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RESEARCH ARTICLE

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Landslides Hazard Assessment Using Soil Physics Approaches as a Determinant Factor on Agricultural Land in Hilly Area

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ABSTRACT

Landslides are natural disasters that most often occur in hilly areas, one of which is in the Manyaran District, and are caused by land use, slope, and rainfall. This study aimed to assess the level of landslides on several slopes and determine the soil characteristics that most determine the level of landslide vulnerability to formulate an appropriate strategy for hilly land management. The sampling points used land map units (LMU) overlaid on thematic maps (land use, soil type, and slope), and were divided into 22 LMUs with three repeats for each LMU. The landslide level was calculated using a cumulative weight score. It was grouped based on the interval formula and modifications to the addition of permeability and soil texture parameters, while the determinants were analyzed using ANOVA and Pearson's correlation. The results showed that the area was not very low (133.2 ha), low (1,015.33 ha), moderate (1,205.46 ha), high (3,248.48 ha), or very high (734.1 ha). The highest landslide hazard was on steep land (25–45%), and the determining factors were permeability and texture. The steeper the slope and the higher the permeability and soil texture values, the higher the landslide. The recommended landslide mitigation strategies are terracing and minimum tillage on agricultural land. Research on the level of landslides and information on determinant soil characteristics helps stakeholders formulate policies and manage agricultural land on hilly agricultural land.

Introduction

Landslides are a common phenomenon that often occur in many regions of the world and are the most dangerous natural hazards in areas with mountainous topography [1,2]. It is a mass movement of rock and soil under the influence of gravity, caused by land use, slope, and rainfall [3,4]. Hilly areas with moderate to steep slopes generally have the potential for landslides at different levels [5]. Slope triggers landslides, the more significant the slope, the greater the potential for landslides [6]. Landslides occur frequently in Indonesia, particularly with intense heavy rains and steep slopes in the highlands [7]. According to the Geological Agency Map, the Manyaran Subdistrict generally has hilly topography with a slope of between 5° and 15° around the valley and between 15° and more than 45° in the hills. Disruption of the balance of forces on the pitch, one of which is characterized by the presence of ground motion.

In 2014, lapping of ground motion occurred in Kopen and Timoyo Hamlet, Bero Village, in the Manyaran Subdistrict. Ground movements in Kopen and Timoyo Hamlets have occurred since the beginning of January 2013 and developed continuously in 2014. In several studies, the occurrence of landslides has increased over time and had a negative impact on environmental conditions [8]. Landslides cause soil instability [9] and degrade agricultural areas [10,11]. As a result of landslides, in 2004–2016, more than 55,000 people lost their lives, casualties due to material losses, and financial losses every year [12–14]. Direct damage can be in the form of destruction or reduced functionality of a facility, whereas indirect damage includes loss of productivity and income [15]. The amount of farmers' land is decreasing and some have to change their livelihoods [16]. This negative impact needs to be reviewed and evaluated regarding the steps that the

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community must take [17]. Land degradation in the agricultural sector is a process of decreasing land productivity and reducing farmers' incomes [18].

In addition, more degraded land caused by landslides has a lower ecological carrying capacity [19]. In addition to farmers, the government overcomes problems in formulating policies related to landslides that occur [20]. An alternative to anticipating landslides is mapping landslide hazards based on Geographic Information Systems (GIS). Remote sensing techniques with Geographic Information Systems are effective for landslide investigations. GIS was used to map landslide susceptibility by applying frequency ratio (FR) and Weight of Evidence (WoE) models. A combination of both FR and WoE models was applied for landslide susceptibility mapping. It is essential to assess landslide-prone areas and highlight critically high and very high hazard zones [21]. GIS modelling and mapping provide evidence of changes in the spatial distribution, such as land use, rainfall, and temperature, which have a substantial impact on landslide susceptibility and frequency, and help in agricultural land evaluation that can be easily displayed on a map scale [22–24].

