ГЛАСНИК Српског географског друштва 105(2) 273-294
BULLETIN OF THE SERBIAN GEOGRAPHICAL SOCIETY 2025

Original scientific paper
UDC 551.44:551.4:551.21:551.578(594.34)
https://doi.org/10.2298/GSGD2502273E

Received: June 9, 2025
Corrected: July 17, 2025
Accepted: July 24, 2025

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HYDROGEOMORPHOLOGICAL CHARACTERISTICS OF PALEOVOLCANIC SPRINGS IN THE SOUTHERN MOUNTAINS OF THE BATURAGUNG ZONE, YOGYAKARTA, INDONESIA

Abstract: Paleovolcanic springs in the Southern Mountains of the Baturagung Zone, Yogyakarta, Indonesia, have an essential role in the local ecosystem and as water resources for the community. This study aims to identify and analyze the hydrogeomorphological characteristics of these springs, including distribution patterns, discharge variations, and water quality. This study used a descriptive-explorative method with a spatial approach, supported by the geography theme of location, place, and region. Data collection was conducted through field observation, review of relevant literature, and documentation. The data were then examined using spatial techniques, statistical methods, and descriptive interpretation. The results show that the distribution pattern of springs is irregularly clustered. Still, a small portion is clustered following river courses and fault structures. Spring discharge in the paleovolcanic complexes of Parangtritis-Sudimoro and Sumberkulon-Dengkeng varies from class V to VIII with a relatively small average. The two paleovolcanic complexes show differences in average discharge, pH, and EC but no differences in average temperature and TDS. Most other springs have TDS in the fresh and very fresh categories. Differences in geologic and geomorphologic conditions between the two paleovolcanic complexes contributed significantly to the variation in spring characteristics. This study is expected to contribute to water resources management and better understand hydrogeomorphologic characteristics in paleovolcanic areas.

Keywords: hydrogeomorphology, paleovolcano, spring distribution, discharge, water quality

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Introduction

Springs are essential both geologically and ecologically and offer many benefits to humans (Glazier, 2009). According to Stevanovic (2009), springs have a variety of benefits, including drinking water supply for power generation, agricultural sources, recreation and balneotherapy, and the bottled water industry. Ratih et al. (2019) also mentioned that springs can be an alternative resource in disaster emergencies. However, population increase, environmental issues, and climate change have significantly increased water demand, making springs one of the increasingly essential water resources to be managed sustainably (Hutton & Chase, 2016). Haverkort and Reijntjes (2007) state that recognizing the role of humans in their relationship with nature and understanding how natural processes occur is the moral and scientific basis for determining environmental sustainability. Therefore, understanding the characteristics of springs is an indispensable initial effort for sustainable water resources management.

Santosa (2006) states that recognizing the characteristics of springs can be done using a hydrogeomorphological approach. The hydrogeomorphology of springs has yet to be widely studied. Some previous studies have explored the relationship between geomorphological factors, such as topography, rock structure and composition, and landform formation and dynamics that play a role in the formation of springs. Hydrogeomorphologic studies conducted on young volcanoes show that volcanic activity dominantly influences spring characteristics (Ervin et al., 2022; Ratih et al., 2018; Wardoyo & Khotimah, 2021). Hydrogeomorphologic studies on old volcanoes and spring characteristics have begun to be affected by denudation activity (Ashari & Widodo, 2019; Santosa, 2006). The distribution pattern of young volcanic springs is more regular and tends to form a spring belt pattern, while the distribution pattern of old volcanic springs is irregular. Meanwhile, in paleovolcanoes, the geomorphic process is a denudation process that has been going on for a very long time and is influenced by tectonic activity. This process causes the visual appearance of the body shape of paleovolcanoes to be irregular and does not resemble a volcano at all. The different processes between young volcanoes, old volcanoes, and paleovolcanoes can affect the characteristics of springs, including distribution patterns, discharge, and water quality. Thus, knowing and analyzing the variation of spring characteristics in paleovolcanic areas is very interesting.

This study aims to explore the hydrogeomorphological characteristics of springs in paleovolcanic areas in the Southern Mountains of the Baturagung Zone, Yogyakarta, Indonesia. Specifically, the study focuses on three main objectives: (1) identifying spatial distribution patterns of springs, (2) analyzing variations in spring discharge, and (3) examining the water quality characteristics of springs. This research is relevant for understanding how geomorphological and geological dynamics influence spring emergence in volcanic terrain that have undergone prolonged denudation and structural deformation. The findings are expected to provide a strong scientific basis for the efficient and sustainable management of water resources, especially in mountainous areas with complex geological conditions.

Study Area

This study was conducted at a paleovolcanic spring in the Southern Mountains of the Baturagung Zone, which is administratively located in the Special Region of Yogyakarta, Indonesia. The research location's UTM coordinates are 424383 m East - 445694 m East and 9113066 m North - 9134030 m North. Hartono (2010) states that the Southern Mountains of the Baturagung Zone are composed of various paleovolcanoes, some of which are the Parangtritis-Sudimoro paleovolcanic complex and the Sumberkulon-Dengkeng paleovolcanic complex. These two paleovolcanic complexes are separated by the Oyo River.

Geologically, the primary constituent rocks in the Parangtritis-Sudimoro area and the Sumberkulon-Dengkeng area include intrusive stones, lava, autoclastic breccia, lapilli tuff, and pumice (Hartono, 2010). Based on the Geological map of Yogyakarta Sheet (Rahardjo et al., 1995), this paleovolcanic complex area is in the Nglanggran Formation and Semilir Formation. Both formations are tertiary age formations. The Nglanggran Formation, above the Semilir Formation, is dominated by volcanic breccia and agglomerate with tuff inserts and andesite lava. (Surono, 2009). Meanwhile, the Semilir Formation is dominated by interbedded tuff-breccia, pumice breccia, dacite tuff and andesite tuffs, and tuffaceous claystone. These materials are the result of volcanic activity and generally have high permeability and porosity, making them good aquifers (Todd, 2005).

The geological structure in the study area has a strong influence on the formation of the Southern Mountains of the Baturagung Zone. The Kali Opak fault, located west of the Southern Mountains, apparently has a genesis relationship with the emergence of paleovolcanoes in southern Yogyakarta. Due to bedrock faulting, Kali Opak is a weak pathway that allows magma to move to the earth's surface, forming a range of paleovolcanoes (Hartono, 2011). In addition to the main fault of Kali Opak, this area is also followed by minor faults that also affect the morphological characteristics of this area.

