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RESEARCH ARTICLE

Geological and Morphometric Characteristics of Quaternary Pyroclastic Aquifers in Salak and Pangrango Stratovolcano

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Abstract

The study area is located in the Lido Catchment Area (LCA), which is situated between two distinct volcanic slopes and not many discovered especially in Indonesia. Springs on the volcano's slopes are widely used for domestic, irrigation, and industry water use. Investigating the characteristics of aquifers and springs is essential to ensure groundwater sustainability by providing a robust geological framework. Geological and morphometric analysis at LCA is the basis of important information. We applied a comprehensive geological and morphometric analysis to obtain detailed information about the aquifer. This study aimed to determine the characteristics of aquifers in pyroclastic rocks and their relationship to the formation of springs. From the research conducted, the characteristic of water can be distinguished based on the geological conditions of its constituents. Hydrogeology setting is distinct into four categories aquifer: Highly Productive Aquifer, Locally Productive Aquifer, Moderately Productive Aquifer, and an extremely rare groundwater region. The results of the morphometric analysis show different value variations based on rock formations related to the processes of spring occurrence. There are 6 different lithological characteristics in the study area: polymict breccia, monomict breccia, lapilli, lapilli tuff, coarse tuff, and fine tuff. From the lithology variations obtained, breccia, lapilli, and coarse tuff can play a good role as aquifers. Thin section analysis of the rock shows the characteristics of the alteration minerals. Geological correlations and groundwater systems in the study area show groups of superficial, mixed, and alteration springs. The system of water flows in aquifers through inter-grains or rock fractures. The types of springs in LCA are dominated by depression and fracture types. These results are fundamental information for understanding hydrogeological systems. Understanding the qualities of aquifers and spring characteristics properly may aid in the construction of more effective studies in the future.

Keywords: Pyroclastic Aquifer, Lido Catchment Area, Spring Characteristics

1. Introduction

1.1 Sub Introduction

Utilization of water sourced from volcanic rocks in the tropics is found in Southeast Asia, Central Africa, and others (Lu et al., 2015; Gourcy et al., 2020; Purwantara, 2020; Gaikwad et al., 2020; Wisitthammasri et al., 2020; Maria et al., 2021; Ligate et al., 2021). Depending on the conditions and characteristics of the geology, hydrogeology, hydrology, and other features of the water cycle, the genesis of water occurs over a period of time that varies (Alfadli and Natasia, 2017). With a relatively large average population, groundwater resources must be effectively and responsibly managed.

Volcanic rocks have complex variations and characteristics in terms of shape, grain size, mineral content, and distribution (Rüpke et al., 2002; Schaefer and Kattenhorn, 2004; Pratama et al., 2018). Hydrogeology systems in volcanic settings result from various interactions and processes that are influenced by the characteristics of minerals and rocks (Delcamp et al., 2016; Baud et al., 2021). However, the study of the geological context of hydrogeological system occurrences is not given specific consideration. In reality, geology is the host of groundwater and its occurrences, such as the dynamics of aquifers, flow processes, and the presence of groundwater in an area.

Several interesting volcanic aquifer research have resulted from advances in science and technology. Numerous studies of groundwater have examined volcanic aquifer characteristics diversely. As a result, springs can have a wide variety of traits. Hawaiian, Canary Island, and Andesitic Volcanism settings are among the models of aquifer characteristics that have been researched using various method approaches. Lowland basal aquifers are characteristic of aquifers in volcanic environments of the Hawaiian type (Ingebritsen and Scholl, 1993). The Canary model describes an aquifer with steep domes and low permeability that is continuous. The Bromo Tengger (West Java) andesitic volcanism model features a perched aquifer system among lava flows and a pyroclastic complex that contributes to the discharge spring (Toulier et al., 2019). The Ciremai volcano, as a stratovolcano type demonstrates the characteristics of the aquifer, which are characterized by being unconfined with a variety of flow patterns (Irawan et al., 2009). It is apparent from the previous mentioned points that various geological circumstances can characterize various aquifer features.

LCA is situated on two distinct quaternary volcanic slopes: the eastern slope of Salak Volcano and the western slope of Pangrango Volcano. LCA features an inter-fingering pyroclastic deposit system with lava flows on the center and medial volcanic facies (Effendi & Hermanto, 1998; Muhardi & Tjahjono, 2014; Mardiana et al., 2019; Alfadli et al., 2021). Hydrogeology setting is distinct into four categories aquifer: Highly Productive Aquifer, Locally Productive Aquifer, Moderately Productive Aquifer, and an extremely rare groundwater region (Ministry of Public Works et al., 1990). In general, there are two types of aquifers: unconfined aquifers and confined aquifers with varying potentials (Rengganis and Harnandi, 2011; Pangestu and Waspodo, 2019). The LCA has much groundwater potential, but it's not been described specifically, especially geological control of groundwater. Deepening is needed, especially in studies on a more precise scale. Properly comprehending the properties of aquifers and spring characteristics might support the development of more effective studies in the future, for instance, on the conservation and sustainability of groundwater. This research aims to determine the kind or types of aquifers and springs in the LCA region by morphometric and geological methods, which need to be deepened. Before conducting more specialized investigations, a more in-depth examination of geological factors can offer information about the mechanisms behind the emergence of groundwater in springs. This is fundamental because geology provides an essential base for hydrogeology study. This work provided updated information that can be used as a basis for future research into hydrogeochemistry and hydrogeology conceptual models.

2. Description of Study Area

LCA is part of the Upper Cisadane Sub-Watershed (Junaidi and Tarigan, 2012). The Upper Cisadane watershed has water sources from the Salak Volcano and the Pangrango Volcano (Delani and Dasanto, 2015). Sources of surface water or groundwater in the upstream Cisadane area play an important role in providing water needs for irrigation, drinking water, and other needs for the Bogor Regency and surrounding areas (Jihad, 2018). Administratively the LCA, located in the Bogor Regency in Indonesia. Geographically the research area situated at the coordinates 106º 45' 3.45" – 106º 55' 42.70" E dan 06º 43' 14.10" – 06º 46' 31.76" S. The LCA study area has an area of 46,348 km2 and a cross-sectional length of 21.2 kilometers. The altitude of the research area is an elevation of 454 – 2165masl (Figure 1).

The average monthly precipitation indicates that LCA has a wet climate (Alim et al., 2018). According to the data provided by Meteorology and Geophysics Agency, Indonesia (BMKG), the Pasir Jaya station is the rain station that fits the study region. Observation of rainfall data at Pasirjaya station in 2010 has the highest value of 6081mm/year (Figure 2). Meanwhile, in the research area which is located in a tropical climate, the lowest rainfall value was 1519mm/year in 1999. The average temperature at Pasir Jaya station was 21.59°C, and the average evapotranspiration value was 88.22mm/year.

