AIMS Environmental Science

AIMS Environmental Science, 10(6): 832–846.
DOI: 10.3934/environsci.2023045
Received: 27 September 2023
Revised: 22 November 2023
Accepted: 10 December 2023
Published: 14 December 2023

http://www.aimspress.com/journal/environmental

Research article

Soil conservation at the gully plot scale in the tropical volcanic landscape of Sumbing

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Abstract: Gully erosion has the ability to transport enormous amounts of soil material, which can degrade tropical volcanic landscapes as the highest potential of agricultural land. It is critical to understand gully erosion control activities in order to reduce the initiation and development of gully erosion. The goals of this study were to: 1) classify the different forms of gully control; 2) pinpoint the advantages and disadvantages of the gully control system; and 3) suggest forthcoming changes to gully erosion control systems in tropical volcanic landscapes. Field surveys employing random sampling were used to collect data on gully erosion points and control system. The findings of the study were explained using exploratory descriptive analysis. The research findings demonstrate that gully erosion control was accomplished through biological (vegetative), mechanical and combination methods, which were classified into nine categories. While mechanical methods have benefits in terms of strength in slowing the rate of gully growth, biological systems have advantages in terms of cost and energy. Adopting a continuous live wicker and wicker check dam system might assist in preventing cracks in the gully dimension. This study's findings can potentially reduce gully erosion susceptibility for local communities and are expected to be implemented globally in settings with similar features.

Further research could be conducted on multiple tropical volcanoes with comparable issues in order to improve the performance of research results.

Keywords: soil conservation; gully erosion; plot scale; tropical volcanoes

1. Introduction

Gully erosion is a global problem in tropical volcanic environments since it can cause landscape alteration. Gully erosion is a type of soil erosion that has developed and cannot be restored to its previous state by conventional procedures. According to Pourghasemi HR, gully erosion is the primary sediment source in a watershed, which also significantly impacts soil redistribution [1]. Raji SA stated that gully erosion can alter the landscape because gullies transport large amounts of surface soil [2]. Gully erosion typically causes soil to move swiftly, endangering land sustainability [3,4]. Furthermore, gully erosion can cause infrastructure damage [5], reduce land productivity [6], cause land degradation [7] and threaten ecological sustainability [8].

Global action is needed to address the unexpected effects of gully erosion on land sustainability. Soil conservation is a method of mitigation to lessen the effects of gully erosion. Soil conservation attempts to protect, manage and ensure land sustainability and ecosystems. Soil conservation can take several forms, including land management [4], soil structure preservation [9], structural techniques [10] and vegetative approaches [11]. Despite several conservation initiatives, erosion-causing issues still exist globally [12,13]. A crucial issue regarding soil conservation that continues to develop is how to most effectively and efficiently minimize the impact of gully erosion, so this gap needs to be addressed.

There are many different forms and types of soil conservation practices; therefore, it is important to emphasize the boundaries of the scale of conservation to determine the type of conservation that is appropriate for the area under investigation. According to Wen X, there were two different types of soil conservation systems: conservation at the plot and watershed scales [14]. Plot scale refers to the specific mechanisms implemented to maintain ecosystem sustainability in a relatively narrow area, such as a slope or agricultural land. Plot scale conservation may involve several forms, including check dam construction [15], terrace construction [16] and various mechanical and bio-engineering systems [17]. The term "watershed scale" refers to conservative worldwide initiatives such as political activities, landscape management and land use planning [18,19]. Studies on gully erosion control are better suited to plot scales because the phenomena naturally occur on slopes.

Indonesia is a tropical country located on the Ring of Fire, with at least 127 active volcanoes. The volcanic terrain in Indonesia is often exploited for intense agricultural activities, making it subject to the issue of soil erosion. The Sumbing Volcano, which is located in Central Java, is one of the volcanoes that is susceptible to the threat of gully erosion [20]. The high threat of gully erosion in the Sumbing environment cannot be separated from the nature of the soil material, which has a high clay content and hilly morphology, thus triggering accelerated transportation of surface material [21,22]. The development of gully erosion is exacerbated by increasing impervious zones and poor management of drainage channels [23]. The presence of gully erosion in the Sumbing environment is a form of warning from nature that the area has the potential to experience land degradation.

