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Research Article

Evaluation of Aggregate Stability Using the Slaking Index Method with Soil Physical Approach in Keduang Sub-Watershed, Indonesia

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Abstract: The Keduang Sub-Watershed area has faced multiple natural disasters like landslides, erosion, and flooding because of the poorly managed terrain in the area. This study examines the distribution of the slaking index on agricultural land in the Keduang Sub-Watershed, analyzes the impact of soil type on it, and identifies the soil physical elements that have the most significant influence on it. The study took place in the Keduang Sub-Watershed, Indonesia, utilizing agricultural land from woods, plantations, drylands, and paddy fields with Andisols, Alfisols, Inceptisols, and Entisols soil types. This survey research was supported by laboratory analysis of the soil's physical and chemical properties and used GIS for data interpretation. Soil samples were collected from 22 Land Map Units (LMUs) with 3 replications each, resulting in 66 samples. The SLAKES software assesses the primary parameter, the slaking index. The supporting parameters analyzed were aggregate stability, bulk density, texture, structure, pH, organic C, and Cation Exchange Capacity (CEC). The research showed that soil types in the Keduang Sub-Watershed significantly affect the slaking index value. The slaking index ranged from 0.13-11.63, with the highest values for Andisols in a forest, while the lowest values were Inceptisols in a plantation. The allophane mineral in Andisols was causing the high slaking index. The soil factors determining the slaking index were bulk density and exchangeable K. The lower the bulk density, the higher the slaking index. Meanwhile, the lower the exchangeable K, the lower the slaking index. The land management recommendations based on determinant factors are adding organic material and reducing soil cultivation practices.

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1. Introduction

A natural disaster occurs in the sub-watershed due to improper land use, decreasing soil resistance to landslides and erosion. Due to poor land management, several disasters occurred, including landslides, erosion, and flooding in the Keduang Sub-Watershed. In 2014–2020, the Wonogiri Regency Central Statistics Agency reported 165 flood disasters, which 5 of them occurred in the Keduang Sub-Watershed, and 431 landslides, which 164 of them occurred in the Keduang Sub-Watershed (Central Bureau of Statistics Wonogiri Regency, 2021). Seventy-nine landslides struck from 2014 to 2021 in

Jatiyoso District, Karanganyar Regency, and the Keduang Sub-Watershed (Karanganyar Regency Government, 2021). Landslides are common due to unstable soil aggregates (Sun and Zhou, 2017). Natural and human factors include increased rainfall intensity, mountainous or hilly topography, land use, and land conversion (LULC), which induce landslides (Rofiq et al., 2022). Keduang Watershed is a water catchment in Wonogiri and Karanganyar Regencies. In the Keduang Sub-Watershed, significant cases of land degradation are caused by erosion and sedimentation. In 2016, the Keduang Sub-Watershed had an erosion rate of 1 829 554.91 ha ton^{-1} year^{-1}; in 2021, it was 1 128 910.89 tons ha^{-1} year^{-1}. Despite a 700 644.02 tons ha^{-1} year^{-1} erosion rate drop from 2016-2021, this number is still significant (Aisy et al., 2023).

Climate change and anthropogenic land degradation worsen soil erosion, a significant challenge to environmental sustainability and agricultural productivity (Zhu et al., 2019; Sengupta and Thangavel, 2023).Due to housing and infrastructure development, tremendous population growth reduces agricultural land, threatening water availability, biodiversity, and biomass production (Wahyuti et al., 2023; Widhiyastuti et al., 2023). The population pressure value on agricultural land in the Keduang Sub-Watershed is 28 978.16, indicating an imbalance between population growth and agricultural land availability, causing extensive erosion and land degradation (Wuryanta and Susanti, 2015). Wonogiri Regency in Central Java has significant agricultural potential, especially for food crops covering 53.80% of the area. Intensive rice cultivation without sustainable agricultural methods could harm the environment (Mujiyo et al., 2023; Romadhon et al., 2023; Şenyer et al., 2023). Furthermore, soil characteristics like soil aggregate stability, which regulates water availability and air circulation, and soil colloids, which affect plant growth, also affect erosion events. Massive deforestation, intensive agricultural practices, temperature, wind, rainfall intensity, human activities, and climate change threaten soil sustainability and productivity by causing erosion. Erosion causes soil degradation by removing topsoil containing humus, changing soil depth, and reducing soil nutrient status, reducing agricultural land productivity. The Keduang Sub-Watershed medium class has the highest soil degradation potential at slope slopes >40% (Istiqomah et al., 2023). Higher slopes increase deterioration risk (Mujiyo et al., 2022; Romadhon et al., 2023). The Keduang Watershed has minimal land cover, especially forest, which causes floods and landslides (Nugrahanto et al., 2022; Romadhon and Aziz, 2022). The impact is that during the dry season, the water source discharge in Wonogiri Regency decreases from 8 dm^3 s^{-1} to 6 8 dm^3 s^{-1} (Radarsolo, 2023). The results of the evaluation carried out by the Bengawan Solo River Basin Center (BBWS) stated that the handling of sedimentation from the Keduang Sub-Watershed still needs to be improved, causing damage to the function of the reservoir (Solopos, 2022).

