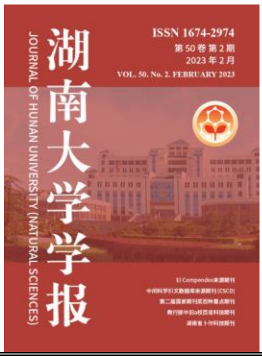

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AHP GIS-Based Gully Erosion Susceptibility Modelling in Tropical Volcano Environment

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Abstract: Gully erosion is the most destructive form of erosion and contributes significantly to the accumulation of water sediment in an area. This study aims to map the gully erosion susceptibility in the Kodil watershed, Central Java, Indonesia. The base data used in this study are from Sentinel-2 with a resolution of 10 m and DEMNAS (National Digital Elevation Model of Indonesia) with a resolution of 8 m. The Analytical Hierarchy Process (AHP) was used to assess the weight of each parameter that influences the gully erosion susceptibility. Overall, there were ten parameters used in this study, namely a) elevation (m); b) slope gradient (0); c) slope aspect; d) slope curvature; e) topographic wetness index; f) distance from the river (m); g) distance from the road (m); h) land use; i) soil texture; and j) soil aggregate. An accuracy test used the AUC (Area under Curve). The results of spatial data analysis proved that 855 ha (6.34%) of land in the Kodil DAS has a high susceptibility to gully erosion. Testing with AUC shows that the AUC training value was 0.742, the AUC test was 0.737, and the accumulative AUC value was 0.73, so the model results fall into the good category. The novel aspect of this study is the use of texture and soil aggregate parameters that have never been studied before. The decision to employ soil parameters is inextricably linked to the characteristics of the research site, which has extremely thick soil layers with high clay content. The gully erosion susceptibility model helps plan the development of land resources in its sustainability aspect.

Keywords: gully erosion, analytical hierarchy process, susceptibility modeling, tropical volcano environment.

熱帶火山環境中基於層次分析法地理信息系統 的溝壑侵蝕敏感性建模

摘要：溝渠侵蝕是最具破壞性的侵蝕形式，對一個地區的水沉積物積累有顯著貢獻。本研究旨在繪製印度尼西亞中爪哇科迪爾流域的溝渠侵蝕敏感性圖。本研究中使用的基礎數據來自分辨率為 10 儀表的哨兵-2 和分辨率為 8 儀表的印度尼西亞國家數字高程模型。層次分析法用於評估影響沖溝侵蝕敏感性的每個參數的權重。總體而言，本研究使用了十個參數，

即海拔（儀表)；坡度(0)；坡向；坡度曲率；地形濕度指數；與河流的距離（米）；與道路的距離（米）；土地使用；土壤質地；土壤骨料。準確性測試使用曲線下面積。空間數據分析結果證明，科迪爾河流流域中有 855 公頃（6.34%）的土地具有較高的溝壑侵蝕敏感性。用曲線下面積測試，曲線下面積訓練值為 0.742，曲線下面積測試為 0.737，累計曲線下面積值為 0.73，模型結果屬於良好類別。這項研究的新穎之處在於使用了以前從未研究過的質地和土壤團聚參數。採用土壤參數的決定與研究地點的特點有著千絲萬縷的聯繫，該地點具有極厚的土層和高粘土含量。溝渠侵蝕敏感性模型有助於規劃土地資源的可持續性發展。

关键词：沖溝侵蝕，层次分析法，磁化率模型，熱帶火山環境。

1. Introduction

Land degradation is a global problem that threatens the sustainability of the environment, especially on agricultural land. Recently, considerable literature has grown around gully erosion because it is one of the leading causes that trigger agricultural land degradation [1, 2]. Gully erosion is the displacement of topsoil along drainage channels by accumulating surface runoff and may develop deeper than 30 cm quickly [3, 4]. At least five main factors influence the formation of permanent gullies: lithology, land use, soil characteristics, rainfall, topography, and vegetation [5].

Gully erosion classifies into two types: permanent gully and ephemeral gully. The main differences between permanent and ephemeral gullies are their nature, size, and location [6]. Temporary gullies are shorter and shallower, with an average depth of <30 cm [7]. The process of forming ephemeral gullies occurs quickly and can even form within three days under heavy rain [8]. A permanent gully is longer and deeper and is commonly found in open or abandoned agricultural land [9]. The process begins with rill erosion, continues in the form of an ephemeral gully, and ends with forming a permanent gully. Gully erosion tends to result in more surface soil loss than other forms of soil erosion. Recent evidence suggests that the contribution of gully erosion to total sediment in Europe, as reported, reaches 60–68%; in North Africa, it ranges from 20–80%, and in China, it reaches 70–92.8% [10]. [3] stated that gully erosion is the primary sediment source and causes damage and loss of soil in the local environment (on-site) and downstream (off-site). Gully erosion is associated with an increased risk of reduced C content in the soil and loss of nutrients in the soil, damage to agricultural land increase in the potential for landslides, land degradation, and siltation of reservoirs [2, 11]. Furthermore, gullies also can threaten human livelihoods because they damage infrastructure such as roads, bridges, and settlements [5]. Concrete efforts need to be made by various parties because gully erosion has a significant impact on people's lives and livelihoods, one of which is mapping the gully erosion susceptibility.