In tropical volcanic environments, there have been numerous attempts undertaken to prevent gully erosion. According to the findings of [24] the study which was conducted in tropical regions as well, gully erosion could be effectively controlled by increasing vegetation. In addition, the study by Zhang Y et al., conducted in Southeast China, discovered that the best approaches were contour ridge cultivation tillage and straw mulching [13]. Surprisingly, in-depth studies on gully erosion control systems still need to be more frequently executed in Indonesia. This research was conducted to identify and assess the types of gully erosion control practices carried out on the Southern Slope of the Sumbing Volcano in Indonesia, in light of the significant effect produced by gully erosion. The study findings can be used by communities in deciding on the preferred approach of gully erosion control that may be implemented. The findings may additionally offer a general overview of gully erosion control systems used in tropical volcanic environments that might be implemented in other regions as well.

2. Materials and methods

2.1. Study area

The study was conducted in the Kodil Watershed, part of the Sumbing Volcano in Central Java, Indonesia. Sumbing is located in three administrative areas, namely Wonosobo, Purworejo and Magelang ($7^0$39’33.41”–$7^0$24’02.10” S dan $110^0$01’40.91”–$110^0$07’19.09” E). The Kodil is located in a region with a humid tropical climate, and the majority is covered by forest (67.77%), shrubs (15.53%) and moorland (10.60%). Geologically, the study site comprises five geological formations: Old Andesite, Sentolo Formation, “Sumbing Tua” Volcanic Deposits, “Sumbing Muda” Volcanic Deposits and Alluvium Deposits. The northern part of Kodil Watershed is covered by very thick volcanic soil material coming from the Sumbing Volcano. The southern region of Kodil is made up of quite thick soil material that coming from altered rock materials due to past hydrothermal phenomenon. The clay content of those soil materials are relatively high. Geomorphic processes were intensified due to three factors: 1) excessive rainfall; 2) high clay content; and 3) steep topography, which has the ability to initiate gully erosion. Figure 1 depicts the detailed appearance of the study site.

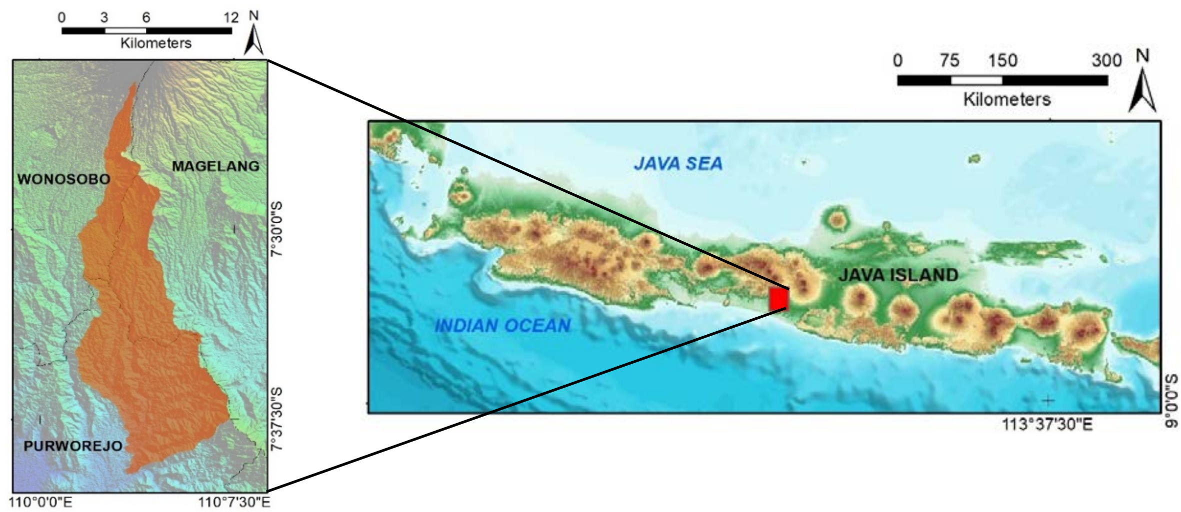

Figure 1. Study site.