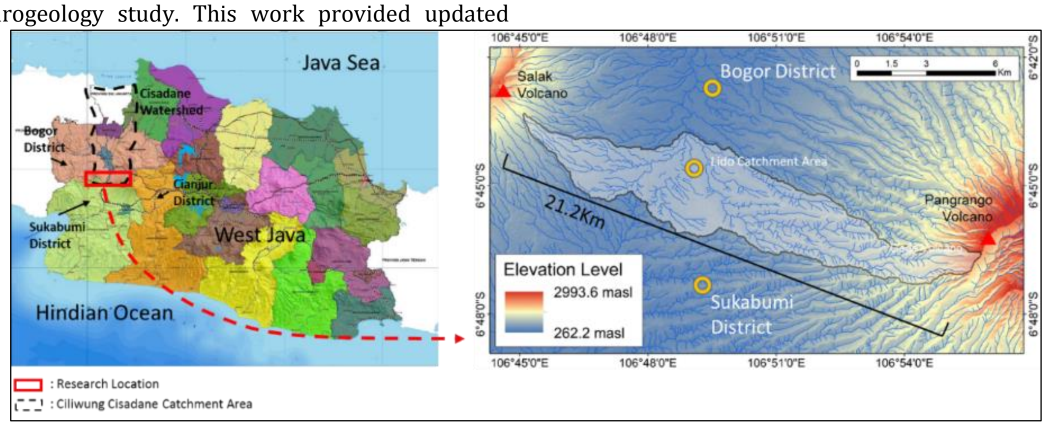

Fig 1. Research locations Lido Catchment Area (LCA) in the upstream Cisadane Watershed area. The yellow circle symbol shows the name of the area.

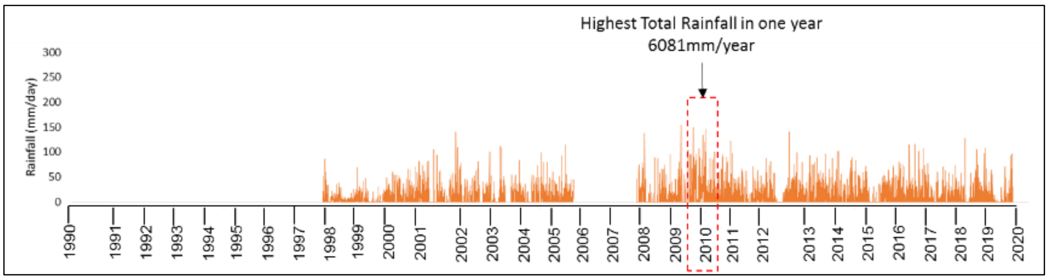

Fig 2. Total monthly rainfall from 1990 - 2020, sourced from Pasir Jaya Station under the Meteorology and Geophysics Agency, Indonesia.

3. Material and Methodology

3.1 Geology and Hydrogeology Mapping

The mapping and collecting geological and hydrogeological data is a crucial step in characterizing the features of the groundwater system (Dianardi et al., 2018; Lo et al., 2021). Collecting of hydrogeological features of the area was completed in the rainy season, and gather 24 springs observation. The objective of this fieldwork is to measure the physio-chemical composition of the water. Physio-chemical measurements of water using a multiparameter water test tool Hanna Instrument HI 9811-

5 series. The measurement data are in the form of pH values, water temperature, Electro Conductivity (EC) and Total Dissolved Solid (TDS). In addition, the results of the earlier study, such as regional hydrogeology map, are incorporated to provide context for the data presented.

Mapping of the geological features of the area was completed to gather primary research data, observations were made at 37 outcrops. These rocks exhibited the characteristics of igneous and pyroclastic rocks, both of which are formed due to volcanic activity. The grain size, grain shape, outcrop thickness, and other characteristics are included in the megascopic description. Rock hand specimens were analyzed using the petrographic method with thin section analysis of the rock.

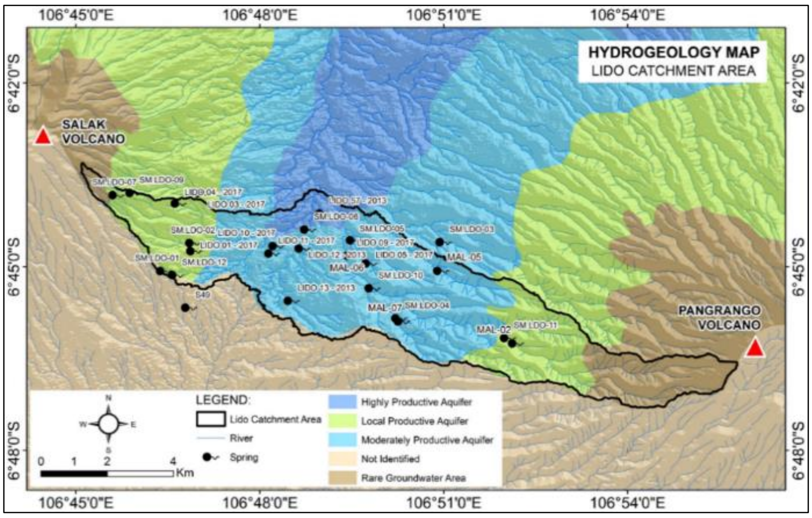

Fig 3. Regional Hydrogeological Map Sheet Bogor Regency (modification, Ministry of Public Works et al., 1990) with dugwells and springs observation data in the study area based on Hydogeological Mapping (2021).

3.2. Soil Infiltration Test

Infiltration tests were conducted to measure the surface soil's ability to absorb water which related to vertical hydraulic conductivity. The infiltration test was carried out using a 3-inch PVC pipe plugged into the ground and then filled with water and calculated how much water infiltrated a certain amount in a particular time. The calculation of the infiltration rate value uses the Eqn.1 formula.

$$V_w = (3.14 \times \emptyset^2 \times h_0) - (3.14 \times \emptyset^2 \times h_1) \qquad \text{(Eqn. 1)}$$

V_w is the volume of water infiltrated, $\emptyset^2$ is the radiant of the PVC pipe, h_0 *and* h_1 consists of the initial water level in the pipe and the end water level. The calculation is based on the formula for determining the volume of a cylinder.

