



Influence of Volcanic Lithology on Soil Physical Properties in the Watugede Sub-watershed

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Abstract

Lithology is one of the primary geological factors that control landform dynamics and soil development, particularly in tropical volcanic regions where weathering is intense. While previous research has emphasized the role of climate, slope, and land cover on soil properties and land degradation, studies that directly address the influence of lithological variation on soil physical properties through geomorphology at the sub-watershed scale remain limited. This study focuses on the Watugede Sub-watershed in Yogyakarta, Indonesia, which comprises three distinct volcanic formations: Kebobutak, Semilir, and Nglanggeran. These formations represent diverse lithological and geomorphological conditions. The objectives of this study are to (1) identify the lithological and geomorphological characteristics of the Watugede Sub-watershed, and (2) analyze the physical properties of soils that develop above each formation. Lithological data were obtained from geological maps and field surveys, while soil data were collected using purposive sampling at two depths (0–30 cm and 30–60 cm) with four replications. Laboratory analyses included bulk density, specific gravity, texture, permeability, maximum water content, and soil cohesion. The results show that lithological differences strongly influence soil physical characteristics and slope stability. Soils on the Kebobutak Formation have sandy to sandy loam textures with moderate cohesion and permeability, indicating relatively stable conditions but prone to local water saturation in fine tuff layers. The Semilir Formation produces heterogeneous soils with very fast permeability and low cohesion, reflecting susceptibility to erosion and slope deformation. The Nglanggeran Formation yields sandy loam soils with fast to moderate permeability and higher cohesion than those of Semilir, but instability persists on steep slopes due to intense fracturing and weathering. This study contributes to a deeper understanding of lithology–geomorphology–soil interactions in tropical volcanic watersheds, providing a scientific basis for watershed management and slope stability assessment.

Keywords *Geomorphology, Lithology, Soil Physical Properties*

INTRODUCTION

Lithology is one of the key geological factors that control landscape dynamics and soil development. Variations in rock type, mineral composition, and degree of weathering not only determine geomorphological features but also influence the properties of the overlying soils (Kahsay et al., 2023; Kübler et al., 2021; Liao et al., 2022). Understanding the relationship between lithology, geomorphology, and soil is particularly important in tropical regions, where weathering processes are highly intense. This study holds academic significance in both geology and pedology and is also relevant to land resource management and watershed conservation.

Previous research has primarily focused on the influence of climate, land cover, and slope on soil characteristics and vulnerability. However, studies that specifically investigate the relationship between lithology and soil physical properties through geomorphological processes at the sub-watershed scale remain relatively limited, particularly in tropical volcanic regions.

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Variations in lithology can generate distinct geomorphological features, ranging from steep slopes formed by volcanic breccias to undulating hills developed in tuff areas, which in turn affect soil physical properties ([Hakim et al., 2024](#); [Indrawan et al., 2024](#)). Therefore, an integrative analysis of lithology, geomorphology, and soil physical properties is essential for developing a more comprehensive understanding of the biophysical conditions within a watershed.

The Watugede Sub-watershed exhibits a unique diversity of volcanic lithologies. It consists of three main formations: the Kebobutak Formation, the Semilir Formation, and the Nglanggeran Formation, each characterized by distinct rock compositions, structures, and degrees of weathering. These lithological variations give rise to diverse geomorphological features, which in turn influence soil physical properties such as texture, porosity, and permeability. This makes the Watugede Sub-watershed a representative site for investigating the relationship between lithology, geomorphology, and soil physical characteristics at the sub-watershed scale. This study aims to: (1) identify the lithological and geomorphological characteristics of the Watugede Sub-watershed; and (2) analyze the soil physical properties that develop within each lithology. The findings are expected to enhance the understanding of the relationship between lithology, geomorphology, and soil physical characteristics in tropical volcanic areas, while also enriching the knowledge base for watershed management in Indonesia and other tropical regions.