Landslide hazard reduction can be achieved by increasing the use of remote sensing systems and focusing on the possibility of early warning of landslide hazards [25]. The effectiveness of using GIS to determine landslide susceptibility has been widely demonstrated by researchers [25–27]. Several models used to determine landslide susceptibility have been based on geomorphology and scoring approaches and statistical methods [27–30]. The advantages of Geographic Information Systems make it easier to map locations and obtain information. In addition to facilitating the community, landslide hazard mapping also assists the government in formulating policies and planning preventive measures for landslides. The aim of this research is to determine the impact of slopes on landslide hazards so that conservation efforts can be made to minimize landslides and anticipate land degradation.

Material and Methods

Study Area

The research was conducted in Manyaran Sub-district, Wonogiri Regency, Central Java, which is located at 110°47'49.4"–110°51'17.35.91" East Longitude and 7°48'37.2355"–7°52'46.1" South Latitude. The laboratory analysis was performed at the Soil Physics and Conservation Laboratory, Faculty of Agriculture, Sebelas Maret University. Manyaran District is a mountainous area with hills and rocks, bordering the Sukoharjo Regency to the north, the Wuryantoro District to the south and east, and the Special Region of Yogyakarta Province to the west.

Data Collection

This exploratory-descriptive research approach was carried out using a field survey and was supported by the results of soil analysis in the laboratory and mapping of the level of landslide hazard. Observations in the field verify conditions in the parameters of the slope, land use, and adequate depth of soil, while analysis in the laboratory determines the permeability conditions. In addition, there is an effective depth measurement in the field determination of the hazard level of landslides using overlay and scoring methods. Observation points were determined by purposive random sampling on Land Map Units (LMU), which consisted of sources of land diversity collected from several thematic maps, including land use, slope, and soil type. Each LMU was performed three times. The distribution of observation points and sampling is shown in Figure 1.

Landslide occurrence is influenced by several factors, including rainfall, slope, land use, geology, permeability, texture, and effective depth. These parameters were observed at each point and were calculated using the cumulative score (Equation 1) and converted to interval scoring (Equation 2). Each parameter has a different percentage. Each parameter has a score, as shown in Tables 1–5. To obtain landslide susceptibility, the score was multiplied by its percentage. The percentage of rainfall factor is 20%, slope is 30%, geology is 15%, permeability is 5%, soil texture is 5%, and effective depth is 5%. The landslide susceptibility values obtained can be classified as shown in Table 6.