It is possible to map the gully erosion susceptibility using various techniques, including manual measurements, the interpretation of remote sensing images, pixel-based extraction models, statistical models, and machine-based learning techniques. Manual measurement with RTK is the most accurate approach for assessing gully erosion, but it is expensive and time-consuming, making it nearly difficult to examine broad areas [12]. The Analytical Hierarchy Process (AHP) is a spatial analysis model that can map gully erosion susceptibility [13]. AHP is a spatial-based statistical model used to weigh various parameters that affect a phenomenon. This method is advantageous in studying the susceptibility of gully erosion because AHP can assess a wide range of variables that affect the most critical variables that affect gully erosion. Furthermore, the AHP is the best method to adopt because [14] stated that AHP has high accuracy in predicting gully erosion susceptibility, with an AUC value of 0.72.

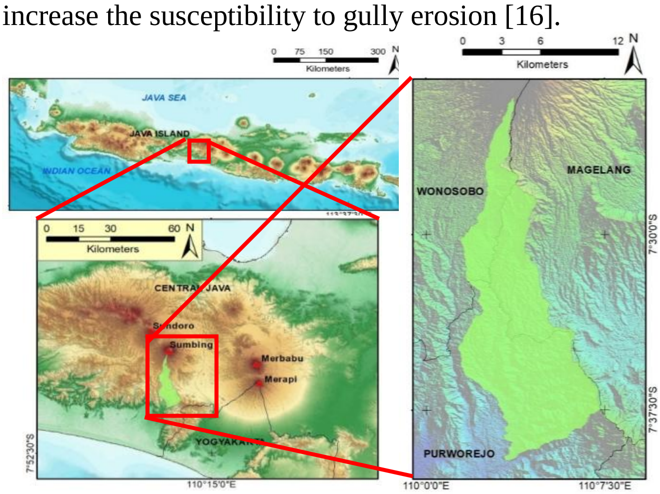
Volcanic areas in tropical rain areas are landforms prone to gully erosion. This phenomenon occurs due to the interaction of the surface soil layer, which has a high probability value with high rainfall in the wet months. The Kodil is a sub-watershed with high susceptibility to gully erosion on the slopes of volcanoes in tropical rain climates. The Kodil is in the south of the Sumbing Volcano, characterized by mountainous regions with deposits of weathered volcanic debris and a high percentage of clay [15]. Furthermore, the topsoil of the Kodil has a thickness of more than 2m, which means gully erosion can develop very deep [15, 16]. The hilly topographical character of the Kodil exacerbates this phenomenon so that surface runoff will trigger channel erosion, which leads to the formation of gully erosion, so systematic and structured efforts are needed to conduct land management in the Kodil. This issue is starting to cause some problems; thus, another possibility is to map the gully erosion susceptibility to reduce the impact of the problems.

Mapping of gully erosion susceptibility still needs to be researched in Indonesia, especially around the Kodil. This study seeks to launch an AHP-based gully erosion susceptibility assessment in Indonesia, where the previous study was absent. What is new in this study is that pedogeomorphological parameters such as texture and soil aggregates are emphasized more in predicting gully erosion susceptibility. The previous study more commonly used geological parameters; however, this study substituted them with pedogeomorphological elements through the following considerations: 1) gully erosion occurs on the soil surface, while geology occurs in deep soil layers; 2) the soil layer at the study site has a thickness of >2m. The final study results in gully erosion susceptibility maps and predisposing factor weights in susceptibility gully can be applied to locations with similar regional characteristics, such as Kodil, and evaluate the constructed AHP model's accuracy. Additionally, the government, community, and private sector can use the gully erosion susceptibility map as a starting point for sustainable land management in the research area.

2. Materials and Methods

2.1. Location Characteristics

This research was conducted in the Kodil, part of the Bogowonto watershed, Central Java, Indonesia (Fig. 1). The research locations are in three administrative regions: Magelang, Purworejo, and Wonosobo Regencies (392162mT - 403196mT and 9153041mU - 9181740 mT). The area studied covers 13,496.09 ha, with the mainland covering: forests, Swampland, and shrubs. Human intervention is seen prominently around the main road, where much cliff-cutting can apply for road accessibility, drainage, settlements, and agricultural activities. Like most other mountainous areas in Java, agricultural and animal husbandry activities dominate the livelihoods of the people in the study locations. From around 42 villages in Kodil, the community's arable land area reached 2,096.35 ha (15.53%). Agricultural land, footpaths around agricultural land, and drainage canals can increase the susceptibility to gully erosion [16].