LITERATURE REVIEW

Lithology, defined as the type and composition of parent material, is a fundamental geological factor that governs landform development and soil characteristics ([Alsbach et al., 2024](#); [Toscani et al., 2025](#)). The rock type, mineralogical composition, and degree of weathering collectively determine the mechanical strength of rock masses ([Jaques et al., 2021](#); [Liu et al., 2022](#); [Pachri et al., 2024](#)). In addition, geological structures such as bedding planes, joints, and faults serve as zones of weakness that can facilitate slope deformation. As a result, lithological variations within a landscape give rise to morphological diversity ([Choudhury, 2024](#); [Oliveira et al., 2025](#)), ranging from steep slopes and undulating hills to gently sloping plains, which directly influence slope stability ([Azarafza et al., 2021](#); [Miklin et al., 2022](#)).

Previous studies have highlighted the significant role of lithology in shaping geomorphology and soil characteristics. The ultramafic rocks generate soils with high cation exchange capacity and elevated pH, whereas silicate sandstones tend to form coarse-textured, acidic, and nutrient-deficient soils ([da Silva et al., 2022](#)). Similarly, parent materials, such as alluvium and aeolian deposits, exert a strong control over bulk density, clay fraction, and nutrient content ([Alnaimy et al., 2023](#); [Mahmood et al., 2022](#)). In volcanic environments, lithologies composed of pyroclastic material, volcanic breccia, and tuff are highly susceptible to intensive weathering driven by the combined effects of tectonic activity, humid tropical climates, and rainwater infiltration ([de Mello et al., 2023](#); [Dill et al., 2023](#); [Gargani, 2023](#); [Siegesmund et al., 2023](#)).

Lithological variation is a primary controlling factor in soil formation, as differences in mineral composition and rock structure give rise to distinct soil characteristics ([Quesada et al., 2020](#)). Such variations have direct implications for soil physical properties. Massive volcanic rocks, such as breccias or andesitic lavas, generally develop soils with relatively higher cohesion compared to fine-grained tuffs, which are more prone to rapid weathering. Fine-grained tuffs, in particular, tend to form clay-textured soils with high porosity but low shear strength, rendering them more vulnerable to deformation under conditions of water saturation ([Indrawan et al., 2024](#)).

Furthermore, lithology governs the texture and distribution of soil fractions, which directly affect permeability, infiltration capacity, and nutrient availability ([Hu et al., 2024](#); [Muslim et al., 2024](#)). Soils derived from tuff weathering typically exhibit fine textures with high water-holding capacity but poor drainage, making them easily saturated and highly susceptible to erosion and

landslides (Xue et al., 2024). In contrast, soils from volcanic breccias with coarse fragments show better drainage and greater stability under saturation, through with lower nutrient retention. Thus, lithological differences create contrasting soil properties that affect fertility and land use potential. Within a watershed, resistant lithologies generally form steep slopes with thin, well-drained soils, while easily weathered lithologies develop into undulating hills with thicker, poorly drained soils. These contrasts strongly influence vulnerability to degradation, highlighting the importance of linking lithology and soil properties to support sustainable watershed management.

RESEARCH METHOD

Study Area

This study was conducted in the Watugede Sub-watershed, which constitutes the upstream part of the Oyo Watershed system and covers an area of approximately 2,283 ha. Geographically, it is located between 7°49'30"-7°53'0" South Latitude and 110°34'0"-110°38'0" East Longitude, crossing four villages: Hargomulyo, Mertelu, and Ngalang in Gedangsari District, and Pengkol in Nglipar District. According to the Wonosari Sheet of the Regional Geological Map (Surono, 2008), the Watugede Sub-watershed consists of three main formations: the Kebobutak Formation, Semilir Formation, and Nglanggeran Formation. These lithological variations produce diverse geomorphological landscapes, ranging from steep hills in volcanic breccias (Nglanggeran), undulating to hilly slopes in tuff-dominated areas (Semilir), to relatively gentle plains and narrow valleys associated with the Kebobutak Formation (Figure 1).

