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**Research Article**

# Landscape design for gully erosion control on the upper slopes of Mount Sumbing, Central Java, Indonesia

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**Abstract**

Gully erosion can cause significant soil loss; thus, it must be controlled. This study aimed to develop a landscape design for controlling gully erosion in a volcanic environment with a thin soil layer. The primary data used was Unmanned Aerial Vehicle (UAV) data combined with field surveys and in-depth interviews. A collaborative approach was used to develop the landscape design to minimize the impact of gully erosion. The finding showed that gully erosion had entered adult to old age since the scars (incisions) at the gully bottom existed. According to the community, gullies must be controlled, although they do not affect land productivity. Vegetative control is the most favored method of gully erosion control. Local vegetation with the potential for additional value is chosen to control gully erosion. Strengthening community capacity is the most favorable way to manage gullies. Through good understanding, local communities can control the development of gullies. Further strengthening of regulations related to gully erosion control will have a domino effect on land sustainability. This finding can be extrapolated globally to locations with similar land characteristics.

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## Introduction.

Gully erosion is a global problem that threatens environmental sustainability. Gully erosion is an intensive soil erosion process where the topsoil has been removed by cumulative water runoff to a certain depth (Saha et al., 2020). Several factors that influence gully erosion development are topography, lithology, rainfall, soil, and land use (Rahmati et al., 2016). This problem is caused by gully erosion, which can move large amounts of soil in a short time (Maulana et al., 2023a). Gully erosion can cause surface soil displacement, decreased ecological quality, decreased land productivity, decreased water quality, sedimentation, and infrastructure damage (Rahmati et al., 2017; Roberts et al., 2022; Raji et al., 2023). Furthermore, land stripping due to gully erosion has the potential to cause the topsoil to be lost so that it cannot be planted (Ionita et al., 2015; Yazie et al., 2021; Maulana et al., 2023b). Soil loss of topsoil through gully construction affects crop production (Mararakanye and Sumner, 2017). Land stripping due to gully erosion can eliminate farmers' livelihoods in tropical volcanic areas with thin soil layers (Nugraha and Sartohadi, 2018; Maulana et al., 2023b).

Gully erosion can increase landscape connectivity, significantly affecting the hydrological system and sediment yield. Gully erosion tends to produce more surface soil loss than other forms of erosion. The ratio of gully erosion contribution to total sediment in Europe is reported to reach 60-68%; in North Africa, it ranges from 20-80%, while in China, it reaches 70-92.8% (Liu and Liu, 2020). Gully erosion contributes to 10-94% of the total sediment produced from a watershed (Verstraeten et al., 2003; Wang et al., 2014; Hosseinalizadeh et al., 2020). Uncontrolled sediment can cause the loss of the topsoil surface layer, known as land stripping. Bean et al. (2017) stated that gully erosion can cause more than 50% of land to be denuded, making it unplantable. The potential losses caused by gully erosion are huge because they can eliminate farmers' livelihoods, especially in areas with thin soil layers, such as tropical volcanic areas. Maulana et al. (2023b) state that landscape changes in tropical volcanoes can occur sporadically if gully erosion development remains uncontrolled. Concrete efforts need to be made by various parties because gully erosion has a significant impact on people's lives and livelihoods.

Numerous projects have been attempted to reduce the harmful impact of gully erosion, including gully erosion studies. Interestingly, until now, detailed studies related to rehabilitation or control of gully erosion at the plot scale have rarely been studied (Maulana et al., 2023a). Controlling gully erosion by encouraging innovative and adaptive planning is needed to ensure land sustainability (Ahmad et al., 2020). Belayneh et al. (2020) highlighted the urgency of soil and water conservation practices in gullies at the plot scale. Furthermore, large-scale gully bank rehabilitation is recommended by involving all stakeholders. Sun et al. (2022) show that managing gullies at the plot scale by controlling surface runoff can reduce the destructive power of gully dimensions.

The study's state-of-the-art integrates terrestrial remote sensing approaches with an adaptive planning framework to increase land-added value. This study employs aerial photography, which provides extensive and periodic monitoring of land characteristics. Data obtained from aerial photography can be used to analyze gully erosion patterns, identify areas susceptible to gully erosion, and monitor changes in gully morphology (Cândido et al., 2020; Meinen and Robinson, 2020). This process is carried out to identify geomorphic processes that develop in gully dimensions. Furthermore, baseline data from aerial photography will also be used as a basis for managing gully dimensions through adaptive planning. Existing research is dominated by unilateral planning that does not mainstream local communities. This study initiates the involvement of local communities as critical informants in designing productive gully control landscape designs.

