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Assessment of Soil Quality and Erosion Hazards Using Statistical and PCA Analysis: A Case Study of the Arjasa Subwatershed

Cindia Mawarni [a], Bambang Hermiyanto [b*], Marga Mandala [b], Luh Putu Suciati [c] and Elida Novita [d]

[a] Department of Water Resources Management, Magister Program, University of Jember, Indonesia.
[b] Department of Soil Sciences, Faculty of Agricultural, University of Jember, Indonesia.
[c] Department of Agribusiness, Faculty of Agricultural, University of Jember, Indonesia.
[d] Department of Agricultural Engineering, Faculty of Agricultural Technology, University of Jember, Indonesia.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study aims to analyze the soil quality and erosion hazard level of each cluster in the Arjasa Subwatershed, which is the upstream part of the Bedadung Watershed, Indonesia. Land use in this area is production forest, dry land agriculture, and mixed dry land agriculture with slopes varying from 3-8% to >40%. The soil types include Andic Dystrudepts, Lithic Hapludands, Typic

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**Corresponding author: E-mail: b.hermiyanto.faperta@unej.ac.id;*

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Dystrudepts, Typic Eutrudepts, and Typic Hapludands. Soil samples were taken at 30 random sample points at a depth of 0-20 cm. Soil physical and chemical parameters were used in this study. Statistical analysis used were Anova, Duncan test, PCA, and regression-correlation. Quantitative analysis of erosion hazard level was conducted using the USLE formula developed by Wischmeier and Smith (1978). This research has identified three main problems, namely the unavailability of soil quality analysis data, the magnitude of the erosion hazard level in the sub-watershed, and the magnitude of the impact of erosion on soil quality. After assessing these issues, the soil quality index data was found to be in the medium (0.47) to high (0.65) range. Meanwhile, the amount of erosion hazard in each cluster has also been obtained, which shows a range of 4.39 tons/ha/year which is categorized as very light, covering 19.91% of the total area, to 184.81 tons/ha/year, which is included in the heavy category, amounting to 33.37%. In addition, it can be seen that there is a negative relationship at a moderate level (r = 0.56) between the level of erosion hazard and the soil quality index, which means that soil erosion can have an impact on reducing the soil quality index. Finally, it can be suggested that good soil conservation practices such as terracing and organic fertilizer application in agricultural practices are needed to prevent increased erosion so that soil quality does not further decline.

Keywords: Sub Watershed; soil erosion hazard; soil quality index.

1. INTRODUCTION

Soil is a component of land that plays an important role in its utilization, depleted soil nutrients can cause land degradation and reduce its productivity (Janečková Molnárová et al., 2023). In recent decades, agricultural and anthropogenic activities have become a concern due to their major influence on land degradation and soil quality degradation, especially activities on land with high erosion rates that cause nutrient depletion (Raiesi & Salek-Gilani, 2020), reduce the soil layer (Pham et al., 2018), decrease the number of soil organisms (Błońska et al., 2018), and increase the toxicity of the soil (Tontsa et al., 2023). A complete analysis of soil quality and its relationship to soil erosion is essential to support agricultural productivity, socioeconomic well-being, and environmental management (Johnson et al., 2022).

In recent years, many studies on soil quality have been developed, concluding that soil quality is influenced by various factors such as conservation techniques practiced, land management and use, and erosion rates (Bekele, 2019a). However, research has mostly focused on land management and use factors. For example, (Budiman et al., 2020) assessed the Soil Quality index on Pasiran Land in Asembagus Situbondo District using spatial methods. (Fagodiya et al., 2024) assessed soil quality after fifteen years of a long-term tillage and residue management experiment on a wheat rice farm. (Uthappa et al., 2023) compared soil quality indexing techniques in different tree-based land use systems in semi-arid India. (P. Wang et al., 2024) improved soil quality with the application of two types of plant biochar. The same study was also carried out in other studies (De et al., 2022; Marion et al., 2022; Zhou et al., 2022). In addition, soil erosion causes the loss of topsoil containing organic matter and other soil nutrients, which reduces soil quality (Veisi Nabikandi et al., 2024). How do land use and management factors affect soil quality, and how does it change with the slope of an area? Further analysis of these issues is important for the development of precision agriculture systems (Ravi et al., 2022).

Research on soil quality has come into focus and increased significantly in the last decade, but the impact of soil erosion on soil quality and its response to slope on farms has not been systematically studied. Soil erosion is the largest driving factor in most soil quality changes (Martín-Sanz et al., 2022). Large amounts of soil loss due to inappropriate land/soil management systems have a serious impact on soil quality levels and sustainable land resource management. (Demir et al., 2023) stated that the greater the erosion will reduce the level of soil quality. Relevant findings were also conducted by (Fiqri Noor Aliffian et al., 2024) in the area of Kedewan District, Bojonegoro Regency. Slope is one of the most important factors affecting soil erosion and soil quality. (Pham et al., 2018) studied the impact of various agricultural land uses and topographic aspects in Central Vietnam. The functional relationship between slope, land use, soil erosion, and soil quality in watersheds was also analysed by (Bekele, 2019b; Derakhshan-Babaei et al., 2021).

Ecosystem sustainability and land use management are important objectives, so a comprehensive analysis of soil erosion impacts on agricultural soil quality is very important (Demir et al., 2023). However, in-depth analysis of the impact of soil erosion on soil quality is lacking on agricultural land in watershed areas.

The Arjasa Subwatershed, with an area of 4,259 thousand square kilometers, is considered important because of its location in the upper watershed of Bedadung, Indonesia. However, large erosion rates have occurred over the last few decades, the thickness of the A horizon in the Arjasa Subwatershed is much reduced, especially in soils with a thickness of more than 90 cm and in some areas, there are visible rock outcrops. Research on soil quality has also been conducted in the Bedadung watershed. However, there has been no research on the soil quality index in the Arjasa Subwatershed. (Fauzan Mas'udi et al., 2021) evaluated the Index of Soil Quality (IKT) on Tegalan Land in Jember Regency using mapping. (Pratiwi et al., 2022) evaluating the Distribution of Groundwater Quality Based on Lithology, Soil Texture, and Waste Parameters in Kaliwates District, Jember Regency. (Kajian et al., 2020) evaluating the Soil Quality Index and Land Utilization of Suco Sub Watershed, Jember Regency. (Basuki et al., 2024) evaluating Soil Erosion on the Argopura Breccia Lithologic Formation on the Slopes of Mount Argopura Using the USLE and GIS Methods. (Andriyani et al., 2020) evaluating the Erosion Hazard Level in the Bedadung watershed Area of Jember Regency. In fact, many studies have ignored the impact of soil erosion and slope on soil quality even though soil erosion has occurred in the Arjasa Subwatershed. The diverse topography of this region greatly influences land morphology and soil quality. An in-depth understanding and analysis of soil erosion patterns and their impact on soil quality in the Arjasa Subwatershed land morphology is essential for implementing efficient soil conservation measures.

The innovation in this study is to explore the impact of soil erosion on the total and minimum data sets obtained from soil quality. Therefore, the objectives of this study are to (i) quantify and evaluate the soil quality index in this region at different slopes, soil types, and land uses using the PCA method (ii) quantify and evaluate the level of soil erosion occurring in this region, and (iii) evaluate the effect of soil erosion on the soil quality index in the Arjasa Subwatershed.