The slaking index has the most significant impact on aggregate degradation. Slaking assessment is a new method to develop erosion management and soil stability faster and more efficiently. According to Xiao et al. (2017), the results show that slaking causes more than 50% of aggregate disturbance when rainfall kinetic energy is between 50 and 800 J m^{-2} h^{-1}. Lower aggregate stability and greater slaking values increase soil erosion (Nciizah and Wakindiki, 2015). Previous research by Jones et al. (2021) shows that slaking value affects soil type and agricultural land use where the slaking index in dry land on mixed crops of wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.), and chickpeas (*Cicer arietinum* L.) in vertisol soil with irrigation is higher than in pasture and forested areas. We investigated the slaking index in the Keduang Sub-Watershed, which has diverse soil types and agricultural land uses. The slaking index is assumed to be affected by soil type. This research intends to investigate the distribution of the slaking index on agricultural land along the Keduang Sub-Watershed, how soil type affects it, and what soil physical and chemical factors most affect it. To reduce erosion risk, to offer soil and land management solutions for agricultural land around river watersheds. By guiding conservation efforts, surveying the Keduang Sub-Watershed slaking index can help reduce erosion and soil damage.

2. Material and Methods

2.1 Research site

The research was conducted in the Keduang Sub-Watershed in Karanganyar and Wonogiri Regencies, Central Java Province, Indonesia, from February to August 2023. Keduang Sub-Watershed is found at 7°42'29.65"-7°55'27.97"S and 111°13'23.51"-110°56'54.61"E. The total area of the research site is 29 242.98 ha. Soil samples have been analyzed in the Soil Laboratory of Universitas Sebelas Maret. Its land use includes forests (1 284.11 ha), moorland (5 947.54 ha), paddy fields (15 380.78 ha), and plantations (6 630.55 ha). Soil types in the research area consist of Andisols (4 380.23 ha), Alfisols (9 540.85 ha), Inceptisols (12 538.92 ha), and Entisols (2 782.98 ha). Those data were obtained from the Indonesian Center for Agricultural Land Resources Research and Development (ICALRD) (ICALRD, 2020). Research area’s slope characterized as flat (1-8%) of 12 471.94 ha, sloping (9-15%) of 8 366.16 ha, fairly steep (16-25%) of 5 859.99 ha, and severe (26-40%) of 2 544.89 ha. Low (1 709.4 mm year^{-1}), medium (2 074 mm year^{-1}), and high (3 359.2 mm year^{-1}) rainfall are found in the research area (Minister of Environment, 2009).

2.2 Soil sampling and analysis

The working map for observation and sampling points is in the form of a Land Mapping Unit (LMU), made at a scale of 1:50 000 and includes the results of a base map overlay, namely a rainfall map (Figure 1), a soil-type map (Figure 2), a slope map (Figure 3), and a land use map (Figure 4) determination of sample points using purposive sampling. The number of LMUs obtained from the overlay results was 22 LMUs, with sampling repeated 3 times, so 66 samples were taken. The thematic maps used to create land unit maps are administrative maps (Indonesian Earth Map, Geospatial Information Agency, 2014), soil type maps (ICALRD, 2020), rainfall maps (Data from the Bengawan Solo River Region Center (BBWS) in 2021), a land use map (Peta Rupa Bumi Indonesia), and a slope map (Digital Elevation Model (DEM) of Indonesia) with a scale of 1:50 000 using ArcGIS 10.4 software.

Soil samples were taken in the tillage layer of the soil, namely a depth of 1-20 cm from the soil surface. The results of the thematic map overlay show the LMU of 22 with a total of 66 sampling points, then each sample taken was ±1 kg (presented in Figure 5). Three points repeated the number of samples taken at 22 LMUs with 66 sampling points. Several parameters of soil physical and chemical properties were analyzed in this research (Table 1).

Table 1. Parameters and methods of soil analysis

Parameters	Units	Methods
Soil Physical Properties (Center for Research and Development of Agricultural Land Resources, 2022)		
Aggregates Stability	%	Double Sieve
Bulk Density	g cm^{-3}	Ring Sample
Texture	%	Pipette
Structure		Qualitative
Soil Chemical Properties (Center for Research and Development of Agricultural Land Resources, 2009)		
pH		Electrometry
Organic-C	%	Walkley & Black
Cation Exchange Capacity (CEC)	cmol (+) kg^{-1}	NH_4OAc N pH 7

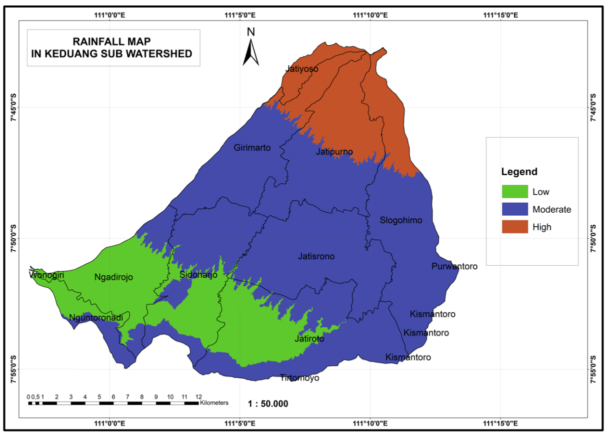


Figure 1. Rainfall map in Keduang Sub-Watershed.