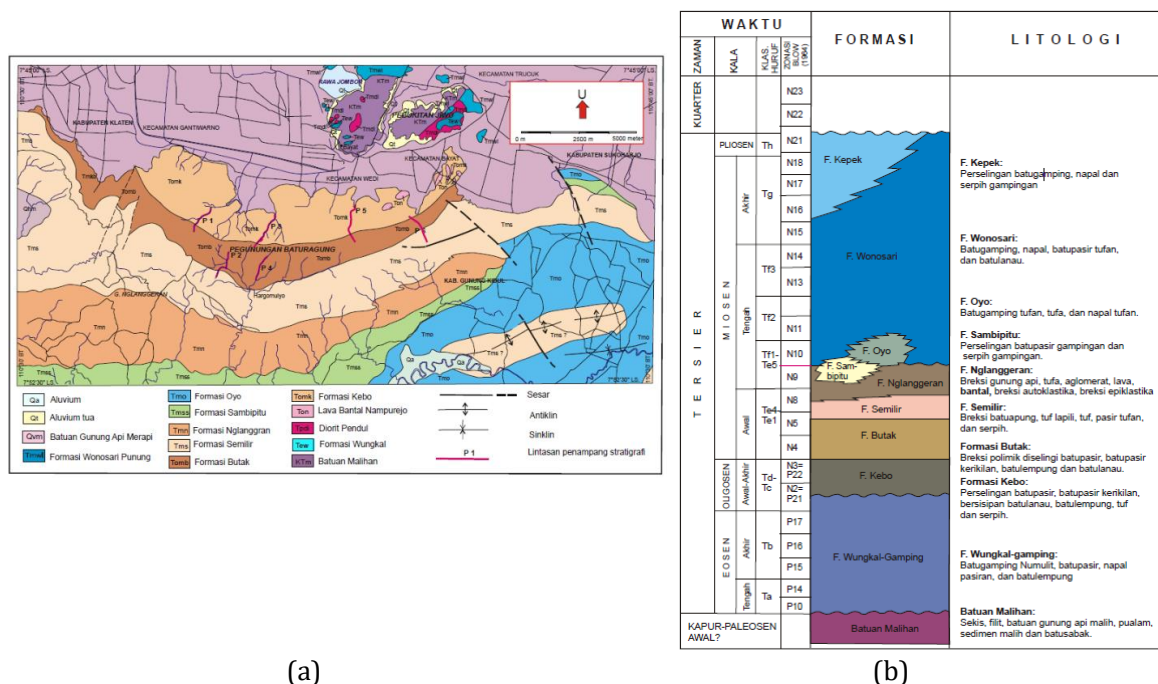


Figure 1. (a) Geological map of the study area (b) Stratigraphy of the Baturagung Mountains and Jiwo Hills

Source: Surono (2008)

Materials and Methods

Lithology Data

Lithological data were obtained from the Wonosari Sheet Regional Geological Map ([Surono, 2009](#)) and complemented by surface geological surveys. Representative lithological samples were collected and analyzed, consisting of one sample from the Kebobutak Formation, four samples from the Semilir Formation, and three samples from the Nglanggeran Formation. Macroscopic observations were conducted using a hand lens, rock comparator, and HCl solution for the identification of carbonate minerals. The analysis included descriptions of color, texture, grain size, sorting, and mineral composition, which were then used to classify and determine the lithological types based on standard geological criteria.

Soil Data

Soil samples were collected at locations representing each rock formation using a purposive sampling method, at two depths: 0–30 cm and 30–60 cm. Each sampling was repeated four times, and the results were averaged to obtain representative values. Laboratory analyses were conducted to identify soil physical properties through the following parameters: (1) bulk density, determined using the ring method with intact soil samples; (2) permeability, measured by the constant head method on intact soil samples in the sample ring; (3) particle density, determined using the pycnometer method on soil samples sieved through a 2 mm mesh; (4) soil texture, analyzed using the pipette method to obtain percentages of sand, silt, and clay fractions; (5) maximum water content, determined using saturated soil samples placed in cups and oven-dried to constant weight, with values calculated from weight differences before and after drying; and (6) soil shear strength, tested using the direct shear method to measure soil response to shear stress under specified normal loads ([Irawan et al, 2022](#)).