2. MATERIALS AND METHODS

2.1 Study Area

The study site is located in the Arjasa Subwatershed, Bedadung Watershed (Fig. 1). The subwatershed is located between 8°0'51.95 "S - 113°41'4.46 'E and 8°5'23.81 'S - 113°44'45.3 "E. This area is the main upstream of the Bedadung watershed (Fig. 1). The parent material units of the Arjasa Subwatershed include two main landforms, namely Argopuro volcanic rocks and Argopuro tuff. The main vegetation cover in the area is secondary dryland forest, plantation forest, open land, dryland farming, mixed dryland farming, and paddy fields with varying slopes; therefore, sensitivity to climate change differs greatly in the study area. The climate of the study area is characterized by a hot and dry tropical climate with limited rainfall and bright sunshine throughout the year. The area has annual rainfall ranging from 1,969 mm to 3,394 mm, with average annual minimum and maximum temperatures of 23º - 31ºC respectively. Soil types in this area include Andic Dystrudepts, Lithic Hapludands, Typic Dystrudepts, Typic Eutrudepts, and Typic Hapludands.

2.2 Soil Sampling and Analysis

Soil samples were collected randomly from the entire sub-DAS at a depth of 0-20 cm, totaling 30 sample points. Soil samples (Fig. 2) was collected representing soil from the root zone. The sample points used represent spatial changes in the area characterized by wide physiographic variations, such as land use, soil type, and slope. Samples were air-dried and sieved through a 2 mm sieve to prepare for physical and chemical analysis according to standard protocols described according to (Chaudhry et al., 2024; Demir et al., 2023; Hyun et al., 2022). Soil physical and chemical analysis measurements were carried out by various methods as shown in Table 1.

2.3 Statistical Analysis

Soil characteristics were analysed by descriptive statistics, including minimum, maximum, arithmetic mean, and standard deviation values, which were calculated using SPSS version 26.0. Duncan's further test was used to confirm the normal distribution of the data. Pearson's correlation coefficient was used to measure the strength and direction of the relationship between two variables. R-Studio software and SPSS version 26.0 were used to perform principal component analysis (PCA). PCA is a multivariate statistical method used to reduce the dimensionality of complex data sets, called principal components, and to avoid multicollinearity between variables. PCA is used to identify patterns hidden in the data and describe them in the form of new variables called principal components. The results of this PCA analysis will provide a deeper understanding of the variation in the original variables under study. Thus, PCA can identify the main factors affecting the soil characteristics under study.

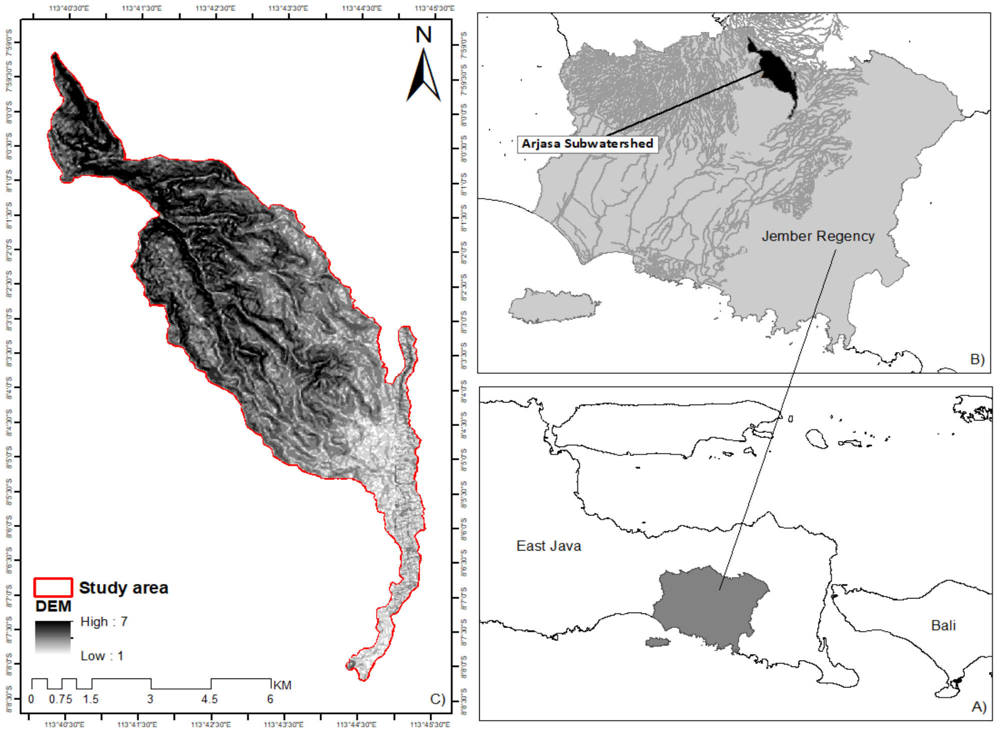


Fig. 1. Study area

Table 1. Soil physical and chemical analysis methods

Parameter analysis	Unit	Method
Erodibility	-	USLE
% Sand	%	Method pipette
% Silt	%	Method pipette
% Clay	%	Method pipette
BD	$g.cm^{-3}$	Silinder method
PD	$g.cm^{-3}$	Silinder method
Porosity	$g.cm^{-3}$	-
pH yus	-	pH meter H2O) (1; 2,5)
pH KCL	-	pH meter KcL (1; 2,5)
Available P	Ppm	Olsen
Exchangeable K	cmol±/kg	AAS, NH4OAC pH 7
Exchangeable Ca	cmol±/kg	AAS, NH4OAC pH 7
Exchangeable Na	cmol±/kg	AAS, NH4OAC pH 7
Exchangeable Mg	cmol±/kg	AAS, NH4OAC pH 7
CEC	cmol±/kg	AAS, NH4OAC pH 7
Organic C	%	Kurmis
Total N	cmol±/kg	Kjeldahl
Base Saturation	%	-
Hydraulic conductivity	µS/cm	EC