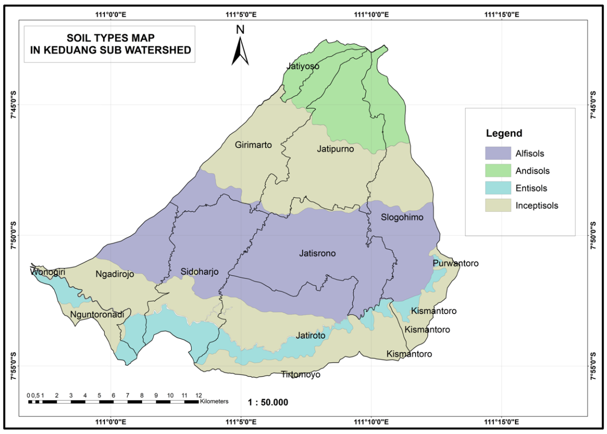


Figure 2. Soil type map in Keduang Sub-Watershed.

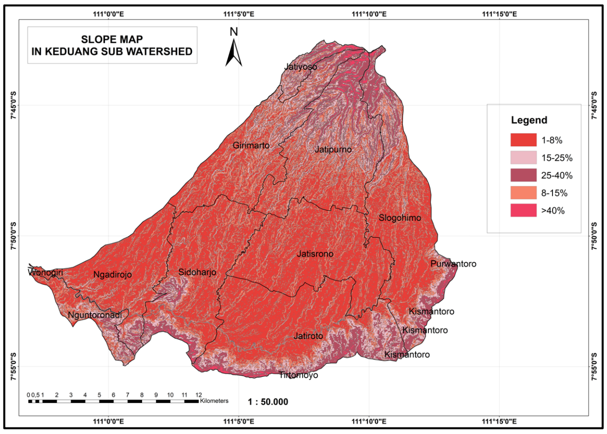


Figure 3. Slope map in Keduang Sub-Watershed.

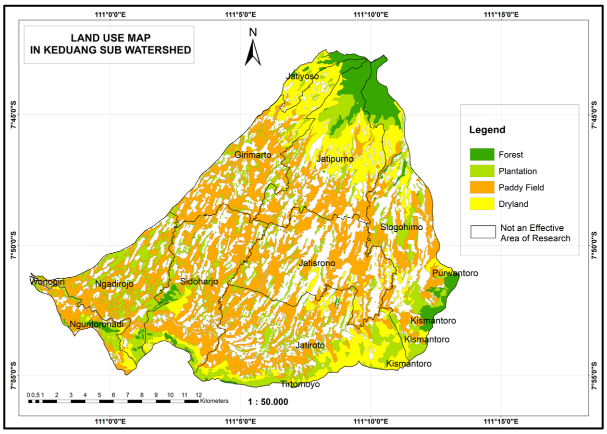


Figure 4. Land use map in Keduang Sub-Watershed.

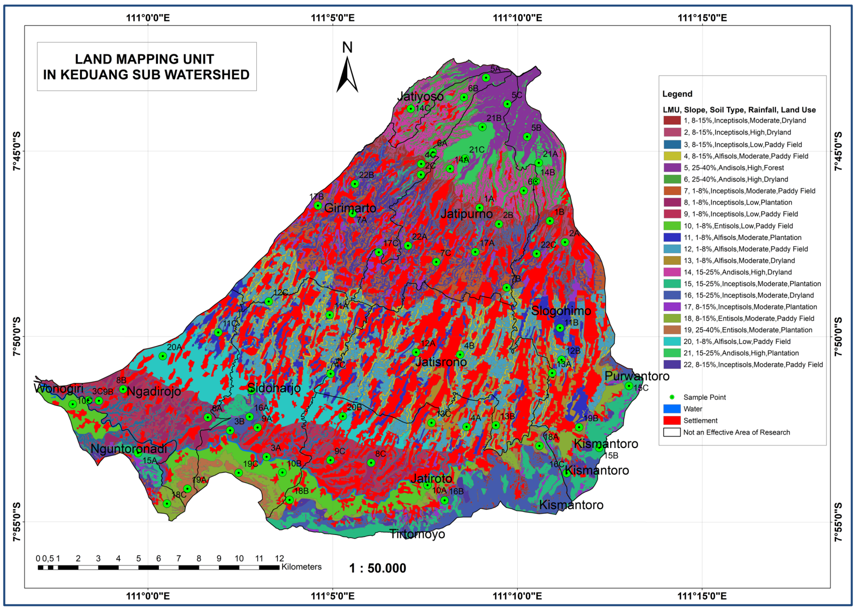


Figure 5. The LMU in Keduang Sub-Watershed.

2.3 Slaking index analysis

The soil samples used were three aggregates measuring 2-15 mm. (1) The first stage for analyzing with the SLAKES application is to place three soil aggregates into the first petri dish and then take a photo of the initial soil condition by pressing the "reference image" button; (2) the first petri dish is then replaced with a second petri dish of the same diameter (9 cm) filled with 3/4 of distilled water; (3) the soil samples in the first petri dish were transferred to the second petri dish in a spread out position (not stuck together); (4) then press the "start" button on the SLAKES application and wait for processing for 10 minutes, then the slaking index value will be displayed on the smartphone application screen (Fajardo and McBratney, 2019). The slaking index obtained from analysis using the SLAKES application was input and then mapped using ArcGIS 10.4 software.