Mount Sumbing in Central Java, Indonesia, is typically susceptible to gully erosion. Specifically, Maulana et al. (2023a) found that the upper slopes of Mount Sumbing have a higher susceptibility than other areas in the Sumbing landscape. Three primary elements are associated with gully erosion susceptibility in Sumbing: loose material characteristics, steep slopes, and excessive land use (Nugraha and Sartohadi, 2018; Sartohadi et al., 2018; Maulana et al., 2023b). Accelerated gully erosion has reduced the agricultural land due to piping and subsidence. Interestingly, subsidence occurs not only in the rainy season but also in the dry season. So far, the studies are still related to semi-detailed scale gully erosion modeling and still need detailing to ensure local communities can directly apply it. This study initiated the development of designs at the plot scale so that farmers can use them to control gully erosion expansion.

This study was conducted to provide input on the management of plot-scale gully erosion to increase land value in tropical volcanic areas. So far, various studies have only been conducted on the susceptibility modeling process and sediment transport measurements in gullies (Verstraeten et al., 2003; Rahmati et al., 2016; Noto et al., 2017). This study initiates how to control gullies so the development can be managed and controlled (Du et al., 2022; Zhang et al., 2023).

## Materials and Methods

This study was conducted on the Upper Slope of Mount Sumbing, Wonosobo, Central Java, Indonesia (7027’10.05” - 7024’07.69” S and 110002’29.42” - 110003’43.73” E). Agricultural land with a relatively thin soil layer predominates in the study site. The surface material is dominated by volcanic soil with a high level of erosion (Maulana et al., 2023b). The measurement point selection was conducted considering the ease of UAV data acquisition. The gully site was chosen on land with a minor canopy so that aerial photo data could clearly and without distortion depict the body of the gully erosion. Gully point one has a micro watershed area of 2829.85 $m^2$, and point two has an area of 5,964.17 $m^2$. Furthermore, gully point three has an area of 442.49 $m^2$ with a steep slope. The micro watershed area influences the amount of water input that enters the body of the gully erosion. Details of the appearance of the study site are presented in Figure 1.

There were four stages involved in the development of landscape design. The first stage was to identify the characteristics of gully erosion. Gullies were identified at three selected points on different land characteristics. The UAV data was converted into mosaic aerial photos and Digital Elevation Models (DEM). Information extracted from aerial photos included the slope length and slope and flow patterns. Ground checks were carried out to assess the dominant gully shape, geomorphological processes, relative age, and land cover. The assessment of gully erosion vulnerability was carried out by considering the dimensions of the gully and the appearance of the results of the gully morphology process. The second stage involved identifying public perceptions of gully susceptibility, erosion impacts, and gully control controls. Twenty respondents were used in in-depth interviews to capture public perceptions related to gully erosion. Furthermore, the responders were local farmers who owned land where gully erosion had progressed to the point where it was a permanent gully. Critical inquiries included: a) how gully erosion affects harvest; b) how gully growth has trended in recent years; c) how gully erosion is treated; and d) potential and actual mitigation measures. Exploratory descriptive analysis was used to assess public perceptions of gully erosion development. Multiple correspondence analysis was used to identify public tendencies in responding to the issue of gully erosion development.

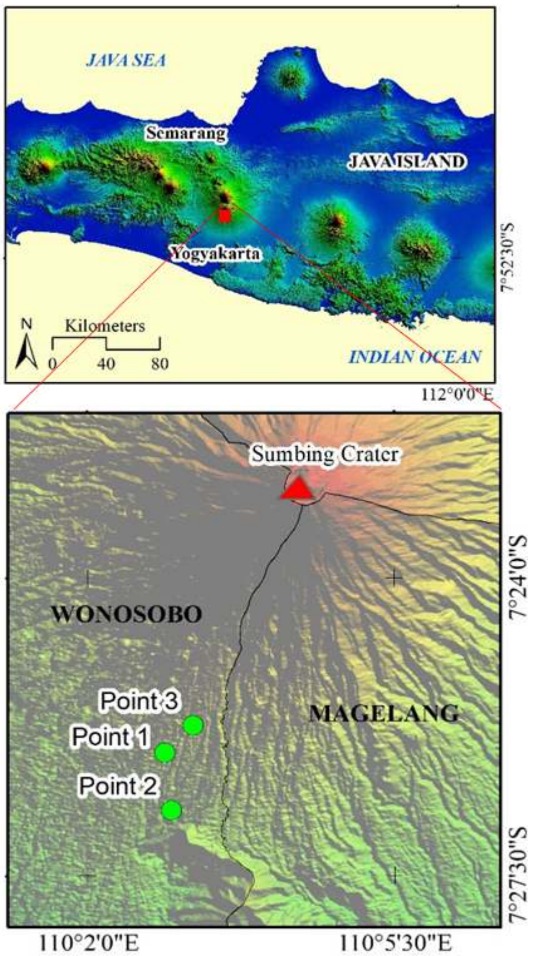



Figure 1. Study site.