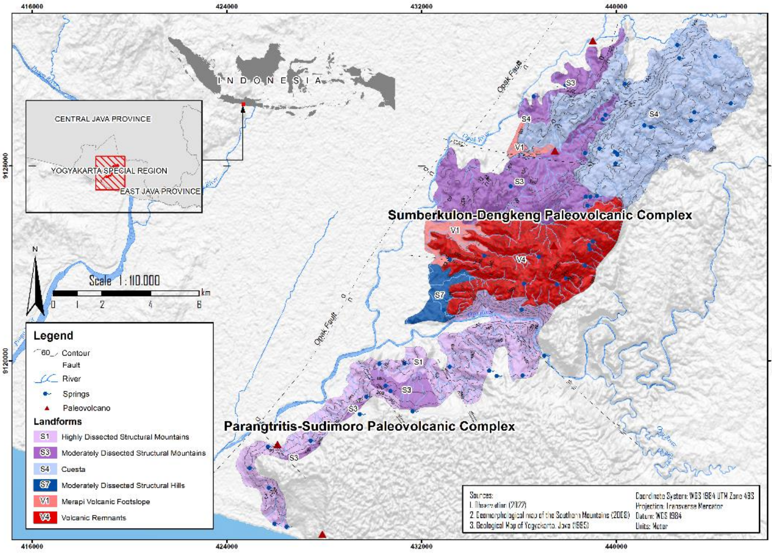


Fig. 1. Geomorphological map of The Southern Mountains of the Baturagung Zone

Srijono. et al. (2008) also mentioned several volcanic, structural, and fluvial landforms in this study area. In more detail with a larger scale, the morphology of the Southern Mountains of the Baturagung Zone consists of highly dissected structural mountains, moderately dissected structural mountains, cuesta, moderately dissected structural hills, Merapi volcanic footslope, and volcanic remnants (Fig. 1 and Table 1).

Table 1. Morphological Classification of Southern Mountains of the Baturagung Zone

Morphology	Geology		Geomorphic Process (Existing)
	Formation	Major rock	
Highly dissected structural mountains (S1)	Nglanggran Formation	Polymictic conglomerate, volcanic breccia, lava	Denudational
Moderately dissected structural mountains (S3)	Semilir Formation, Nglanggran Formation	Tuff, claystone breccia, volcanic breccia, agglomerate, and tuffaceous sandstone	Denudational
Cuesta	Semilir Formation, Nglanggran Formation	Interbedded sandstone-tuffaceous claystone, agglomerate, volcanic breccia	Denudational
Moderately dissected structural hills (S7)	Wonosari Formation	Tuffaceous limestone	Denudational
Merapi volcanic footslope (V1)	Young Volcanic deposits of Merapi Volcano	Tuff, ash, breccia, and agglomerate	Fluvial
Volcanic remnants (V4)	Semilir Formation, Nglanggran Formation	Lava and andesitic intrusions	Denudational

Source: Srijono. et al. (2008)

In addition to its geological complexity, the Southern Mountains of the Baturagung Zone also play an essential role in supporting the availability of freshwater for the local population. The springs in this region are vital for domestic needs, according to data from the Central Bureau of Statistics of Bantul and Gunungkidul, 2012, there were 174,894 inhabitants, and in 2022 this number increased to 189,398. This demographic growth is particularly evident in the Parangtritis-Sudimoro paleovolcanic complex, which is crossed by the construction of a new land transportation route known as the "Jalur Lintas Selatan". These dynamics indicate increasing water demand and potential pressure on spring sustainability. Therefore, understanding the hydrogeomorphological characteristics of springs in this region is crucial to provide data-driven insights for managing groundwater resources in rapidly develoving paleovolcanic areas.

Methods

This research is a descriptive-exploratory study supported by a spatial approach and geography themes, including location, place, and region. These approaches and geographical themes were used to analyze the problem of spring characteristics, such as spring distribution patterns, water discharge, and water quality under geomorphological conditions. A systematic sampling approach was applied in the Southern Mountains of Baturagung Zone, where measurements and observation were conducted using a grid system with each cell representing a 2-kilometer area in the field.

Data were collected through observation, documentation, and literature. Field observation were carried out to collect data on spring locations, discharge rates, and water quality, with a particular focus on water temperature, pH, total dissolved solids (TDS), and electric conductivity (EC). Documentation was conducted to obtain supporting data on geomorphologic, geologic, and land use conditions near the spring. In addition, a literature review was undertaken to gather supporting information from relevant books and scholarly articles related to this study. Details regarding the types of data, data collection methods, and data sources/instrument are presented in Table 2.

Table 2. Types of data, data collection techniques, and instruments/sources of data

Types of data	Data collection techniques	Instruments/sources of data
Spring location	Observation	GPS essential
Geological and geomorphological conditions		Instrument survey geomorphology (van Zuidam & van Zuidam-Cancelado, 1979).
	Documentation	Geological map of Yogyakarta Sheet, Java.; Topographical Map of Indonesia: Sheet 1407-543 Dringo, 1408-221 Bantul, 1408-222 Imogiri, 1408-224 Timoho, 1408-213 Jabung.
	Literature study	(Hartono, 2010; Srijono. et al., 2008)
Spring water discharge	Observation	Measurement instruments using volumetric measurements (Gentry & Burbey, 2007; Segadelli et al., 2021; White et al., 2016)
	Literature study	(Ashari & Widodo, 2019; Ervin et al., 2022; Salsabila et al., 2022; Santosa, 2006; Wardoyo & Khotimah, 2021)
Water quality	Observation	Multiparameter Probe (HI 767982)
	Literature study	(Ashari & Widodo, 2019; Ervin et al., 2022; Salsabila et al., 2022; Santosa, 2006; Wardoyo & Khotimah, 2021)

The data obtained were analyzed using spatial, statistical, and descriptive analysis. To identify the spatial distribution pattern of springs in the study area, spatial analysis was performed using the Average Nearest Neighbor (ANN) tool in ArcGIS software version 10.6. Previous studies have used this method of analysis to determine the distribution pattern of springs in young volcanoes, old volcanoes, and paleovolcanoes (Ashari & Widodo, 2019; Ervin et al., 2022; Ratih et al., 2018; Salsabila et al., 2022). The ANN tool was applied to the entire study area, as well as separately to the Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complexes. This approach allowed for the identification and comparison of spring distribution pattern within each paleovolcanic complex. To support this comparison, spatial analysis is supplemented with descriptive analysis that emphasize geomorphological characteristics and basic geomorphological principles. This approach aims to explore the possible influence of geomorphological condition on the similarities and differences in the distribution patterns of springs throughout the study area, including the Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complexes.