The SLAKES application uses an image segmentation approach to calculate the footprint area of an aggregate expressed as several pixels. Then, it tracks the relative increase in the area of individual aggregates as they decompose over a certain period (Fajardo et al., 2016). The aggregate slaking index within a certain period after the dyeing process is calculated using a number formula (1)

$$SI_t = \frac{At - A0}{A0} \text{ (Jones et al., 2021)} \quad (1)$$

Where A0 is the initial site area of the aggregate; At is the aggregate site at time t; SI = 0 means the aggregate site area does not change; SI = 1 means the footprint area increases by 100%, etc. The SI value obtained from the SLAKES application is the average of parameters calculated individually for each aggregate. The SI values obtained were then classified based on the slaking index coefficient (Table 2). The higher the SI value, the lower the aggregate stability, and vice versa.

Table 2. Slaking index coefficient (Fajardo and McBratney, 2019)

Slaking Index Coefficient	Aggregate Stability Class
<3	High
3-7	Moderate
>7	Low

2.4 Statistical analysis

Research data obtained from field surveys and laboratory analysis carried out using One-way Analysis of Variance (ANOVA) to determine the effect of soil type on the slaking index, and if there any significant value ($\alpha \leq 0.05$; $\alpha \leq 0.01$), it continued further by Duncan Multiple Range Test (DMRT) to determine whether the mean value. Pearson Correlation Analysis with p-value <0.05 using the SPSS ver. 25.0 to find the determining factors of the relationship between soil parameters and the slaking index. The series of statistical analyses aims to develop recommendations for appropriate soil management in managing erosion risk by controlling the research area's determining factors.

3. Results

3.1 Physical and chemical characteristics of soil in the Keduang Sub-Watershed

The results of analyses on the physical and chemical (Table 3) parameters of the soil were analyzed to determine which soil properties support the interpretation of the slaking index data and which parameters are related. Aggregate stability in Keduang Sub-Watershed, analyzed using the double sieve method, is included in the unstable classes, not very stable, pretty stable, durable, and very stable (Center for Research and Development of Agricultural Land Resources, 2022). The less stable class is only at SPL 9, while the LMUs included in the less stable class are LMU 1 and 19. Aggregate stability is relatively stable at LMU 6, 11, 12, 13, 14, 15, 16, 18, 20, 21, and 22. The bulk density in the Keduang Sub-Watershed is in the range of 1.03 g cm^{-3} up to 1.66 g cm^{-3}. The lowest BD value is at LMU 5, and the highest is at LMU 10. The soil's clay content in the Keduang Sub-Watershed ranges between 5.95% to 75.01%. The texture in the Keduang Sub-Watershed consists of clay loam, clay, silt clay, silt clay loam, loam, silt loam, and silt. Clay textures are the most dominant textures in the research area. pH value is in the range of 6.56 to 7.25, where the highest value is at LMU 8 while the lowest is at LMU 10. Organic C in the study area is 0.68-2.15%, with an average of 1.27%. The organic C grade is included in the low, low, and medium classes, with the average being in the typical class. The Cation Exchange Capacity (CEC) in the Keduang Sub-Watershed is 54.83-92.02 cmol(+) kg^{-1}, included in the very high class. Na^+ is in the value range of 0.19-1.71. The K^+ value is in the value range of 0.24-1.29. The Ca^{2+} is in the value range of 10.69-45.40, and Mg^{2+} values are 1.45-19.36.

