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Relationship between Topographic Wetness Index and Soil Physical Properties in Cikapundung Sub-watershed Using Geographic Information Systems

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ABSTRACT: Purpose: This study aimed to analyze the relationship between Topographic Wetness Index (TWI) and soil physical properties (permeability, porosity, bulk density, and soil moisture content) and their spatial distribution in the Cikapundung Sub-watershed.

Methods: A survey method was conducted through descriptive, correlation, and interpolation approaches. Thirty soil samples were collected based on a two-way stratification method using TWI and slope gradient. TWI was derived from Digital Elevation Model (DEM) data using GIS. Soil physical properties were analyzed in laboratory and their spatial distribution was mapped using interpolation techniques.

Results: TWI showed varying degrees of correlation with soil physical properties: significant positive correlation with soil permeability (r = 0.37), weak negative correlation with soil moisture content (r = -0.30), and very weak correlations with bulk density and soil porosity (r = -0.03 and r = 0.03). Spatial analysis revealed heterogeneous distribution patterns of soil physical properties across the sub-watershed.

Conclusion: TWI can only be effectively used as a single predictor for soil permeability, but not for bulk density, porosity, and soil moisture content in the Cikapundung Sub-watershed. This suggests the need for additional environmental parameters when predicting these soil physical properties.

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KEYWORDS: Empirical Bayesian Kriging, Environmental Monitoring, Geostatistics, Landscape Analysis, Soil Conservation

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INTRODUCTION

Watershed degradation has become a critical environmental issue globally, particularly in developing countries experiencing rapid land-use changes. The Cikapundung Sub-watershed, located in West Java, Indonesia, has undergone significant land-use transformations that have led to soil degradation problems. This degradation can be assessed through various soil physical properties, including permeability, porosity, bulk density, and soil moisture content[1].

Traditional methods of soil property assessment often require extensive field sampling and laboratory analysis, which can be time-consuming and resource-intensive[2]. The Topographic Wetness Index (TWI), derived from Digital Elevation Models (DEM), has emerged as a potentially valuable tool for predicting soil physical properties across landscapes[3]. TWI, which combines local upslope contributing area and slope gradient, can provide insights into soil moisture distribution patterns and related soil physical characteristics[4].

Previous studies have shown varying degrees of success in using TWI to predict soil properties. Some researchers have found strong correlations between TWI and soil moisture content[5], while others have reported mixed results for different soil physical properties[6]. However, there is limited research on the relationship between TWI and multiple soil physical properties in tropical watershed environments, particularly in Indonesia.

Geographic Information Systems (GIS) have revolutionized our ability to analyze and visualize spatial relationships in watershed management[7]. By integrating TWI analysis with GIS capabilities, it becomes possible to develop more efficient methods for predicting and mapping soil physical properties across large areas[8].

This study aims to analyze the relationships between TWI and soil physical properties (permeability, porosity, bulk density, and soil moisture content) in the Cikapundung Sub-watershed using GIS. Additionally, it seeks to evaluate the spatial distribution patterns of these soil properties and assess TWI's effectiveness as a predictor for each property. Understanding these relationships could provide valuable insights for watershed management and soil conservation efforts while potentially offering a more efficient approach to soil property assessment.

METHODS

Study Area

The study was conducted in the Cikapundung Sub-watershed, located in West Java, Indonesia. This area was selected due to its significant land use changes that have led to soil degradation issues. The sub-watershed covers approximately 18.530 hectares with elevations ranging from 652 – 2.201 meters above sea level.

Topographic Wetness Index Calculation and Mapping

Topographic Wetness Index (TWI) was calculated using Digital Elevation Model (DEM) data with 8 meter resolution. The TWI was computed using the formula:

$$TWI = \ln(\alpha/\tan\beta)$$

where α is the local upslope contributing area and β is the local slope gradient. ArcGIS Pro 3.0.36056 software was used for TWI calculation and mapping.

Sampling Design

A total of 30 soil sampling points were determined using a two-way stratification method based on TWI values and slope gradients. The sampling points were distributed to represent different TWI classes and topographic positions within the study area.