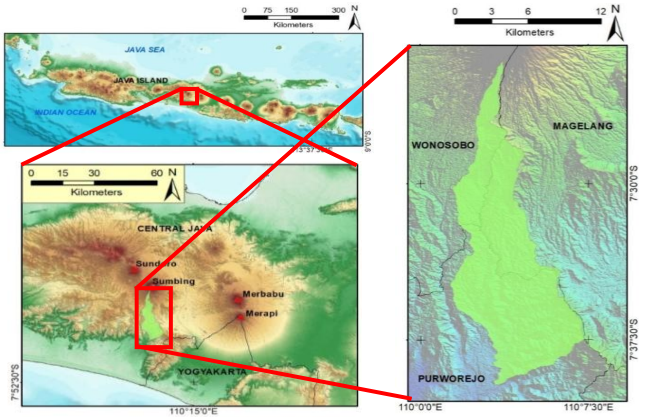


Fig. 1 Study site (Developed by the authors)

Generally, the Kodil has a radial flow pattern, with the center point being at the cone of the Sumbing Muda Volcano. Land on the upper slopes of volcanoes tends to erode quickly following slope gradients, and flow patterns control this. This process, known as gully initiation, occurs mainly on the upper slopes of the Sumbing Muda Volcano because intensive agriculture without canopy and conservation dominates the land cover. The progressive transition of the gully shape will tend to enlarge in the middle and bottom of the slope due to the control of the flow and slope gradient. The process of widening the gully's dimensions results from a hydrometeorological process mainly triggered by high rainfall. High rainfall accompanied by heavy surface runoff causes slope' leaching, triggering gully erosion.

2.2. Data Collection and Analysis

This study involved five stages. The first stage was to conduct a literature review to determine the research parameters. Each parameter was paired using a cross table to determine its weight and consistency. The basic data were then executed into thematic maps following the literature reviews. The third stage involves combining the thematic maps that affect gully erosion susceptibility with the weights calculated by the AHP. The natural break method is applied to intersect and grade the gully erosion susceptibility. The final stage was to validate the accuracy of the AHP-modeled gully erosion susceptibility map.

The gully erosion susceptibility mapping for this research was done at a scale of 1:25,000, using 2D and 3D data, followed by a field survey. The base data used in this study are Sentinel-2 Imagery with a resolution of 10 meters and DEMNAS (National Digital Elevation Model of Indonesia) with a resolution of 8 meters for data extraction of distance from the river (m), distance from road (m), and land use. Buffering the distance from rivers and roads was carried out using the automation method in the ring buffers per 50 meters with modifications [17]. The extraction of land-use elements from Sentinel-2 used guided classification using the maximum likelihood approach and corrected by ground check at locations where the classification was doubtful.

Through 3D data, specifically DEMNAS, watershed geomorphometric factors influencing gully erosion were derived. At least five geomorphometric characteristics, including elevation (m), slope degree (0), slope aspect, slope curvature, and topographic wetness index (TWI), were used in this investigation. The elevation in this study was classified into five classes by considering the living conditions of plants, where plants play an essential role in efforts to conserve gully erosion [18]. The slope class was classified into six classes in the range of 50 by considering the rough relief of the study site. The aspect of the slope direction is closely related to vegetation because the land unit insulation capacity affects it. Furthermore, [14] also slightly alluded to the influence of the slope aspect on the evapotranspiration phenomenon and its effect on gully erosion.

The slope curvature is one of the geomorphometric elements influencing the level of gully susceptibility [3, 4]. This study classified slope aspects into nine classes: flat, east, north, northeast, northwest, south, southeast, southwest, and west. This study classified the slope curvature into three classes, namely Convex, Flat, and Concave, where the concave shape significantly influences gully erosion. TWI is part of the hydro-topographic model vital in the flow direction. The TWI terminology was first introduced by [19] and is currently widely applied in the study of gully erosion susceptibility. The equation used for the TWI calculation is presented in equation 1, where α is the cumulative slope area per unit contour length, while β is the slope angle at that location. The examined TWI values were then divided into five categories.

$$TWI = In\ (\alpha/\tan\beta) \quad (1)$$

The phenomenon of gully erosion occurs on the soil surface, a product of geological processes, so the study used two pedogeomorphological parameters, namely soil texture and aggregates. In contrast to some earlier studies (such as [5]), which considered geological aspects in gully susceptibility mapping, this study only considered geological factors in descriptive analysis. [20] stated that texture significantly influences erosion phenomena because it is the most undersized physical material of the surface soil, and the surface runoff easily transports it. Furthermore, the stability of soil aggregates can make the surface soil layer more resistant to gully erosion [21]. Soil texture and aggregate analysis used a quick print based on the theory developed by [22].

AHP is crucial in making future predictions about gully erosion susceptibility. A pairwise comparison matrix was used to examine the relative impact of each parameter on the susceptibility to gully erosion. The weight of each parameter was tested for consistency by calculating the consistency ratio (CR) of the weights. The testing phase begins with calculating the consistency index (CI) by subtracting the principal Eigen max (λ max) and the number of parameters (n), then dividing by the reduction between the numbers of parameters minus one. The final stage was to perform the CR calculation by dividing the CI by the random coefficient index (RI) value. If the CR value <0.1, then the weight obtained from the AHP calculation is acceptable. The formula for calculating AHP refers to the [23] equation (formulas 2 and 3).

$$CI = (\lambda\text{-}n) / (n\text{-}1) \quad (2)$$

$$CR = CI / RI \quad (3)$$

The scores and weights obtained from the AHP were then integrated into the spatial data attributes. Furthermore, the score for each parameter was multiplied by the weight value to know the value of the class criteria in each parameter analyzed. Spatial data for each parameter were superimposed, and on the attribute data, the value of the criteria class is added to obtain a gully erosion susceptibility value for each mapping unit. Furthermore, these values included three classes: low, medium, and high. The basic calculation uses simple mathematical logic: the highest score divided by the lowest score was divided by the number of susceptibility classes.