Table 3. Soil physical and chemical characteristics in the Keduang Sub-Watershed

LMU	Aggregate Stability (%)	Bulk Density (g cm^{-3})	Clay (%)	pH	Organic-C (%)	CEC (cmol(+) kg^{-1})	Exc. Na^{+} (cmol(+) kg^{-1})	Exc. K^{+} (cmol(+) kg^{-1})	E (cm
1	44.92±4.82	1.25±0.13	68.27±32.84	6.96±0.16	1.23±0.06	54.83±10.03	0.46±0.05	0.26±0.54	1
2	75.49±16.73	1.35±0.13	60.96±7.96	6.84±0.10	1.47±0.59	72.13±9.24	0.55±0.23	0.41±0.05	32
3	88.18±18.18	1.53±0.03	51.11±8.29	6.97±0.04	1.12±0.02	54.93±1.33	0.75±0.33	0.36±0.10	3
4	125.80±10.66	1.26±0.10	69.72±11.20	6.97±0.07	0.74±0.45	66.06±7.96	0.59±0.10	0.60±0.22	2
5	73.73±13.44	1.03±0.21	39.68±10.71	6.78±0.06	2.09±1.10	62.56±5.07	0.68±0.08	1.12±0.36	1
6	62.04±13.89	1.20±0.17	60.72±21.43	6.76±0.33	1.47±0.79	55.98±21.45	0.64±0.07	0.42±0.17	1
7	96.14±9.36	1.38±0.14	59.10±4.95	6.88±0.03	1.37±0.50	69.09±10.82	1.71±0.96	0.38±0.17	2
8	73.74±10.88	1.56±0.17	62.85±10.70	7.12±0.06	0.83±0.51	83.39±15.61	0.79±0.26	0.54±0.46	2
9	34.31±12.08	1.57±0.07	57.13±25.91	6.77±0.34	0.97±0.49	79.44±4.03	1.03±0.38	1.29±0.48	3
10	104.43±33.46	1.66±0.19	46.98±11.74	6.56±0.40	1.23±0.55	92.02±5.33	0.69±0.40	0.40±0.08	3
11	64.09±7.13	1.42±0.17	75.01±7.63	6.98±0.07	1.38±0.32	83.82±2.15	0.19±0.11	0.61±0.39	1
12	62.91±5.30	1.48±0.12	64.23±13.50	6.98±0.19	2.15±1.53	79.67±3.26	1.00±0.18	0.31±0.24	2
13	50.67±11.93	1.38±0.15	45.90±22.23	6.83±0.02	0.68±0.16	72.84±14.07	0.89±0.29	0.36±0.06	2
14	50.97±14.33	1.46±0.18	61.47±14.61	6.97±0.03	1.20±0.51	70.12±5.54	0.74±0.41	0.44±0.22	2
15	60.13±13.12	1.46±0.17	17.59±15.06	7.25±0.02	1.36±0.12	84.57±4.22	0.97±0.22	0.62±0.20	4
16	50.19±5.26	1.50±0.21	20.27±9.17	7.08±0.09	0.70±0.39	72.73±6.90	0.43±0.27	0.66±0.31	30
17	81.12±12.43	1.59±0.20	64.03±12.90	6.62±0.18	1.79±0.40	65.74±5.92	0.60±0.23	0.24±0.04	2
18	52.92±8.96	1.15±0.02	14.88±10.77	7.17±0.16	0.90±0.39	82.45±8.68	1.35±0.69	0.39±0.15	4
19	40.48±2.89	1.36±0.19	5.95±3.03	7.11±0.12	0.95±0.37	77.46±10.48	0.30±0.04	0.77±0.25	3
20	61.65±17.96	1.54±0.13	40.93±18.71	7.04±0.19	0.84±0.36	72.57±6.09	0.34±0.02	0.57±0.17	2
21	61.87±4.07	1.42±0.19	21.09±19.11	6.96±0.03	2.04±1.39	64.12±8.94	1.04±0.34	0.38±0.28	1
22	60.09±10.93	1.20±0.20	22.33±12.42	6.81±0.03	1.48±0.37	58.69±9.67	0.27±0.05	0.33±0.18	1

3.2 The distribution of slaking index under different soil types

The slaking index value in the Keduang Sub-Watershed varies from 0.13 to 11.63, as shown in Table 3. The results were classified according to the slaking index coefficient class (Table 2), with the aggregate stability in the Keduang Sub-Watershed falling into low and high classes. The SLAKES provides a slaking index converted into an aggregate stability class and displayed on a map (Figure 6). The low aggregate stability class, covering 1284.11 hectares, is situated in the northern or upstream section of the Keduang Sub-Watershed and is represented by a brown color. The yellow color represents the high aggregate stability class covering 27 958.87 hectares, predominating most of the Keduang Sub-Watershed area.