Field Sampling and Laboratory Analysis

Soil samples were collected from 0-30 cm depth using standard soil sampling procedures. The following soil physical properties were analyzed:

- Soil permeability using constant head permeameter method
- Soil porosity using gravimetric method
- Bulk density using core method
- Soil moisture content using gravimetric method

Spatial Analysis and Statistical Methods

Spatial distribution maps of soil properties were generated using Empirical Bayesian Kriging in ArcGIS Pro. Pearson correlation analysis was performed to examine relationships between TWI and soil physical properties. Statistical analyses were conducted using SmartstatXL Version 3.6.5.3 in Microsoft Excel 365 Version 16.0.17928.20156 at $p < 0.05$ significance level.

RESULTS

This study was conducted in the Cikapundung Sub-watershed, located in West Java Province, Indonesia. The research area spans approximately 18,530 hectares and encompasses parts of Bandung City, Bandung Regency, and West Bandung Regency.

Spatial Distribution of Soil Physical Properties

The spatial distribution of soil physical properties in the Cikapundung Sub-watershed was analyzed using GIS-based interpolation. Figures 1, 2, 3, and 4 illustrate the spatial patterns of soil permeability, porosity, bulk density, and soil moisture content, respectively.

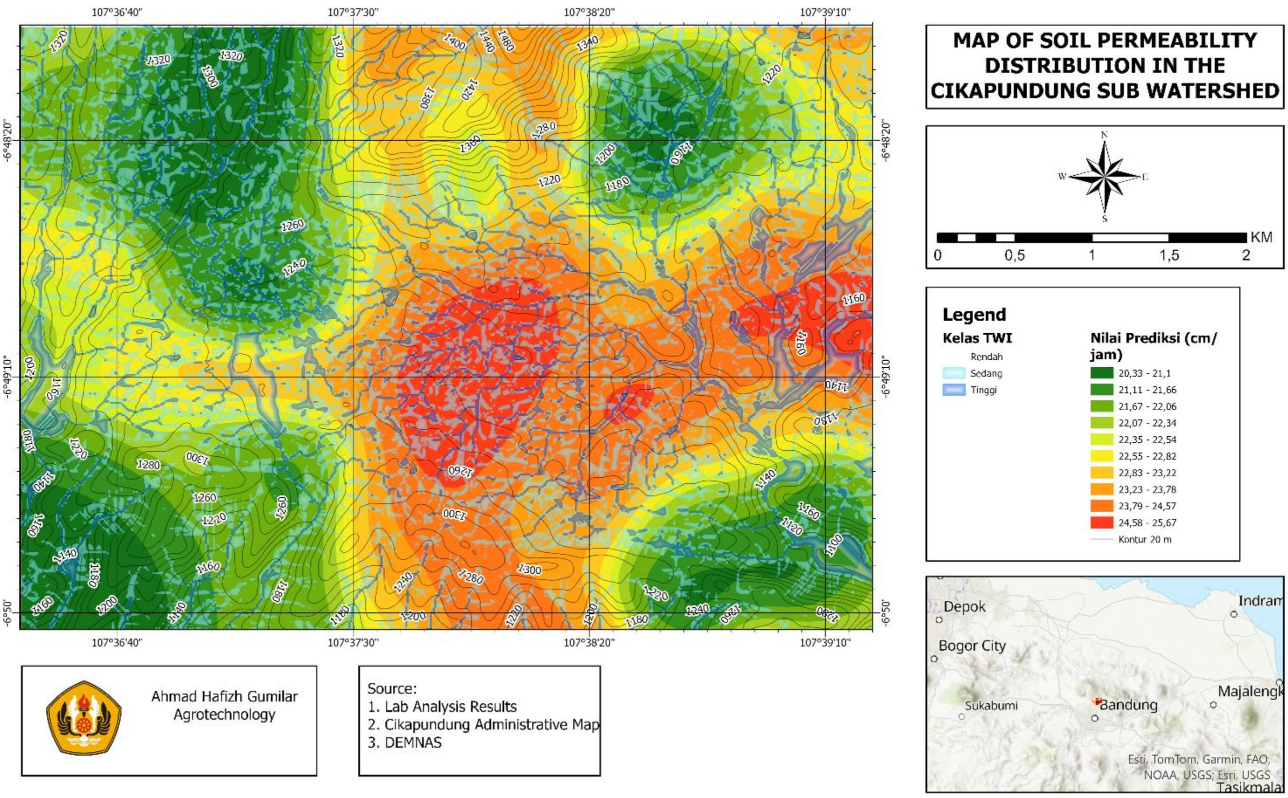

Figure 1. Spatial Distribution of Soil Permeability in the Cikapundung Sub-watershed