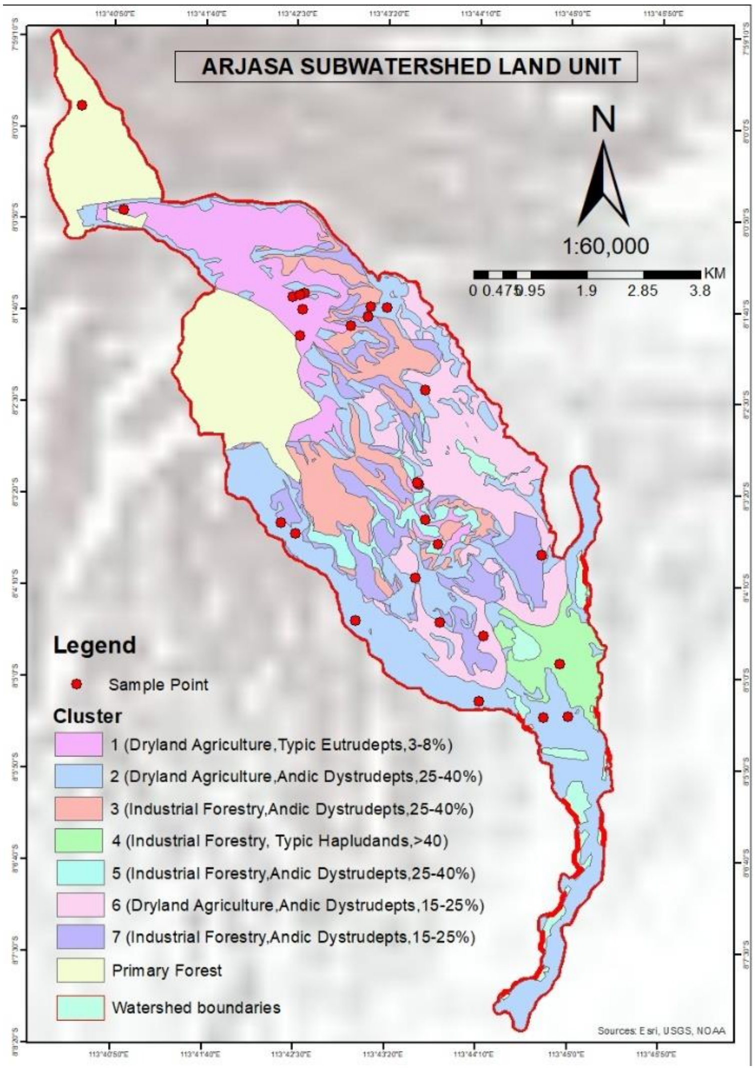


Fig. 2. Land unit and sampling point

2.4 Soil Quality Index (SQI)

The SQI was developed based on the method of (Bedolla-Rivera et al., 2020; Hermiyanto et al., 2016), using equation (1) and the indicator scoring equation (2). An additive weighting equation is used, using the PC variability obtained from the SQI development process, which provides greater precision in determining soil quality. SQI has advantages over other techniques (fixed additive weighting equation, expert opinion and linear additive index).

$$SQI = \sum_{i=1}^{n} Wi \times Si \quad (1)$$

where: Wi is the proportion of PC variability correlated with the indicator, Si is the indicator value resulting from the redundancy reduction process, obtained from soil sample analysis. Equation (2) is used to evaluate indicators whose function in soil is "the more the better" or "the less the better":

$$Si = \frac{a}{1+(\frac{x}{xm})^{b}} \quad (2)$$

where: a is equal to the maximum standardized value of the indicator, Xm is the average value of the indicator obtained from the analysis, X is the value of the indicator and b is the slope of the indicator scoring function. (-2.5 for indicators whose function is "the more the better" and 2.5 for indicators whose function is "the less the better"). Equation (3), used to assess indicators whose function in the soil is considered "optimal" and whose maximum or optimal value is 0.5:

$$Si = \frac{1}{[1+(\frac{(B-L)}{(X-L)})^{2L(B+X-2L)}]} \quad (3)$$

Table 2. Soil quality index classification

Soil Quality	Scale	Class
Very High	0.80–1.00	1
High	0.60–0.79	2
Moderate	0.40–0.59	3
Low	0.20–0.39	4
Very Low	0.00–0.19	5

where: B is the indicator value with a slope of 0.5, L is the lowest limit value of the indicator and X is the indicator value. The purpose of the SQI is to assign a value between 0 and 1, thus to determine soil quality according to the classification shown in Table 2.

2.5 Cluster Analysis

Cluster analysis was performed using SPSS software version 25.0. In selecting the number of clusters, clustering trials were conducted with 9, 8, and 7 clusters. The test that produced usable and sufficient members was the test with 7 clusters, with members of 3, 12, 3, 3, 2, and 4 groups, respectively. This cluster analysis was used for erosion calculations, but the SQI was also clustered for correlation and regression with erosion.

2.6 Erosion Calculation

The determination of the erosion hazard level was carried out using the USLE method based on rainfall data, soil properties, slope length and slope, crop management and soil conservation management based on clustering. Analysis of the level of erosion hazard quantitatively using the Universal Soil Loss Equation (USLE) formula. Systematically the USLE model is expressed by:

$$A = R \times K \times LS \times C \times P$$

where: A is soil loss (tons/ha/year), R is the rainfall erosivity index, K is the soil erodibility index, LS is the slope length and slope index, C is the vegetation cover index, P is the land management/soil conservation measures index. The results of the calculation of the amount of soil loss are used in determining the Erosion Hazard Level according to the classification of erosion hazard levels shown in Table 3.

2.7 The Research Framework

The research framework used in analysing the soil quality index and the level of erosion hazard in the Arjasa Subwatershed is shown in Fig. 3. The research framework is determined according to the research steps to be carried out. The main analysis of soil quality index and the level of erosion hazard using USLE resulted in the level of influence between the two in Arjasa Subwatershed.

3. RESULTS AND DISCUSSION

3.1 Soil Characteristics of the Study Area

The ANOVA test results (Appendix) showed that the 17 observed parameters had varying significant values in each condition. In different land uses, the values of available p, exchangeable Na, volume weight, and porosity showed significant values. ANOVA values based on soil type showed more significant values, such as exchangeable Mg, CEC, exchangeable Ca, organic C, base saturation, exchangeable Na, and volume weight. Slope as the basis of ANOVA, showed significant values in the parameters of exchangeable Mg, exchangeable Ca, exchangeable Na, and volume weight.

Significant exchangeable Na and volume weight parameters are close to ($p<0.001$) in all three conditions, suggesting an even distribution throughout the Arjasa Subwatershed. (Shuite et al., 2025) stated that volume weight and exchangeable Na are the main data sets of soil quality that affect the amount of organic matter in the soil. Duncan's further test results in Table 4 reinforce these findings by showing pairs between groups that have significant differences in mean values. This study shows that soil quality in the Arjasa subwatershed has significant variations depending on land use factors as well as topographic variations. Based on the results of ANOVA and Duncan's further test, it was found that in some soil quality parameters such as BD, K, Na, Mg, pH H_2O and Ca, showed significant impact values on soil quality.

In Typic Eutrudepts soil type, the available P and Exchangeable Na contents were higher than the other two soil types. Phosphorus is available from the decomposition of organic matter such as crop residues, which enriches the soil with phosphorus (Yustika et al., 2023). The Na content in this soil type is very high compared to other soil types (Qalati et al., 2023). The use of chemical fertilizers containing sodium such as complex fertilizers can increase the sodium content in the soil. In production forest land use BD and Mg have the highest median values compared to dryland agriculture. High BD and Mg in production forest land use indicates high organic matter content in this land use (X. Wang et al., 2024).

Although the pH in all land uses is neutral, the pH in production forest land use is greater than the pH in other land uses. Soil pH that is close to neutral can support the availability of nutrients for plants (Gondal et al., 2019.; Neina, 2019). The findings (Hyun et al., 2022) support evidence that physical soil parameters, such as bulk density and cation exchange capacity, play an important role in determining soil quality. Low bulk density and high cation exchange capacity generally indicate good soil quality and high ability to support plant growth, which was also found in this study in the Arjasa subwatershed.

