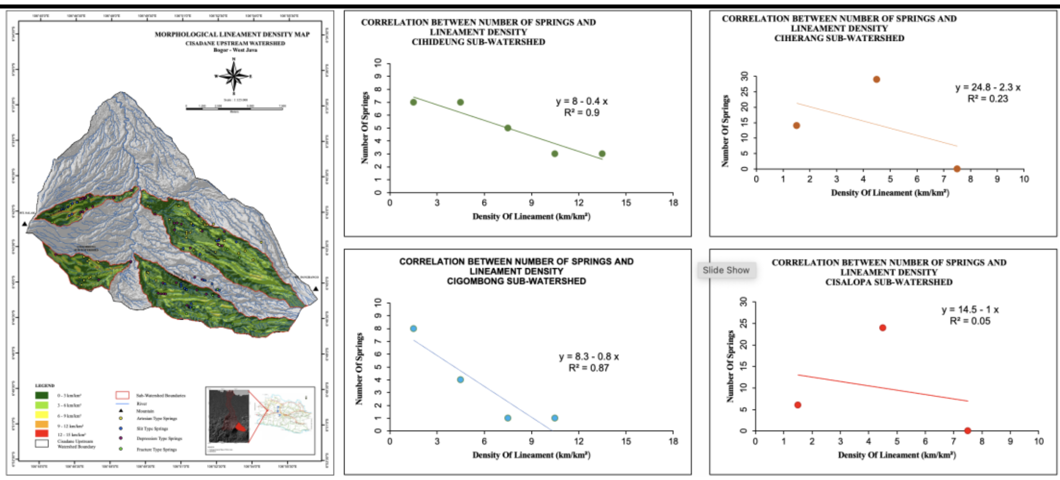

Figure 12. Correlation analysis of lineament/structure density on spring hydrogeological systems

A correlation analysis was conducted to assess the relationship between lineament density and the distribution of springs in the volcanic slopes of Mount Salak and Mount Pangrango in Indonesia. The analysis focused on four sub-watersheds, two on the east slope of Mount Salak and two on the west slope of Mount Pangrango (Figure 13). The results of the analysis showed a strong correlation between lineament density and the number of springs, especially on the east slope of Mount Salak. In the Cihideung sub-watershed, the correlation coefficient was 0.92, indicating a highly significant relationship. In the Cigombong sub-watershed, the correlation coefficient was 0.85, indicating a significant relationship. The results of the analysis suggest that geological structures, such as lineament alignments, can influence the occurrence of springs. The lineament alignments may provide pathways for groundwater to flow to the surface. The findings of this study have implications for the management of natural resources in the study area. The presence of springs in the area indicates the potential for groundwater resources. However, the springs may be vulnerable to contamination from surface pollutants. Further research is needed to understand the specific impacts of groundwater contamination in the area.

A study of the geological structures on the slopes of Mount Salak in Indonesia found that the structures are dominated by fractures, especially in andesite lava flows and pyroclastic breccias. These fractures are thought to have formed as a result of Neotectonic activity in the region, which is characterized by the presence of the Ciliwung-Cisadane fault system. The presence of fractures can have a significant impact on the hydrogeological system. Fractures can increase the porosity and permeability of rocks, making them more permeable to water. This can lead to the formation of fracture aquifers, which are important sources of groundwater. Additionally, fractures can provide pathways for groundwater to flow from one area to another, influencing the interconnectivity of the hydrogeological and riverine systems. In the case of the slopes of Mount Salak, the fractures are thought to be responsible for the formation of springs. The fractures provide pathways for groundwater to flow to the surface, where it emerges as springs.

Conclusion

In conclusion, this investigation into the volcanic slopes of Mount Salak and Mount Pangrango in Indonesia revealed a complex interplay between geological structures, hydrogeological systems, and tectonic activity. The study identified several key findings:

- Active Tectonics: Evidence from lineament analysis, SMF, VF, and AF values confirms the presence of ongoing tectonic activity in the area, shaping the landscape through uplift, subsidence, and fault formation.
- Structural Influence: Lineament density shows a strong correlation with spring distribution, particularly on the east slope of Mount Salak, suggesting geological structures like fractures control groundwater flow and spring emergence.
- Fracture Aquifers: Fractures identified in andesite and breccia rocks, likely caused by Neotectonic

activity, contribute to the formation of fracture aquifers, offering potential groundwater resources.

- Hydrogeological Impact: Interconnected systems of fractures and lineaments influence the overall hydrogeological system, potentially impacting groundwater flowpaths, spring formation, and potential vulnerability to contamination.

These findings have implications for water resource management and hazard mitigation in the study area. The presence of fracture aquifers holds promise for groundwater resources, but requires careful management to prevent contamination. Understanding the influence of active tectonics on geomorphology and hydrogeology is crucial for assessing potential hazards and ensuring sustainable resource management in this dynamic volcanic landscape. The findings also have implications for the management of natural resources in the study area. The presence of springs indicates the potential for groundwater resources. However, the springs may be vulnerable to contamination from surface pollutants. Further research is needed to understand the specific impacts of groundwater contamination in the area.

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* Singgih Irianto; email: singgihirianto@unpak.ac.id