Statistical analysis determined differences in spring characteristics, including water discharge and quality, between the Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complexes. Statistical analysis was performed using an independent sample t-test with the aid of SPSS software. The spring water comparison test between the paleovolcanic areas included spring water discharge, water temperature, water pH, total dissolved solids (TDS), and electric conductivity (EC). This analysis was also supported by descriptive analysis to interpret the results with due consideration of geomorphological aspects. A simple linear regression analysis was also carried out to examine the relationship between correlated water quality parameters, particularly the effect of total dissolve solids (TDS) and water temperature on electrical conductivity (EC).

Results

Distribution of paleovolcanic springs in the Southern Mountains of the Baturagung Zone

Field observations revealed 53 springs. In total, 35 springs were found in the Sumberkulon-Dengkeng paleovolcanic complex, while only 18 were found in the Parangtritis-Sudimoro paleovolcanic complex. The presence of paleovolcanic springs in the Southern Mountains of the Baturagung Zone does not indicate the usual spring distribution pattern forming a spring belt. The result of the Average Nearest Neighbor analysis for all springs in the study area a z-score of -1.68 with a p-value of 0.09 (Fig. 2a). This z-score indicates that the distribution of springs throughout the study area is clustered. The distribution pattern of these springs tends to be irregularly clustered; a small number occur in river channels, and some springs also occur in fault zones. Based on the buffer analysis results, four spring occurrence locations are close to fault structures, i.e., less than 200 meters. Meanwhile, the analysis for each paleovolcanic area yielded different results from the general pattern. The distribution of springs in the Parangtritis-Sudimoro paleovolcanic complex is random, with a z-score of 1.24 and a p-value of 0.21 (Fig. 2b). The same random pattern is also found in the Sumberkulon-Dengkeng paleovolcanic complex with a z-score of -0.85 with a p-value of 0.39 (Fig. 2c).

The distribution of springs in the Southern Mountains of the Baturagung Zone based on morphology also shows variation (Table 3). More springs are generally found in the moderately dissected structural mountain morphology, with 15 springs. Nine springs are found in the Sumberkulon-Dengkeng paleovolcanic complex area, while the other six are found in the Parangtritis-Sudimoro paleovolcanic complex area. The dominance of rocks such as tuff, breccia, and tuff sandstone has high porosity, allowing rainwater to be well absorbed. Combining permeable and impermeable rocks such as claystone helps water collect in the aquifer and eventually emerge as springs.

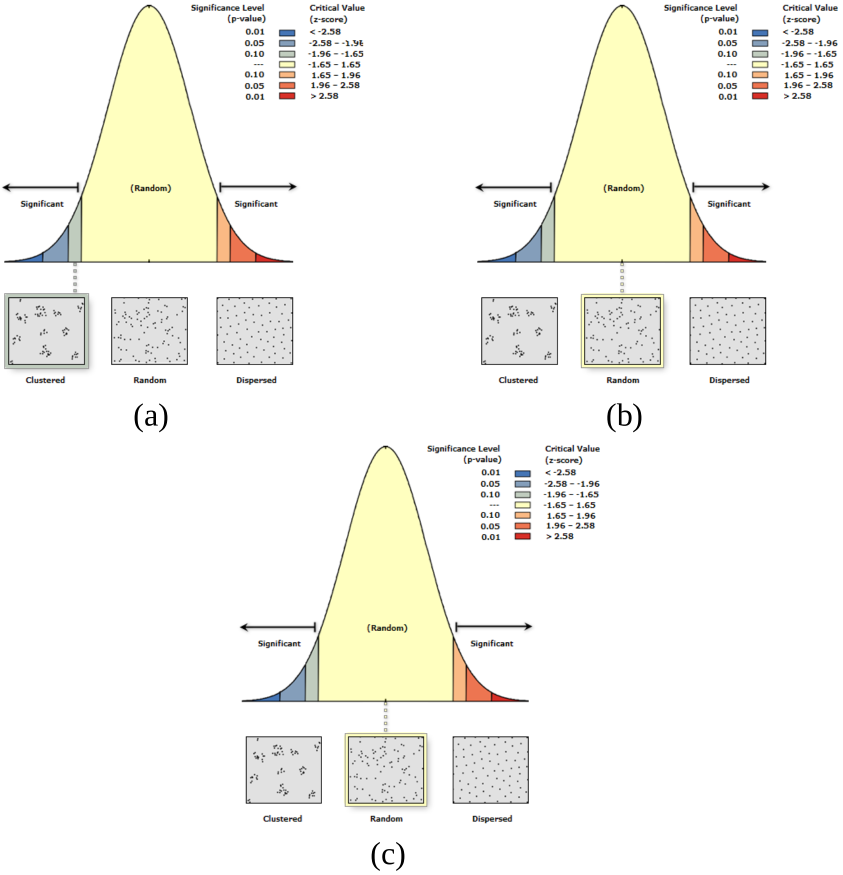


Fig. 2. Results of the analysis of spring distribution patterns (a) the entire study area, (b) in the Parangtritis-Sudimoro paleovolcanic complex, and (c) in the Sumberkulon-Dengkeng paleovolcanic complex.

Table 3. Distribution of paleovolcanic springs based on morphology in the Southern Mountains of Baturagung Zone

Morphology	The entire study area	Parangtritis-Sudimoro	Sumberkulon-Dengkeng
Highly Dissected Structural Mountains (S1)	13	12	1
Moderately Dissected Structural Mountains (S3)	15	6	9
Cuesta (S4)	14		14
Moderately Dissected Structural Hills (S7)	1		1
Merapi Volcanic Footslope (V1)	1		1
Volcanic Remnants (V4)	9		9
Total number of springs	53	18	35

The cuesta morphology also contains 14 springs, all found in the Sumberkulon-Dengkeng paleovolcanic complex area. The characteristics of the primary constituent rocks of the cuesta morphology, which consist of interbedded sandstone, tuffaceous claystone, agglomerate, and volcanic breccia, mean that this area has a high potential for springs. The permeable sandstone layers allow good water infiltration, while the impermeable claystone layers act as flow barriers and direct water out as contact springs in these layers. The cuesta structure, which is gentle on one side and steep on the other, contributes to the formation of the springs, as water trapped in the permeable layers relatively collects and escapes on the more gentle slopes.