3.3. Morphometric Analysis

Lineament Density (LD), Drainage Density (DD), and slope are the results of a morphometric analysis of Digital Elevation Model (DEM) data. This data is one of the important instruments in analyzing LD and DD because it is related to the topography or morphology feature. Data were collected from the site's source https://tanahair.indonesia.go.id/demnas/#/. The image used is Geospatial Information Agency - Indonesia's DEMNAS (Seamless Digital Elevation Model and National Bathymetry). DEMNAS imagery is a combination of IFSAR (5m resolution), TERRASAR-X (5m resolution), and ALOS PALSAR (5m resolution) image analysis (11.25m resolution). Using the EGM2008 vertical datum, a DEMNAS image with a 0.27-arcsecond resolution. DEMNAS data has been widely used to analyze topography, morphometric features, or watershed management with an accuracy of 8m resolution (Iswari and Anggraini, 2018; Bawasir and Handayani, 2021).

DD or LD values are determined using a formula developed by (Horton, 1932) (Eqn. 2 and Eqn. 3):

$$DD = \frac{\Sigma L_D}{A} \qquad \text{(Eqn. 2)}$$

$$LD = \frac{\Sigma L_L}{A} \qquad \text{(Eqn. 3)}$$

ΣL_D is the total length of the stream flow in a certain area and A is the total area calculated. For value calculation LD, ΣL_L is the total length of the lineament in a certain unit area.

Table 1. The results of morphometric analysis on different geological units along with the number of occurrences of springs and the type of rock.

Topography Slope	Geology Formation	Lithology		LD (m/km2)	DD (m/km2)	Slope (°)	Number of Spring
		Effendi & Hermanto (1998)	Geological Mapping				
Salak	Qvsb	Lahar Tuffaceous Breccia	Monomict Breccia, Polymict Breccia, & Breccia Tuff	19,49-1.952,30	9,56-137,97	1.12-28.09	9
Pangrango	Qvt	Pumiceous Tuff	Breccia Tuff	19,49-506,50	9,56-22,45	0.88-24.63	3
Pangrango	Qvpo	Older Deposit lahar	Lapilli, Lapilli Tuff, & Tuff	506,50-1.952,30	0,96-22,45	2.08-46.56	13

4. Rock Thin Section Analysis

Handspecimens collected from outcrops in the field are studied using the thin-section petrography method. The Zeiss Primotech series microscope was used to identify the composition of primary minerals, secondary minerals, and porosity in thin sections of rock in percent form. This is necessary to determine the precise rock characteristics. The results of the rock thin section analysis can be seen in Thin section analysis of rocks is based on theoretical and technical approaches to petrographic analysis (Philpotts, 2003).

4. Result and Discussion

4.1. Morphometric and Spring Characteristics

Morphometric analysis consisting of lineament density (DD), drainage density (DD), and slope. Twenty-four spring observation stations are dispersed across two of the volcano's slopes—eleven spring observation stations on the slopes of Salak. Meanwhile, thirteen spring observation sites are located on the slopes of Pangrango (Table 1). Generally, the spring distribution follows the analysis of topographic lineaments and stream lineaments interpretation in LCA. The spring location was plotted on the LD, DD, and slope maps to assess the relationship between the presence of springs and the study area's morphological features.

Springs on the slopes of Salak are located at intervals of ±0-30°, while on the slopes of Pangrango are found at intervals of ±0-50° (Fig 4.A). The appearance of springs on a steep slope characterizes the type of depression spring due to gravity (Bryan, 1919; Erlinawati et al., 2021). This type of spring is caused by the surrounding topography cutting off the groundwater table, exposing the groundwater table, and forming a conduit for overflowing water (Bryan, 1919; Gilbert, 2016). On the slopes of Salak, the spring data plot on the DD map depict five locations at 9,56-22,45m/km2 value intervals and four data at 22,45-137,97m/km2 value intervals. The LD analysis reveals three spring data are located at intervals of 795,66-1.952,30m/km2 on the Salak slopes, two spring data at intervals of 506,50-795,66m/km2, while four are at intervals of 19,49-506,50m/km2. On the Salak slopes, two data are not included in the DD and LD analysis zones. (Fig 4.A and B). On the slopes of Pangrango, three springs are located at DD 0,96-9,66mm/km2, and the other five are located at 22,45-137,97m/km2 (Fig 4.B). The LD analysis reveals that six spring data are located at 795,66-1.952,30m/km2 intervals, one spring data are located at 506,50-795,66m/km2 intervals, one spring data are located at 19,49-506,50m/km2, and one spring data is not included in the analysis zone (Fig 4.C).

Endogenous and exogenous factors influence the formation of topographic lineament patterns, stream, and slopes. Tectonic activity or faults are two examples of endogenous processes. The greater the LD value in a region, the greater the endogenous activity, which affects the rock properties that are better at infiltrating or discharging water, and vice versa (Sener et al., 2005; Mogaji et al., 2011). The results of the collected field data show the association between the DD value and the infiltration rate value. DD can be associated with the features of the constituent rocks or the amount of surface runoff water value (Dingman, 1978; Sukristiyanti et al., 2018). A high DD value indicates that the rocks are often lenient and significantly better at storing water (Dingman, 1978; Pallard et al., 2009). A high DD value suggests a soil infiltration rate of 0.550cm/s on average. However, the average infiltration rate is 0.188cm/s at a low DD value (Fig 4.C). This proves that a high DD value is better at infiltrating water. LD and DD values are often directly proportionate in LCA. The larger the soil or rock's LD and DD values, the greater its capacity to recharge or discharge water. The association between LD and DD values at each observation point depends on the groundwater spring type. However, uncertainty in this interpretation can occur due to limited data on infiltration rate measurements in the field. More dense data can result in better information.

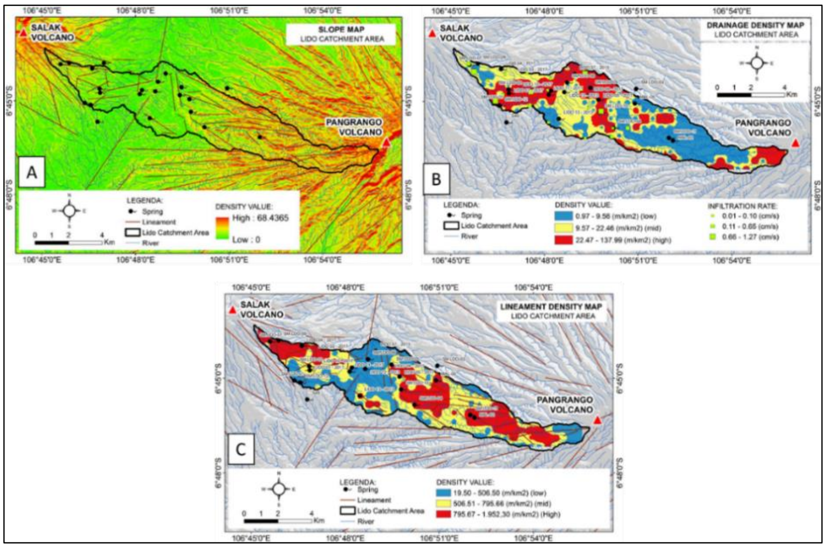

Fig 4. [A] Slope map with lineament analysis of topography and rivers. The density value means the slope angle in degree units. [B] Drainage density map with the distribution of the symbols of the infiltration rate test observation stations, denoted by the green box symbol. [C] Lineament density map.