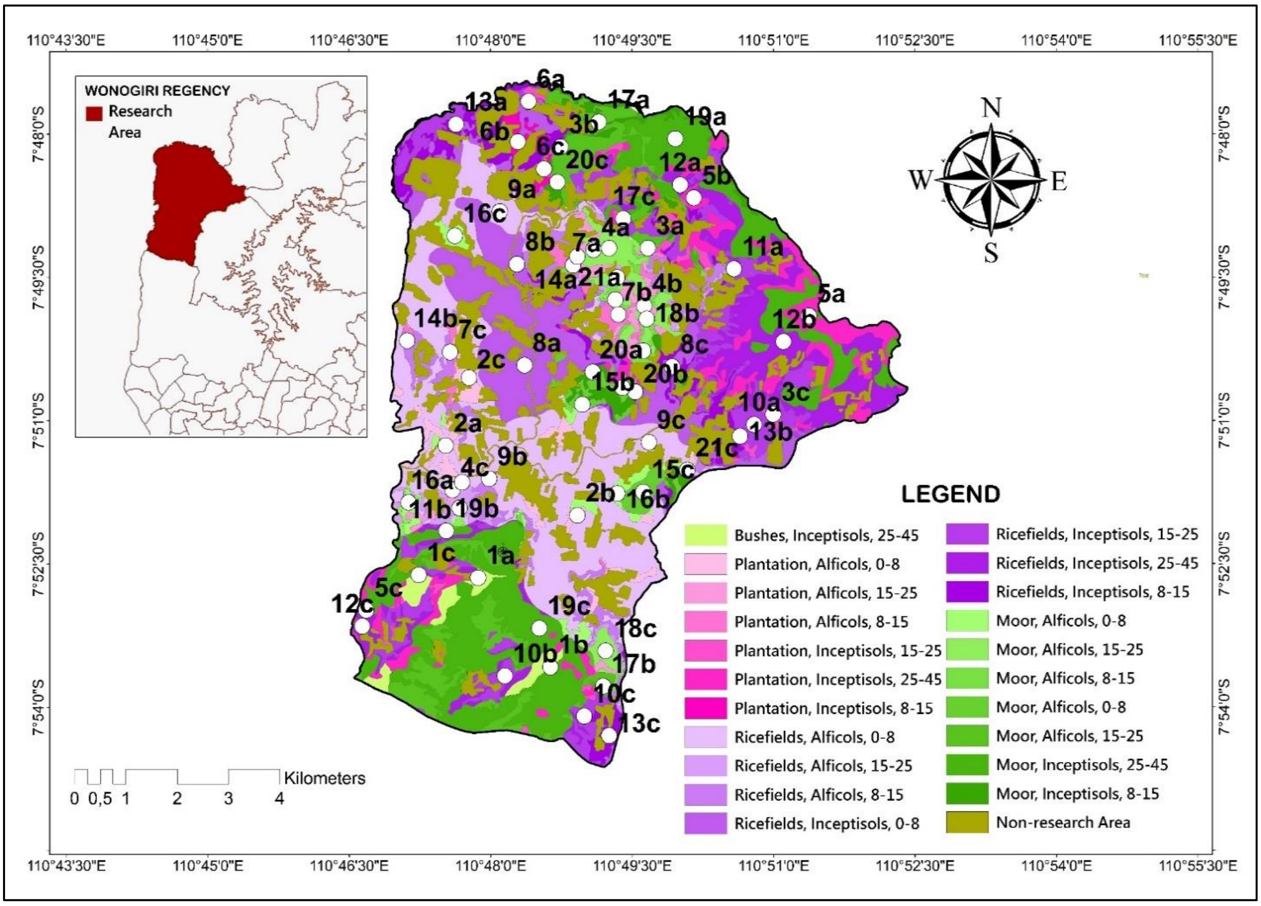

Figure 1. Map of research location.

Data Analysis

Qualitative data were obtained from field notes, documents, pictures, and audiovisual data. The data analysis method used is the qualitative data analysis method, which goes through three activity streams simultaneously, namely reduction, presentation, and drawing conclusions or data verification, according to Umaroh and Ritohardoyo [16]. First, the reduction stage classified the data into categories of record groups according to the research objectives. Second, the presentation stage organizes information and data, which are grouped into a series of words, charts, pictures, and tables. The third stage draws conclusions from the results of the data processing and field verification. These three methods are intertwined activities carried out before, during, and after the data collection.

Rainfall

The distribution of landslides depends on the characteristics of the local area, which are also affected by rainfall [31]. The rainfall parameter has a total weight of 20% at the level of landslide vulnerability. The amount of rainfall determines the magnitude of landslides that will occur. The highest number of landslide disasters occurred in areas with a rainfall of 2,000 mm/year [32]. Manyaran Sub-district has one rainfall station of the same amount, about 2186 mm/year. The rainfall classification is presented in Table 1.

Table 1. Rainfall classification.

Rainfall intensity (mm/year)	Score
< 1,000 (dry)	1
> 1,000–2,000 (rather dry)	2
> 2,000–3,000 (moderate)	3
> 3,000–4,000 (rather wet)	4
> 4,000 (very wet)	5

Source: [33].

Slope

Mountainous or hilly areas are one of the characteristics of areas prone to landslides [34]. The principle of landslide occurrence is that the driving force exceeds the resistance force on the upper slope. The factor that influences the driving force is the slope [35]. Most landslide disasters in Indonesia occur on steep slopes, namely, in the range of 15°–45° or more [32,36]. The landslide hazard assessment based on slope gradient is presented in Table 2.

Table 2. Slope classification.

Slope	Score
0–8	1
> 8–15	2
> 15–25	3
> 25–45	4
> 45	5

Source: [33].