2.2. Data collection and analysis

The first stage of this study was to carry out an inventory of data on the gully erosion distribution. Data on gully points and control systems were collected from May until August 2023. Evidence on the gully distribution was gathered to demonstrate that the study site was susceptible to gully erosion. The information was gathered as point data with coordinates, elevation and gully dimension properties. In order to collect precise gully dimension data, gully point measurements are undertaken manually with a meter. A descriptive statistical method was used to examine the data from the gully erosion points. The appearance of gully erosion is presented in spatial form to show the distribution of gully points at the study site. The next stage was an inventory of gully control systems. The gully erosion control systems at the plot site were picked using a random sampling approach. The information collected includes photo information, locations, slope angle, land cover and gully dimension. Gully erosion control was photographed in three sections, namely the top, middle and lower slopes. This procedure is carried out in order to acquire a comprehensive image of the success rate of gully control in each segment. A summary of the gully erosion control systems made was included in the table formatted (Table 2). Exploratory descriptive analysis were used to explain the gully erosion control systems as well as the advantages and disadvantages of each gully control plot design.

Finding the gully morphology allows for identifying the parameters of the gully erosion control system in terms of gully dimensions. The primary identification of gully morphology was completed by taking into account the findings of numerous earlier studies (such as: [25,26]) and connecting the findings to the features of the gully in the study site. A general to specific approach is used to analyze erosion control characteristics based on morphological units. This method is based on reduction theory, which seeks to identify the model that best describes the control of gully erosion. The existing theoretical literature is deliberately chosen and narrowed down to evaluate the benefits and drawbacks of the conservation system that is put in place at the study site. Literature reviews pertaining to field phenomena are used to formulate the best possible gully erosion management strategies. To gather information about the effectiveness of the current gully control strategies, short field interviews with members of the local community were undertaken. A structural approach based on accepted theories examines the possibility of strengthening gully erosion control systems (e.g., [15,27]).

3. Results

3.1. Characteristics of gully erosion at the study site

The Kodil is highly threatened by gully erosion. The findings of a field investigation at 55 gully points revealed that the predominant gully type at the study site was a permanent U-shaped gully. The formation of a U-shaped gully shows that the development process has reached the stability stage. The gully was considered permanent because its average depth was 68.42 cm. The deepest gully in a forest area was 232 cm high. At its most significant point, the gully had a surface width of 238 cm and a bottom width of 137 cm. Most gullies with a surface width of over one meter were found in forested areas, where people prefer to neglect them and do nothing to prevent them from getting more expansive. Even though the number of gullies in forest areas tends to be small (9.09%), the gully has the potential to transport large amounts of soil material because they do not receive much attention. Furthermore, the gully depth indication has the biggest standard deviation (58.97 cm), while the bottom width has the lowest (29 cm). Table 1 provides comprehensive descriptive statistics of the gully at the study site.

Table 1. Descriptive statistics of gully dimensions at the study site.

Parameters	Max	Min	Mean	Median	Mode	Std. Deviation
Surface width (cm)	238	14	59.85	46	42	48.52
Bottom width (cm)	137	11	36.30	27	13	29
Depth (cm)	232	9	68.42	49	81	58.87

The presence of gullies was most significant in moor, with 35 (63%) followed by shrubs (12.8%). Many gullies in moors suggest a fault in the land management system, which allows gullies to develop. Ideally, moors were always cultivated regularly to restrict the development of gullies. However, when there were gaps, the gully dimensions may expand. The findings were supported by the analysis of Nugraha SS et al. [23], which reveals that drainage was poorly managed, resulting in gully formation. Surprisingly, higher terrain has fewer gully erosion points than mildly inclined slopes (8-15°). The number of gully spots on sloping terrain reached 23 (41.81%), which was higher than on sloping terrain (10.9%), slightly steep (1.81%) and steep (7.27%). This phenomenon demonstrates the bias in the link between the presence of gully erosion points and slope gradient, prompting the need for further investigations. The distribution and appearance of gully erosion spots at the study site is presented in Figure 2.