The slopes of Salak is a relatively plain slope compare to the slopes of Pangrango. Steep slopes can be controlled by erosion factors or subsidence due to water-resistant bedrock, which causes the soils on the surface to be eroded (Liu et al., 2000). Based on the previous discussion, it can be concluded that the groundwater depression zone influences the emergence of springs on the slopes of Salak and Pangrango due to topographic collapse, which causes the contour of the groundwater table to be cut. In addition, the springs on the slopes of Salak and Pangrango are influenced by fracture zones that serve as pathways for the springs to discharge. The results of morphometric analysis and its correlation to the emergence of springs show a difference between the slopes of Pangrango and Salak. The slope factor causes differences in the ability to recharge, store, and discharge water. In this case, the Pangrango slope is relatively better for recharged water than the Salak slope.

On the slopes of Salak, the LD and Slope values in the Qvsl formation show the highest LD but lowest DD values. Meanwhile, the LD and slope values in the Qvsb formation show the lowest value but the highest DD value. On the Pangrango slope, the Qvpo formation has the highest LD, DD, and slope values, in contrast to the Qvt Formation, which has the lowest LD, DD, and slope values (Table 1). Therefore, the Qvsb formations on the Salak slopes and Qvpo on the Pangrango slopes are rock formations that can recharge or discharge better than other formations. The Qvsb and Qvpo formations may acts as aquifers. These results are consistent with the morphometric analysis and spring emergence that the Qvsb and Qvpo formations constitute the majority of rocks on both the Salak and Pangrango slopes. In addition, these results relate to several previous researchers regarding the conductivity values of volcanic rock, which have similarities with well-sorted sand - well-sorted gravel with a value of 10^{-3}-1cm/s and can act as an aquifer properly (Fetter, 2014).

Table 2. Thin section analysis results from several rock around LCA.

Geology Formation	Lithology (Geological Mapping)	Petrography Result													Lithology
		Sample Code	Fragment (%)				Matrix (%)		Altered Mineral (%)					Total Porosity (%)	
			Feldspar	Amphibole	Pyroxene	Plagioclase	Volcanic Glass	Plagioclase Microlite	Chlorite	Iron Oxide	Sericite	Clay Mineral	Total Altered Mineral		
		GPSG-31	7	0	0	0	35	0	2	5	3	0	10	50	Lithic Tuff
	Monomict Breccia, Polymict Breccia, & Breccia Tuff	GPSG-28A	0	3	5	25	7	40	3	5	7	0	15	25	Andesite
Qvsb		GPSG-28B	10	0	2	0	30	0	5	20	15	0	40	5	Vitric Tuff
		GPSG-28C	10	0	0	0	10	0	15	5	5	0	25	5	Lithic Tuff
		GPSG-44	15	0	0	0	5	0	5	10	5	0	20	25	Lithic Tuff
		GPSG-30	10	0	0	0	40	0	15	5	20	0	40	5	Vitric Tuff
		GPSS-6	5	0	0	0	40	0	15	10	5	0	30	10	Vitric Tuff
		GPSG-26	5	0	0	0	20	0	20	10	5	0	35	15	Lithic Tuff
Qvt	Breccia Tuff	GPSG-2	5	0	0	0	15	0	10	5	5	0	20	20	Lithic Tuff
		GPSG-29	5	0	0	0	10	0	10	10	5	0	25	10	Lithic Tuff
		GPSG-11	3	0	0	0	10	0	7	10	3	0	20	35	Lithic Tuff
		GL-06 A	10	3	0	0	45	0	5	5	0	10	20	30	Vitric Tuff
		GL-02	5	0	0	0	60	0	2	3	0	0	5	25	Vitric Tuff
		GL-05	0	0	0	0	5	0	40	20	10	0	70	0	Crystal Tuff
	Monomict Breccia, Breccia Tuff, Coarse Tuff	GL-04	5	2	3	0	40	0	5	8	2	5	20	30	Vitric Tuff
		GL-07	3	2	0	0	30	0	3	5	0	0	8	55	Lithic Tuff
Qvpo		MAL-02	5	0	0	0	60	0	2	3	10	0	15	25	Vitric Tuff
		MAL-06	5	3	0	0	20	0	0	10	7	15	32	20	Lithic Tuff
		GPSG-27	5	0	0	0	50	0	0	0	0	5	5	10	Vitric Tuff
		GPSG-35	5	0	0	0	25	0	3	7	0	10	20	40	Lithic Tuff

4.2 Volcanic Geology and Aquifer Characteristics

LCA is comprised of four distinct geological formations. The Salak slope is composed of Qvsl formations formed of lava flows and andesitic basalt. Lahar and tuffaceous breccias constitute the Qvsb Formation. The older lava deposits of the Qvpo formation dominate the Pangrango slope. On the downstream side of the Pangrango slope, pumiceous tuff deposits comprise the Qvt geological formation. The general stratigraphic correlation of the studied region indicates that the rocks on the Salak slopes are younger than those on the Pangrango slopes (Effendi et al., 1998; Agustin and Bronto, 2019).

On the slopes of Salak Volcano, the Qvsb formation has two lithological characteristics (Fig 5 and Fig 7). In the north part of the Qvsb formation on LCA, polymict breccias predominate, while monomict breccias predominate in the southern part. According to the sorting between rock fragments and matrix, the Qvsb formation's rock was deposited by a flow mechanism (Natasia et al., 2018; Mutaqin et al., 2019a, 2019b; Alfadli et al., 2021). Polymictic breccias (Qvsb 1) are thought to have been deposited after monomict breccias (Qvsb 2) (Fig 8.A). Plagioclase and feldspar minerals are easily distinguishable in the megascopic matrix fragments of Qvsb 2 and Qvsb 1 rocks hand specimens. The results of thin rock sections and petrographic investigation indicate that the porosity value range for polymict breccias in the Qvsb formation is between 5 and 50%. In contrast, monomict breccias have a porosity percentage of 5%. (Table 2). The identified alteration mineral at Qvsb 2 depicts components are Chlorite, Iron Oxide, and Sericite, with a total percentage value range of 10% to 40%. (Table 2).