The slopes in the study area varied, ranging from 0–8%, 8–15%, 15–25%, and 25–45%. The most dominant slopes in the study area were 0–8% and 25–45%. The 0–8% slope is spread across Pijiharjo Village, Pagutan Village, Punduhsari Village, and Karanglor Village, whereas a 25–45% slope is found in Kepuhsari Village, Gunungan Village, and Bero Village.

Land Use

Degradation owing to changes in land use increases the occurrence of landslides [37]. Land use is an important conditioning factor that influences landslides, and many researchers have argued that land use might increase landslide susceptibility, especially in agricultural land [38]. Land use in the Manyaran Sub-district is divided into bushes, rice fields, moors, and plantations. Rice fields have an area of 2,875.63 ha. Moor area of 1,574.10 ha. Bushes area of 64.37 ha, and plantation area of 602.94 ha. The land-use classifications are presented in Table 3.

Table 3. Land use classification.

Land use	Score
Pond, reservoir, waters	1
Settlement	2
Forest, plantation	3
Bushes	4
Ricefields, moor	5

Geological

Geological formations in the Manyaran District consist of Mandalika, Semilir, Wonosari, and Old Alluvium. The Mandalika Formation has an area of 1,557.6 ha, the Semilir Formation covers 3,396.56 ha, the Wonosari Formation covers 1,356.41 ha, and the Old Alluvium covers 26.54 ha. Geological structure influences landslide vulnerability. Rocks intensively exposed to geological structures accelerate weathering. The geological structure is a weak rock zone that forms fractures. Fractures become water inlets so that the weathering process becomes faster and the rock's resistance level is reduced. The closer it is to the geological structure zone, the higher the landslide vulnerability [39]. The geological classification is presented in Table 4.

Table 4. Geology classification.

Geology	Score
Andesit, Desit	1
Nglanggran, Semilir, Lava Sidoramping, Mandalika, Lahar Lawu, Breksi Jobolarangan, Lava Jobolarangan	2
Wuni, Arjosari, Jaten, Nampol	3
Tuf Butak, Tuf Jobolarangan, Batuan gunungapi Lawu, Baturetno, Sampung, Dayakan, Wonosari, Cendono	4
Aluvial, Old Alluvium, Alluvial Deposits	5

Source: [40].

Permeability

Soils with high permeability will slow down the occurrence of landslides compared to soils with low permeability. Soil with low permeability saturates the soil. Saturation results in pressure on the soil grains, causing the soil mass to move and landslides to occur [41]. The soil permeability was analyzed in the laboratory using the head constant permeameter method. The soil sample used was undisturbed soil that was collected using a ring sampler. The classification for scoring each soil permeability value was based on Arsyad [42].

Texture

Soil texture was analyzed in the laboratory using the granular pipette method, and wind-dried soil samples (< 2 mm and < 0.5 mm) were used to determine the proportions of sand, clay, and silt and to classify texture classes according to Fletcher and Gibb [43].

Effective depth

The effective depth of the soil is the depth until the layer is impenetrable by roots and is good for plant root growth. Effective depth measurements can be started from the soil surface to the hard impermeable layer [44]. The effective depth is related to the conditions for the growth of plant roots in maintaining a stable slope [45]. The effective depth of the soil was observed using a soil biopore drill, which excavated the soil to the limit of the roots and rock in the soil. The landslide hazard assessment based on the effective soil depth is presented in Table 5.

Table 5. Effective depth classification.

Effective Depth	Score
< 30	1
> 30–60	2
> 60–90	3
> 90–120	4
> 120	5

Source: [46].

Data Analysis

The level of landslide hazard is determined by overlaying the map of the slope, land use, rainfall, and geology maps, and then scoring the weight of each landslide hazard parameter using the following formula by [47] as follows Equation (1):

$$\text{Cumulative Score} = (20\% \times \text{Rainfall Factor}) + (30\% \times \text{Slope Factor}) + (20\% \times \text{Land Use Factor}) + (15\% \times \text{Geological Factor}) + (5\% \times \text{Soil Permeability Factor}) + (5\% \times \text{Soil Texture Factor}) + (5\% \times \text{Soil Effective Depth Factor}) \quad (1)$$

The scoring calculation is continued with the calculation of the landslide class (Table 6), which is divided into five intervals using Equation (2):

$$\text{Interval score} = \frac{maximum\ value - minimum\ value}{number\ of\ classes} \quad (2)$$

Table 6. Landslide level classification.