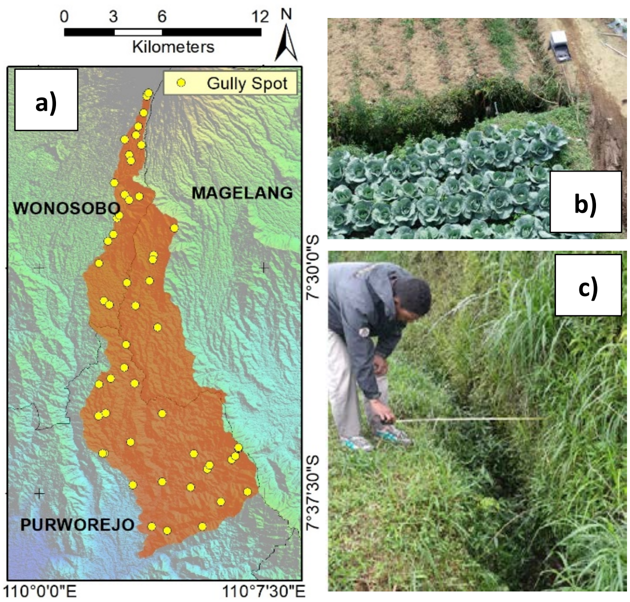

Figure 2. a) gully spot at the study site; b) gully spot on agricultural land; c) gully spot in a grazing field.

3.2. Gully erosion control at the study site

Gully erosion control is performed in order to reduce soil transport in the gully dimension when surface flow emerges. According to Liu X et al. [15], there were two forms of conservation systems: biological and engineering. Biological systems refer to all techniques that involve biological factors (particularly vegetation) in reducing the gully susceptibility. The biological system is also called the vegetative system because the fundamental conservation components are made of vegetation [28]. Furthermore, engineering systems, also known as mechanical systems, were attempts to reduce gully erosion susceptibility by installing retaining structures with rocks, block structures or other equipment. In addition, there were combination systems, which combined biological and engineering systems.

The field survey findings revealed that the community and the government were engaged in nine gully control systems. The biological system used at the research site consists of three different plantings: 1) bushes on the gully walls and bottom (Figure 3a); 2) shrubs (Figure 3b); and 3) grass on the gully walls (Figure 3c). Due to their propensity to be simple to implement and their affordability, biological systems constitute the control system used most frequently at the study sites. The gully erosion control system using an engineering system was carried out in five forms, namely: 1) layering the bottom of the gully with sacks (Figure 3e); 2) hardening the gully walls with concrete structures (Figure 3f); 3) sacks covered with bamboo on the gully walls (Figure 3g); 4) hardening the dimensions of the gully with block structures (Figure 3h); and 5) installation of sacks filled with soil on the gully walls (Figure 3i). The combination system used was planting shrubs on the gully walls combined with rock installation at the gully bottom (Figure 3d). Descriptive statistics of the gully control system at the study site are presented in Table 2.

Table 2. Descriptive statistics of gully erosion control at the study site.

No	Type	Coordinate		Slope	Landuse	Dimensions (cm)		
		Latitude	Longitude			Surface	Bottom	Width
1	Shrub the gully walls and bottom	07°25'10’’	110°03'19’’	0–2°	Agriculture	46	31	57
2	Planting shrubs	07°25'22’	110°03'11’’	3–8°	Shrubs	205	107	107
3	Planting grass on the gully walls	07°25'04’’	110°03'16’’	0–2°	Agriculture	28	21	34
4	Combination shrubs with rocks	07°28'25”	110°02'39”	3–8°	Shrubs	224	130	232
5	Layer the gully bottom with sacks	07°25'39”	110°03'29”	0–2°	Agriculture	28	19	13
6	Hardening of gully walls with concrete structures	07°25'18’’	110°03'17’’	8–15°	Settlement	42	37	34
7	Sacks covered with bamboo on the gully walls	07°25'22’’	110°03'10’’	0–2°	Agriculture	53	29	57
8	Hardening of gully dimensions with block structures	07°32'43”	110°04'33”	8–15°	Shrubs	56	56	76
9	Install sacks filled with soil on the gully walls	07°25'39”	110°03'29”	0–2°	Agriculture	28	21	34

Biological control systems were installed on slopes 0–8°, with agricultural land and shrubs as the dominant land cover. Gully with a vegetative control system tend to have a surface width between 28–205 cm and a depth between 34–107 cm. Local plants that naturally grow in the gully dimensions predominate in gully vegetation, and were known as indirect conservation in this study. The community adopts vegetative control systems such as planting shrubs and grass in the gully walls with

3–8° slopes. The community was planting vegetation on the gully walls to achieve three main goals: 1) to restrict water flow; 2) to stop subsidence; and 3) to collect grass and bushes for livestock feed. The combination method was used on terrain with 3–8° slopes covered in shrubs. The community also embraces the combination system, but the lack of stone makes installation expensive and necessitates using communal funds.