3.2 Boxplot of Duncan Variation in Different Cluster

The boxplot analysis in Fig. 4 shows the effect of soil type, land use and slope on the value of each soil physical and chemical parameter in each cluster. The parameters Mg, Ca, CEC, Na, and BD have the best significant difference value with the highest parameter Exchangeable Na. Chemical properties show a more significant difference with an even distribution of data, compared to physical properties in the Arjasa Subwatershed.

Table 3. Classification of erosion hazard levels

Soil Solum (cm)	Erosion Hazard Class				
	I	II	III	IV	V
	Erosion (Ton/Ha/Year)				
	<15	15-60	60-180	180-480	>480
Deep >90	SR 0	R I	S II	B III	SB IV
Medium 60-90	R I	S II	B III	SB IV	SB IV
Shallow 30-60	S II	B III	SB IV	SB IV	SB IV
Very shallow <30	B II	SB IV	SB IV	SB IV	SB IV

Notes: SR "Very light", R "Light", S "Medium", B "Heavy" SB, "Very heavy"

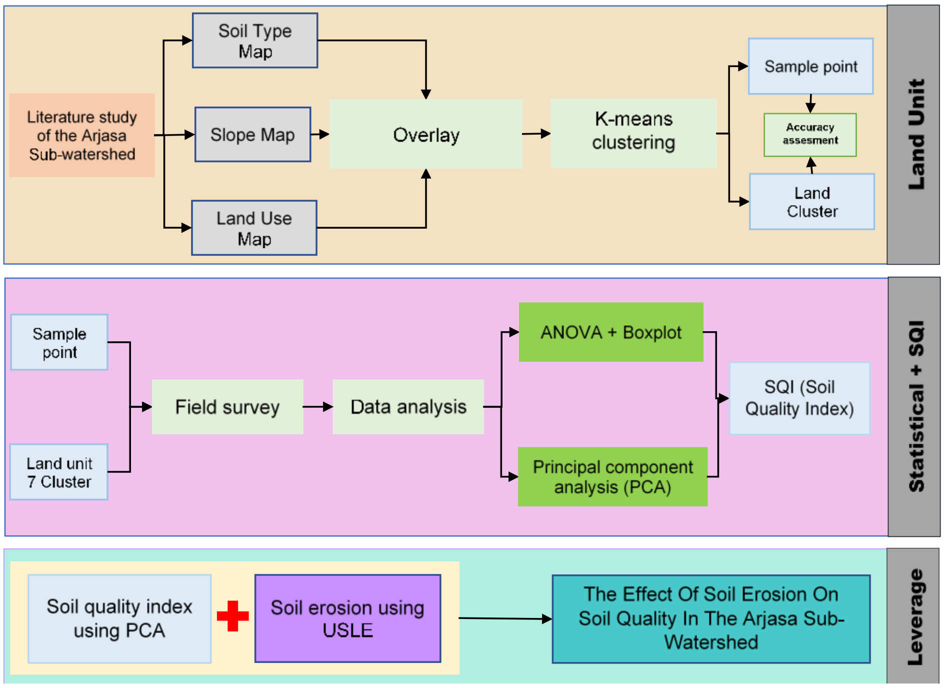
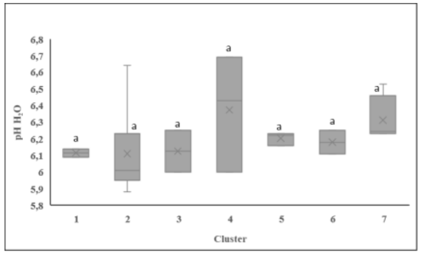


Fig. 3. Research framework

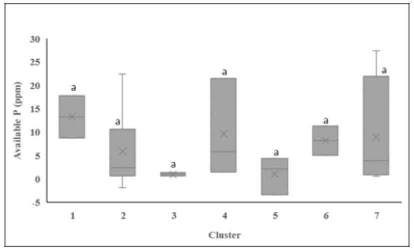
Table 4. Soil Characteristics of Arjasa Sub Watershed

Property	**Land use**			**Soil type**			**Slope**			
	DA	**IF**	**DMA**	**AD**	**TE**	**TH**	**F**	**SS**	**S**	**VS**
pH H_2O	6,13^{a}	6,25^{a}	6,19^{a}	6,23^{a}	6,05^{a}	6,14^{a}	6,07^{a}	6,20^{ab}	6,21^{ab}	6,35^{b}
Available P (Ppm)	7,41^{a}	3,24^{a}	24,85^{b}	4,37^{a}	12,79^{a}	10,77^{a}	12,26^{b}	8,79^{ab}	2,29^{a}	4,05^{ab}
Total N	0,61^{a}	0,61^{b}	0,53^{b}	0,60^{a}	0,59^{a}	0,65^{a}	0,59^{a}	0,58^{a}	0,62^{a}	0,65^{a}
Exchangeable Mg (cmol±/kg)	1,10^{a}	0,99^{ab}	1,17^{b}	1,01^{a}	1,17^{b}	1,14^{ab}	1,18^{b}	1,08^{ab}	0,95^{a}	1,09^{b}
Exchangeable Ca (cmol±/kg)	2,50^{a}	2,18^{a}	2,64^{a}	2,16^{a}	2,78^{b}	2,91^{b}	2,74^{b}	2,38^{ab}	2,07^{a}	2,65^{b}
Exchangeable K (cmol±/kg)	0,83^{a}	0,87^{a}	0,90^{a}	0,84^{ab}	0,78^{a}	0,99^{b}	0,81^{a}	0,89^{ab}	0,80^{a}	1,00^{b}
Exchangeable Na (cmol±/kg)	2,77^{a}	4,49^{a}	2,21^{b}	3,89^{b}	2,25^{a}	3,23^{ab}	2,32^{a}	3,21^{ab}	4,30^{b}	4,21^{b}
CEC (cmol±/kg)	22,64^{a}	19,16^{a}	22,50^{a}	19,47^{a}	24,47^{a}	24,79^{a}	23,40^{a}	21,29^{a}	18,58^{a}	24,19^{a}
Base Saturation (%)	5,99^{a}	5,80^{a}	6,29^{a}	5,71^{a}	6,29^{a}	6,57^{a}	6,37^{a}	5,96^{a}	5,55^{a}	6,28^{a}
Organic C (%)	0,07^{a}	0,12^{a}	0,10^{a}	0,08^{a}	0,02^{a}	0,28^{b}	0,03^{a}	0,10^{a}	0,09^{a}	0,28^{b}
Sand (%)	71,57^{a}	67,60^{a}	71,86^{a}	69,10^{a}	72,33^{a}	69,85^{a}	72,22^{a}	72,12^{a}	65,54^{a}	72,24^{a}
Silt (%)	10,21^{a}	12,43^{a}	11,24^{a}	11,35^{a}	11,13^{a}	11,36^{a}	10,86^{a}	10,60^{a}	12,84^{a}	9,01^{a}
Clay (%)	18,22^{a}	19,97^{a}	16,09^{a}	19,55^{a}	16,54^{a}	18,79^{a}	16,92^{a}	17,28^{a}	21,62^{a}	18,75^{a}
BD $(g.cm^{-3})$	1,05^{a}	1,25^{b}	1,15^{ab}	1,19^{b}	1,01^{a}	1,11^{ab}	1,03^{a}	1,14^{ab}	1,21^{b}	1,22^{b}
PD $(g.cm^{-3})$	1,36^{a}	0, 32^{a}	1,51^{a}	1,32^{a}	1,55^{a}	1,28^{a}	1,55^{a}	1,33^{a}	1,28^{a}	1,43^{a}
Porosity $(g.cm^{-3})$	3,54^{a}	2,25^{a}	2,92^{a}	2,68^{a}	3,51^{a}	3,23^{a}	3,31^{a}	3,06^{a}	2,67^{a}	2,31^{a}
Hydraulic conductivity (µS/cm)	0,27^{a}	0,13^{a}	0,39^{a}	0,18^{a}	0,06^{a}	0,18^{a}	0,07^{a}	0,03^{a}	0,35^{a}	0,11^{a}