Level	Value
Very low	2.15–2.45
Low	> 2.45–2.75
Moderate	> 2.75–3.05
High	> 3.05–3.35
Very high	> 3.35–3.65

The slope variety factor for landslide susceptibility was tested using One-way Analysis of Variance (ANOVA). ANOVA in SPSS ver. 25.0 application to determine the effect of slope variety on the level of landslide hazard; if it had a significant effect, Duncan's Multiple Range Test (DMRT) was used to determine the difference in the average distribution of landslide hazard on each slope variation.

Results and Discussion

Landslide Hazard Level

The level of landslide hazard in this study was categorized as very low, low, moderate, high, or very high (Figure 2), with each slope presented in Table 7. However, soil erosion vulnerability was dominated by the high category, reaching 3,248.6 ha, and very few areas in the low (1,015.33 ha) or very low (133.2 ha) categories. This shows that the Manyaran area has a serious threat of erosion on its agricultural lands, which is also triggered by slope topography. Slopes with a slope of 25–45% have vulnerabilities ranging from moderate to very high, meaning that on these slopes, the risk of landslides is guaranteed to be as low as moderate. The movement of soil on a steep slope is supported by the pushing force of a large soil mass, which causes the soil aggregate material to move from a high location to a lower surface through gravity. The vulnerability of landslides on steep slopes to agricultural land is triggered by natural factors such as rainfall, physical characteristics of the soil, vegetation planted, and human activity factors in cultivating the land before and after the planting period.