Collecting the gully erosion points used as the basis for the validation test used the interpretation of high-resolution satellite imagery (0.5 m) combined with field surveys. The validation test of the gully erosion susceptibility map was carried out using the area under the Receiver Operating Characteristic (ROC) curve, known as the AUC curve (Area under Curve) [3, 16]. The AUC values range from 0.5-1, where 0.5-0.6 is bad; 0.6-0.7 is average; 0.7-0.8 is good; 0.8-0.9 is very good; and 0.9-1 is classified as extraordinary [5].

3. Results

AHP was used to determine the weight value of each parameter of this study through several stages. Weighting through a pairwise comparison matrix was carried out to determine the hierarchy between the parameters studied. The analysis showed that the principle eigenvalue calculated from the pairwise comparison matrix was 10.35. The CI value was calculated based on equation 2, which was 0.04. The effectiveness of the AHP was also evaluated through CR testing. The CR value in this study using ten parameters was 0.025. Referring to the index released by [23], the CR value in this study was acceptable and relatively consistent.

The AHP results for the ten parameters used in this study indicate that three parameters have a high role in gully erosion: soil texture, aggregates, and slope. The hypothesis put forth by [24] confirmed this finding; this hypothesis states that the nature of the soil and steep slopes (gravity) could exacerbate the susceptibility of the gully to erosion. Furthermore, [21] also revealed a close relationship between slope attributes and soil type in the form of gully erosion. In a previous study in the same area, [25] suggested that the unconsolidated material in the Kodil watershed makes it easier for the surface soil to move. Table 1 shows the detailed criteria, class, and weight of each parameter.

Table 1 Parameter class and AHP weighting (Developed by the authors)

Criteria and Class	Area	%	Score	Weight
Elevation (m)				0.03
0-500	4561.93	33.80	1	
501-800	6631.63	49.14	2	
801-1100	1337.22	9.91	3	
1101-1400	650.36	4.82	4	
> 1400	314.93	2.33	5	
Slope degree (^{0})				0.16
0-5	1589.89	11.78	1	
6-10	3465.75	25.68	2	
11-15	3479.95	25.78	3	
16-20	2483.33	18.40	4	
21-25	1206.81	8.94	5	
> 25	1270.35	9.41	6	
Slope aspect				0.04
East	1476.93	10.94	3	
Flat	177.04	1.31	1	
North	884.39	6.55	2	
Northeast	1046.62	7.76	3	
Northwest	1608.64	11.92	2	
South	2194.58	16.26	1	
Southeast	1977.41	14.65	3	
Southwest	2181.77	16.17	2	
West	1948.70	14.44	2	
Plan curvature				0.04
Convex	5327.50	39.47	1	
Flat	2883.27	21.36	2	
Concave	5285.32	39.16	3	
TWI				0.08
0-5	4667.05	34.58	1	
5-7.5	6869.39	50.90	2	
7.5-11	1231.58	9.13	3	
11-14	555.67	4.12	4	
> 14	172.40	1.28	5	
Distance from road (m)				0.09
201-250	4039.28	29.93	1	
151-200	1526.20	11.31	2	
101-150	2083.54	15.44	3	
51-100	2662.97	19.73	4	
0-50	3184.11	23.59	5	
Distance from river (m)				0.09
201-250	2651.59	19.65	1	
151-200	1655.36	12.27	2	
101-150	2423.77	17.96	3	
51-100	3145.15	23.30	4	
0-50	3620.22	26.82	5	
Land use				0.13
Forest	9145.67	67.77	1	
Waterbody	57.12	0.42	1	
Settlement	725.43	5.38	2	
Shrub	2096.35	15.53	3	
Swamp	1430.52	10.60	4	
Bareland	40.98	0.30	5	
Soil Texture				0.19
Sandy Clay	2280.57	16.90	1	
Silt Clay Loam	3569.76	26.45	2	
Silt Clay	2558.85	18.96	3	
Clay	5086.91	37.69	4	
Soil Aggregate				0.17
Firm	5261.48	38.99	1	
Friable	4541.09	33.65	2	
Very friable	3693.52	27.37	3	