Data Analysis

The lithological and soil physical properties data were compiled to identify the relationships among lithology, geomorphology, and soil physical properties. The analysis involved describing the variations in lithological characteristics within each formation and the corresponding soil physical properties developed above them. These relationships were then interpreted to explain how differences in parent material influence soil physical attributes, with emphasis on their implications for landscape development and watershed-scale processes.

FINDINGS AND DISCUSSION

Lithology and Geomorphology Sample Analysis

Lithological analysis of the Kebobutak Formation was conducted on a single sample located at coordinates 454089, 9131142. The outcrop exhibits pyroclastic breccia overlain by tuff and lapilli layers in semi-weathered conditions (Figure 2). The pyroclastic breccia is black to grayish, massive, with angular igneous rock fragments measuring more than 64 mm. Mafic minerals, particularly pyroxene, dominate the fragments, while the matrix consists of sand-sized particles with non-carbonate cement and poor sorting. Overlying the breccia is a sequence of tuff and lapilli (Figure 3). The tuff is grayish-white, massive, fine-grained (<2 mm), and characterized by scattered quartz mineral spots. In contrast, the lapilli are grayish-white to brown, massive, with coarser angular fragments (2–64 mm), poorly sorted, and composed of quartz, pyroxene, and volcanic ash.



Figure 2. Pyroclastic breccia in the Kebobutak formation

This lithological combination reflects an explosive volcanic eruption phase that produced layered fallout deposits. The pyroclastic breccia, dominated by pyroxene-rich mafic fragments, suggests a parent material that is relatively susceptible to weathering. The overlying tuff promotes the development of clay-textured soils with low permeability, while the lapilli layers contribute to the formation of coarser-textured soils with relatively better drainage. Geomorphologically, the Kebobutak Formation is typically associated with narrow valleys and steep to dissected slopes, indicating the influence of both easily weathered lithologies and active erosional processes. These lithological variations highlight that, although the breccia appears massive and resistant, the presence of intercalated tuff and the effects of advanced weathering render this unit vulnerable to morphological change and the development of soils with contrasting physical properties.



Figure 3. The presence of (a) lapilli stone and (b) tuff in the Kebobutak formation

Lithological analysis of the Semilir Formation was conducted at three representative locations. At the first location (coordinates 455070, 9132700), the outcrop consists of fresh, massive white tuff with a grain size of 0.25–0.5 mm (Figure 4). The deposit exhibits good grain sorting with close packing and is composed of lithic fragments, quartz, pyroxene, and volcanic ash. At the second location (coordinates 455252, 9132862), alternating layers of tuffaceous sand and fine tuff were identified (Figure 5). The fine tuff is pale white, with a grain size of 0.004–0.06 mm, well sorted, and dominated by silt-sized material. In contrast, the tuffaceous sand layer is brownish-white, with a grain size of 0.25–0.5 mm, well-sorted, closely packed, and contains lithic minerals

along with plagioclase and quartz. At the third location (coordinates 453503.22, 9132230.74), an interbedded sequence of volcanic sandstone and lapilli was found (Figure 6). The sandstone is black, finely laminated, with a grain size of 0.06–0.125 mm, and well sorted. Meanwhile, the lapilli are white, massive, poorly sorted, with grain sizes of 2–64 mm, and composed of lithic fragments, plagioclase, and volcanic ash.

Lithological variations in the Semilir Formation reflect a combination of quiet sedimentation processes (fine-grained tuff, laminated sandstone) and higher-energy depositional events (lapilli, tuffaceous sand). This pattern indicates repeated cycles of eruption and deposition, generating a diverse lithological composition. Geomorphologically, the formation is typically associated with undulating to gently sloping hills, reflecting its relatively less compact and easily dissected materials. Fine-grained tuff tends to weather into clay-rich soils with high porosity but low permeability, making them prone to water saturation. In contrast, tuffaceous sand and lapilli support the formation of soils with relatively better drainage. Together, these lithological variations result in soils of the Semilir Formation exhibiting high physical heterogeneity, ranging from fine- to coarse-textured soils, with significant implications for water storage capacity and soil stability.