The engineering conservation system was implemented at the study site in slope classes 0–2° and 8–15°. The land cover engineering system was most frequently found on agricultural land, but also in settlements and bushy locations. To instantly lessen gully erosion effects, communities have another option: engineering systems. Typically, engineering system selection was done at gully locations where the community believed there was a high risk of subsidence. Systems based on sacks and bamboo were chosen since they were simpler to install and the raw materials were more accessible. Handling the impact of erosion with engineering systems was carried out independently by landowners where there were gully spots. Government support was frequently provided for engineering systems that harden with concrete or rock, particularly at the grassroots level because these systems have high expenses. Figure 3 displays a broad overview of the gully control system's architecture at the study site.

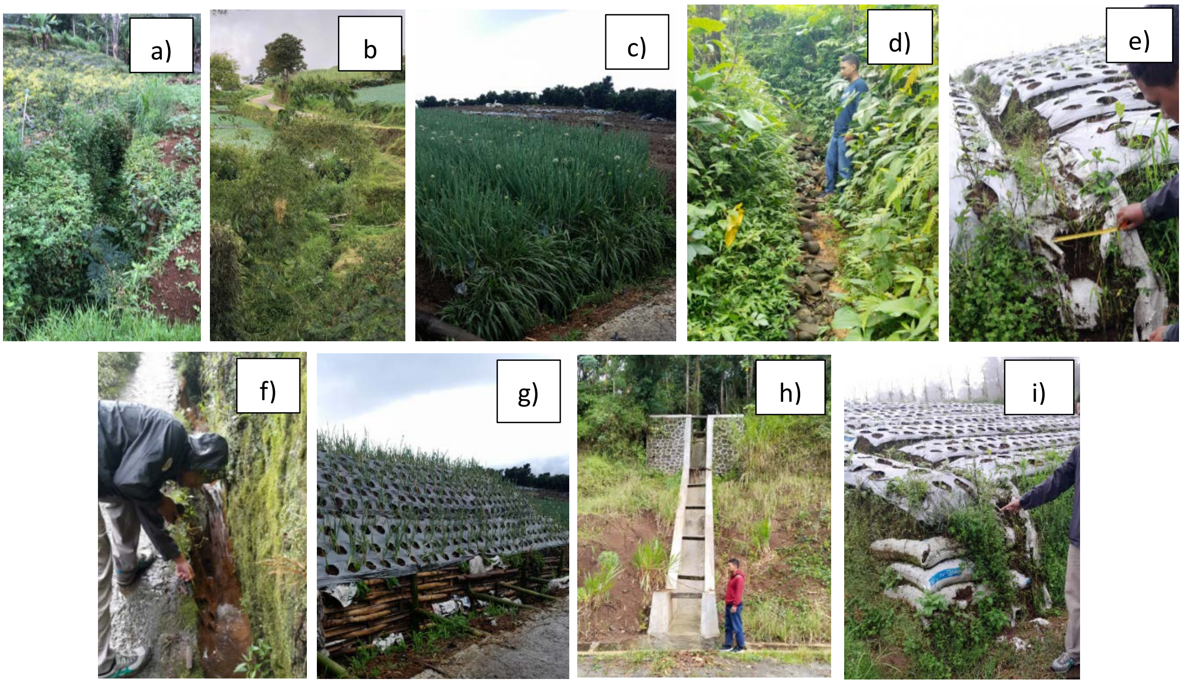

Figure 3. Various of control systems at the study site: a) planting shrubs on the walls and bottom of the gully; b) planting shrubs; c) planting grass on the gully walls; d) planting of shrubs combined with stone installation at the bottom of the gully; e) layering the bottom of the gully with sacks; f) hardening of gully walls with concrete structures; g) installation of sacks covered with bamboo on the gully walls; h) hardening the dimensions of the gully with structural block; i) reinforcement of the gully walls with sacks filled with soil.

Table 3. Strengths and weaknesses of gully erosion control at the study site.