The least number of springs is found in the moderately dissected structural hills and Merapi volcanic footslope morphologies. These two morphologies have a narrow area coverage with flat to rather steep slopes, thus minimizing the potential for springs to appear in these areas. In addition, the primary constituent rocks of the moderately dissected structural hills and Merapi volcanic footslope morphologies are tuffaceous limestone and tuff, ash, breccia, and agglomerate, respectively, which both have high straightness values for groundwater flow.

Spring water discharge on paleovolcanoes in the Southern Mountains of Baturagung Zone

Sprinng discharge was measured in August 2022, a period characterized by the Indonesian monsoonal climate, which corresponds to the height of the dry season in the study area. Despite the dry season peak, nearly all springs in the area continued to flow. Most springs are perennial springs that continue to flow throughout the year, although the spring discharge is only sometimes significant. There are only a few intermittent paleovolcanic springs in the Southern Mountains of the Baturagung Zone. Measurements of spring discharge at 53 location within the study area revealed an average flow rate of 0.75 l/s, but the median discharge was only 0.14 l/s (Table 4). This difference between the mean and median indicates that many springs have small discharges, while only a few springs have more significant spring discharges, increasing the overall mean value. This is also reinforced by the high standard deviation value of 1.40 l/s, indicating a considerable variation in the discharge of each spring. The highest spring discharge reaches 7 l/s, while the lowest discharge is only 0.02 l/s, indicating a vast difference between all springs.

Table 4. Summary of water discharge (l/s) data of paleovolcanic springs in the southern mountain of Baturagung Zone

	The entire study area	Parangtritis-Sudimoro	Sumberkulon-Dengkeng
n	53	18	35
Mean	0.75	1.64	0.29
Median	0.14	0.74	0.07
St. Dev	1.40	2.06	0.52
Max	7.00	7.00	2.65
Min	0.02	0.08	0.02

The Parangtritis-Sudimoro paleovolcanic complex (18 springs) has an average discharge of 1.64 l/s with a median of 0.74 l/s and large variation (standard deviation of

2.06 l/s). The highest discharge reached 7 l/s, while the lowest was 0.08 l/s. In contrast, the Sumberkulon-Dengkeng paleovolcanic complex (35 springs) has a minor mean discharge of 0.29 l/s with a median of 0.07 l/s. The variation in discharge is lower (standard deviation 0.52 l/s) and ranges from 0.02-2.65 l/s, indicating a more uniform discharge than Parangtritis-Sudimoro.

Referring to the classification of spring discharge according to Meinzer, spring discharge throughout the study area is distributed into four classes (Table 5). Most springs (21 springs) fall within class VI (0.1 - 1 l/s), indicating that water discharge in the study area is generally in the middle range. Class V (1-10 l/s) is the highest discharge class; only eight springs fall into this class. Meanwhile, class VII (0.01 - 1 l/s) has 18 springs, and class VIII (less than 0.01 l/s) has six springs. This shows that although some springs have significant discharge rates, many also have small discharge rates, thus illustrating considerable variation across the study area.

Table 5. The water discharge class of paleovolcanic springs in the southern mountain of Baturagung Zone based on Meinzer's classification

Class	Discharge (l/s)	The entire study area	Parangtritis-Sudimoro	Sumberkulon-Dengkeng
V	1 - 10	8	7	1
VI	0.1 - 1	21	7	14
VII	0.01 – 0.1	18	2	16
VIII	< 0.01	6	2	4
Total number of springs		53	18	35

The Parangtritis-Sudimoro paleovolcanic complex has a relatively more significant discharge, with seven springs in class V and seven in class VI, while only two springs are in class VII and 2 in class VIII. In contrast, the Sumberkulon-Dengkeng paleovolcanic complex is dominated by springs with minor discharge, with 14 springs in class VI and 16 in class VII, with only one spring falling into class V. This pattern shows the difference in water discharge characteristics between the two paleovolcanic areas, where the Parangtritis-Sudimoro paleovolcanic complex has more springs with high discharge than the Sumberkulon-Dengkeng Paleovolcanic Complex, which is dominated by slight discharge.

The average spring discharge associated with morphology in the Parangtritis-Sudimoro and the Sumberkulon-Dengkeng paleovolcanic complex shows significant variation. Differences in morphological characteristics and constituent rocks in each area explain these variations in discharge. Generally, morphologies with more complex and permeable rocks tend to produce higher spring discharge than those with impermeable rocks. In this case, the morphology of the Parangtritis-Sudimoro paleovolcanic complex has a higher discharge than that of the Sumberkulon-Dengkeng paleovolcanic complex, reflecting the different hydrogeologic properties between the two paleovolcanic complexes.

In particular, the Parangtritis-Sudimoro paleovolcanic complex contains only two morphologies, namely highly dissected structural mountains and moderately dissected structural mountains. Highly dissected structural mountains have springs with an average discharge of 1.56 l/s, while moderately dissected structural mountains are slightly higher, with an average of 1.77 l/s. Both morphologies are dominated by a polymictic conglomerate, volcanic breccia, lava, tuff, and agglomerate, potentially having greater infiltration capacity and groundwater flow. In addition, the area is geologically associated with the Wonosari Formation, whose primary constituent rocks are reef limestone, calcarenite, and tuffaceous calcarenite (Fig. 3). These rocks provide conditions that support more stable water flow and more significant discharge compared to other morphologies.