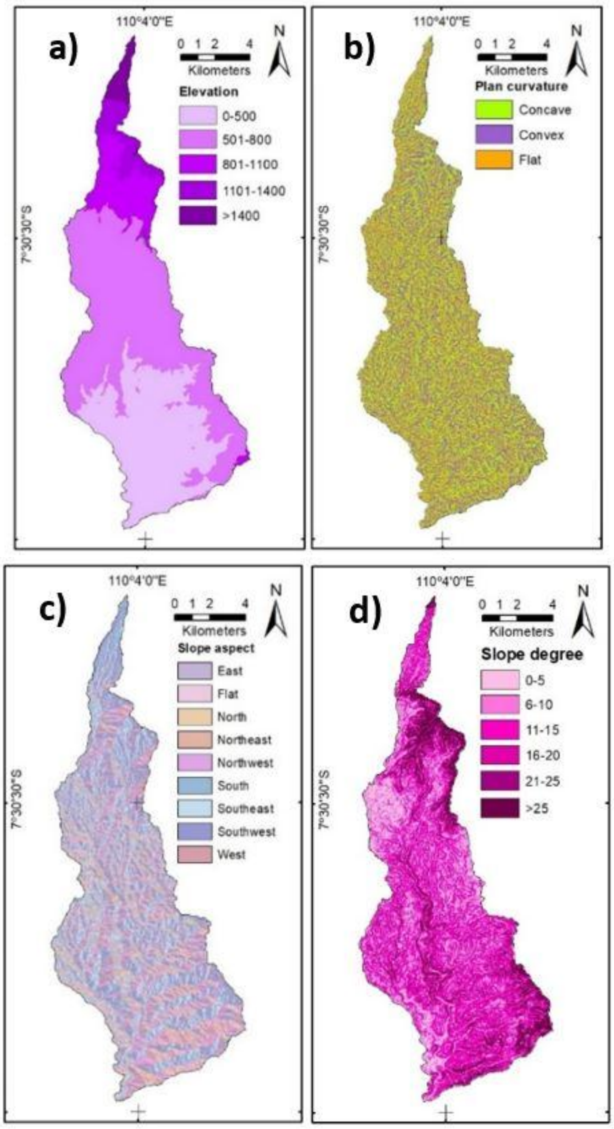
The AHP analysis inserted the weight of each parameter set of criteria into the spatial data attribute, categorizing each parameter into a class based on literature reviews and field observations. Geomorphometric parameters played an essential role in gully erosion mapping because different geomorphometric characteristics lead to various processes that develop on the surface soil. The slope was the geomorphometric parameter with the highest weight value in this study, which was 0.16, and the maximum value (NMax) was 0.78. The results of this analysis align with the research by [26], who highlighted the importance of the slope parameter in gully erosion mapping. TWI was inversely proportional to the gully erosion rate and decreases with increasing gully erosion [27]. A TWI of 5-7 with an area of 6,869.39 ha (50.90%) dominated the study location. The most interesting in this data was that from a TWI perspective, the medium class has the highest likelihood of gully erosion susceptibility (Fig. 2e).

In this research, the slope aspect and curvature had the same weight, 0.4, with an NMax = 0.12. The slope aspect involved ten classes, with the highest score being the slope with an eastward orientation, namely, east, southeast, and northeast (Fig. 2c). The direction of sunrise, namely, from east to west, and the direction of local rain supported this assumption. The curvature was the shape of a local slope that affects water flow. The concave curvature had the highest susceptibility to gully erosion [26]. The concave-shaped slopes in this study covered 5285.32 ha (39.16%) and were scattered randomly (Fig. 2b). Furthermore, elevation was also analyzed in this study, considering that elevation has a close relationship with rainfall characteristics and vegetation types. The elevation weight in this study was 0.03 and was the lowest. The distribution of the highest slope class area (>1400m) includes the upper slopes of the Sumbing with an area of 314.93 ha (2.33%).

Anthropogenic factors analyzed in this study consisted of land use, distance from roads, and distance from rivers. Land use has the highest weight compared to the other two factors, 0.13, with an NMax of 0.65. Swamp areas (1,430.52 ha) and bare land (40.98 ha) should be highlighted because they have a high susceptibility to the initiation of the ephemeral gully, given that the study site has hilly slopes (Fig. 2h). This study's distance from the road and river has the same weight, 0.009, with NMax reaching 0.45. Rivers were almost evenly distributed in all areas, but tended to be denser in the upstream area (Fig. 2f). The existence of roads in the research location was dominated in the middle and downstream areas (Fig. 2g). The highest NMax dominates the distance class from roads and rivers, with an area of 3,184.11 ha (23.59%) and 3,620.22 ha (26.82%), respectively.

Parameters related to the physical properties of the soil in this study had the highest weight by considering the typology of the research location, namely 1) hilly slopes; 2) super thick soil layer; 3) high clay content; and 4) high land exploitation. This analysis was in line with research [28], which highlighted the importance of soil parameters in determining gully susceptibility. Soil texture is significant in soil formation because it is the smallest unit of soil, easily transported, and influences the gully piping. Soil texture weight was the highest in this study, with a value of 0.19 and an NMax of 0.76. From a textural perspective, the most susceptibility areas were on the upper slopes of Sumbing (Fig. 2i). Soil aggregates in this study were also considered a physical property of the soil that influences the gully erosion susceptibility, in line with the findings of [29]. The aggregate weight in this study was 0.17 with an NMax of 0.51, and the most susceptibility area was 3,693.52 ha (27.37%) (Fig. 2j). The weight value was then integrated into the spatial data attribute using formula 4.

$$GESM = (Elevation \times 0.03) + (Slope\ degree \times 0.16) + (Slope\ aspect \times 0.04) + (Plan\ curvature \times 0.04) + (TWI \times 0.08) + (Distance\ from\ road \times 0.09) + (Distance\ from\ river \times 0.09) + (Landuse \times 0.13) + (Texture \times 0.19) + (Aggregate \times 0.17) \quad (4)$$