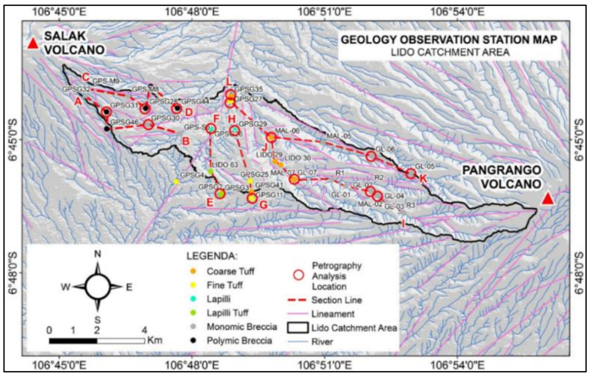

Fig 5. Geology observation station map. The red-dash line describes the geology cross section on each geology formation. The red circle describes the petrography analysis location.

The greater vitric concentration is the result of comparatively low-temperature eruptive activity (Ma et al., 2016; Aulia and Setiawan, 2019). Qvsb 1 contain major minerals such as Feldspar, Amphibole, Pyroxene, and Plagioclase. This differs from Qvsb 2, which are feldspar-dominated. Volcanic geology research revealed that the Qvsb formation consists of two rock groups. There are four springs with water flowing through fractures and rock pores on the Qvsb 1 and Qvsb 2 sections near GPSG 31, GPSG 30, GPSM 9, and GPSM 8 stations. Stratigraphic analysis of Qvsb is in the Proximal – medial facies from 500-1462 masl (Fig 8).

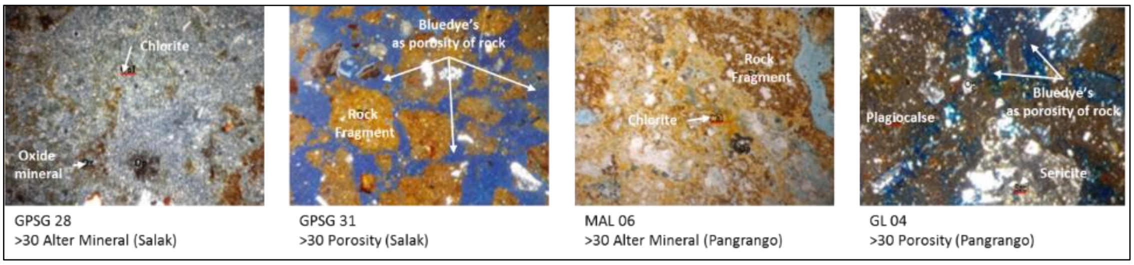

Fig 6. The results of rock thin section analysis on several samples from the Salak slopes and Pangrango slopes. GPSG 28 Vitric Tuff, GPSG 31 Lithic Tuff, MAL 06 Lithic Tuff, and GL 04 Vitric Tuff.

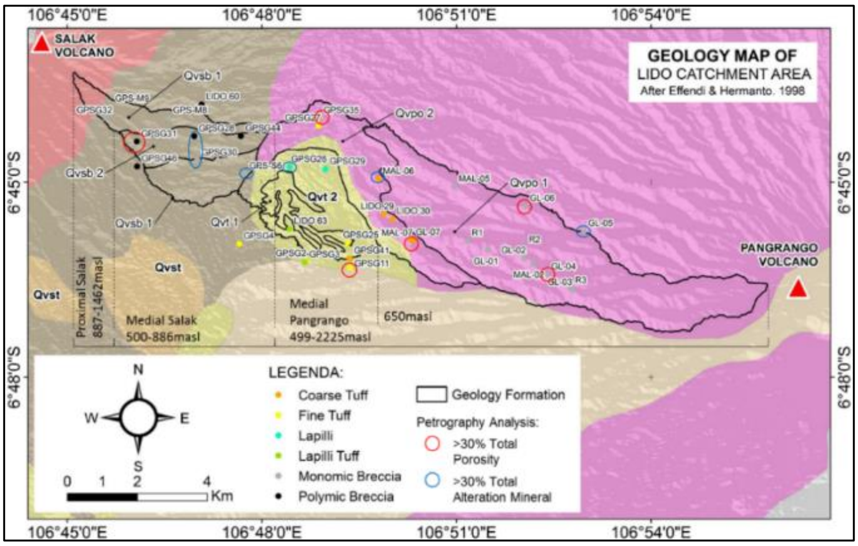

Fig 7. LCA geological map along with distribution of outcrop points and distribution of volcanic facies. The red and blue circles represent the rock thin section analysis results for porosity and alteration minerals.

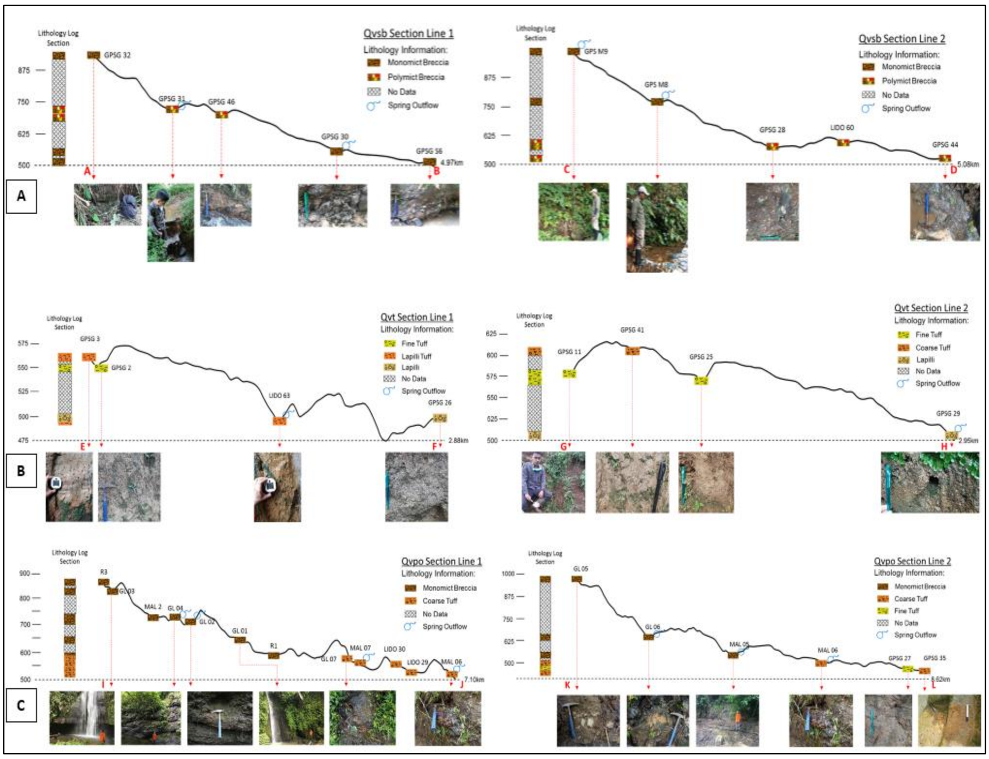

Fig 8. Cross section of outcrops correlation results. [A] Qvsb Formation. [B] Qvt Formation. [C] Qvpo Formation. Line Section on Fig 5