The landscape design of gully erosion control was carried out using UAV data. Each sample was divided into several gully segments based on the slope gradient. Additionally, the slope gradient calculation is done by considering the height difference (x), the slope angle (a), and the flat distance (y) (Equation 1).

$$x = \tan \alpha \times y \quad \text{.......................... Equation 1}$$

The database used to support the analysis was data: a) dimensions, b) shape, c) process, d) geomorphic, e) slope, and f) hazard level (Table 1). Recommendations for selecting the most effective gully erosion control were made by considering the results of previous studies, such as those conducted by Yitbarek et al. (2012). The next stage is to interpret the suitability of gully erosion control in landscape design.

Sustainable land management design is obtained from the approach developed by Karrasch et al. (2017). The first stage involves designing collaborative planning with the government, academics, and the community. Data collection was carried out through semi-structured interviews, which began by explaining the study's problems, units, and objectives. The introduction of the subject was precisely executed by describing how gullies contribute to sedimentation and worldwide land degradation. In addition, an in-depth investigation of the erosion on Mount Sumbing's Upper Slope was conducted to present an in-depth understanding of the phenomenon. The results of the interviews were transcribed and analyzed through content analysis (qualitative), especially by identifying expert statements relevant to the collaborative land management planning process.

## Results

### *Characteristics of gully erosion development*

According to this study, the gully's shape was remarkably comparable to the letter U. The U-shape indicates that the gully is already at an advanced stage of development. The slope conditions in the gully tend to be steep (27-34$^o$) (Figure 2). Steep slopes can accelerate surface flow in the gully, causing more soil loss. Interestingly, gullies on steep slopes are short, so the water accumulated in the gully body should be less than on long slopes. However, study findings show that there are scars in short gullies (≤25 m). Scars are incisions at the bottom of the gully that indicate that the gully development has reached the parent material. These two large frames show that although the water input is small, the thin soil factor (≤30 cm) and the slope's gravitational force also accelerate the gully development.

Evidence of scar appearance on the gully bottom provides precise information regarding the relative age of the gully. Field measurement results show that scars are found at points one and three, so it can be concluded that the relative age of these two points is in the mature-old stage. The mature to old age of the gully indicates that vertical development will occur slowly so that the development of the gully will proceed laterally. Point one is additionally impacted by the piping, which could lead to subsidence. Furthermore, gully point one has an axial (centralized) flow type, so the destructive power of surface runoff has the potential to increase. The scar phenomenon, flow type, and piping make gully point one more susceptible than others.

Gully age is estimated to be young and mature because the base of gully point two has not yet reached the bottom. Gully point two tends to be long (117.7 m) with a flat slope (5-8$^o$) so that the water velocity tends to be stable and not destructive (Table 1). However, the gully walls and bottom at point two are not yet stable, so strong water flow can erode the soil quickly, causing cliff collapse and deepening of the gully. This often results in deep and wide gullies, especially in areas with damaged or minimal vegetation. Control efforts must be carried out effectively and efficiently, considering that the vertical, lateral, and sedimentation development processes are still occurring at gully point two. Careful guidance for gully erosion control is necessary since human intervention and incorrect land management can expedite the shift from young, mature to older gullies.

***Community response towards gully erosion susceptibility***

Public perception of gully erosion is critical to identify because this assumption will influence public treatment of the threat of gully erosion. Most people consider that gully erosion does not affect crop yields (68.75%), while the rest assume the opposite (31.25%) (Figure 3a). People who assume that gullies do not affect crop yields have land with small gully dimensions (ephemeral) and do not cause further problems. People who assume that gullies can affect crop yields say that if there is subsidence in the gully.

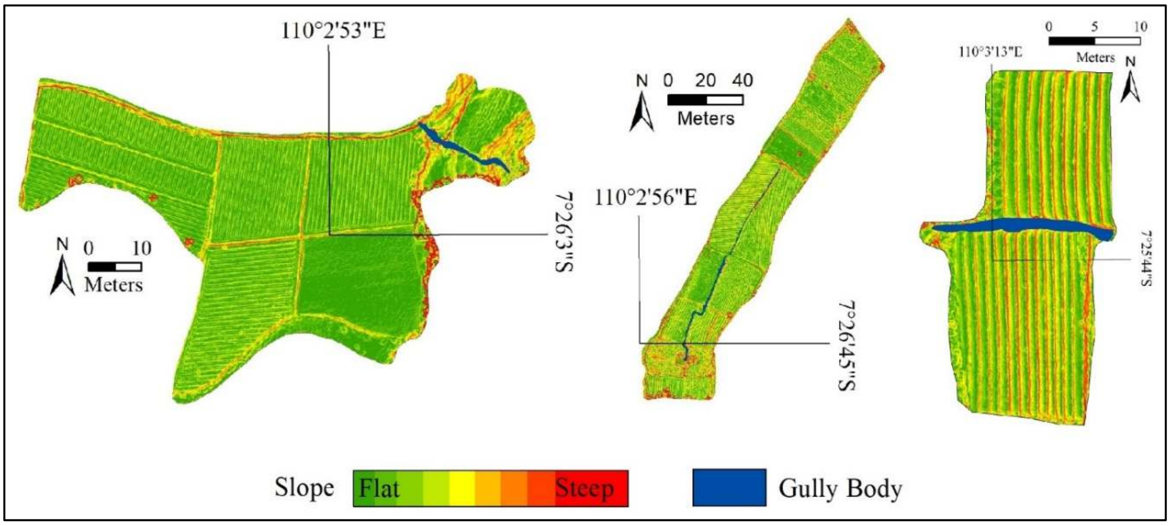
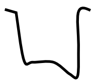
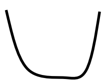
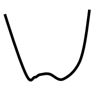