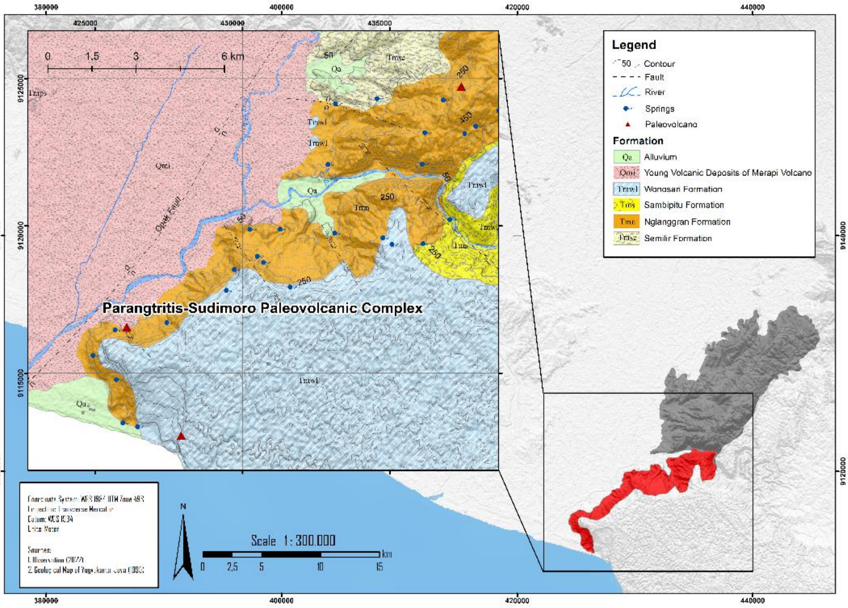


Fig. 3. Geological Map of the Parangtritis-Sudimoro Paleovolcanic Complex

On the other side, the Sumberkulon-Dengkeng paleovolcanic complex shows a much smaller spring discharge across the morphology in this region. The highly dissected structural mountains here have an average discharge of 0.06 l/s, and the moderately dissected structural mountains have 0.05 l/s. Cuesta shows a more significant increase in discharge of 0.53 l/s, likely influenced by sandstone and tuffaceous claystone layers that allow better water infiltration. Other morphologies, such as the Merapi volcanic footslope and volcanic remnants, show more excellent discharge rates but are generally smaller than the springs in the Parangtritis-Sudimoro paleovolcanic complex.

The difference in water discharge between these two areas can be explained by the characteristics of the rocks underlying each morphology. In the Parangtritis-Sudimoro paleovolcanic complex, the more complex volcanic and sedimentary rocks provide better water storage capacity. In contrast, in the Sumberkulon-Dengkeng paleovolcanic complex, rocks such as tuffaceous limestone and andesite intrusions with low permeability produce minor discharge.

Spring water quality on paleovolcanoes in the Southern Mountains of Baturagung Zone

The quality of spring water showed diverse outcomes in the measurements taken. This study measured five main parameters of water quality namely temperature, total dissolved solids (TDS), pH, and electrical conductivity (EC). The results of the measurements of each parameter within the Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complexes are detailed as follows. Spring temperatures throughout the study area show that most springs fall into the hypothermal springs category (20-30°C), with an average temperature of 27.26°C. The temperature range in the study area ranged from 24.94°C to a maximum of 33.80°C, with a standard deviation of 1.32°C, indicating that temperature variations were relatively small. The highest water temperature was at Parang Wedang Spring, the only spring in the thermal springs category (30-50°C).

Springs in the Parangtritis-Sudimoro paleovolcanic complex have a mean temperature of 27.71°C (standard deviation 1.74°C), with a range of 25.88 - 33.80°C, indicating more significant temperature variation. In contrast, the Sumberkulon-Dengkeng paleovolcanic complex has a lower mean temperature of 27.03°C (standard deviation 0.99°C), with a narrower range of 24.94 - 28.61°C, suggesting more excellent temperature stability. The mean temperatures of these two complexes were not statistically different. Elevation analysis showed little effect on water temperature ($R^2 = 0.23$).

The spring water pH in the study area ranged from 6-9, and it was suitable for drinking water based on the Regulation of the Minister of Health of the Republic of Indonesia Number 492/Menkes/Per/IV/2010. Based on the classification of Subtavewung et al. (2005), 36 springs are neutral (6-7.5), and 17 are weak alkaline springs (7.5-9). The average pH in the Parangtritis-Sudimoro paleovolcanic complex is 7.6 with a range of 6.5-9.2, while in the Sumberkulon Dengkeng palevolcanic complex, the average is 7.2 with a range of 6.3-9. Weak alkaline water is generally not harmful to health but can cause aesthetic problems such as alkaline taste, scale, and residue on clothing (Dirisu et al., 2016).

Measurement results showed that the average TDS of springs in the study area was 363 ppm with a median value of 192 ppm and a standard deviation of 1337 ppm, indicating a significant variation. The highest TDS was recorded at Parang Wedang (9899 ppm) in the Parangtritis-Sudimoro paleovolcanic complex, while the lowest was at Sumberkulon-Dengkeng (43 ppm). The Parangtritis-Sudimoro paleovolcanic complex has a higher mean TDS (773 ppm) with a range of 163-9899 ppm, showing significant variation. In contrast, the Sumberkulon-Dengkeng paleovolcanic complex has a lower mean TDS (152 ppm) with a narrower range of 43-381 ppm. Despite the difference in values, statistically, the TDS of these two complexes does not show any difference.

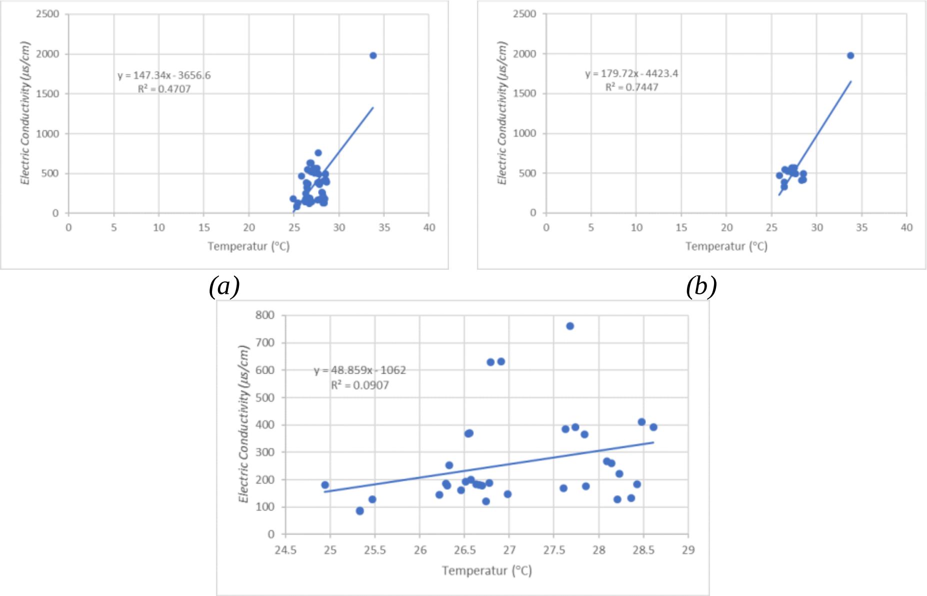
Based on the classification of springs categorized by Subtavewung et al. (2005) as hyperfresh (<100 ppm), there are 18 springs, and all are found in the Sumberkulon-Dengkeng Paleovolcanic Complex (Table 6). However, springs throughout the study area are mainly categorized as fresh (100-1000 ppm). Meanwhile, a spring also falls into the brackish category (1000-10,000 ppm), namely Parang Wedang spring. The high TDS and EC values are dominated by chloride concentrations caused by seawater contamination (Tae et al., 2018).