The southernmost slope of the LCA to the north is composed of the Qvt geological formation. Outcrop investigations of the Qvt formation reveal four distinct lithological characteristics: fine tuff, coarse tuff, lapilli tuff, and lapilli (Fig 8. Section E-F and Section G-H). Fine tuff, coarse tuff, lapilli tuff, and lapilli form a reverse grading pattern when examined in order (Cas and Wright, 1995). Texture grading of rocks in the Qvt formation permits various pyroclastic material deposition events or depositional events of the same material. However, different volcanic activity occurs during the same period (Cas and Wright, 1995). The results of field observations show that fine tuff (Qvt 1) has a relatively diverse sorting and fragment size, which is the key to the flow deposition system (Fisher and Schmincke, 1984). Likewise, coarse tuff, lapilli tuff, and lapilli (Qvt 2). This was also proven by the petrographic analysis of thin sections, which showed the presence of alteration minerals around the rock pores, which were controlled by flow/hydrothermal processes. Other analyzes show that chlorite, iron oxide, and sericite are found in rock tip incisions as alteration minerals. The percentage of the total value of alteration minerals in coarse tuff, lapilli tuff, and lapilli ranges from 25-35%, while in fine tuff, it is 20% (Table 2). The percentage of rock porosity in the Qvt geological formation ranges from 10-35%, with the dominance of rock fragments (lithic tuff) (Fig 6). In addition, Feldspar was determined to be the predominant mineral in the rock. Analysis reveals that the Qvt formation consists of two distinct rock groups. At the LIDO 63 and GPS 29 observation stations, there are two springs in the Qvt formation in the form of water seepage through the pores of the lapilli rock. Qvt is located in the Pangrango medial facies between elevations 499 and 650 masl.

The Qvpo Formation comprises monomict breccias, fine tuff, and coarse tuff. Monomict breccias and coarse tuff have diverse rock fragment sortations and sizes, one of the characteristics of flow deposit type (Mutaqin et al., 2017). Fine tuff at GPSG 27 has the same features as fine tuff at the Qvt formation. According to its depositional position, the Qvpo formation is younger geologically than the Qvt formation. Qvpo 2 is below Qvpo 1 based on its position (Fig 8. Section G-H and Section K-L). This indicates that Qvpo 2 is older than Qvpo 1. The composition of Qvpo 1 is monomict breccias. The constituents of Qvpo 2 are Coarse Tuff and Fine Tuff. Qvpo 1 has a blackish-brown color and is different from monomict breccia on the Salak slopes. The fragments of rock are composed of andesitic igneous rocks. The thickness of Monomict Breccia on Qvpo 1 is between 1.5-35m. The results of thin section analysis show that the matrix tuff belongs to the types of Lithic Tuff, Vitric Tuff, and Crystal Tuff (Fig 6 and 7)

Qvpo is generally composed of feldspar, amphibole, and pyroxene minerals. At station GL-05 the total alteration minerals are around 70%, consisting of chlorite, sericite, iron oxide, and clay minerals. The overall susceptibility of alteration minerals at Qvpo 1 is between 5-70%, with a susceptible porosity percentage ranging from 0-35% Qvpo 2 has a reddish brown fresh color. The rock fragments with various sorting and grain sizes show a flow pattern of pyroclastic deposition (Cas and Wright, 1995). The thickness of the Qvpo 2 formation from field observations is only around ±0.4-1.5m. Lithic Tuff and Vitric Tuff are types of pyroclastic material in Qvpo 2, resulting from rock-thin section analysis (Fig 6). Comparable to Qvpo 1, Qvpo 2 is formed of similar alteration minerals but in a different proportion. The total percentage of alteration minerals in Qvpo 2 is 8-20%. The percentage value of vulnerable rock porosity is 10-55%.

Based on this value, the Qvpo Formation can recharge and discharge water; this is evidenced by the many springs that appear in the Qvpo formation with a larger discharge than Qvsb on the Salak slopes. From the cross sections of the I-J and K-L line, a total of 7 springs overflowed into the Monomict Breccia and Coarse Tuff. Qvpo enters the Medial Pangrango facies from a height of 499-2225masl (Fig 8. Section I-J and Seciton K-L).

4.3 Spring Occurrence

The results of the geological analysis in the Qvsb geological formation demonstrate that water can flow with a flow system between rock pores or fractures, which generate aquifers. The springs in the Qvsb formation are distributed over the proximal-medial facies based on the volcanic facies. The morphometric analysis reveals that the spring emergence pattern aligns with a lineament or a meeting of two separate lineaments. The relative emergence of springs at 10-35° is shown by slope analysis, with low DD values but high LD values. Fractures and depressions characterized the appearance of springs in the Qvsb formation, according to field observations from 9 spring locations. According to the geological analysis, breccias have a high potential to serve as aquifers. Furthermore, the soil conditions on the Salak slopes have a higher average infiltration rate than Qvpo and Qvt. Spring occurrences in the Qvsb formation are usually found in topographical collapse, which creates depression springs and is found in quite intense rock fractures (Fig 9). According to additional evidence, the average spring discharge value on the Salak slopes is 5.12l/s. According to the description, springs in the Qvsb formation can properly discharge and infiltrate, causing more water to seep rather than runoff (Endyana et al., 2016). This can result in a comparatively high number of springs but a lower surface runoff than the Pangrango slopes.

The Qvt Formation is included in the Pangrango middle facies. Coarse Tuff and Lapilli in the Qvt formation have the potential to become aquifers because water can flow through the rock's inter-porous system (Fig 9). In contrast to the Qvsb and Qvpo formations, there are no springs on the lineaments of the Qvt formation. Morphometrically, springs are found on slopes between 10-35°, with low DD values or in the zone between low and high DD values. In the LD analysis, most springs have low values, whereas only one has high ones. In general, five springs denote the type of depression or contact. However, several Qvt formation springs have a relatively low discharge. A soil cover with a low infiltration rate may result in a limited infiltration process and a high surface runoff rate. Comparing the Qvt formation to the Qvsb and Qvpo formations, the Qvt formation is the geological formation with the least potential of groundwater.