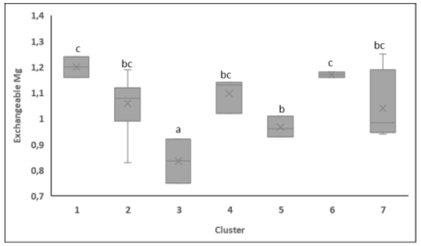
Description: The same letter in the same row in each factor shows no significant difference, while different letters in the same row in each factor show significant difference.Land use: DA "Dryland Agriculture",IF "Industrial Forestry", DMA " Dryland Mix Agriculture" Soil type: AD "Andic Dystrudepts", TE "Typic Eutrudepts", TH "Typic Hapludands" Slope: F "Flat", SS "Somewhat steep",S "Steep",VS "Very steep",



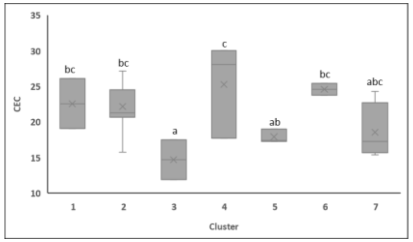
(a) pH H_2O



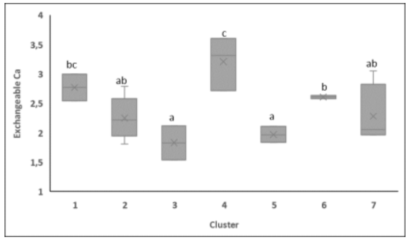
(b) Available P (ppm)



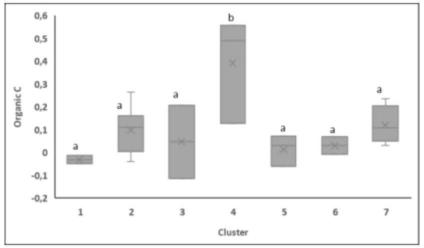
(c) Exchangeable Mg (cmol+/Kg)



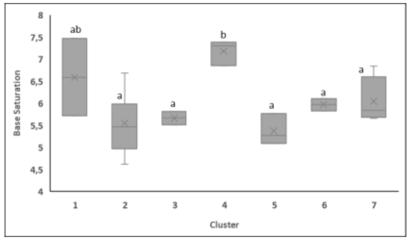
(d) CEC (cmol±/kg)



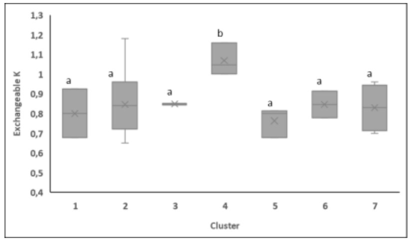
(e) Exchangeable Ca (cmol+/Kg)



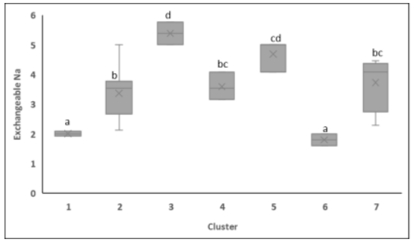
(f) Organic C (%)



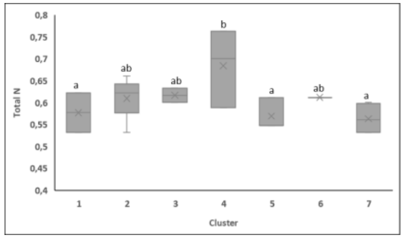
(g) Base Saturation (%)



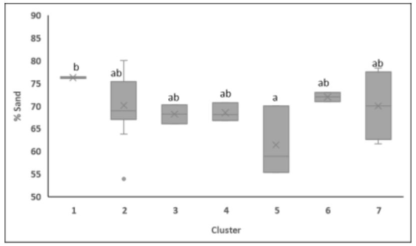
(h) Exchangeable K (cmol+/Kg)



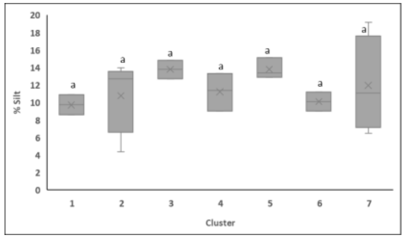
(i) Exchangeable Na (cmol+/Kg)



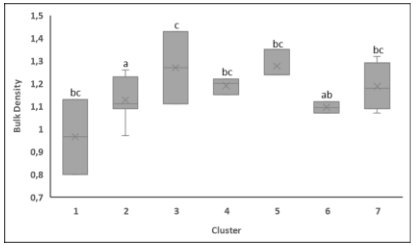
(j) Total N (cmol±/kg)



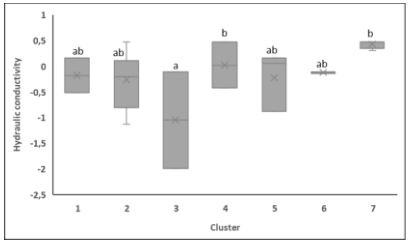
(k) Sand (%)



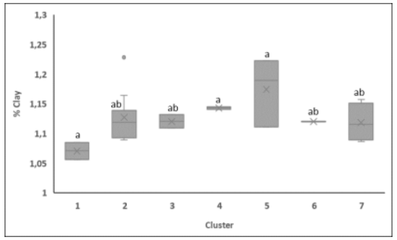
(l) Silt (%)



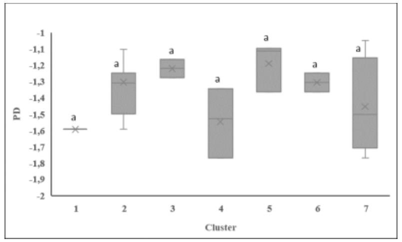
(m) BD ($g.cm^{-3}$)



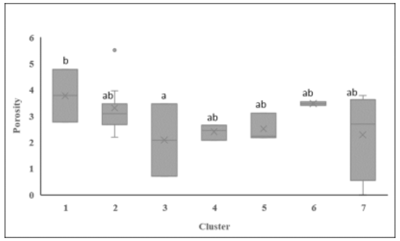
(n) Hydraulic conductivity (μS/cm)