No	Type	Strengths	Weaknesses
1	Shrub the gully walls and bottom	Shrubs can withstand the impact of rainwater and reduce the speed of water flowing in the gully [17]. Shrubs also tend to be easier to cultivate than other plants.	Vegetation with fibrous roots causes the soil to become loose and distinct from the soil layer beneath, making it easily eroded at the start of the rainy season. At the peak of the dry season, shrubs die easily.
2	Planting shrubs	Shrubs have a sturdier structure than bushes in steep areas to withstand larger flow volumes [30].	Planting shrubs takes a relatively long time, so they cannot be used for short-term control.
3	Planting grass on the gully walls	Planting grass on gully walls can strengthen the gully dimension, especially for plants with fibrous roots, because grass can strengthen the soil structure so that it is more resistant to the threat of erosion [17,31].	Grass cannot reduce large volumes of flow, so it needs to be combined with plants or other structures if the potential flow is large enough.
4	Combination shrubs with rocks	Shrubs combined with rocks can withstand the force of the flow. This model can also prevent runoff, reduce hydrological connectivity and sediment transport [15].	The force of the flow has the potential to move rocks, so it is necessary to arrange the rocks at the gully bottom and walls so that they can cover the top layer of soil.
5	Layer the gully bottom with sacks	Layering the gully bottom with sacks means that the soil at the bottom will not be carried away by water flow, retaining sediment and potentially allowing plants to grow [32].	The joints between sacks have the potential to come loose so that water can enter the gully bottom and transport the soil layer at the gully bottom.
6	Hardening of gully walls with concrete structure	Hardening of gully walls with concrete structures tends to be solid and durable and able to withstand the collapse of the gully walls.	Hardening of the gully dimensions tends to impact other locations (off-site) negatively.
7	Sacks covered with bamboo on the gully walls	This system is easy to apply to gully walls at a low cost and has a good ability to resist the collapse of gully erosion walls.	This system cannot be applied at the bottom of gullies and cannot be used to hold deep gullies (>3m).
8	Hardening of gully dimensions with structural block	Hardening using block structures is the best system for gully erosion control because the strength of the structure can adapt to all of the gully morphology.	This control system cannot be implemented on a massive scale because installing sacks at the gully bottom requires much effort, money and energy.
9	Install sacks filled with soil on the gully walls	Sacks have large dimensions to protect the gully walls [33]. This system is also easy to install and more flexible, so it can be moved when needed.	Heavy sack loads can cause the gully walls to become overloaded, and the sacks will not last long if exposed to rain and sunlight for an extended period.

Each conservation approach has some advantages and disadvantages concerning various factors. According to Lufira RD et al. [28], biological systems play a significant effect in lowering the probability of sedimentation owing to gully erosion by increasing plant cover. In addition to reducing flow velocity, increasing infiltration capacity and preventing gully wall collapse, vegetation protects the soil from rainfall. Gábris G et al. [29] emphasized that the vegetative system is beneficial in lowering the susceptibility to gully erosion as long as the slope gradient was lower than ≤12% or equal to 8°. Engineered systems were typically more reliable, but installation and maintenance are time and money-consuming. The engineering system could only be used at a limited number of gully spots [28]. The engineering system additionally benefited from flexibility because it may be used on gullies with any class of slope gradient. The benefits and drawbacks of each gully erosion control system at the study site are presented in additional detail in Table 3.

3.3. The spatial arrangement of the gully erosion control from the perspective of morphology

The main goal of Gully erosion control is to reduce the quantity of soil that is carried away by rainwater. Gully control systems cannot be applied universally to every aspect of its morphology due to variations in the soil and slope. A thorough investigation was required to ensure that control systems were more effective and efficient for every aspect of gully erosion. The first step was to determine the gully morphology in order to ensure that each portion of the gully body's susceptibility characteristics were understood. In this study, the body of gully erosion was divided into four morphological units, including the gully head, walls, bottom and outlet. An illustration of the gully morphology is presented in Figure 4.