Figure 2. Slope gradient related to gullies position: a) gully point 1, b) gully point 2, c) gully point 3.

Table 1. Characteristics of gully development.

| Location | Dominant Shape | Bottom Slope | Length (m) | Relative Age | Gully Character | Active Process | Susceptibility Level |
|---|---|---|---|---|---|---|---|
| Gully Point 1 |  | Steep (29°-34°) | 20.65 | Adult - Old | Axial | Vertical and Lateral Erosion, Pipe Erosion, Scar, Subsidence | High |
| Gully Point 2 |  | Gentle (5°-8°) | 117.7 | Young - Adult | Axial - Digitate | Vertical and Lateral Erosion, Sedimentation | Low |
| Gully Point 3 |  | Steep (27°-31°) | 19.31 | Adult - Old | Axial | Lateral and Vertical Erosion, Scar, Subsidence | Medium |

Several plots of land have the potential to be lost. This can cause land that has cultivated plants on it to be transported. Land area reduction due to gully erosion also occurs in various parts of the world due to landslides on gully walls (Yazie et al., 2021). Valentin et al. (2005) added that gully erosion can reduce soil moisture and productivity of agricultural land plots close to gullies. Another important finding was that the local community assumed the gully's dimensions and shape were generally steady (50%) (Figure 3b). The shape of the gully tends to be stable because the bottom of the gully has mostly reached the parent material. After all, these phenomena happen because the soil layer is thin (≤30 cm). Some people with land near the upper slope stated that vertical and lateral development occurs slowly but surely, especially in the rainy season

(28.57%). This opinion is supported by the findings of Wang et al. (2022), which state that the incision and roughness of the gully walls have the potential to increase the amount of sediment during the wet months. An interesting finding shows that several sides of the gully experience shallowing in the dry season. This phenomenon is due to soil particles falling into the gully body when land processing occurs in the dry season. The most outstanding possibility is that this phenomenon is influenced by the dominance of volcanic soil with a more dominant dust composition so that the surface soil tends to move quickly, including moving into the gully dimensions.

It is interesting to note that 41.18% of the community ignored the gully erosion. Considering that the community believed the harmful effects of gully erosion were negligible, they decided to disregard it. Instead, the community believed that it was necessary to stop vertical and lateral erosion, so they decided to control the water flow accumulation (35.29%). Flow management was carried out to control the amount of water discharge entering the gully so that it did not cause secondary effects (subsidence, sediment, or landslides). Manual repairs (23.53%) were performed on gully dimensions that had experienced landslides or sedimentation (Figure 3c). In order to restore the gully's dimensions and increase the walls' resistance, repairs were made using conventional tools like sickles and hoes. This prevented obstructions to the water flow (Maulana et al., 2023b).

Interestingly, the community believes that the most effective way to prevent the development of gullies is through the vegetative approach (56.25%) (Figure 3d). Planting harvestable indigenous vegetation is a prime example of the community's vegetative approach. Efforts to manage the flow (31.25%) are another option the community takes to prevent the gully development. Flow management is made by making sediment traps or gully plugs to reduce the flow speed and control the amount of water discharge in the gully dimensions. The last option taken by the community but most avoided is the mechanical approach (6.25%). Mechanical approaches are made when the gully is in critical condition, such as installing sacks or bamboo to support the walls so they do not collapse.