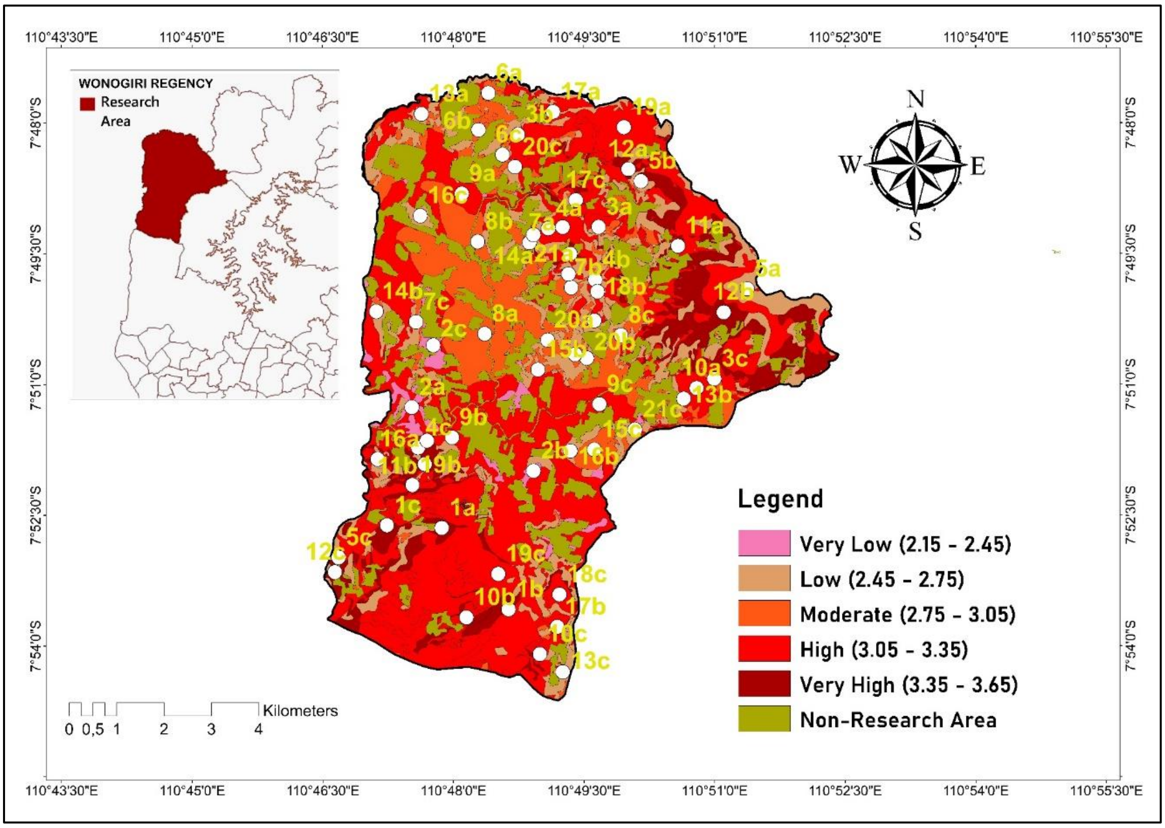

Figure 2. Landslide hazard map of Wonogiri Regency.

Table 7. The distribution of landslide hazard levels on several slopes.

Slope	Landslide Hazards Level				
	Very Low	Low	Moderate	High	Very High
0–8%	133.2	817.4	107.1	1,160.38	0
> 8–15%	0	119.04	610.1	0	0
> 15–25%	0	78.89	96.36	1,032.8	91.9
> 25–45%	0	0	391.9	1,055.3	642.2

This was linked to the contribution of land use. The lowest landslide hazard values on slopes of 0–8% were found for plantation land use. Slope triggers landslides, and the greater the slope, the greater the potential for landslides [6]. Apart from the flat slope, the plantation also affected the landslide hazard. Plantations have strong roots. Therefore, reducing the tensile forces and subsurface flows affects the slope stability and the risk of landslides [48]. The 25–40% slope had a high level of landslide hazard. Ricefields, which are used as paddy fields, had the highest values. Rice fields contain soil that dominates with high water saturation, which detains soil development [49]. This is similar to Inceptisol soil, which has the potential to cause landslides.

Effect of Slope on Landslide Hazard

Terrain characteristics, such as the slope gradient, play an important role in assessing landslide potential areas. Slope is an important parameter for evaluating the stability of landslide susceptibility. The results of the analytical test showed that the diversity of slope degrees had a significant effect on landslide hazard levels (Figure 3). Slopes with a degree greater than 40% have high potential for landslides [50]. In addition, the dominant part of the texture in the study area is dust content. Higher slopes are more significant in causing landslides. Slope has a significant effect on landslide hazards. The best landslide hazard occurred on slopes in the range of 0–8%. This is because the average value of landslide hazards is lower on slopes of 0–8% than on other slopes. The higher the slope, the higher is the slope level [6]. In addition, the dominant part of the texture in the study area had a dusty texture. The characteristic of dusty soil is that water tends to move through it quite well, but the soil resistance to water is weak, which accelerates the occurrence of landslides [51].

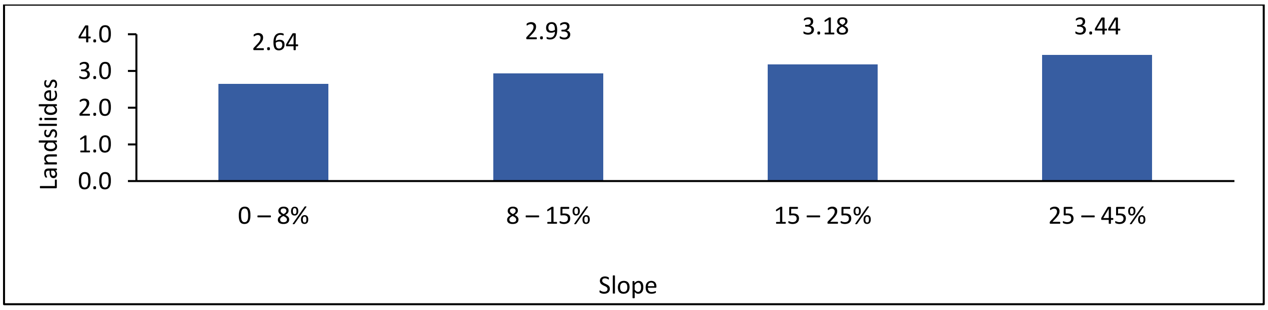

Figure 3. Average landslide hazard on several slopes.