Table 6. Classification of TDS levels of paleovolcanic springs in the Southern Mountain of the Baturagung Zone

TDS Classification	The entire study area	Parangtritis-Sudimoro	Sumberkulon-Dengkeng
Hyper fresh (<100 ppm)	18	0	18
Fresh (100-1000 ppm)	34	17	17
Brackish (1000-10,000 ppm)	1	1	0
Total number of springs	53	18	35

Water quality in the study area showed variations in electric conductivity (EC) values, reflecting differences in dissolved ion content due to geological conditions. The mean EC was 359 µS/cm with a median of 327 µS/cm, standard deviation of 283 µS/cm, and ranged from 86 - 1979 µS/cm. The Parangtritis-Sudimoro paleovolcanic complex has a higher mean EC (555 µS/cm) with a median of 494 µS/cm, a standard deviation of 363 µS/cm, and a range of 327-1979 µS/cm, showing large fluctuations. In contrast, the Sumberkulon-Dengkeng paleovolcanic complex has a lower mean EC (258 µS/cm) with a median of 185 µS/cm, a standard deviation of 160 µS/cm, and a range of 86 - 761 µS/cm, suggesting a lower and more consistent dissolved ion content.

The maximum value of EC is found in the Parang Wedang thermal springs. According to Davie (2008), temperature influences electrical conductivity (EC) because it affect the mobility of ions in the water. In the Parangtritis-Sudimoro paleovolcanic complex, the influence of water temperature on EC was quite considerable, with R^2 of 0.74 (Fig. 4b). However, the impact of temperature on EC is not very strong, with R^2 0.47 for the entire study area (Fig. 4a), and the Sumberkulon-Dengkeng paleovolcanic complex with R^2 0.09 (Fig. 4c). This suggests that other factors influence EC, such as TDS.

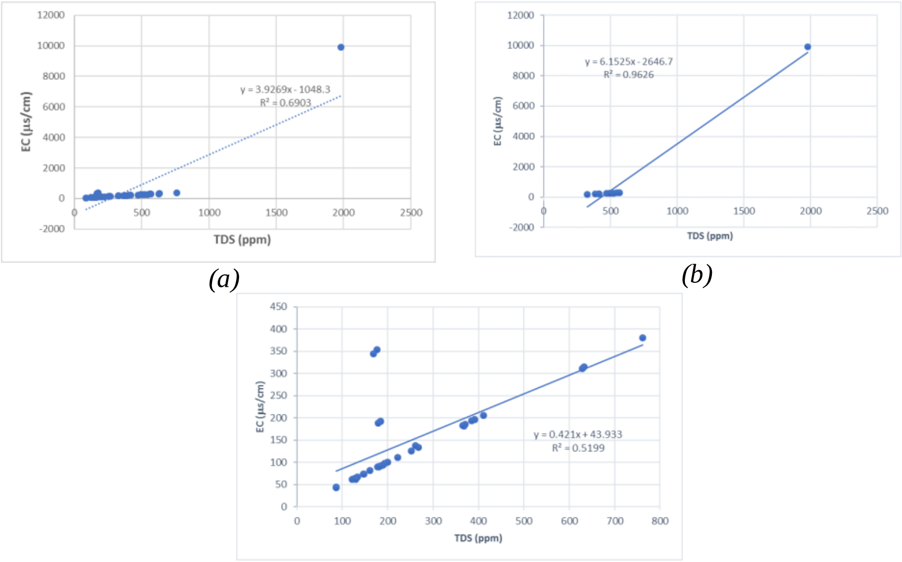


(a) *(b)*

(c)

Fig. 4. Influence of water temperature on the electric conductivity (EC) of spring water in (a) the entire study area, (b) Parangtritis-Sudimoro Paleovolcanic Complex, and (c) Sumberkulon-Dengkeng Paleovolcanic Complex

The results of electrical conductivity (EC) measurements tend to be the same as those of TDS measurements, which are reasonable conditions because TDS is a factor that significantly affects EC. An increase in the total dissolved solids (TDS) will increase the water's ability to conduct electricity. Davie (2008) explains that electrical conductivity (EC) is the ability of water to conduct electrical current, which is influenced by the concentration of the solution, the total valence of the dissolved ions, and the mobility of these ions in the water. Based on this theory, a simple regression analysis was conducted to test the relationship between TDS and EC. The findings revealed a strong positive correlation between TDS and EC, with coefficient of determination (R^2) of 0.69 across all spring samples (Fig. 5a). Springs in the Parangtritis-Sudimoro paleovolcanic complex showed a robust correlation with R^2 of 0.96 (Fig. 5b), and springs in the Sumberkulon-Dengkeng paleovolcanic complex had a strong correlation with R^2 of 0.51 (Fig. 5c). This indicates that there are significant differences in influence between water temperature and EC and between TDS and EC. The TDS parameter has a more substantial impact on EC than water temperature. A summary of the measurement results of all water quality parameters is presented in Table 7.



(a) *(b)*

(c)

Fig 5. Influence of total dissolved solids (TDS) on the electric conductivity (EC) of spring water in (a) the entire study area, (b) Parangtritis-Sudimoro paleovolcanic complex, and (c) Sumberkulon-Dengkeng paleovolcanic complex

Table 7. Summary of water quality data of paleovolcanic springs in the southern mountain of Baturagung Zone

Parameters		Parangtritis-Sudimoro	Sumberkulon-Dengkeng
Temperature (°C)	n	18	35
	Mean	27,71	27,03
	Median	27,30	26,78
	St. Dev	1,74	0,99
	Max	33,80	28,61
	Min	25,88	24,94
pH	n	18	35
	Mean	7,68	7,26
	Median	7,55	7,20
	St. Dev	0,50	0,53
	Max	8,90	9,00
	Min	7,00	6,30
EC (µs/cm)	n	18	35
	Mean	555,94	258,57
	Median	494,50	185,00
	St. Dev	363,22	160,20
	Max	1979,00	761,00
	Min	327,00	86,00
TDS (ppm)	n	18	35
	Mean	773,78	152,80
	Median	252,00	126,00
	St. Dev	2277,68	93,54
	Max	9899,00	381,00
	Min	163,00	43,00