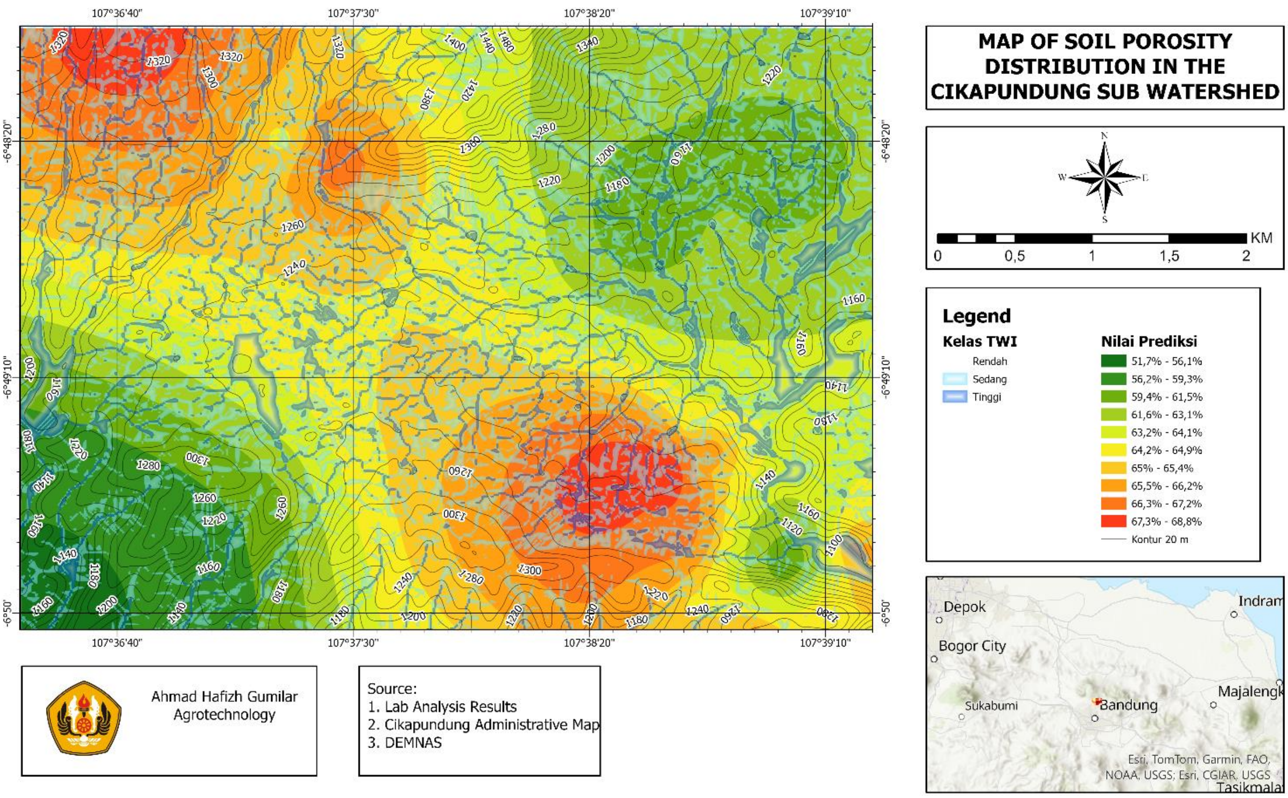

Figure 2. Spatial Distribution of Soil Porosity in the Cikapundung Sub-watershed