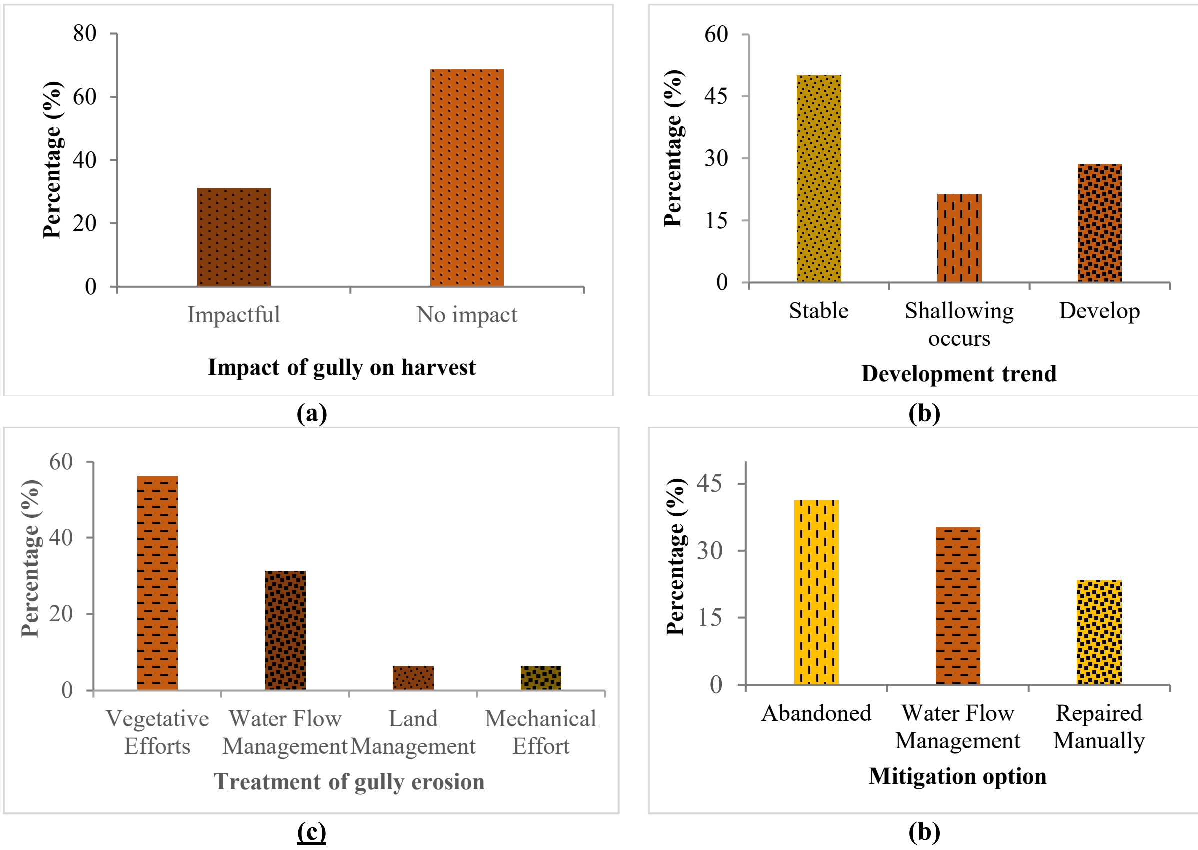



Figure 3. Recapitulation of community perceptions: (a) impact of gully erosion on harvests, (b) development trend of gully erosion, (c) treatment of gully erosion, (d) options for preventing gully erosion development.

A significant value of community perception is that gully erosion is still not considered an urgent environmental problem to be addressed. The finding shows that although it is considered to have less impact (68.75%), more people are subconsciously responding to gully erosion (58.82%). Unconsciously, people also plant vegetation on the gully walls to prevent subsidence. This opinion shows that people care, but their understanding of the gully erosion susceptibility needs to be improved. The results of the multiple correspondence analysis show that the closeness of perception between communities is quite close (Figure 4). Overall, the perception and understanding of the community towards gully erosion tends to be negative. This phenomenon shows that there is a need to increase the capacity of the community to understand and respond to the phenomenon of gully erosion.