Discussion

The findings outlined in the previous section highlight key aspect of this study, especially related to the distribution pattern of springs, their discharge rates, and the different parameters of springs water quality. In general, the distribution of springs in the Southern Mountains of the Baturagung Zone is irregularly clustered, with a small number appearing to follow river courses and some appearing close to fault structures. This is an interesting finding because of the similarity of the clustering pattern with the results of previous studies conducted on volcanic landforms of different stages of development, namely young volcanoes, old volcanoes, and other paleovolcanoes in Central Java. Studies conducted by Aurita and Purwantara (2017) and Ratih et al. (2018) on young volcanoes such as Merapi also show a clustered distribution pattern, with the characteristics of appearing on the break of slope and river channels to form a relatively regular spring belt. This is due to the influence of volcanic processes that are more intensive than exogenous processes. In volcanoes that have advanced development, such as Merbabu Volcano and Old Lawu Volcano, there are also clustered patterns that form a springbelt but with irregular patterns (Ashari & Widodo, 2019; Hermawan et al., 2024; Santosa, 2006). This condition is caused by exogenous processes such as erosion and mass movements on volcanic slopes characterized by intensive valley widening and deepening. Other similar spring distribution patterns are also found in paleovolcanoes. A study by Salsabila et al. (2022) on the Gajah and Menoreh Paleovolcanoes found clustered spring distribution patterns but predominantly on fault zones. However, fewer springs are located on fault lines in the Southern Mountains of the Baturagung Zone than in the Paleovolcano of Gajah and Menoreh. Distribution patterns influenced by fault structures were also found in Santosa's (2006) study, which showed that springs appear clustered around the main fault of the Old Lawu Volcano. This indicates that the level of landform development and tectonic activity influences the characteristics of spring distribution. The older the level of landform development, the more irregular the pattern of spring distribution becomes. However, in areas with high tectonic activity, spring distribution patterns generally follow the pattern of the underlying geological structure.

Based on its morphology, paleovolcanic springs in the Southern Mountains of the Baturagung Zone show a different distribution from the findings of Salsabila et al. (2022) in the Gajah and Menoreh paleovolcano. The distribution of paleovolcanic springs in the Southern Mountains of the Baturagung Zone is dominantly found in the moderately dissected structural mountains morphology followed by cuesta morphology. In Gajah and Menoreh, paleovolcano is dominant in intermontane valley morphology. Rock conditions in the Moderately Dissected Structural Mountains morphology of tuff, breccia, and tuffan sandstone have high porosity (Kresic & Stevanovic, 2010). The combination of permeable and impermeable rocks, such as claystone, helps water collect in the aquifer and eventually appear as springs. In addition, the morphology of moderately dissected structural mountains has an average slope of moderately steep (15-25%). This slope has an ideal balance between gravity and hydrostatic pressure, so water collected in the aquifer can be pushed into springs. Geomorphological factors contribute to determining the distribution of springs. Santosa (2006) states that the presence of springs in an area is influenced by geomorphological conditions, as el as rainfall, rock permeability, lithological characteristics, land use, and geological structure.

The pattern of spring distribution, specifically in each Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complex, shows a random pattern. This is due to the strong influence of geomorphologic processes, such as landform denudation, which has shifted spring locations from their original positions. The dynamics of the erosion process are extreme, causing changes in the slope's morphology so that the slope's boundaries are no longer visible and making springs appear randomly and irregularly (Santosa, 2006).

Spring discharge with considerable variation from class V (1 - 10 l/s) to VIII (<0.01 l/s) with an average discharge of 0.75 l/s, including class VI (0.1 - 1 liter/second) is found in paleovolcanoes in the Southern Mountains of the Baturagung Zone. These findings have similarities in spring discharge conditions with the studies of Salsabila et al. (2022) and Santosa and Narulita (2020) on the Gajah and Menoreh Paleovolcanoes but have different findings on young volcanoes such as Merapi Volcano, Sumbing and Sindoro Volcanoes, and Ciremai Volcano (Aurita & Purwantara, 2017; Ervin et al., 2022; Irawan et al., 2009; Ratih et al., 2018), and old volcanoes including Merbabu Volcano and Lawu Volcano (Ashari & Widodo, 2019; Hermawan et al., 2024; Santosa, 2006). The findings of spring discharge on the paleovolcano show a relatively small flow equation; the average spring discharge is class

VI (0.1 - 1 liter/second). The old rock development factor in paleovolcanoes causes the compaction and gluing process to run more intensively. Hence, the cavity between grains becomes small, and it is challenging to drain large amounts of groundwater.

Different conditions in young volcanoes show relatively more significant spring discharge than those in paleovolcanoes. The results of studies conducted by Aurita and Purwantara (2017) on the western slopes of Merapi Volcano, Ratih et al. (2018) on the southern slopes of Merapi Volcano, Ervin et al. (2022) between the slopes of Sumbing and Sindoro Volcanoes, and Irawan et al. (2009) on Ciremai Volcano, which represents young volcanoes, show that the average spring discharge is included in class IV (10 - 100 l/s) and V (1 - 10 l/s). The characteristics of young volcanoes whose development level is still strongly influenced by volcanic activity, with a relatively new arrangement of loose material, make young volcanic areas ideal as aquifers because they can store and drain water efficiently. However, rock age development is not the only factor affecting spring discharge. Lithology also plays a vital role in influencing variations in spring discharge. Variations in spring discharge on old volcanoes in studies conducted by Ashari and Widodo (2019) and Hermawan et al. (2024) on the slopes of the Merbabu Volcano and Santosa (2006) on the slopes of the Old Lawu Volcano generally have an average discharge included in classes V (1 - 10 l/s) and VI (0.1 - 1 liter/second). However, in his study, several springs also belonged to class IV (10 - 100 l/s) and even class III (100 - 1000 l/s). This is due to the lithologic composition of the volcanic slope morphology, where pyroclastics are located at the top as aquifers, while relatively impermeable older volcanic rocks are located below (Santosa, 2006).

In particular, the spring discharge between Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complexes also shows different averages. The Parangtritis-Sudimoro paleovolcanic complex has a more significant average spring discharge of 1.64 l/s and belongs to class V. The Parangtritis-Sudimoro paleovolcanic complex is geologically associated with the Wonosari Formation, which is above the Nglanggran Formation and is composed of reef limestone, calcarenite, and tuffaceous calcarenite. The Wonosari Formation's limestone constituent material causes an intensive dissolution process, resulting in a more excellent graduation value. Consequently, the spring discharge that emerges through the dissolution zone will also increase (Santosa, 2006). Meanwhile, spring discharge in the Sumberkulon-Dengkeng paleovolcanic complex averages 0.29 l/s and is class VI. The relatively old level of development and the dominant material composition of sandstones and tuffaceous mudstones give this area suitable aquifers but with smaller straightness. Wardoyo and Khotimah (2021) state that the characteristics of spring discharge are inseparable from the characteristics of the aquifer, which are influenced by local conditions in the area of spring emergence.