Figure 4. Coarse tuff of the Semilir Formation at observation location 1

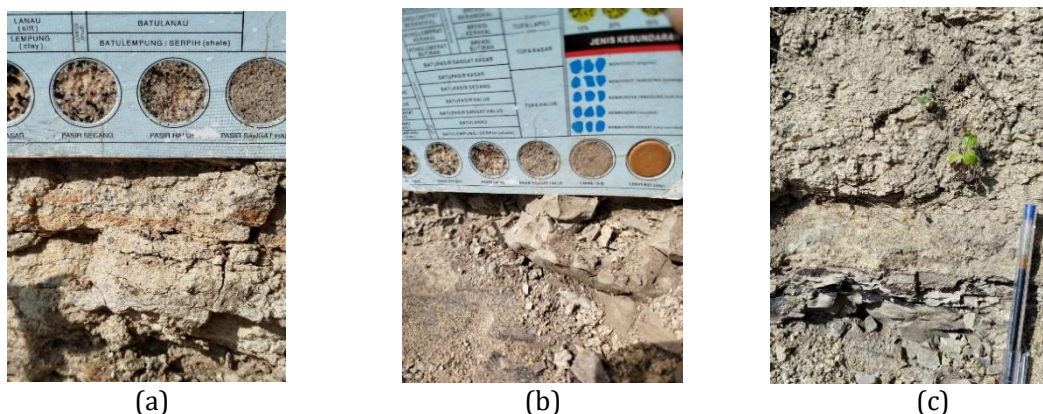


Figure 5. (a) coarse tuff, (b) fine tuff, and (c) interbedded coarse and fine tuff of the Semilir Formation at observation location 2



Figure 6. Occurrence of Volcanic Sandstone and Lapilli in the Semilir Formation at Observation Location 3

Lithological analysis of the Nglanggeran Formation was carried out on three samples from different locations. At the first location (coordinates 454089, 9131142), the outcrop consists of brownish-gray, massive, and poorly sorted pyroclastic breccia (Figure 7). The breccia contains vesicular fragments of extrusive igneous rocks measuring >64 mm, angular in shape, and rich in mafic minerals (pyroxene), while the matrix is composed of sand-sized material with non-carbonate cement. At the second location (coordinates 45410, 9131442), pyroclastic breccia was also identified, but the lithology is highly weathered and appears brown in color (Figure 8). The fragments are angular and >64 mm in size, but their mineral content is no longer visible macroscopically due to advanced weathering. The matrix consists of sand with non-carbonate cement and remains poorly sorted. This outcrop exhibits extensive fracturing, which has accelerated the degree of weathering compared to Nglanggeran 1. This condition is supported by the presence of a local well capable of producing groundwater and the observation of a river channel on the western side of the outcrop.