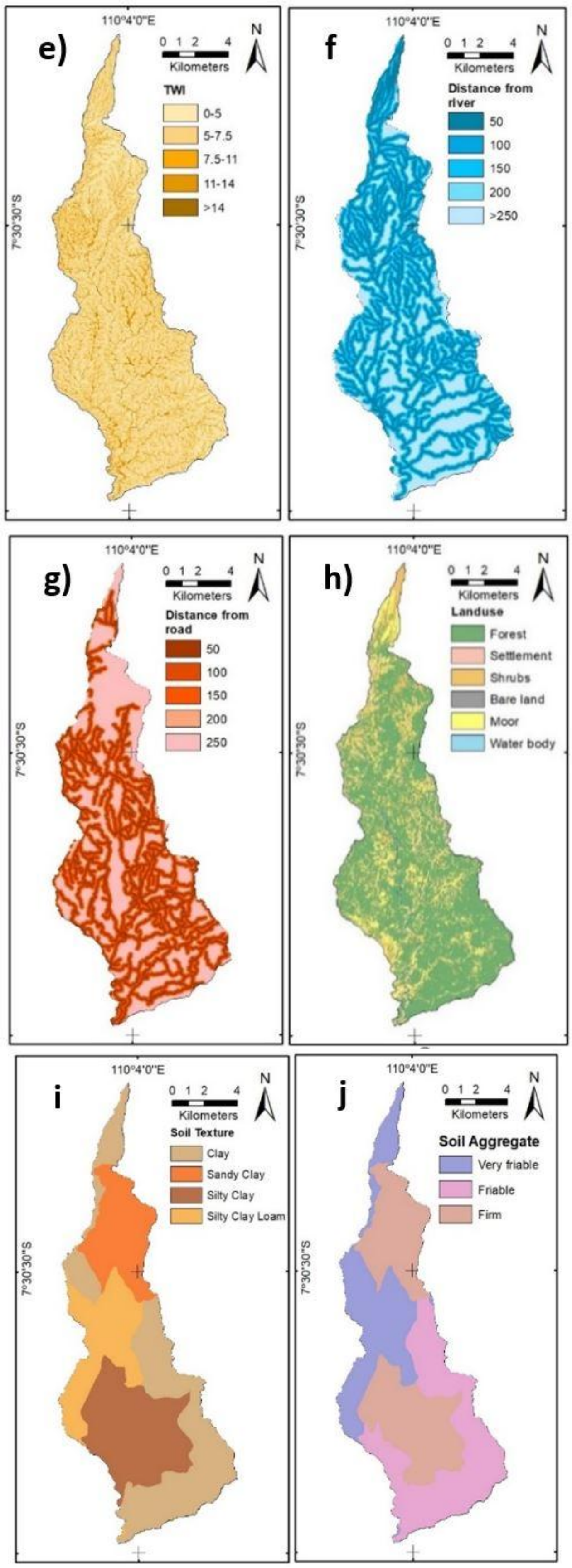


Fig. 2 Factors affecting gully erosion: a) elevation; b) plan curvature; c) slope aspect; d) slope; e) TWI; f) distance from the river; g) distance from the road; h) land use; i) texture; j) aggregates (Developed by the authors)

According to the AHP modeling outcomes, 855 hectares (6.34%) of the study site had a high gully erosion susceptibility value (Table 2). The calculated value of high susceptibility at the study site consists of land units with a value of 3.01-4.02, characterized by a typology of clay texture, very loose aggregate, and slope >250. The distribution of areas with gully erosion susceptibility was more commonly found on the upper slopes of Sumbing. This situation was suspected of coming from heavy land exploitation and the existence of an order of one river, which might cause the river wall to collapse and cause gully erosion. The fact that there was still very little conservation being undertaken, which increases the risk of land degradation, should be brought to light.

Table 2 The susceptibility value and the gully ratio in Kodil (Developed by the authors)

Classes	Area (ha)	%	Gully ratio
Low	1,958.31	14.51	0.39
Moderate	10,682.78	79.15	0.63
High	855	6.34	7.07
Total	13,496.09	100.00	-

Areas with medium gully erosion susceptibility had an area of 10,682.78 ha (79.15%), with total attribute values ranging from 2.01-3. A moderate level of susceptibility dominates the research location and spreads from upstream to downstream of Kodil. Because forests cover more than 65% of the study site, they operate as a controller for high values of gully susceptibility. Furthermore, another factor that causes the moderate value to dominate is the TWI value in the range of 5-7.5, with an area of > 50%, making the medium class dominant.