Several water quality parameters showed interesting findings, including water temperature, pH, total dissolved solids (TDS), and electric conductivity (EC). The temperature of spring water observed in this study was within a narrow range. Statistically, there was no significant difference in the average water temperature between the two paleovolcanic complexes. Overall, the springs are dominated by hypothermal springs, but there is one thermal spring in the Parangtritis-Sudimoro paleovolcanic complex, namely the Parang Wedang spring. According to Pratiwi and Kiswiranti (2021), the Parang Wedang spring is a manifestation of geothermal heat whose emergence is caused by the Girijati descending fault and is located in a lowland morphology. In addition, the low Boron (B)/Chloride (Cl) ratio value indicates that the spring falls into the older hypothermal category. The Parang Wedang

Spring is located at 200-300 meters (Sari & Listiyanto, 2018). This condition is described by Rosli et al. (2022). Their study results also mentioned that thermal springs are formed due to subsurface temperatures increasing with depth, and the deeper the rock becomes hot. Another finding in this study also shows that the elevation factor also affects the variation in water temperature. However, it only contributes slightly to paleovolcanic springs in the Southern Mountains of the Baturagung Zone. This finding is similar to the findings of Ashari and Widodo (2019), Hermawan et al. (2024), and Wardoyo and Khotimah (2021) in Merbabu and Merapi Volcanoes, which showed that elevation correlates with spring temperature variations. However, elevation is not the only factor affecting water temperature.

Water pH measurements show that all paleovolcanic springs in the Southern Mountains of the Baturagung Zone are relatively neutral, and a few tend to be weak alkaline. This finding is interesting because the morphology of former active volcanoes should have volcanic rock material that affects the pH characteristics of the water to be more acidic. Irawan and Puradimadja (2015) also mentioned that water pH in volcanic rocks is generally acidic because mineral components such as silica and mafic can release specific ions into water when scientific weathering occurs. However, paleovolcano environments dominated by intense denudation processes by geomorphic agent activities such as erosion, weathering, and material transportation become factors that affect the pH characteristics of water. Volcanic rock material that is fragmented and mixed with other minerals, including carbonates in the surrounding sedimentary or alluvial layers, can increase water alkalinity, reduce acidity, and bring water pH closer to neutral or even alkaline (Davie, 2008; Erlanger et al., 2021; Ran et al., 2015). This condition is more evident in springs in the Parangtritis-Sudimoro paleovolcanic complex, which is geologically associated with the Wonosari Formation, which is composed of limestone material, so this area has more weak alkaline springs (Kusumayudha, 2005).

The water quality parameters total dissolved solids (TDS) and electric conductivity (EC) also show interesting findings. These two parameters differed between springs in the Parangtritis-Sudimoro and Sumberkulon-Dengkeng paleovolcanic complex. The average TDS and EC values of springs in the Parangtritis-Sudimoro paleovolcanic complex are higher than those in the Sumberkulon-Dengkeng paleovolcanic complex. The presence of the Wonosari Formation of the middle to late Miocene age has a decisive role in influencing the variation of TDS and EC in the Parangtritis-Sudimoro Paleovolcanic Complex. Santosa (2006) states that the development of this Miocene-age limestone underwent a more intensive dissolution process. This condition causes rain that falls on the limestone surface to dissolve and increase the sediment material dissolved in water. Higher levels of total dissolved solids (TDS) in water enhance its electrical conductivity (Davie, 2008). This factor also makes the correlation between TDS and EC very strong in the Parangtritis-Sudimoro paleovolcanic complex but lower in the Sumberkulon-Dengkeng paleovolcanic complex springs. The difference in TDS and EC values between the two paleovolcanic complexes reflects that local lithological variations and geomorphic processes are essential in determining water quality in each region.

Conclusion

Paleovolcanic terrains exhibit unique hydrogeomorphological features, characterized mainly by irregularly clustered springs, a small number of which follow river courses and appear close to fault structures. In particular, the Parangtritis-Sudimoro and Sumberkulon-Dengkeng Paleovolcanic Complex, respectively, have random distribution patterns. The more advanced level of landform development in paleovolcanoes and tectonism contribute significantly to the spring distribution pattern, making this finding different from previous studies on young and old volcanoes. The geomorphologic process of intensive landform denudation is also a factor in the irregular pattern of spring distribution in paleovolcanic areas.

Differences in local geologic and geomorphologic characteristics also cause spring discharge to be more variable. The findings of this study are that the discharge of paleovolcanic springs has a relatively small average compared to both young and old volcanoes. As with the pattern of spring distribution, these discharge characteristics are also influenced by the rocks' age and the landforms' lithological composition. One of the key findings of this study is that, even at the height of the dry season, many springs continue to flow, although the discharge is not always substantial. Water quality characteristics using water temperature parameters, pH, total dissolved solids (TDS), and electric conductivity (EC) in springs at Parangtritis-Sudimoro and Sumberkulon Dengkeng Paleovolcanic Complex show some differences. The differences in water quality characteristics in some of these parameters are strongly influenced by the surrounding geological conditions, especially the presence of the Wonosari Formation in the Parangtritis-Sudimoro Paleovolcanic Complex. Nevertheless, paleovolcanic springs in the Southern Mountains of the Baturagung Zone generally have good water quality and are suitable for consumption.

The results of this study provide an important basis for understanding the characteristics of paleovolcanic springs in the Southern Mountains of the Baturagung Zone. Findings on distribution patterns, discharge and water quality suggest distinctive dynamics compared to spring systems in other volcanic regions. This study represent a preliminary investigation into paleovolcanic springs within the Southern Mountains of the Baturagung Zone. Consequently, the analysis of water quality parameters is limited and insufficient for detailed classification according to the National Water Quality Standards listed in Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management. Future research is recommended to further explore water quality by analyzing additional parameters to provide more detailed recommendations, particularly regarding the utilization of water from various springs according to their water quality. It is also advised to conduct temporal studies on spring discharge, especially during the rainy and dry seasons, so that the findings can support efficient spring management by considering fluctuations in discharge, thereby aiding in the conservation and sustainability of spring resources.

Acknowledgment: The authors thank all staff and assistants at the Physical Geography Laboratory, Universitas Negeri Yogyakarta, who have provided equipment, research instruments, support in fieldwork, and constructive discussions during the preparation of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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