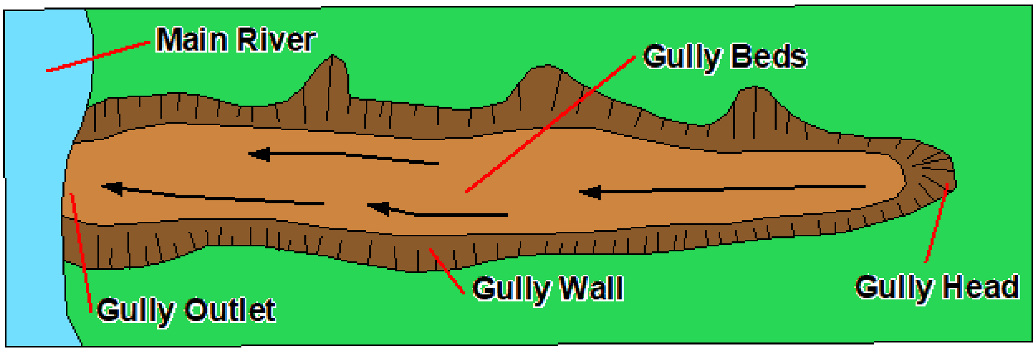

Figure 4. Illustration of the morphological appearance of gully erosion at the study site.

The gully head is the topmost section of the gully and is usually the first initiation point before the gully develops. According to Tang J et al. [6], the gully head was typically situated in a steep place with soil that was quickly moved and had dimensions that were typically smaller than other parts. The gully head is one of the gully inlets, but because it is upstream, the amount of water flowing from it would be smaller, making it easier to maintain. Nine control system strategies could be implemented at the gully head, although installing plants and rocks together was not suggested. The placement of the stones is feared to weigh the slopes, and if a sudden large flow occurs, the mixture of the stones and bushes may operate as a bottleneck that causes collapse.

Gully walls refer to the soil structures on the right and left. Gully walls are one of the fundamentals in the gully classification system (permanent or ephemeral), where the walls represent gully depth. Since it was highly prone to gully crack phenomena and collapse, gully walls are the major sources of sediment. As stated by Lufira RD et al. [28], gully walls comprise around 85% of the sediment in gully erosion bodies. The biological control system was the most commonly suggested type of gully wall because it can strengthen the durability of soil aggregates, preventing them from collapsing [28,34]. It was common practice to plant grass on gully walls at study sites since shrubs serve two purposes: grass maintains the gully's dimensions and can feed livestock.

The gully bottom is the lowest point of the gully and is particularly susceptible to surface runoff. In accordance with Wang R et al. [35], the gully bottom is the most easily distorted due to the influence of surface flows and serves as a location for silt buildup. In order to keep the gully's dimensions stable, the gully bottom is crucial. If the gully bottom collapses, the gully walls and head would additionally grow unstable. The gully bottom at the study site comprises various materials due to the diverse soil depth. Areas with thin soil (less than 30 cm) begin exposing parent material, making the biological control system impracticable. However, the biological control system was particularly feasible in locations with deep soil. Attempts might be performed to retrieve and reduce sediment velocity by combining bushes with rocks or growing shrubs. Mechanical techniques, such as inserting bamboo-lined sacks or layering the gully bottom, should be reevaluated since it requires enormous costs, time and energy.

Previous investigators paid less attention to gully outlets, even though the outlets were where the flow velocity reaches the peak. The issue was exacerbated when the flow from the gully outlet met the flow from the main river, generating turbulence that could collapse the gully outlet and walls. High levels of consistency were required for control system practices at outlets to remain resilient against water flow. Gully outlets favor structural effort because of their great consistency. Planting shrubs or grass, for example, might be reconsidered since biological systems with low consistency tend to be more easily transported when surface runoff occurs in tremendous amounts and at high speeds. A general description of the suitability of the control system with the gully morphology is presented in Table 4.

Table 4. Spatial arrangement of gully erosion control system based on gully morphology.

No	Type	Head	Wall	Bottom	Outlet
1	Shrub the gully walls and bottom	SA	SA	SA	NA
2	Planting shrubs	SA	SA	SA	SA
3	Planting grass on the gully walls	SA	SA	SA	NA
4	Combination shrubs with rocks	A	A	SA	SA
5	Layer the gully bottom with sacks	SA	SA	NA	A
6	Hardening of gully walls with concrete structure	SA	SA	SA	SA
7	Sacks covered with bamboo on the gully walls	SA	SA	NA	A
8	Hardening of gully dimensions using block structure	SA	SA	SA	SA
9	Install sacks filled with soil on the gully walls	SA	SA	A	SA

Notes: SA: Strongly Applicable; A: Applicable; NA: Not Applicable.