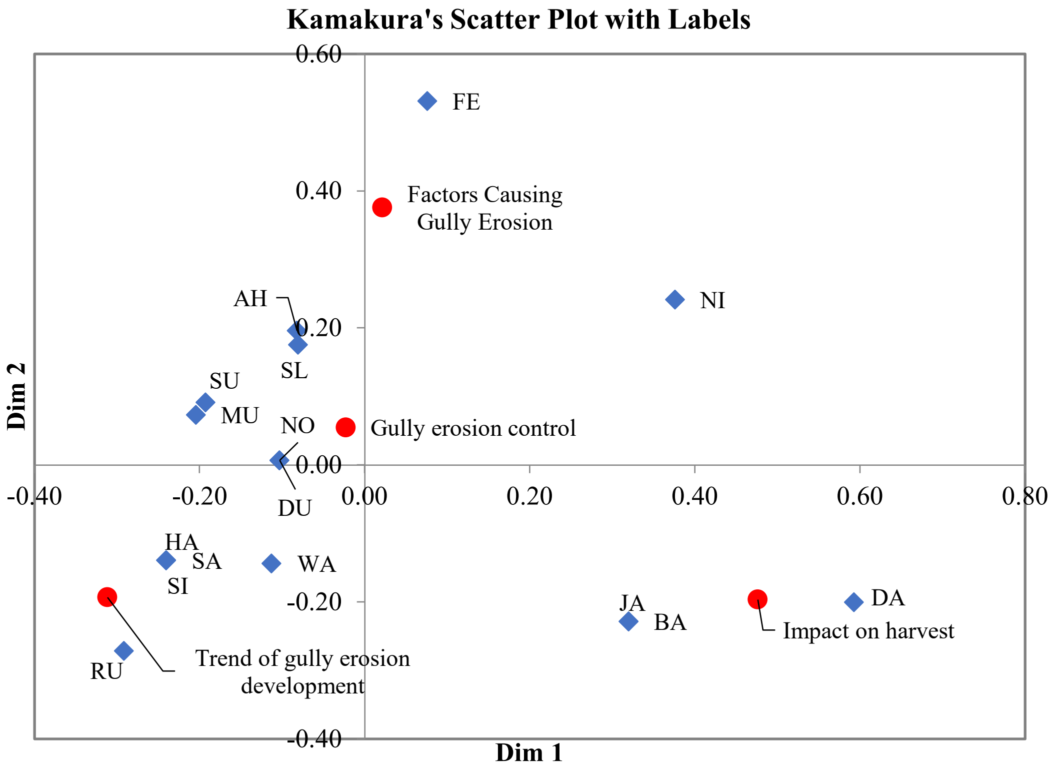



Figure 4. Multiple correspondence analysis of community perceptions towards gully erosion.

***Plot scale gully erosion control***

Gully erosion has various shapes, sizes, and dimensions, thus requiring different treatments. The preparation of landscape design for gully management needs to be done to ensure the suitability between gully characteristics and gully control plans. Landscape design can provide an initial overview of various gully control efforts to maintain ecosystem sustainability (Hancock et al., 2014).

The gullies used as samples in the design preparation consist of three susceptibility classes, namely high (Figure 5), medium (Figure 6), and low (Figure 7). Segments of the examined gullies are separated based on the local slope gradient. Gully point one (Figure 5) is a gully with a high susceptibility class divided into three segments. It has a steep slope class and is an outlet for several agricultural lands, so it has a more significant discharge than other points. The appearance of geomorphological processes in the gully dimensions also varies, namely vertical and lateral erosion, pipe erosion, scars, and subsidence.

It is unambiguous that the erosion level at point one is already deemed critical because the scar on the gully bottom in Segment II has also reached the parent material. Handling in Segment I carry out this by installing rocks at the gully bottom to hold the flow from upstream and adding Elephant Grass (*Pennisetum purpureum*) to the gully walls. Prevention in Segment II is carried out by installing rocks at the gully bottom because there is a reasonably extreme gradient difference at the border between Segments I and II. Bamboo installation needs to be carried out in Segment II because the gully's peak flow velocity and depth reach their maximum point in Segment II. Segment III at gully point one is classified as rather steep but tends to have a shallower depth than other segments. Prevention can be done by installing shrubs and Elephant Grass on the gully walls and bottom. Details of the landscape direction at gully point one are presented in Figure 5.

Gully point five (Figure 6) is a gully with a medium susceptibility class divided into three segments. Gully point five has a slope class between 11-340 with land cover in agricultural lands. Gully point five does not have a controller, so if left unchecked, it has the potential to cause large amounts of soil loss. The appearance of scars in Segment II is evidence that if not controlled, all parts of the gully can erode vertically until they reach the parent material. Segment I is classified as having low susceptibility because its dimensions are the most minor compared to other segments. Sweet potato (*Ipomoea batatas*) or Taro (*Colocasia esculenta*) can be put on the top of the gully wall for control, while Elephant Grass can be planted on the gully's bottom and walls.

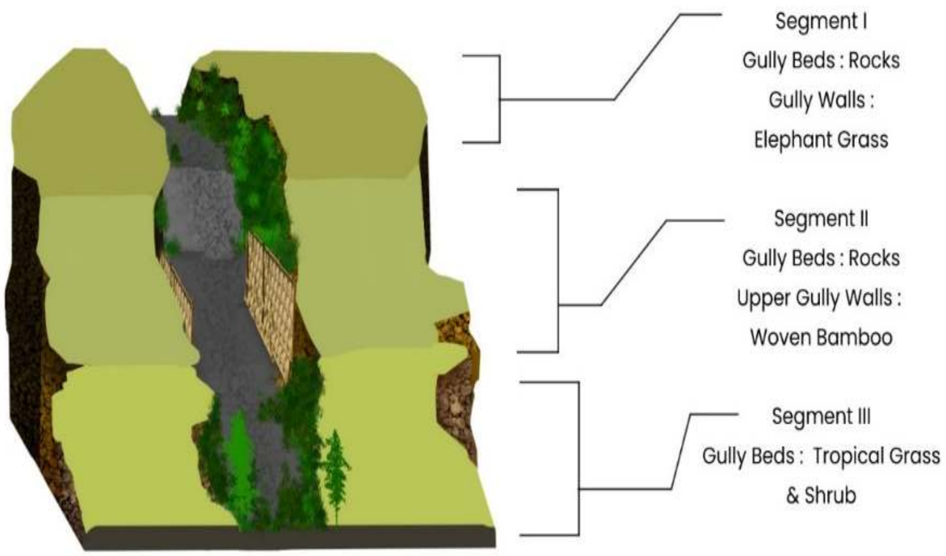



Figure 5. Illustration of high-susceptible gully control landscape design.