In the Qvpo formation, springs appear in breccias and lapilli in the Pangrango medial facies. In general, springs appear directly on a lineament or at the intersection of two or more lineaments. In general, springs are located on slopes values >35°. The majority of spring types observed at eight stations were depression types. Breccia has the potential to become an aquifer in the Qvpo formation. The results of the geological interpretation indicate that monomictic breccias within the Qvpo formation can function as effective aquifers. This is indicated by the average discharge rate of 4,083l/s from the observed springs. The occurrence of springs in the Qvsb formation is common in the topographical collapse, which causes the groundwater table to be cut off and causes a depression-type spring to appear. The relatively greater porosity percentage value compared to the Qvsb formation makes it easy for water to overflow into springs within the breccia (Endyana et al., 2016). In addition, the value of the water infiltration rate in the soil on the Pangrango slopes is relatively smaller than on the Salak slopes. Based on DD, LD, and soil infiltration value, it can be synthesised that the amount of water that seeps, overflows, and flows on the surface will be the same depending on the amount of rainfall in Qvsb formation.

Fig 9. Groundwater Spring on the Field Observation. The Red Box on the SM LDO-07 Spring indicates the spring discharge at the rock's fracture and pores. Spring discharge in rock pores is indicated by the yellow box on SM LDO-09 (breccia).

4.4 Groundwater Electrical Conductivity (EC)

The EC content correlates with the study area's elevation data of springs. The decreasing altitude indicates an increasing EC concentration. The spatial distribution of the EC value is determined by several variables, groundwater movement, water temperature, soil or rock dissolution characteristics, discharge magnitude, groundwater flow velocity, and the distance between the infiltration area and the discharge (Dahaan et al., 2016). The plot of the EC value to the elevation on the scatter graph shows 3 different types of springs in the LCA (Fig 10). Superficial springs occur due to the recharge process, and the discharge is relatively short (C. Winter et al., 1998). EC value on the superficial spring <100μS/cm. Superficial spring recharge processes can occur in local recharge systems. The mixed spring type is a spring that has varies EC values of 100 to 230μS/cm. This group of springs occurs because the flow process of recharge to discharge area is relatively short, with intensive water-rock interaction related to the porosity and permeability factor. In addition, when springs flow through aquifers and interact with rocks, surface water intercepts can occur, which causes this type to be categorized as a mix. The last type of spring is the alteration type. This type of spring has an EC value of >300μS/cm.

The results of the geological analysis show that the rocks around this type of spring have a higher percentage of alteration minerals than the others (Fig 10). When water-rock interactions occur, this can cause the enrichment of minerals in the water, which causes the EC value to increase. In addition, factors that can affect the high EC content are the relatively long process of groundwater flow in the aquifer or the influence of deeper water flows (Dahaan et al., 2016). This relates to the fact that the Qvsb formation contains three different kinds of springs, while the Qvt formation contains two types of springs (superficial and mix), and the Qvpo formation contains three distinct types of springs as well (Fig 10).

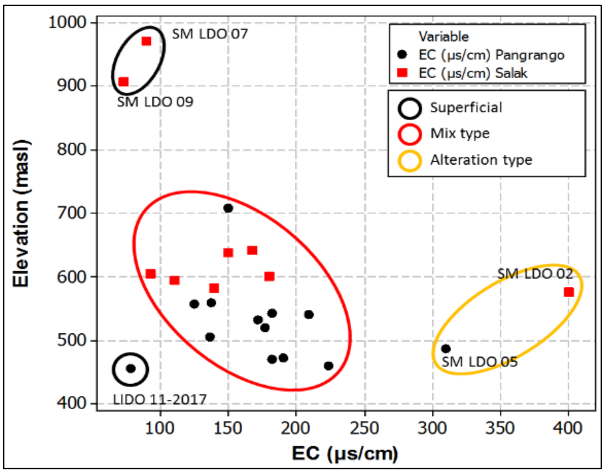

Fig 10. Scatterplot of EC and elevation values from spring data on Salak and Pangrango slopes.

4.5 Discussion

The first step in the investigation was to analyze the geological setting using outcrop data, thin rock sections, and morphometric analysis. Developing a geological framework is critical to comprehend the process and occurrence of groundwater or its aquifer features (Hadian et al., 2017). Even though it cannot determine the condition of the rocks beneath the surface, this study is essential. However, the methods employed yielded satisfactory results regarding the groundwater system in the research area. Spring occurrence is closely related to geological control and the physical properties of its elements. As a result, changes in the geological and physical features of the constituents might result in a variety of spring types (Falah et al., 2017; Ghimire et al., 2019). The study's application of analytical methods and techniques revealed some essential basic information. The pattern of spring occurrence on the Salak and Pangrango slopes differs. This difference stems from the lithological composition of each slope (Effendi et al., 1998; Mutaqin et al., 2017, 2019a; Alfadli et al., 2021).

LD, DD, and slope are morphological features related to the characteristics of the material or the constituent rocks. A high LD value indicates a higher fracture zone than a low value (Mogaji et al., 2011). High DD values indicate greater surface runoff rates and are formed of rocks that get saturation rapidly (Dingman, 1978; Moglen et al., 1998; Pallard et al., 2009). In addition to causing higher surface runoff flows, high DD values represent the permeability or porosity values of the rock, which are related to the rock saturation level. A high slope value illustrates a higher surface runoff velocity compared to areas with relatively low values (Altın and Altın, 2011; Anitha, 2020). LD, DD, and slope are closely related to the rock's porosity and permeability. In general, porosity and permeability have a positive correlation; an increase in porosity can increase permeability (Šperl and Trckova, 2008). This physical characteristic is important, because it is related to the process of infiltration or discharge of water into springs. In addition, EC is another important parameter in studying the process and occurrence of springs (Dahaan et al., 2016).

The Salak and Pangrango slopes contain aquifer rocks composed of pyroclastic rock. Field observations, morphometric analysis, and rock-thin section analysis prove this. The origin and occurrence of springs on the slopes of Pangrango and Salak have distinct patterns and characteristics. The Salak pattern consists of aquifers formed of polymict and monomict breccias with porosities ranging from 5-50%. In general, springs are found with fractures and depressions where the water flows through rock fractures and the spaces between them. The alteration of rock on the slopes of Salak causes a higher EC content during the water-rock interaction process (Ludwig et al., 2012). Generally, springs are found on steep slopes formed by topographical collapse. High LD and DD values followed by a high slope value indicate a relatively small spring EC value (superficial spring type). A high LD value, a low DD value, and a downward slope show a relatively small – moderate EC value (mix spring type). A low LD value and a high DD value at a low slope value indicate a rather large spring EC value due to the interaction of water with altered rock (alteration spring type) (Fig 11).