4. Discussion

Gully erosion is a primary driver of land degradation because it transports significant volumes of surface soil layers. Due to edaphic and climatic variables, Sumbing upper slopes were susceptible to gully erosion. More than 70% of the upper slopes of the Sumbing have intermediate erosion susceptibility, and just 8% have high susceptibility [20]. The government and the community have taken multiple initiatives to lessen the gully erosion susceptibility. Unfortunately, numerous areas of gully erosion have not been adequately treated until now. The low level of public and governmental knowledge of potential hazards of gully erosion was one of the fundamental causes. According to a compilation of studies by Liu J [36], gully erosion supplied between 60.2% and 68.1% of all sediment in Europe, between 20.0% and 80.0% of all sediment in North Africa and between 70.0% and 92.8% of all sediment in China. These findings indicate that gully erosion needs to be taken seriously because it contributes significantly to a watershed's sediment load.

The key to the control system is that every detail must decrease gully development and have economic benefits. The control system must reduce erosion risk by having monetary value while benefiting the local community. Biological systems (vegetative) can express fruitful control systems in several ways. The effects of gully erosion can be lessened with a biological system, and local communities can use plants planted in the gully's dimensions as sources of nourishment for livestock. This system was frequently observed in Indonesia's volcanic landscapes, although few studies of the phenomena of soil conservation have been fruitful.

The community can easily install and operate several alternative gully erosion control system strategies at the plot level. Simple and inexpensive systems were typically those that relate to biological control systems. Based on the characteristics of the gully at its study site and its productive land conservation, biological control systems with continuous living wicker, a structured wooden installation on the gully bottom and walls, is one of the most preferred control system solutions. This technique could be used on terrain with a slope of around ≤35°, logs spaced 0.5 meters apart and logs with a diameter of about 2 cm [15]. This technique has been used successfully in numerous sites in China to lessen surface runoff [37]. A high-density wooden structure in the shape of a check dam called a "wicker check dam" was another design option. The optimum log diameter was 3 cm. Nevertheless, wicker check dams can be erected on slopes steeper than 35° [15]. The retention of sediment by vegetation-based dams was good [32,38]. Additionally, local communities may employ the vegetation that grows on the gully walls and bottoms as a source of nourishment for livestock. These two systems could be considered productive land conservation because they have added economic benefits.

5. Conclusions

The most destructive type of erosion is gully erosion, particularly in tropical volcanic environments, including Indonesia. Inventory data acquired in the Sumbing Volcano reveal that the arrangement of permanent gullies dominates gully erosion features. These findings suggest that gully preservation initiatives were urgently required at the plot scale. Fieldwork conducted during 2023 reveals that three methods were used to carry out control system actions: biological (three forms), mechanical (five forms) and mixed (one form). The mechanical approach has the advantage of stabilizing the gully dimensions, while the biological approach was simple to install and maintain. The biological approach's shortcoming was its inability to survive significant volumes of surface runoff, whereas the mechanical approach's drawback was its propensity for suffering off-site effects.

In terms of morphology standpoint, gully control system can be done at the gully head, bottom, walls and outlets. The mechanical approach was the most adaptable control system strategy used in all gully morphologies, though local communities frequently shun it because of the installation's complexity as well as high time, cost and effort constraints. Biological strategies with added value, referred to as "productive land conservation" in this study, were considered best by local communities since they were simple to implement and could indirectly benefit the local economy. The concept of productive land conservation can add value by cultivating vegetation in gully dimensions that can be used as an essential resource for providing food for livestock. Continuous live wicker and wicker check dams were strategies for strengthening gully morphology that can be used at the study site. These two strategies have been effectively used in China and can be utilized, thereby utilizing resilient native vegetation options whose leaves can be harvested. Communities and stakeholders can use the research's findings to clarify decisions for gully prevention on a plot-by-plot basis. However, there is still a gap in this study because it was only conducted in one watershed. Additional evidence would be required to sharpen research findings on other tropical volcanoes with diverse geological ages, volcanic types and material properties.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The authors would like to thank Transbulent Research Group and GeoArcScience Co. for their assistance in collecting information on gully points and control system sites. The author also wants to express gratitude to the author's colleagues at the Geospatial Information Agency for their time spent discussing the study's analytical findings.

Conflict of interest

The authors declare no conflict of interest.

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