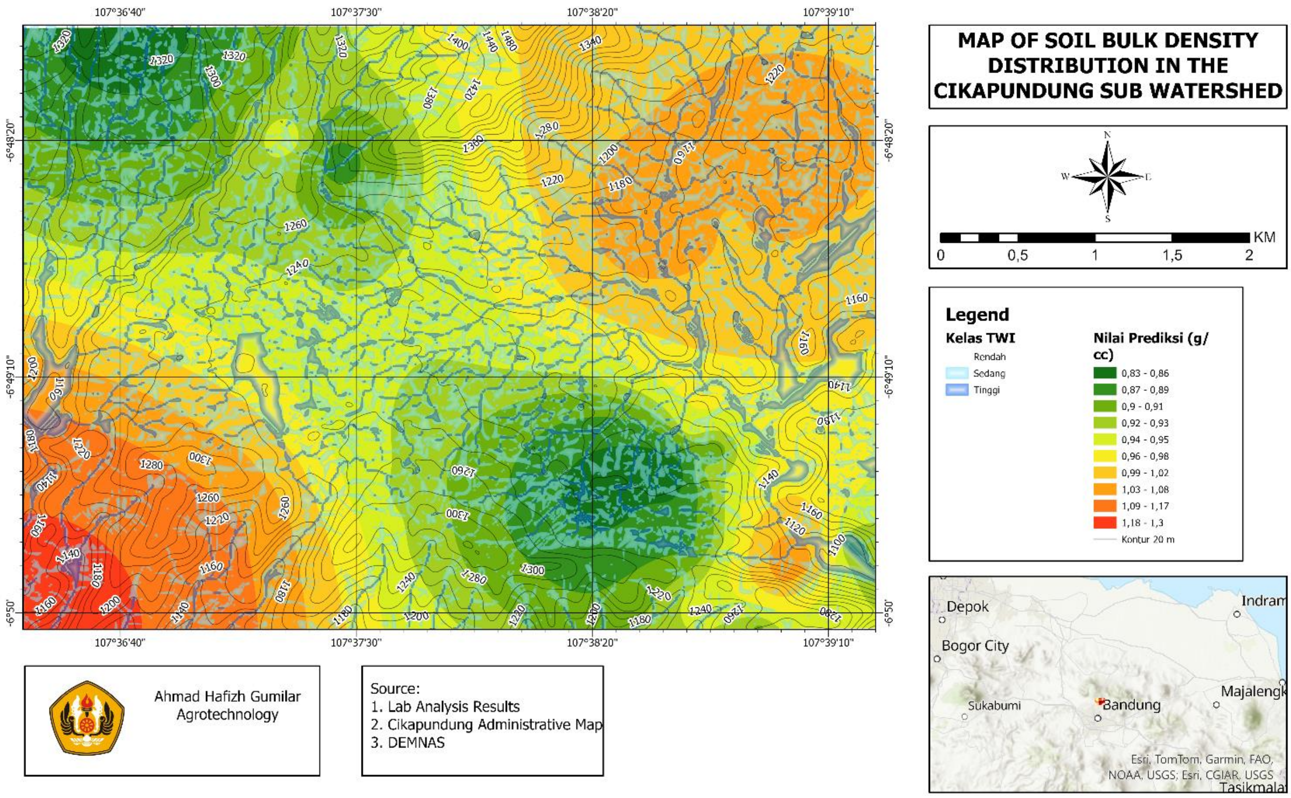

Figure 3. Spatial Distribution of Soil Bulk Density in the Cikapundung Sub-watershed