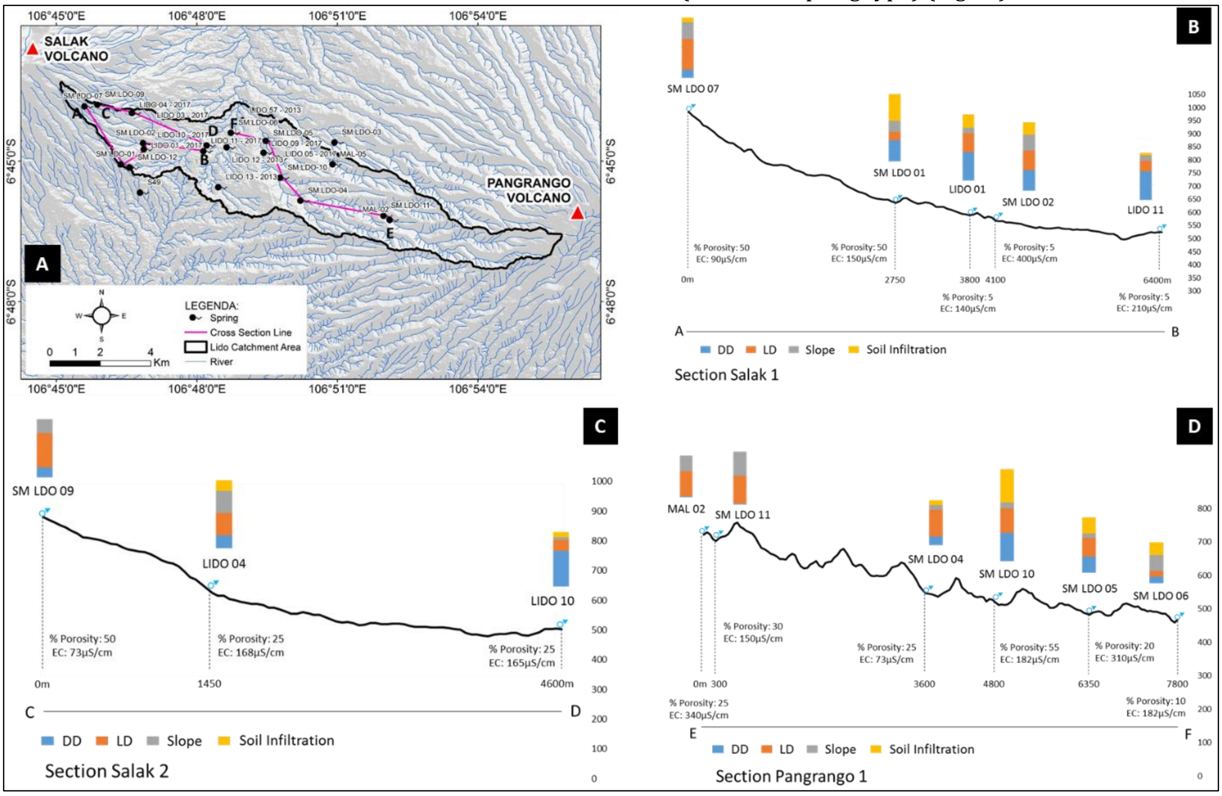

Fig 11. [A] distribution of springs and cross-sectional lines between springs. [B] Cross-section of salak 1 with variations in the values of DD, LD, Slope, and Soil Infiltration in a bar graph. [C] Cross section of salak 2 with the same description as picture B. [C] Pangrango cross-section with the same description as pictures B and C.

The Pangrango pattern comprises aquifers consisting of monomict breccias, lapilli, and coarse lapilli. What differentiates the features of the aquifers on the Pangrango slopes from those on the Salak slopes is the significantly different discharge value. Typically, the porosity ranges from 0 to 55%. On the slopes of Pangrango, most springs are depressions in which water flows through the spaces between grain fragments. Most springs on the Pangrango slope are located on the river-wall body with a high slope value due to erosion or topographical collapse. High LD and DD values followed by low slope values indicate relatively small-medium EC values (mix spring type). A high LD value but a low DD and slope value indicate a relatively small spring EC value (superficial spring type). Low LD, DD, and slope values indicate large EC values (alteration spring type) (Fig 11).

Both slope and DD demonstrate the inverse function. However, a low slope value suggests an enormous DD. The EC concentration is proportional to the potential water flow velocity, more significant when the slope value is lower. The decreased water transmittance in the aquifer results in more intense water-rock interactions and a high saturation state with an increasing EC concentration. Therefore, high EC values are typically associated with high DD values, and vice versa (Fig 4.B). High DD values indicate rock layers with relatively low permeability, whereas low DD values indicate rock layers with relatively high permeability. 17 spring, or around 73%, have low-to-moderate DD levels or transition from high to medium or low DD values. Thus, the presence of springs in volcanic geological settings on the Salak and Pangrango slopes is governed by weathering and rock erosion processes, primary genetics, and secondary rock development, which generates varying K values along the slopes.

The geological and morphometric investigation that has been conducted indicates that the Pangrango slope has greater potential than the Salak slope. Different chemical conditions might result from each slope's specific physical characteristics—the proximity of the Salak and Pangrango volcanic facies in the middle influences the potential of water mixing. The findings of this study enhance knowledge of the groundwater system from the perspective of geological control in a region over the aquifer's features and spring.

5. Conclusions

The implemented method generates positive findings to perform a geological study to comprehend the groundwater system in the research region. The classification of rock types based on the results of mapping and analysis of thin rock sections elucidates the state of the rock and its properties, particularly for identifying the condition of aquifer rock. In addition, the use of remote sensing in the conducted morphometric analysis is associated with the presence of springs in the research area. Understanding the geological setting and its relationship to the occurrence of groundwater springs in the study area is one of the most important outcomes of the analysis results.

The geological analysis reveals six distinct rock properties in three geological formations. Some area show geology regions with an alteration mineral content greater than 30%. In addition, certain regions have a porosity value >30%, as determined by examining thin rock sections. In the Qvsb Formation, Polymict Breccias serve as suitable aquifers; in the Qvt Formation, lapilli and coarse tuff; and in the Qvpo Formation, monomictic breccias. The mineral concentration of groundwater is correlated with variations in rock properties. Based on the results of the geological and morphometric investigation, six possible chemical properties of groundwater can be identified. In the meantime, the findings of the EC value study reveal three types of springs with distinct flow systems (superficial, mix, and alteration types). This spring discharges through a network of inter-porous rocks and fractures. Based on the magnitude of the discharge value, breccia has a greater capacity to discharge water than coarse tuff and lapilli. In displaying the distribution of aquifers, it is impossible to describe the subsurface geometry. Incorporating geophysical survey data can provide a more comprehensive depiction of subsurface conditions. Verifying some of the results with groundwater chemical and isotope data can provide a strong foundation for reconstructing the occurrence of springs and the conceptual hydrogeological system in the studied area.

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