(o) Clay (%)



(p) PD ($g.cm^{-3}$)



(q) Porosity (%)

Fig. 4. Boxplot of soil characteristics in different cluster

Note : Clutser 1 (Dryland Agriculture,Typic Eutrudepts,3-8%); Cluster 2 (Dryland Agriculture,Andic Dystrudepts,25-40%); Cluster 3 (Industrial Forestry,Andic Dystrudepts,25-40%);Cluster 4 (Industrial Forestry, Typic Hapludands,>40); Cluster 5 (Industrial Forestry,Andic Dystrudepts,25-40%); Cluster 6 (Dryland Agriculture,Andic Dystrudepts,15-25%); Cluster 7 (Industrial Forestry,Andic Dystrudepts,15-25%)

High contents of Mg, Ca, and CEC are found in dryland farmlands, this is due to the use of chemical fertilizers containing these elements in the process of agricultural cultivation. The factor that can affect the high Ca content in this soil is the parent material that forms the soil (Selim, 2020). Ca in the soil comes from the soil-forming parent material, as well as the weathering and dissolution of limestone which has a high calcium content (Luo et al., 2023; Zhang et al., 2021). The Arjasa Subwatershed area with Typic Hapludands soil type contains higher CEC elements. According to (Alaboz et al., 2021) Minerals that undergo weathering will release nutrients into the soil, besides that the Typic Hapludands soil type tends to have a high cation exchange capacity that allows the soil to store and retain large amounts of nutrients.

The high Na value is partly due to the addition of Na fertilizer which can increase the Na content in the soil. In addition, in irrigated drylands, sodium-containing irrigation water and inefficient soil management practices can cause salinization, where salts including sodium will settle in the soil. Soil physical properties such as BD and soil texture in the Arjasa Subwatershed show stable values, this is due to its unchanging conditions and land use dominated by production forests in areas with high slopes.

3.3 Principal Component Analysis

The Principal Component Analysis (PCA) in Table 5 shows that five principal components successfully explain the variability of soil quality. Based on the 5 principal components (PCA), 5 parameters were selected into the MDS. In PC 1 is represented by Ca. PC 2 is represented by % sand. PC 3 is represented by N. PC 4 is represented by porosity. On PC 5 represented by pH H_2O. The lowest value in the porosity parameter is 0.636 with the highest Ca value of 0.903.

The first component (PC1) is the highest because the results of the analysis of the Ca parameter are significant in various land units. The second component (PC2) is more related to soil physical properties such as sand and dust, this variable indicates that the second component describes soil texture. However, % sand was chosen because it has a greater eigenvalue than other parameters. The third component (PC3) also shows a relationship with soil chemical properties, especially sodium and nitrogen. The value of total N is the highest so this parameter was selected compared to the others. The parameter values of % sand, total N, and pH H_2O show a small difference, which suggests that the three parameters affect soil quality to the same extent.

The fourth (PC4) and fifth (PC5) components have a smaller contribution in explaining the variability of the data and may represent more specific variations in the data. The pH H_2O parameter is an indicator of soil quality due to the level of management and land use applied in the Arjasa Subwatershed. According to (Kahsay et al., 2025) the selection of plants that are in accordance with environmental characteristics maintains the stability of soil physical properties and soil pH. The selected parameters in the MDS indicate the development of physical and chemical conditions in the Arjasa Subwatershed, increasing the potential for better land utilization.

3.4 Analysis of Soil Quality Index

The level of MDS contribution used in determining soil quality according to Table 6 and Fig. 5 with the order is exchangeable Ca, percentage of sand, N, porosity, and pH H_2O. The highest SQI value is 0.65 with the lowest value of 0.48, the average SQI value in Arjasa Subwatershed is 0.5. The average value of standard deviation is 0.5, this is supported by the results of the real difference to the entire cluster.

In each cluster shows that Ca content has the highest contribution in compiling soil quality, then the percentage of sand is the second highest order in compiling soil quality, and for the third highest order is Nitrogen. The Typic Hapludands soil type contributes the highest Ca content to soil quality. This type of soil is formed from volcanic material that is rich in minerals. Mineral weathering releases nutrients into the soil. Weathering contributes to soil nutrient richness and can improve soil quality. Calcium plays an important role in the formation and stability of soil aggregates. Calcium helps to bind soil particles into more stable structures, supporting the formation of good soil aggregates. A stable soil structure is important for optimal plant root growth.

In dryland agricultural land use, nitrogen content has a high contribution to soil quality. The more frequent application of nitrogen fertilizers in dryland agriculture is one of the factors that cause high nitrogen in this land use. In addition, the addition of straw can also increase soil nitrogen, this is in line with research (X. Wang et al., 2023) which revealed that the addition of straw can increase soil nitrogen compared to fertilizer treatment. A slope of 3-8% contributes the highest Ca content to soil quality. At this slope, Ca content is higher due to fertilizer inputs given in agricultural practices. The high Ca content on lower slopes can also be caused by runoff that carries nutrients from top to bottom, so that Ca concentration increases on lower slopes (Yustika et al., 2023). Soil erosion can transport nutrients in the topsoil, leading to nutrient loss (Yustika et al., 2023).

At this slope, applied fertilizers are more easily absorbed by the soil and plants, without experiencing much loss due to erosion or runoff that often occurs on upper slopes. This allows nutrients to remain available in the root zone, thus supporting optimal plant growth. On slopes >40%, exchangeable Ca shows the second highest contribution to soil quality. At this slope the movement of water and soil material occurs more intensively, but the content of exchangeable Ca still shows a high contribution compared to the slope of 25-40% and 15-25%, this can be caused by the vegetation cover on the slope is still in good condition. On this slope the vegetation is woody trees. Woody trees can help hold soil and minimize excessive erosion. Good land cover can also slow down water flow and reduce the risk of soil erosion so as to keep nutrients available (Wu & Hu, 2020).

The 25-40% slope showed slightly lower Ca content compared to the 15-25% slope. The exchangeable Ca content on this slope shows a contribution to soil quality but not as much as the 3-8% and >40% slopes. This can be caused by less than optimal land management and little vegetation protection that can trigger erosion. As explained above, erosion can transport nutrients in the top soil layer, which can trigger nutrient loss. The contribution of Nitrogen content on each slope increases from the lower to the upper slopes. The highest nitrogen content is found on slopes of 25-40% and >40%. Besides exchangeable Ca and nitrogen, porosity is the fourth contribution to soil quality.

3.5 Erosion Hazard Level Based on Cluster

Analysis of erosion data in Table 7 shows the level of erosion hazard in the Arjasa Subwatershed based on clusters in each cluster is different and influenced by several factors such as length and slope, soil erodibility, land cover, and soil conservation measures. The results of the analysis on the 7 clusters show significant variations in the erosion value (A) between clusters. This indicates that the level of vulnerability to erosion in each cluster is different.