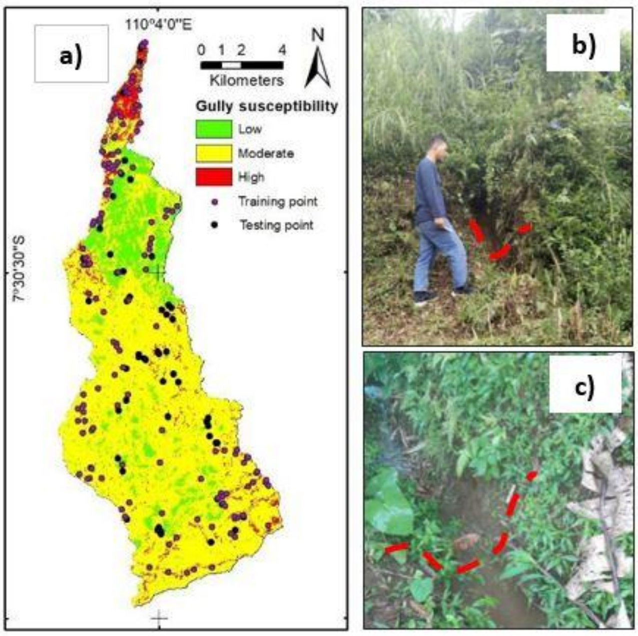


Fig. 3 a) Gully erosion susceptibility map; b) gully on the upper slopes of the Sumbing Volcano; c) a gully on the middle slope of the Sumbing Volcano (Developed by the authors)

A validation test is one of the most critical components in modeling because it determines the accuracy of the produced model. The test results on the gully susceptibility map from 192 interpretation points and field surveys yielded a training AUC value of 0.742, a test of 0.737, and an accumulative AUC value of 0.73. The training set was 70% (134 points), while the test set was 30% (58 points). Referring to [5], the AUC value of 0.73 belongs to the good class, so it applies to model gully susceptibility at research locations with the same characteristics. These results suggest that the most prominent gully grouping occurs in areas with a value of 2.81–3.2, totaling 79 (41.14%) gully points. Land characteristics with this value had slopes of 21–250 with very loose soil aggregates and clay textures. The findings from these studies suggest that steeper slopes sometimes have more gullies.

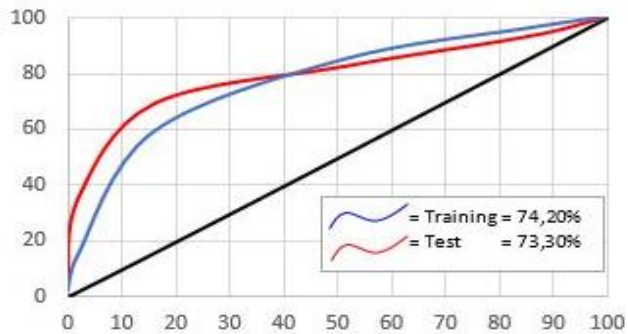


Fig. 4 ROC curve and AUC value of gully erosion susceptibility with AHP (Developed by the authors)

4. Discussion

Gully erosion susceptibility mapping is a fascinating scientific issue to investigate. This study kicked off research on mapping gully erosion susceptibility in Indonesia using AHP. Since [14] used the same model and achieved an accuracy of 0.72, the cumulative accuracy produced by AHP in this investigation was 0.73, which was better. Another statistical model, such as that conducted by [30], showed a different conclusion. The developed weights-of-evidence (WofE) model has an AUC value of 0.70, while the frequency ratio (FR) produces a value of 0.78. These facts indicate that the AHP model of this study was better than WofE but was close to the results of the FR modeling. A reasonable approach to tackle this issue could be using the FR model to map gully erosion susceptibility in Indonesia.

For doubt for subsequent countermeasures, an in-depth analysis of the typical gully erosion at the research site should be undertaken. A sampling of gully dimensions was performed at 11 convenience sample spots with a medium-high susceptibility class. Areas around the vegetation gully were found, thus requiring more effort to identify the distribution of gully points relying solely on the land cover approach. Object-Oriented Analysis (OOA)-based research, as carried out by several previous researchers (such as [11, 31]), is not suitable for application in research locations because 72.7% of the gully at the study site is under plants.

Table 3 Descriptive statistics of field measurements of gully erosion (Developed by the authors)

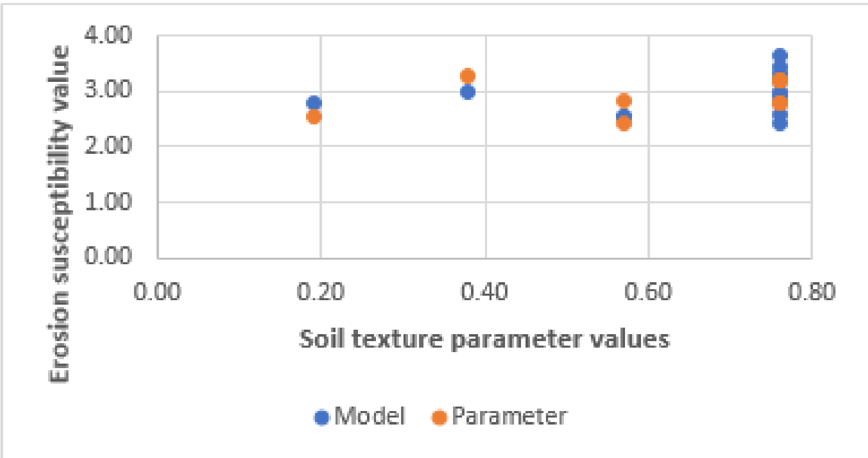
Parameters	Min	Max	Mean	Median
Surface width (m)	0,14	2,24	0,54	0,43
Base width (m)	0,12	1,31	0,33	0,22
Depth(m)	0,9	2,32	0,54	0,33