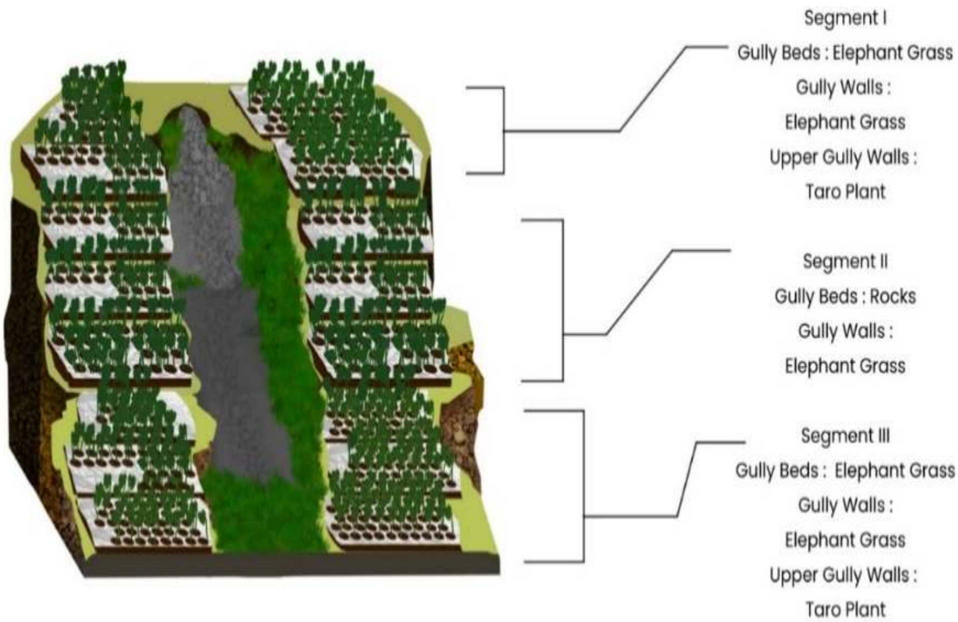



Figure 6. Illustration of moderate-susceptible gully control landscape design.

Planting Elephant Grass is expected to prevent subsidence on the gully wall. The most active geomorphological process occurs in Segment II, where lateral and vertical erosion, scars, and subsidence appear. Rocks can protect the gully base, while the gully wall can be protected by planting Elephant Grass. Protection of the gully base and walls is expected to prevent subsidence due to the flow acceleration in Segment II. Planting Elephant Grass on the walls and base of the gully in Segment II is done to break and reduce the flow speed. Cracks downstream of the gully are visible during the peak of the dry season. It takes work to "bind" soil particles with roots; therefore, Elephant Grass is a locally grown plant that is valued locally. Gully point two (Figure 7), with a low vulnerability slope class, consists of four segments. Segment I is the most extended segment (71.94 m) with a slope of 6.24°.

Since the geomorphic process causes lateral erosion in small quantities, attempts might be made to protect the walls by planting elephant grass. Furthermore, it can be added to planting Sweet Potatoes or Taro on the top of the gully. Vertical erosion begins in Segment II due to the flow accumulation from Segment I. The appearance of natural erosion with small sizes also occurs randomly in Segment II due to the absence of vegetation on the gully walls. A possible remedy is to plant elephant grass on the gully's walls and bottom, sprinkling sweet potatoes or taro on top of the gully.

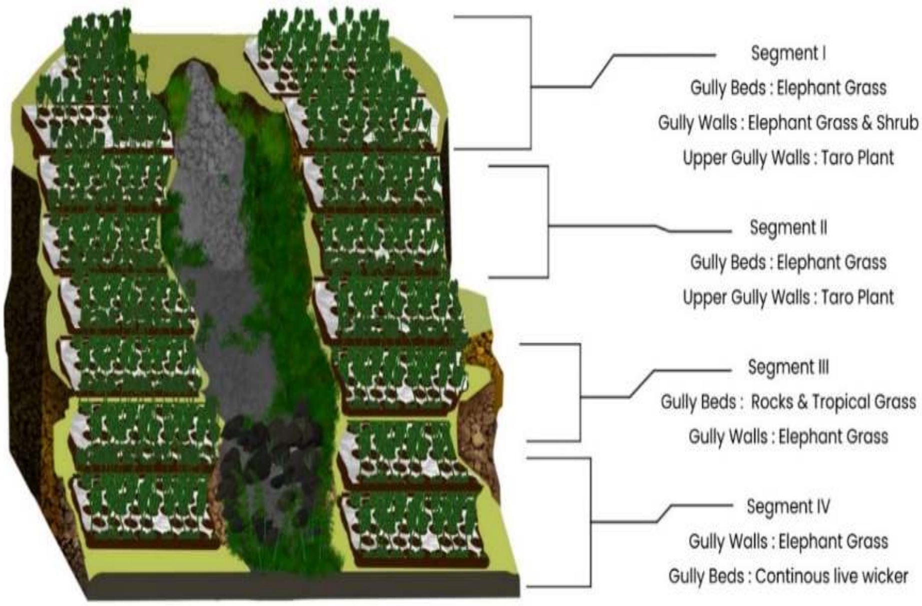



Figure 7. Illustration of low-susceptible gully control landscape design.