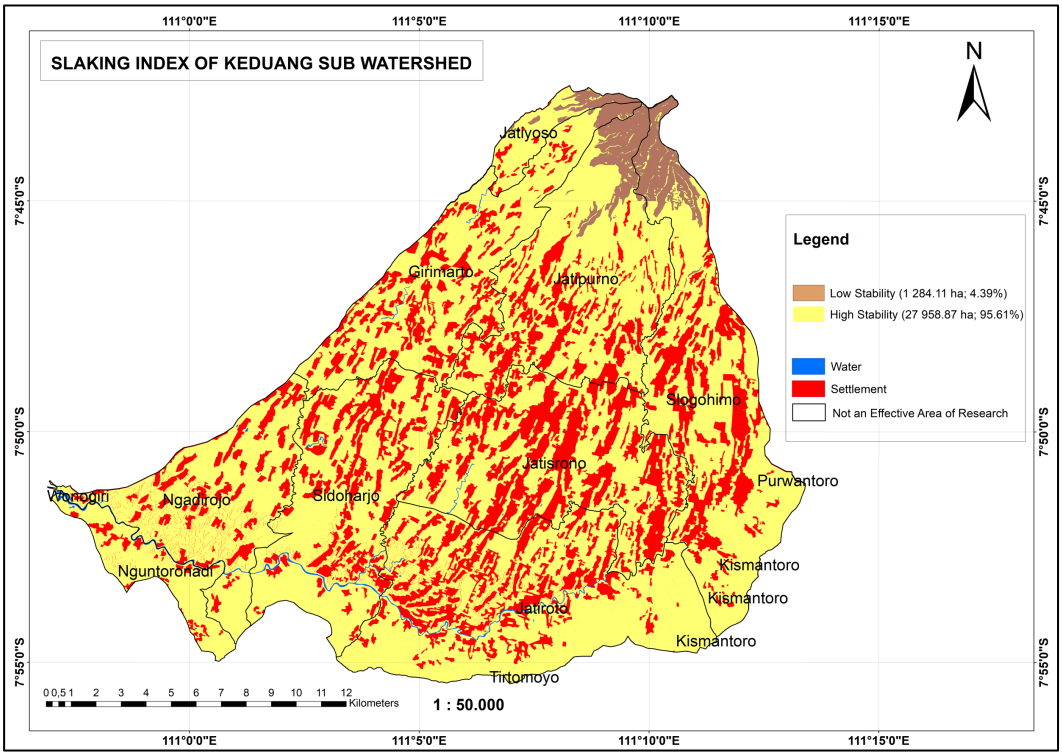
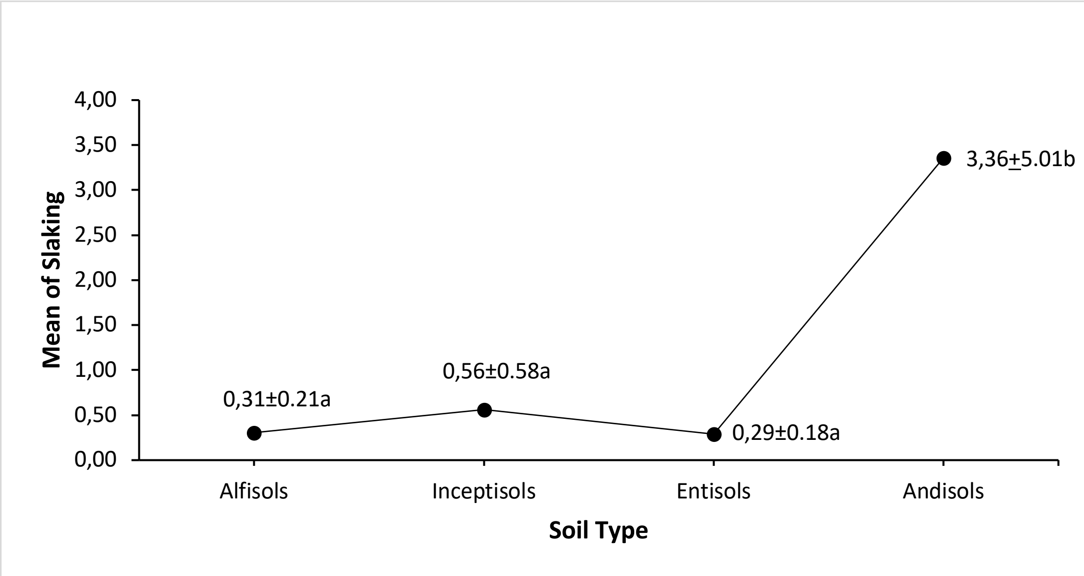


Figure 6. Aggregate stability on a slaking index.

The ANOVA was done to determine the effect of soil type on the slaking index. The variability of soil type is significantly affected by the slaking index in the Keduang Sub-Watershed (F-count = 6.082; p-value = 0.001; N = 66). The DMRT was conducted to determine whether the mean values differed significantly. Based on DMRT between soil types on the slaking index, Andisols are significantly different from Entisols, Alfisols, and Inceptisols (Figure 7). This condition shows that different types of soil cause other slaking indices. The Andisol soil type, which is located upstream of the sub-watershed and located at an altitude of > 1000 meters above sea level, has the characteristics of a more crumbly soil and low bulk density, so it is very easily destroyed during the soaking process for slaking index analysis.



*.Numbers followed by the same letter notation indicate there is no significant difference based on the DMRT test at the 5% level

Figure 7. Average index value of slaking under different soil types.

3.3 Determinant Factors

Defining factors can be used as a reference to provide recommendations for land management in the research area. The statistical analysis to help determine the determining factors is the test between sources of diversity and the slaking index. The correlation test results (Table 4) can be used as a supporting basis for the test to provide land management recommendations.

Table 4. Relationship between aggregate stability, soil physical characteristics, soil chemistry, and slaking index

	Agr Stability	BD	Clay	pH	Org-C	CEC	Exc. Na	Exc. K	Exc. Ca	Exc. Mg	Slaking
Agr Stability	1										
BD	.036	1									
Clay	.281*	.102	1								
pH	-.242*	.067	-.337**	1							
Org-C	.082	.047	.066	-.186	1						
CEC	.011	.339**	-.079	.194	-.216	1					
Exc. Na	.144	-.101	-.028	-.026	.043	.155	1				
Exc. K	-.240	-.056	.024	-.038	-.112	.012	-.130	1			
Exc. Ca	.023	.233	-.406**	.243*	-.133	.496**	.281*	-.064	1		
Exc. Mg	-.157	.109	-.473**	.359**	-.349**	.369**	.136	.042	.742**	1	
Slaking	.031	-.374**	-.016	-.146	.237	-.190	-.049	.394**	-.166	-.242	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

4. Discussion

4.1 Soil characteristics in the research site

Soil characteristics, especially aggregate stability, are closely related to soil sensitivity to erosion (Liu et al., 2023; Yao et al., 2020). Aggregate stability is influenced by management strategies and soil type, typically rising with higher levels of soil organic matter, clay surface area, and CEC (Temgoua et al., 2019). This is in line with the results of our research, which show that the average CEC value is high, with the most dominant texture being clay, so the aggregate stability class based on the slaking index is dominated by high stability. A high slaking index with low aggregate stability occurs in forest land use with Andisols soil type, 26-40% slope, and high rainfall. Areas with steep elevations usually have high erosion on the same slope. Forests on Andisol soils with lower crop cover have higher erosion because infiltration is low (Henry et al., 2013; Neris et al., 2013).