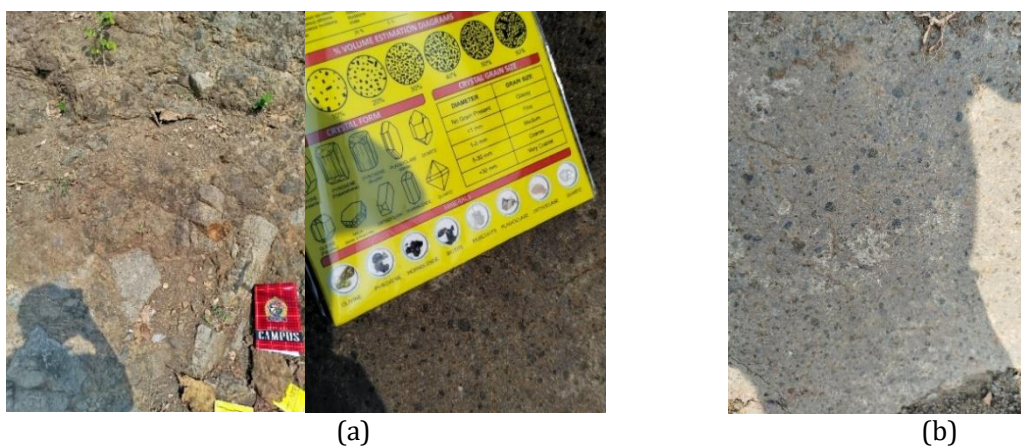


Figure 7. (a) Pyroclastic breccia, and (b) spots of pyroxene minerals in the Nglanggeran Formation at observation point 1

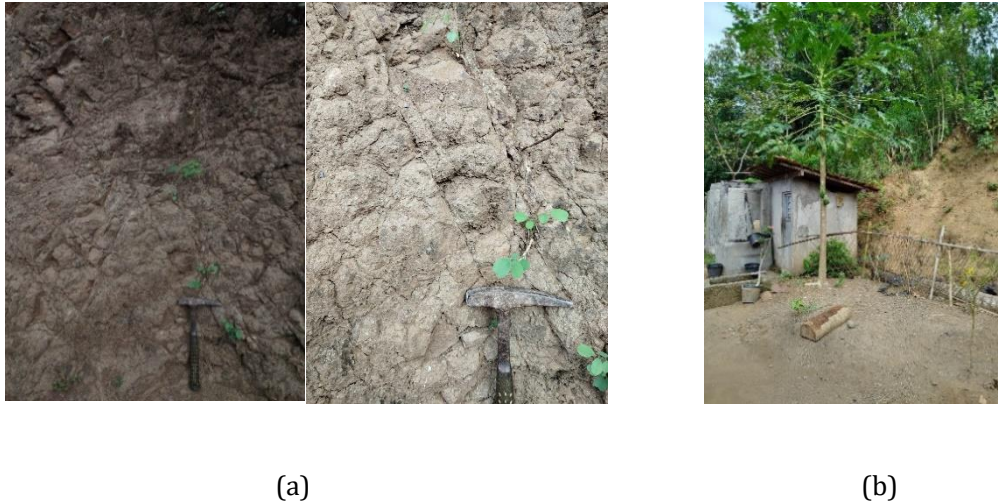


Figure 8. (a) Weathered pyroclastic breccia with massive fracturing, and (b) the occurrence of a well at the second observation point of the Nglanggeran Formation

In general, the Nglanggeran Formation is dominated by pyroclastic breccia with large, angular, and poorly sorted fragments, reflecting high-energy explosive eruption processes. The contrasting conditions between the fresh outcrop (Nglanggeran 1) and the weathered outcrop (Nglanggeran 2) emphasize the strong influence of both physical and chemical weathering. Intense fracturing enhances water infiltration and accelerates mineral alteration, leading to soils that are highly permeable but have low cohesion. Geomorphologically, the Nglanggeran Formation is therefore associated with steep hills and relatively unstable slopes. Overall, the results indicate that the three volcanic rock formations exhibit significant differences in lithological composition, which in turn influence geomorphological development and the physical properties of the soils formed upon them. These lithological and geomorphological variations are not only expressed in landform diversity but also strongly reflected in the physical characteristics of the soils developed on them.

Soil Sample Analysis

Soil analysis results indicate that the physical properties of the soil in the Watugede Sub-watershed vary significantly between formations (Table 1). These differences are closely related to the lithology and geomorphology of each formation. In the Kebobutak Formation, the upper layer (0–30 cm) exhibits a sandy to sandy clay texture with a permeability value of 18.3 cm/hour, categorized as fast and moderate cohesion. This condition is consistent with the lithology of pyroclastic breccia interbedded with tuff, where coarse breccia fragments enhance macroporosity and drainage, while the presence of tuff layers increases water storage capacity but also creates the potential for localized water saturation. In contrast, the lower layer (30–60 cm) shows a sandier texture with somewhat slower permeability. This suggests that at greater depths, the influence of fine-grained tuff becomes more dominant, reducing permeability while increasing the likelihood of water saturation. Therefore, although the upper layer is relatively stable, the lower layer can act as a weak plane when saturated, which is critical for slope stability, particularly in steep terrain.