The level of erosion hazard in the Arjasa Subwatershed is categorized in the very mild to severe class. The table shows that cluster 3 has the highest erosion hazard level categorized as severe and clusters 1 and 7 have the lowest erosion hazard level categorized as very light. According to (Kahsay et al., 2025; Quinton & Fiener, 2024) erosion rates are influenced by various factors, including CP and LS factors. The influence of the LS factor on erosion depends on the slope and length of the slope, which affects the flow of water on the soil surface. The steeper the slope, the greater the velocity of surface water flow, which has the potential to transport soil more efficiently. The most dominant factor affecting erosion values is the length and slope (LS). The greater the LS value, the higher the potential for erosion. This can be seen in clusters 3 and 4 which have the highest LS values and high erosion values.

Second, the soil erodibility factor (K) also contributes to the amount of erosion. Although the variation in K value is not as large as LS, the difference in K value still affects the final erosion value. Soils with high K values tend to erode more easily than those with low K values. The influence of CP factors on erosion is influenced by land use, where the greater the forest area can reduce the erosion rate (Ashwini Suryawanshi et al., 2022). Reduced forest area can increase soil erosion, as well as reduce water infiltration capacity and the ability to store water, which can accelerate erosion.

Erosion that occurs on the same land use often varies due to the influence of conservation techniques applied. The use of appropriate conservation techniques that suit the land conditions can significantly reduce erosion rates. Land cover (C) and soil conservation measures (P) also need to be considered. Clusters with low C and P values generally have higher erosion values. This suggests that lack of land cover and ineffective conservation measures can increase the potential for erosion. There are several erosion classes in the Arjasa Subwatershed, from very light to heavy. This uneven distribution of erosion classes indicates that there are areas that are highly vulnerable to erosion and require special handling.

Table 5. Principal component analysis

Component Matrix[a]					
% of Variance	32,312596	15,964325	14,418758	9,5950782	8,0489048
Eigenvalue	0,4021998	0,1987104	0,1794725	0,1194314	0,1001859
	PC1	PC2	PC3	PC4	PC5
pH H_2O	-0,094	0,512	0,078	-0,001	**0,769**
Available P (Ppm)	0,684	0,032	-0,432	-0,222	-0,204
Exchangeable Mg (cmol±/kg)	0,762	0,081	-0,373	0,201	-0,081
CEC (cmol±/kg)	0,723	0,152	0,051	0,456	-0,176
Exchangeable Ca (cmol±/kg)	**0,903**	0,344	0,044	-0,007	-0,073
Organic C (%)	0,537	0,358	0,625	0,171	0,065
Base Saturation (%)	0,710	0,274	0,082	-0,415	0,067
Exchangeable K (cmol±/kg)	0,571	-0,060	0,547	-0,171	0,121
Exchangeable Na (cmol±/kg)	-0,603	-0,150	0,594	-0,251	0,087
Total N	0,199	0,236	**0,714**	0,361	-0,150
Sand (%)	0,555	**-0,759**	0,121	-0,174	0,199
Silt (%)	-0,477	0,607	-0,259	-0,156	-0,374
Clay (%)	-0,482	0,724	0,020	0,320	-0,045
Hydraulic conductivity (µS/cm)	0,138	0,326	-0,520	0,016	0,586
PD $(g.cm^{-3})$	-0,587	-0,352	0,010	0,501	0,087
Porosity $(g.cm^{-3})$	0,348	-0,398	-0,241	**0,636**	0,162
Extraction Method: Principal Component Analysis.					
a. 5 components extracted.					

Table 6. Soil quality index in various clusters

Cluster	**Land use**	**Soil type**	**Slope**	**SQI**
1	Dryland Agriculture	Typic Eutrudepts	3-8%	0.60 ± 0.076^{cd}
2	Dryland Agriculture	Andic Dystrudepts	25-40%	0.55 ± 0.039^{abc}
3	Industrial Forestry	Andic Dystrudepts	25-40%	0.48 ± 0.049^{a}
4	Industrial Forestry	Typic Hapludands	>40	0.65 ± 0.092^{d}
5	Industrial Forestry	Andic Dystrudepts	25-40%	0.52 ± 0.039^{ab}
6	Dryland Agriculture	Andic Dystrudepts	15-25%	0.58 ± 0.003^{bc}
7	Industrial Forestry	Andic Dystrudepts	15-25%	0.52 ± 0.046^{abc}

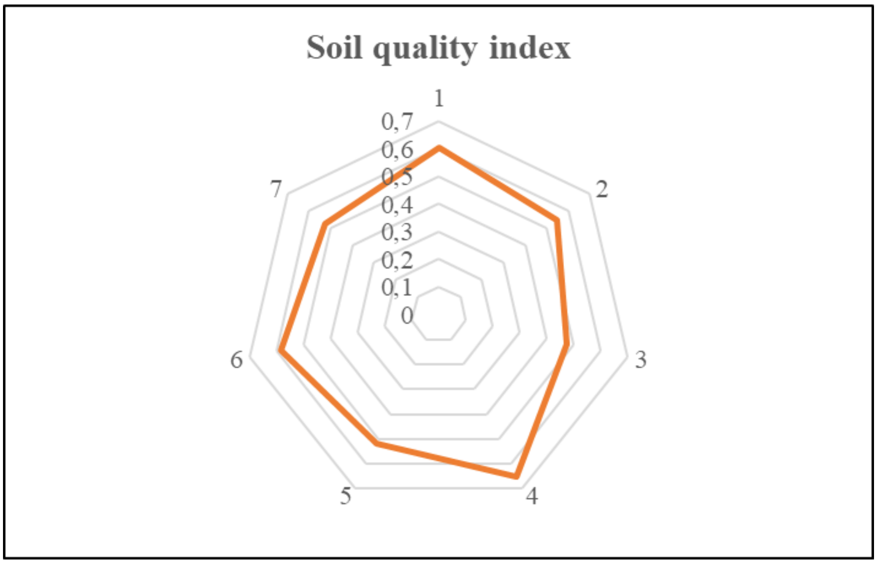


Fig. 5. Diagram hexagon of soil quality index

3.6 Relationship of Erosion to Soil Quality Index Based on Cluster

Erosion is the process by which the fertile topsoil is eroded by water or wind, resulting in the loss of essential nutrients and organic matter essential for plant growth. Soil quality degradation due to erosion is caused by poor land use practices and management. Through plot data analysis, (Fauzan Mas'udi et al., 2021) also revealed that the soil quality index (SQI) decreases as soil erosion increases, according to the analysis in Arjasa Subwatershed Fig. 6.

Based on the graphical image of the relationship between erosion and soil quality in the Arjasa Sub-watershed based on the cluster. The graph shows an r value of 0.56 or the correlation between erosion and soil quality has a moderate level of relationship. The effect of erosion on soil quality in the Arjasa Subwatershed has a negative regression direction with a regression value of 0.31 or it can be said that the erosion factor has an influence of 31% on soil quality in the Arjasa Subwatershed. The graph above shows the relationship between erosion rate and soil quality. There is a tendency for soil quality to decrease as the erosion rate increases. This is indicated by the downward sloping regression line. The regression line equation obtained is y = -0.0005x + 0.5884. The coefficient of determination (R^2) of 0.3138 and the correlation coefficient (r) of 0.56 indicate that there is a moderate negative relationship between the two variables.