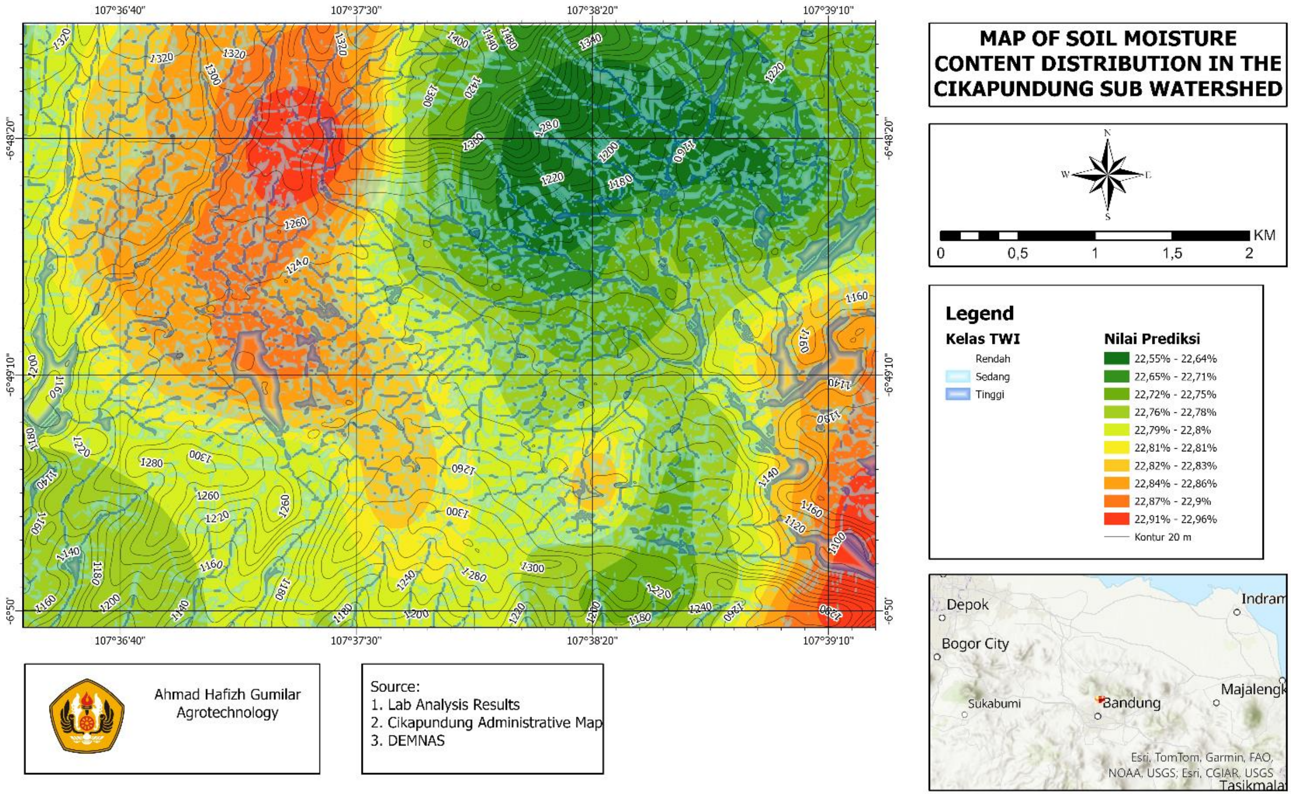

Figure 4. Spatial Distribution of Soil Moisture Content in the Cikapundung Sub-watershed

Descriptive Statistics of Soil Properties and Topographic Wetness Index

Table 1 presents the descriptive statistics of the measured soil properties and TWI values across the 30 sampling points in the study area.

Table 1. Descriptive Statistics of Soil Properties and Topographic Wetness Index (TWI)

Statistical Value	TWI	Water Content (%)	Permeability(K) (cm/hour)	Porosity (%)	Bulk Density (g/cm^3)
Mean	8,031	23,327	31,109	63,786	0,960
Standard Deviation	2,874	2,742	32,701	4,894	0,130
Coefficient of Variation (%)	35,786	11,756	105,116	7,673	13,513
Minimum	1,7508	19,22	0,53	48,3	0,74
Maximum	13,3962	30,12	135,08	72,08	1,37
Confidence Interval95% (±)	1,073	1,024	12,211	1,828	0,048

Correlation Analysis

The relationships between TWI and soil physical properties were analyzed using Pearson correlation analysis. Table 2 summarizes the correlation coefficients and their statistical significance.

Table 2. Correlation Matrix between Topographic Wetness Index (TWI) and Soil Physical Properties

	TWI	Water Content	Permeability	Porosity	Bulk Density
TWI	1	-0,3	0,37 *	0,03	-0,03
Water Content	-0,3	1	-0,33	0,1	-0,1
Permeability	0,37 *	-0,33	1	0,14	-0,14
Porosity	0,03	0,1	0,14	1	-1,00 *
Bulk Density	0,03	-0,1	-0,14	-1,00 *	1

DISCUSSION

This study reveals complex spatial patterns in soil physical characteristics across the Cikapundung Sub-watershed and their relationships with Topographic Wetness Index (TWI). The discussion focuses on two main aspects: the spatial distribution of soil physical characteristics and their correlation with TWI.

Spatial Distribution of Soil Physical Characteristics

The spatial analysis reveals distinct patterns in soil physical properties across the study area. Soil moisture content shows relatively uniform distribution (CV = 11.756%), despite high TWI variability (CV = 35.786%). This suggests that while topography influences soil moisture, other factors such as soil texture and vegetation cover likely play significant moderating roles in moisture retention and distribution.