4.2 The distribution of slaking index in various soil types

Slaking is the process of clay disintegration upon contact with water, leading to erosion and stability issues (Gautam and Shakoor, 2016). The LMU 5 is the only one classed in the low aggregate stability class. The rest are classified as high. The LMU 5 is a land map unit characterized by heavy rainfall and Andisols-type forest land use on a slope ranging from 26% to 40%. The LMU 5 indicates a slaking index value of 11.63, signifying a 1 163% expansion of the sample area after a 10 minute soaking period. Andisol soil is characterized by a crumb structure with easily disintegrating particles. Additionally, according to Hanifa and Suwardi (2022), soil on steep slopes has low stability and high erosion susceptibility due to its coarse texture.

The aggregate of LMU 5 is significantly different than others, caused by the mineralogical properties of Andisol soil in the form of allophane. Allophane is a non-crystalline mineral with many fine pores that is soft when wet, has a high water binding capacity, and does not have a defined crystal structure, making it extremely soluble (Suryani et al., 2015). Allophane minerals found in Andisols are likewise less stable than crystalline minerals. Andisols are young volcanic ash containing organic glass, so they dissolve easily and quickly weather in humid conditions into non-crystalline minerals (Suratman et al., 2018). This condition causes soil with Andisols aggregate to have a high slaking index because the aggregate easily expands and disintegrates when soaked. The expansive capacity of soil depends on the type and amount of minerals and their cation exchange capacity (Schäbitz et al., 2018). Differences in clay content in each soil type cause the slaking index results to vary. The clay-dominated fraction will tend to be dispersed moderately, but if it is bound by organic material, it will be slightly dispersed (Karahan and Yalim, 2022; Umam et al., 2022).

Other LMUs have better aggregate stability since fewer soils expand during soaking than LMU 5. The lowest slaking index is 0.13 at LMU 8: Inceptisols with plantation land use, 1-8% slopes, and low rainfall. The clay content at LMU 8 (62.85%) is higher than at LMU 5 (39.68%). Even though the total clay is higher, the different soil types cause LMU 8 to be more stable, and Inceptisols do not have allophane. Inceptisol soil colloids are included in crystalline silicates. Clay 2:1 smectite type can expand and contract, containing illite and montmorillonite minerals. The ability to develop each soil aggregate depends on the amount of montmorillonite mineral content (Li et al., 2020).

The LMU 9 (Inceptisols on paddy fields) has the lowest aggregate stability in the unstable class. Processing the land as rice fields with a hoe or agricultural machinery damages the aggregate at LMU 9, making it unstable. Continuous planting damages paddy aggregates, reducing aggregate stability (Gu et al., 2023). The source of diversity in the form of soil type significantly affects the slaking in the Keduang Sub-Watershed. Andisols are pretty different from other soil types, while Alfisols, Inceptisols, and Entisols are closely alike. This condition means that the Andisols experience aggregate disintegration and the highest slaking index value compared to others. Andisols have the highest slaking value, with a clay content of 39.68%, BD 0.12 g cm^{-3}, and CEC 62.56 cmol(+) kg^{-1}. Research by Jones et al. (2021) shows that land use and soil type are correlated with the slaking, with vertisol soil having a clay content of >25% and a CEC: clay ratio of >0.5, it has the highest slaking index value with land use, and differences in soil type cause different slaking indexes. This condition matches our studies showing that clay concentration >25% has a high slaking index. The slaking index of dry land in this study is similar to that of rice fields and plantations; however, it tends to be high. With vertisol soil having a clay content of >25% and a CEC: clay ratio of >0.5, it has the highest slaking index value with land use, and differences in soil type cause different slaking indexes. Intensive tillage on moorland causes a decrease in the physical quality, including aggregate damage (Mamta et al., 2023).

Organic C is one of the fundamental parameters in sustainable agriculture (Alaboz et al., 2022; Rahayu et al., 2024; Romadhon et al., 2024) and plays a role in nutrient availability, improving soil's physical, chemical, and biological properties (Farrasati et al., 2019; Meilani et al., 2023; Smith et al., 2013). The results of organic C analysis show that organic C at the research location is in the very low to medium category (Center for Research and Development of Agricultural Land Resources, 2009). The medium class, organic C content, is at LMU 5, 12, and 21 (forests, rice fields, and plantations). The organic C content varies depending on land use (Romadhon et al., 2024), with higher levels found in plantation land use (Dadgar, 2018; Supriyadi et al., 2021), while research by Eleftheriadis et al. (2018) shows the highest average organic C in forests, other research states that rainfed paddy fields have the organic C content is higher than in plantations (Rekwar, 2022). Rainfall affects the organic C content (F-count = 3.946; p-value = 0.024; N = 66). This condition can occur because decreased rainfall causes reduced accumulation of soil organic matter, resulting in poor soil fertility (Gong et al., 2013).