The results of this analysis indicate that erosion has a significant impact on soil degradation. Erosion causes the loss of the topsoil layer which is rich in nutrients and organic matter, thus reducing the soil's ability to support plant growth. In addition, erosion can also damage soil structure, increase soil density and reduce the soil's ability to retain water.

Table 7. Erosion hazard level of Arjasa Sub Watershed

Cluster	R	K	LS	C	P	A (tons/ha /year)	Solum (cm)	EHL	Class
1	1617.72	0.32	0.4	0.53	0.04	4.39	>90	SR 0	Very light
2	1617.72	0.27	3.1	0.64	0.04	34.66	>90	R I	Light
3	1617.72	0.28	6.8	0.6	0.1	184.81	>90	B III	Heavy
4	1617.72	0.25	9.5	0.1	0.1	38.42	60-90	S II	Medium
5	1617.72	0.28	6.8	0.1	0.15	46.20	>90	R I	Light
6	1617.72	0.24	3.1	0.4	0.15	72.22	>90	S II	Medium
7	1617.72	0.29	3.1	0.1	0.1	14.54	>90	SR 0	Very light

Note ; Erosion Hazard Level (EHL) Rainfall erosivity (R) Soil erodibility (K) Slope length (L) Slope (S) Crop management and erosion prevention measures (CP) Erosion rate (A)

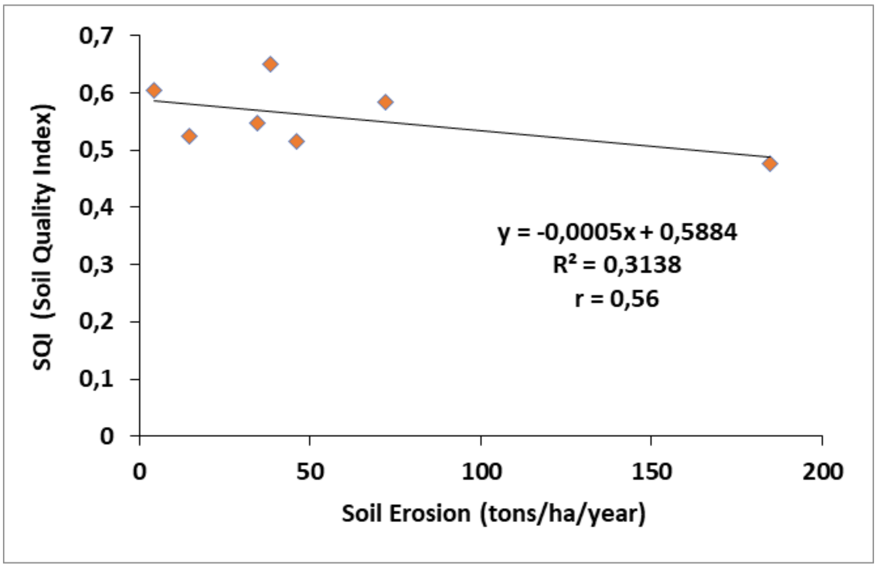


Fig. 6. Correlation between soil erosion and soil quality index

4. CONCLUSION

The soil quality indicators included in the MDS, in order of greatest contribution to the SQI, are Exchangeable Ca, percentage of sand, total N, soil porosity, and pH H_2O. The soil quality index ranges from 0.47 to 0.60 which is categorized as low to high, respectively. The soil quality index in the study area is influenced by soil type and slope, while land use has no effect. The level of erosion hazard in the study area is categorized in the class of very light (4.39 tons/ha/year) to heavy (184.81 tons/ha/year). There is a negative relationship at a moderate level (r = 0.56) between the level of erosion hazard and soil quality index, which indicates that the greater the erosion the lower the soil quality index. Since the soil erosion has negative impacts to the soil quality through reduction of productive soil layer, decreased soil nutrients, increased soil density, and changes in Soil pH. We have added some recent references to improve the quality of our manuscripts.

Limitations: This research has not considered the biological properties of the soil which can influence the soil quality index value.

5. SUGGESTION

It would be best for further research to consider soil biological properties, such as microbial biomass, soil respiration, enzyme activities, and soil fauna and flora.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

The author has declared that there is no conflict of interest.

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APPENDIX

Table 1. ANOVA test of Land use, Soil type, and Slope vs Soil characteristics

ANOVA	Land Use					Soil Type					Slope				
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
pH H_2O	0,113	2	0,057	1,479	0,246	0,149	2	0,075	2,021	0,152	0,175	3	0,058	1,557	0,224
Available P (Ppm)	833,583	2	416,792	10,809	0,000	366,282	2	183,141	3,278	0,053	463,859	3	154,620	2,849	0,057
Exchangeable Mg (cmol±/kg)	0,116	2	0,058	3,782	0,036	0,143	2	0,071	4,990	0,014	0,221	3	0,074	6,234	0,002
CEC (cmol±/kg)	89,674	2	44,837	2,071	0,146	166,817	2	83,409	4,439	0,022	130,290	3	43,430	2,076	0,128
Exchangeable Ca (cmol±/kg)	0,864	2	0,432	1,792	0,186	2,940	2	1,470	8,955	0,001	2,059	3	0,686	3,358	0,034
Organic C (%)	0,016	2	0,008	0,353	0,706	0,168	2	0,084	4,790	0,017	0,134	3	0,045	2,282	0,103
Base Saturation (%)	0,525	2	0,262	0,456	0,639	3,288	2	1,644	3,472	0,045	3,144	3	1,048	2,107	0,124
Exchangeable K (cmol±/kg)	0,013	2	0,006	0,329	0,723	0,105	2	0,052	3,247	0,054	0,126	3	0,042	2,623	0,072
Exchangeable Na (cmol±/kg)	24,473	2	12,236	20,048	0,000	11,312	2	5,656	5,152	0,013	17,758	3	5,919	6,635	0,002
Total N	0,012	2	0,006	2,337	0,116	0,009	2	0,004	1,614	0,218	0,016	3	0,005	2,077	0,128
Sand (%)	119,920	2	59,960	1,438	0,255	42,189	2	21,095	0,473	0,628	305,850	3	101,950	2,819	0,059
Silt (%)	34,533	2	17,266	1,818	0,182	0,196	2	0,098	0,009	0,991	47,828	3	15,943	1,705	0,191
BD ($g.cm^{-3}$)	0,260	2	0,130	12,864	0,000	0,143	2	0,071	4,939	0,015	0,148	3	0,049	3,328	0,035
Porosity ($g.cm^{-3}$)	11,697	2	5,848	6,827	0,004	3,317	2	1,659	1,421	0,259	2,875	3	0,958	0,780	0,516
Clay (%)	0,003	2	0,002	1,011	0,377	0,004	2	0,002	1,267	0,298	0,011	3	0,004	2,722	0,065
Hydraulic conductivity (μS/cm)	0,768	2	0,384	1,201	0,317	0,054	2	0,027	0,078	0,925	0,590	3	0,197	0,579	0,634
PD ($g.cm^{-3}$)	0,065	2	0,032	0,605	0,554	0,194	2	0,097	2,008	0,155	0,246	3	0,082	1,706	0,193

Table 2. ANOVA test of the clusters vs SQI

ANOVA					
SQI	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	0,084	6	0,014	5,420	0,001

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