## Discussion

The findings indicate that the gully development has entered an advanced stage, as evidenced by its shape resembling the letter "U." It was not adequately controlled when it was still in the ephemeral stage. This abandonment is confirmed by the results of in-depth interviews, which show that local communities tend to ignore the existence of gully erosion (Figure 3d). Preventive approaches tend not to be carried out, but what is done is rehabilitation and reconstruction. This is exacerbated by converting forest land to agricultural land, thereby increasing the acceleration of gully development (Lesschen et al., 2007; Rahmati et al., 2016; Conoscenti and Rotigliano., 2020).

Neglected gullies on agricultural land can initiate the process of cracks, incisions, seepage, or collapse of gully walls, causing ephemeral gullies to become permanent and more extended (Ireland et al., 1939; Poesen et al., 2002; Eloudi et al., 2022). Ignoring the gully erosion on the Upper Slopes of Mount Sumbing might lead to broader soil erosion and interfere with the local hydrological cycle. This condition is exacerbated by open land farming with lower gully erosion control, which enhances the study site's sensitivity to gully erosion. Furthermore, this study's findings align with the study of Rahmati et al. (2022), which states that the axial pattern forms a concentrated flow, increasing the vulnerability to gully erosion.

Anthropogenic factors play an essential role in the development of gully erosion. Interestingly, local communities on the Upper Slope of Mount Sumbing tend to ignore the gully erosion development. The core issue is that local communities do not yet realize the severe consequences of gully erosion. Masi et al. (2015) corroborated this conclusion, stating that ignorance leads people to overlook gullies. Increasing community capacity is an essential component in controlling gully erosion. An exciting finding from Peterson et al. (2018) shows that assistance from Non-Governmental Organizations (NGOs) can increase community awareness and knowledge of gully erosion management. This assistance concept can be adopted on the Upper Slope of Mount Sumbing, considering that the research location is quite close to several universities concerned with environmental issues. Furthermore, capacity building can be done by issuing laws and regulations and providing community assistance. The issuance of laws and regulations also provides an opportunity to allocate funding to control gully erosion development.

Landscape design guidelines in gully control focus more on a vegetative approach (Figure 3c). Currently, farmers on the Upper Slopes of Mount Sumbing prefer vegetative efforts because they are simple to execute. Specifically, the choice of using a vegetative approach is made because 1) it is easy to install; 2) it is effective in binding soil; 3) it slows down surface runoff; 4) it can slow down flow speed; 5) it helps in the soil infiltration process; and 6) can provide additional value for the community (Arabameri et al., 2019; du Plessis et al., 2020). Mararakanye and Sumner (2017) stated that the tendency for gully erosion increases on slopes with a gradient of >4.5° and overgrazing.

As stated in the previous chapters, the slope factor at the study site (dominantly >4.5°) cannot be manipulated, so the land cover management factor through planting productive local plants is the primary option that is often required. Conventional controls, such as revegetation, are sometimes seen as less important but can have a significant impact (Helman and Mussery, 2020; Vanmaercke et al., 2021). Finally, the limitation of this study is that the landscape design has yet to be precisely tested. Subsequent investigations could utilize the proposed design to evaluate the efficacy of this cooperative design in managing the gully erosion progression.

## Conclusion

The key finding of this study is that tropical volcanic areas with thin soil (<30 cm) are susceptible to gully erosion. According to the investigation, scars have been identified in multiple permanent gullies. This indicates that gully erosion development is increasingly intensive until the parent material is clearly visible. However, the community thinks this is not harmful since it does not affect the harvest. Interestingly, gullies cause subsidence in several locations, reducing the area of agricultural land. Similarly to other types of erosion, communities still need to understand the long-term impacts when erosion continues to develop wildly.

Each gully has unique characteristics, so the gully erosion control design cannot be applied universally. In preparing the design of the gully control, at least the slope gradient, material, and land cover must be considered. To ensure that efforts to conserve land are productive, the sort of control chosen must also be able to add value for the surrounding community. The form of productive gully management in this study is by installing elephant grass, which can reduce the speed of surface runoff, bind the soil, and be used as animal feed. Increasing community capacity and strengthening regulations to support land conservation programs is the most urgent response.

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