Furthermore, the upper soil layer of the Semilir Formation exhibits a loamy texture with low bulk density. Permeability is very fast, reaching 26.16 cm/hour, while cohesion is relatively low. This condition is consistent with the fine-grained tuff lithology, which weathers easily and produces highly porous and permeable soils with low shear strength. Such characteristics highlight the susceptibility of the upper soil to surface erosion, particularly when high-intensity rainfall

infiltrates rapidly while mobilizing fine particles. In the lower layer (30–60 cm), permeability decreases slightly to 18.21 cm/hour, categorized as fast. The high permeability observed in both the upper and lower layers indicates that soils in the Semilir Formation are prone to rapid percolation and reduced cohesion when saturated, which helps explain their tendency for slope deformation within undulating geomorphological settings.

Meanwhile, the Nglanggeran Formation exhibits a sandy loam texture in the upper layer, with a permeability value of 16.15 cm/hour (fast) and relatively higher cohesion compared to the Semilir Formation. This condition corresponds to the pyroclastic breccia lithology, which is characterized by large fragments and massive fractures. Such features facilitate rapid water infiltration and enhance drainage. However, cohesion remains relatively low on steep slopes, creating potential for slope deformation, particularly under saturated conditions. In the lower layer (30–60 cm), the soil shows a sandier texture with permeability decreasing to 5.43 cm/hour (moderate), reflecting denser, less porous soil with fewer active fractures.

Table 1. Soil analysis data in the laboratory

Formation	Soil depth (cm)	Bulk density (g/cm ³)	Particle density (g/cm ³)	Permeability (cm/jam)	Texture	Cohession (kg/cm ²)	Maximum water content (%)
Kebobutak	0-30	1.223	2.123	18.307	Sandy loam	0.400	50.881
	30-60	1.229	2.155	1.694	Sandy		74.427
Semilir	0-30	1.025	1.829	26.163	Loam	0.280	111.974
	30-60	1.026	1.903	18.211	Loam		116.509
Nglanggeran	0-30	1.036	2.127	16.146	Sandy loam	0.450	81.094
	30-60	1.040	2.362	5.433	Sandy		79.455

This information is essential for determining priority areas for conservation, planting erosion-controlling vegetation, and managing land use within each sub-watershed. Based on these findings, the recommended watershed management strategies include: (1) soil and vegetation conservation on steep slopes composed of easily weathered lithologies, (2) implementation of drainage systems and surface flow control in areas with highly porous soils, and (3) the use of appropriate vegetative cover to enhance slope stability and soil water retention. A data-driven approach, based on lithology and soil properties, enables more effective and sustainable watershed management focused on mitigating land degradation risks.

CONCLUSIONS

This study demonstrates that lithological variation plays a key role in shaping soil physical properties and geomorphology in the Watugede Sub-watershed. The Kebobutak Formation produces soils with moderate cohesion and permeability, relatively stable but prone to local saturation in fine tuff layers. The Semilir Formation develops highly porous soils with very fast permeability but low cohesion, making them more vulnerable to erosion and slope deformation. The Nglanggeran Formation yields soils with fast to moderate permeability and relatively higher cohesion, though still susceptible to instability on steep slopes.

The results highlight that differences in lithology directly control soil heterogeneity, slope stability, and potential land degradation in volcanic tropical environments. These findings contribute to a better understanding of lithology–geomorphology–soil interactions, which are

important for watershed management and disaster risk reduction. Limitations of this study include the focus on soil physical properties without chemical or biological aspects, and the limited sampling scope. Further research should incorporate soil chemistry and hydrology, field-based geotechnical tests under saturated conditions, and long-term monitoring of slope stability to strengthen the understanding of land resource dynamics in tropical volcanic regions.

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