The most striking result that emerged from the data was that a permanent gully dominates the erosion of the study site. The opinion of [7] states that the ephemeral gully has a width and depth of <30cm, so the average gully at the study site was classified as a permanent gully. Accumulatively, the width of the surface and bottom of the gully in the study area each have an average length of 54.9 cm and 33.67 cm, while the average depth reaches 54.54 cm. Additionally, as most studies on gully erosion were conducted in arid regions (e.g., [13, 17, 24]), their dimensions were greater and look simpler to identify because there was not much vegetation there. Gully erosion in tropical areas, such as in the Kodil, tends to be more complex to model because its appearance is often not visible in images with medium to low resolution.

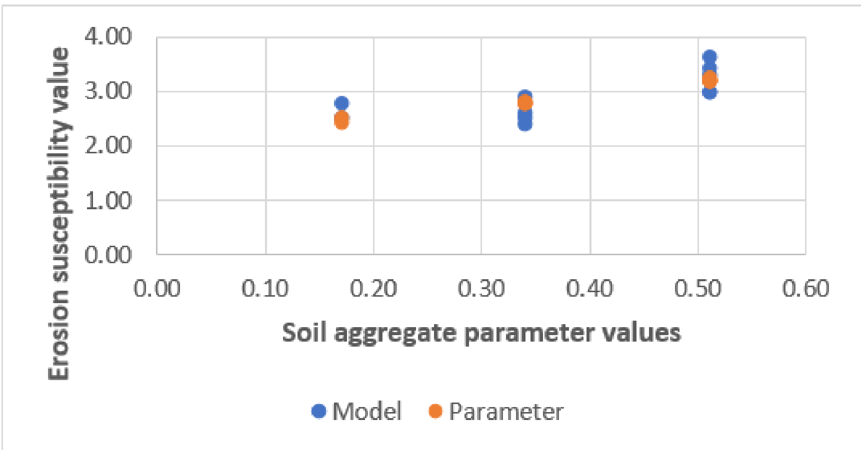
The novelty of this research, exclusively the adoption of soil texture and aggregates for estimating the susceptibility to gully erosion, was investigated using statistical tests. The statistical approach was multiple regression and ANOVA using 11 value extracts from the study site. The analysis results showed that the correlation value of the texture and aggregate parameters (multiple R) was 0.73, indicating that the correlation between the two parameters was relatively strong (Table 4). The line fit plot in Fig. 5 shows the close correlation of the parameter numbers with the modeling results. The coefficient of determination (Adjusted R Square) for the texture and aggregate parameters was 0.41. This value suggests that these two parameters explain 0.41 of the model's outcomes, whereas the remaining eight parameters affect 0.59 of the model's results. There was a significant relationship between the texture and aggregate parameters because the model value of the gully erosion susceptibility in the Kodil given that the F significance value of these two parameters was 0.04, categorized under the alpha coefficient (0.05).

Table 4 Regression and ANOVA results between soil variables and the results of the gully erosion susceptibility model (Developed by the authors)

Multiple R	R Square	Adjusted R Square	Standard Error	Significance F
0,73	0,53	0,41	0,30	0,048



(a)



(b)

Fig. 5 Line fit plot explaining the correlation of parameters (a) soil texture and (b) soil aggregates with the value of the gully erosion susceptibility model using AHP (Developed by the authors)

5. Conclusion

Gully erosion mapping becomes an essential step in planning processes of sustainable land resource development. Ten predisposing factors answered the research objectives by considering the physical characteristics of the research location and literature study. The choice of AHP to model gully erosion susceptibility was due to its simplicity and high accuracy. The deployment of AHP in the Kodil demonstrated that the biggest gully erosion susceptibility was on the upper slopes of the Sumbing Volcano. In addition, the number of erosion points was significantly greater in areas with moderate susceptibility than in areas with high ones. Even so, this study found that the ratio of occurrence of erosion points in areas with high susceptibility was much higher (7.07) compared to areas with moderate (0.63) and low (0.39) susceptibility classes.

Overall, the performance of AHP in this study was in good class. This fact shows that the AHP model could be used to predict the gully erosion susceptibility in areas with a typology similar to the Kodil. Additionally, the inclusion of pedogeomorphological characteristics in the form of soil texture and aggregates significantly impacts model outcomes, making it intriguing to investigate further elsewhere. The combination of these findings supports the conceptual premise that the role of soil parameters is high in modeling gully erosion susceptibility. Because gully erosion occurs in the soil's upper layer, the perspective of soil science, particularly pedology, is crucial in modeling and measuring gully erosion. The limitation of the AHP model developed in this study is the necessity to adjust the AHP parameter weights when applied to significantly different locations. To reduce the risk of gully walls collapsing owing to surface runoff and slope instability, it is reasonable to add natural plants to the gully walls, the bare minimum mitigation measure. Further studies must identify the gully's susceptibility to erosion at a more detailed scale to improve the accuracy of the developed model.

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