Soil permeability exhibits the highest variability (CV = 105.116%) among measured parameters, with values ranging from 0.53 to 135.08 cm/hour. This extreme variation indicates complex interactions between topographic position, soil structure, and local drainage conditions. Higher permeability values are generally observed in well-drained upland areas, while lower values occur in valley bottoms and convergent zones.

Porosity distribution shows moderate uniformity (CV = 7.673%), ranging from 48.3% to 72.08%. This relatively consistent pattern suggests that soil structural development is influenced by long-term pedogenic processes rather than solely by topographic position. The spatial distribution of porosity values indicates better soil structure in areas with established vegetation cover and minimal disturbance.

Bulk density exhibits moderate variability (CV = 13.513%), with values ranging from 0.74 to 1.37 g/cm^3. Lower bulk density values are generally observed in areas with higher organic matter content and less anthropogenic disturbance, while higher values occur in compacted areas, particularly in locations with intensive land use.

Relationship between Topographic Wetness Index (TWI) and Soil Physical Characteristics

The relationship between TWI and soil physical properties reveals interesting patterns that reflect the complex interplay between topography and soil development. TWI shows a significant positive correlation with soil permeability (r = 0.37), suggesting that areas with higher TWI values tend to develop better drainage characteristics over time, possibly due to increased biological activity and organic matter accumulation in these moisture-rich zones.

The weak negative correlation between TWI and soil moisture content (r = -0.30) is somewhat counterintuitive, as TWI typically indicates potential soil moisture accumulation. This unexpected relationship might be attributed to temporal variations in sampling, local drainage patterns, or the influence of land use practices that modify natural moisture distribution patterns.

The very weak correlations between TWI and both bulk density and porosity (r = -0.03 and r = 0.03, respectively) suggest that these properties are more strongly influenced by factors other than topographic position, such as land management practices, vegetation cover, and soil texture. This finding emphasizes the complexity of soil property development and the importance of considering multiple factors in soil management strategies.

Implications for Soil Health Monitoring

The findings from this study have significant implications for soil health monitoring and degradation assessment. The varying relationships between TWI and soil physical properties suggest that topographic indices alone may not be sufficient for predicting soil characteristics comprehensively. Future soil health assessment strategies should integrate TWI with other environmental variables to better predict and monitor soil physical properties.

The study demonstrates that while TWI can serve as a useful predictor for certain soil physical properties, particularly permeability, it should be combined with additional environmental parameters for effective soil health assessment. This integrated approach would enable more accurate monitoring of soil degradation processes in the Cikapundung Sub-watershed, supporting early detection and prevention of soil quality decline.

The spatial variability observed in all measured soil properties across the watershed emphasizes the need for site-specific management approaches rather than uniform management strategies. This is particularly important in the Cikapundung Sub-watershed where land use changes have created a complex mosaic of soil conditions.

Limitations

The limitations of TWI as a single predictor for most soil physical properties (except permeability) suggests that future studies should consider:

- Incorporating additional terrain attributes
- Including land use/land cover data
- Considering soil type and parent material information
- Accounting for management history

These findings contribute to the growing body of literature on the use of terrain indices for predicting soil properties, while highlighting the complexity of soil-landscape relationships in tropical watersheds affected by land use change.

CONCLUSION

This study evaluated the relationships between Topographic Wetness Index (TWI) and various soil physical properties in the Cikapundung Sub-watershed, leading to several important conclusions:

1. The Topographic Wetness Index showed varying degrees of correlation with different soil physical properties:
    a. A significant positive correlation with soil permeability (r = 0.37)
    b. A weak negative correlation with soil moisture content (r = -0.30)
    c. Very weak correlations with both bulk density (r = -0.03) and soil porosity (r = 0.03)
2. Spatial distribution analysis revealed significant variability in soil physical properties across the watershed, indicating the complex nature of soil-landscape relationships in this region.
3. Topographic Wetness Index can be effectively used as a single predictor for soil permeability in the Cikapundung Sub-watershed, but it is not reliable as a standalone predictor for bulk density, porosity, or soil moisture content.
4. The findings suggest that integrated approaches combining TWI with other environmental variables would be more appropriate for comprehensive soil physical property prediction in watershed management.

These conclusions have important implications for soil and water conservation planning in the Cikapundung Sub-watershed and similar environments. Future research should focus on developing multiple-parameter models that incorporate additional terrain attributes and land use factors to better predict soil physical properties.

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DISCLOSURE

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