4.3 Defining factors

Based on the results of the correlation analysis, it was found that bulk density had a significant negative correlation with slaking and a significant positive correlation with exchangeable K^+. This interrelated relationship shows that improving bulk density and exchangeable K determinants can improve the slaking index. The positive correlation between the slaking index and BD (Table 4) shows that the smaller the BD, the higher the slaking index value. The large number of micropores in Andisols makes the BD low at 1.03 g cm^{-3}. Bulk density will affect the pore space of the soil; the lower the BD value, the higher the pore space will be (Juarti, 2016). Andisols, which is generally located at an altitude of >1,000 meters above sea level, has a low bulk density value, so the slaking index value is high, in line with research results where LMU 5 with the Andisol soil type in the upstream sub-watershed has the highest slaking index value.

The CEC value supports the bulk density, which can be seen from the analysis results and has a significant positive correlation. Andisols are characterized by low density, friable to very friable consistency, mineralogical composition dominated by allophane, and high P retention, organic matter content, and cation exchange capacity (Yatno et al., 2016). In line with the results of this research, which show that the CEC on Andisols soil is in the very high category. Apart from CEC, the slaking index has a significant positive correlation with other soil chemical properties, namely exchangeable K^+ cations, meaning that the higher the SI, the higher the K cation. The exchangeable K content in the soil is influenced by clay minerals, namely smectite, texture, organic C, and CEC (Volf et al., 2017; Toprak and Seferoğlu, 2023). Vertisols, Alfisols, and Inceptisols contain the mineral smectite. It means that the minerals contained in the soil tend to consist of illite and a small amount of montmorillonite, and the low increase in aggregate area proves this. Illite and vermiculite are 2:1 type clay minerals that can bind potassium, which plays a role in determining the availability of K in the soil (Bilias et al., 2022). Illite has bonds with K cations, which can be substituted by H^+ ions when H_2O is present. The amount of exchangeable K^+ at the research location is correlated with the slaking index. It means that the minerals found in the soil tend to consist of illite and a small amount of montmorillonite, and the low increase in aggregate area proves this.

Aggregate stability is strongly linked to soil characteristics that enhance aggregation, such as CEC and the percentage of polyvalent cations (Ca^{2+}, Al^{3+}). These properties support disaggregation, such as quartz content and monovalent cations (especially K^+), while clay dispersion is closely related to pH, power content, texture, and Na^+ adsorption ratio (Almajmaie et al., 2017). Based on the correlation test results, aggregate stability is supported by clay content, pH and is indirectly related to exchanged Ca and exchanged Mg. Clay content was significantly negatively correlated with exchangeable Ca and Mg, while pH was positively correlated with exchangeable Ca and Mg. It means that the higher the clay content, the higher the aggregate stability, while the amount of Ca and Mg that can be exchanged is lower. The low availability of polyvalent cations (Ca^{2+} and Mg^{2+}) causes soil to be more susceptible to dispersion due to the repulsive force between negatively charged clay particles. Polyvalent cations such as Ca^{2+} and Mg^{2+} function to react with clay or organic material to strengthen soil aggregates. The Ca and Mg content can be exchanged in soil pH, resulting in higher stability due to the negative bonds of clay particles, transforming them into more stable microparticles.

4.4 Erosion risk management strategy through management of soil slaking determinants

Reducing soil bulk density will reduce the slaking index. Adding soil organic matter can reduce the bulk density and soil compaction, thereby increasing the total porosity and infiltration rate (Brar et al., 2015; Syamsiyah et al., 2023). In general, returning plant residues to the soil can increase the organic matter content of the soil, thereby helping to improve the nutrient content in the soil, especially in the tillage layer (Stošić et al., 2020; Mujiyo et al., 2021; Dewi et al., 2022). The organic solid waste from sugar factories, called *blotong* can reduce the bulk density to a reduction of 0.103 g cm^{-3} in the tillage layer (Hartono et al., 2018) and increase the soil pore space. Apart from that, conservation practices can be carried out by cultivating contours and improving terraces (Dewi et al., 2023), as well as using organic mulch as core reinforcement has been proven to be able to reduce erosion by 15, 51% in Andisol (Suyana et al., 2017). The aggregate stability is correlated to soil properties such as sand/quartz content smectite. It is highly correlated with Ca^{2+} exchange capacity, indicating that soil hardening can be reduced by applying calcium products such as gypsum and dolomite (Almajmaie et al., 2017; Fitria and Soemarno, 2022; Cahyono et al., 2023).

Conclusion

The slaking index is evaluated using the software as a unique, basic, cost-effective, and practical approach to ascertain aggregate stability and formulate erosion control strategies in the study site. Andisols in the forest have the highest slaking index value. The minimum value is associated with Inceptisols in the planting. The slaking index is significantly influenced by soil type, with Andisols having the greatest value. In Andisols, aggregate rises due to the mineral allophane, which is non-crystalline and less stable than the minerals and swells of other soil types and disintegrates when moistened. The key factors are the soil's bulk density and exchangeable potassium levels. Soil with lower bulk density has a higher slaking index, and a decrease in exchangeable potassium is directly related to a fall in the slaking index. To reduce erosion risk in the Keduang Sub-Watershed, incorporate organic material and limit intense tillage methods. The research on slaking index assessment in different soil types in the area reveals its ability to analyze the distribution of slaking index across diverse soil types. The determinant factors can be a recommendation for creating erosion risk management in the Keduang Sub-Watershed. The slaking index will evaluate erosion estimates, saving time, effective analysis, and efficient economics.

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