Soil Characteristics as Determinant Factor of Landslides Hazard

Unconditional soil also has great potential for landslides. where the poor physical properties of the soil tend to shift and collapse suddenly when it rains. Among the physical properties of soil, soil texture and permeability are factors affecting landslides. In our research. The soil conditions that correlated with the dynamics of landslide hazards were permeability ($p = 0.000$, $r = -0.338$) (Figure 4) and soil texture ($p = 0.000$, $r = 0.417$) (Figure 5). Permeability significantly determines landslide hazard. The lower the permeability of the soil, the greater the landslide hazard. Soils with low permeability hold more water at the surface during the rainy season. Unabsorbed water causes the soil to become saturated, and the pressed soil grains cause the soil mass to move. This process increases the risk of landslides [41]. The soil texture was dominated by dusty loam texture. Soils with a texture dominated by silt have a lower ability to hold water than soils with high clay content. The finer the texture of the soil, the more saturated it is with water. Silt is a fine soil texture with the potential to cause landslides [52].

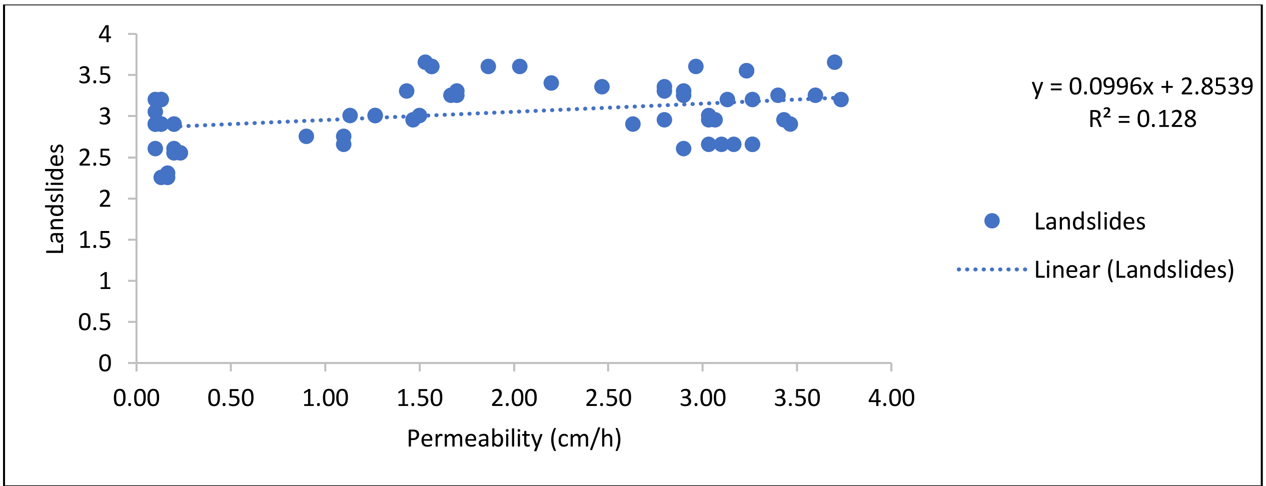

Figure 4. Correlation between permeabiliy and the level of landslides.

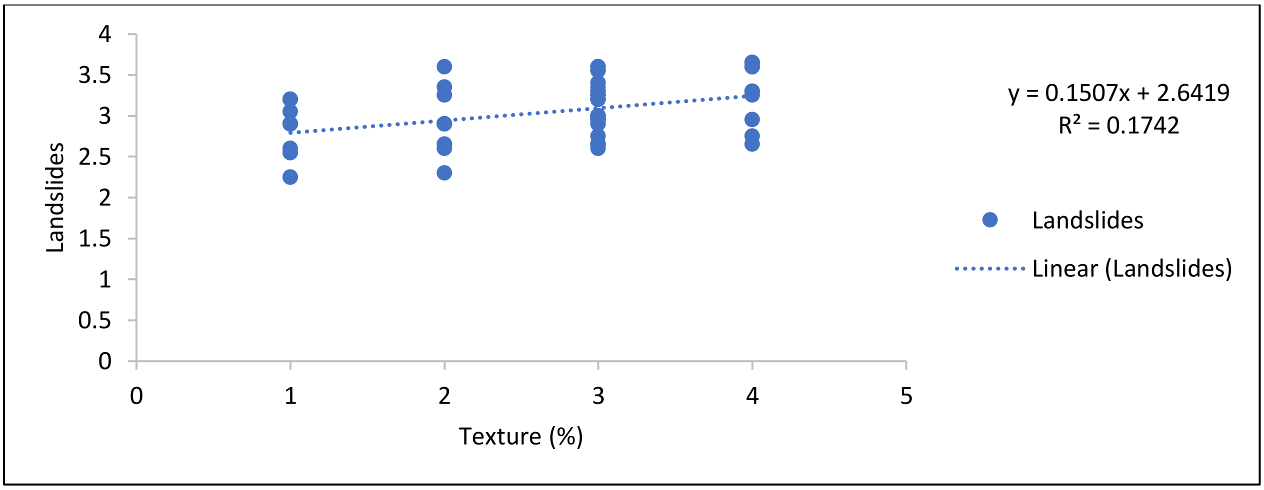

Figure 5. Correlation between the class texture and the level of landslides.

Agricultural Land Landslide Hazard Mitigation Strategy

Mechanical conservation is an effort to prevent landslides, and one of the methods is to make terraces. Terraces are embankments that are adapted to the nature of the soil and its slope to control landslides [53]. The results of research by Rutebuka et al. [54], showed traditional terracing using progressive soil sedimentation behind napier grass (*Penissetum purpureum*) succeeded in preventing soil movement during landslides in the range of 50–93%in sloping farming practice on slopes > 45%. Terraces are mechanical conservation methods that are easily accepted by Indonesian farmers [55]. The mechanical terrace implemented by Tando et al. [56] on a slope of 40% in Karangkobar, the catchment area is a bench terrace and waterways for soil and water conservation. The results of research by Hairiah et al. [48] show that in Indonesia vegetative terrace with woody roots such as mahogany (*Swietenia mahogani*), gmelina (*Gmelina arborea*), suren (*Toona sureni*), coffee (*Coffea canephora*), and bamboo (*Bambusa arundinacea*) can mitigate landslides.

The use of vegetation on slopes provides erosion control measures, and vegetation covers steep slopes; for example, bamboo is not only able to mitigate landslides but also has the potential to sequester carbon and store carbon in the soil for a longer period [57]. Meanwhile, coffee has limiting environmental factors that must be adjusted for altitude and rainfall [58]. This is because vegetation minimizes soil movement by binding and holding the soil by wood roots. However, each type of tree has a different root diameter, therefore, mixed vegetation with woody roots is still recommended to hold the soil of landslides. In addition to terrace production, minimum tillage is a type of soil conservation.

According to Jambak et al. [59], minimum tillage is performed to strengthen soil. The results of a meta-analysis showed that minimal tillage results in lower landslide movement [60]. Minimum tillage is considered to be a landslide disaster mitigation method because it can reduce the vulnerability of landslides on sloping land. The application of minimum tillage can be combined with natural soil improvement through the addition of organic materials, such as compost and biochar, to increase the soil's physical ability to bind water and have stable soil aggregates. Compost is useful for reducing high soil density, increasing the ability of the soil to hold water in the soil [61], and minimizing damage to crops on agricultural land that has the potential for landslides [62].

Conclusion

Hilly areas in Indonesia are vulnerable to landslides, which have a negative impact on the environment and local economy. From the results of our research, it was found that slope is a determining factor in the occurrence of landslides. The slope has a significant effect on landslide hazards. The highest landslide hazard levels occurred on slopes with a range of 25–45%. The greater the slope and angle of inclination, the greater the hazard of landslides. Land conservation can be achieved by making terraces and using minimum tillage to manage the agricultural land. The benefits obtained include minimizing the risk of landslides to prevent land degradation.

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