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Understanding gully erosion development through a geomorphological approach

Edwin Maulana[1], *Junun Sartohadi*[2,3]*, *Muhammad Anggri Setiawan*[4,5]

[1]*Department of Environmental Science, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[2]*Department of Soil Science, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[3]*Research Center for Land Resources Management, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[4]*Department of Environmental Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia*
[5]*Center for Disaster Studies, Universitas Gadjah Mada, Yogyakarta, Indonesia*

**Corresponding author: junun@ugm.ac.id*

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Abstract: This study aims to identify the gully erosion typology and development using a geomorphological approach. Gully geomorphology features were executed using combined photogrammetric approaches: aerial photography (unmanned aerial vehicle, UAV) and terrestrial photo data (structure from motion, SfM). The UAV data are used to identify the gully orientation, while SfM derives the geomorphological features in the gully dimensions. Five canopy-free gully erosion points were selected for the UAV-SfM data acquisition. Typically, SfM data offer higher resolution (0.11–0.57 cm) than UAV data (0.61–2.08 cm). Modelling using SfM can provide an in-depth illustration of gully dimensions such as rill erosion, scars, and cracks. The findings demonstrate that the gully depth and width are larger on the middle slope. This phenomenon is influenced by the strength of the flow and the silt transported by the water, which reaches a peak on the middle slope. The lower slopes have a solid form since the power of the flow weakens as it transports the accumulated silt from the upper and middle slopes. The study's findings can be relied on to guide communities in strengthening the gully body in the middle slope. Furthermore, the findings can be tested and adopted globally with comparable typologies.

Keywords: erosion; geomorphology; gully; structure from motion

Gully erosion is a geomorphic phenomenon that may contribute to significant soil loss. Gully erosion is responsible for around 30–80% of the total sediment loss (Wasson et al. 2002; Ben Slimane et al. 2018). The topography, soil characteristics, and land use play a significant role in controlling surface flow, which causes gully development (Fashae et al. 2022). Allowing a gully to continue uncontrolled can lead to shallowing reservoirs, land degradation, and decreased soil fertility (Ben Slimane et al. 2018; Kariminejad et al. 2023).

An in-depth understanding of the gully development is required to prevent higher soil loss. Photogrammetry approaches have lately gained popularity for monitoring soil erosion (Yang et al. 2021). Photogrammetry can generate precise point clouds with high resolution without altering the appearance of the land surface (He et al. 2022). Multiview-stereo (MVS), multi video stereo (MVS), structure from motion (SfM), and unmanned aerial vehicles (UAVs) have been developed to model gully dimensions (Gómez-

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Gutiérrez et al. 2014; Fernández et al. 2020). Recently, Dai et al. (2022) and Fernández et al. (2020) have combined SfM-UAV to simulate a microtopography, which is essential for a gully appearance analysis.

SfM is a terrestrial photogrammetry technology that has been applied extensively in studies pertaining to gully erosion and other subjects. SfM is more user-friendly, affordable, and adaptable than conventional laser scanners (Dai et al. 2022; He et al. 2022). It is well-recognised that using UAVs may bridge the gap between the field resolution and satellite size and offers great flexibility in terms of the cost, time, and energy (Wang et al. 2022). The simultaneous use of UAV and SfM has demonstrated efficacy in producing three-dimensional data that are beneficial for analysing gully erosion (Ben Slimane et al. 2018; Dai et al. 2022).

The development of remote sensing technologies, such as UAV-SfM data, allows users to obtain detailed data on the geomorphological features. Microrelief changes in each segment of the gully section make it easier for users to predict the mechanism of the gully erosion development process. Remarkably, no site-scale study on the evolution of gully erosion using a geomorphological technique has been conducted in Southeast Asia, particularly in Indonesia. Against this backdrop, this paper highlights the geomorphological approaches based on combined remote sensing data to identify the gully erosion development. Specifically, this study was conducted to (1) identify the characteristics of gully erosion through a morphometric approach and to (2) analyse the mechanism of gully erosion development at the study site.

MATERIAL AND METHODS

Large-scale gully erosion modelling remains understudied in volcanic environments, particularly in Indonesia. Previous investigations were conducted on a semi-detailed scale, making it difficult to describe the gully dimension appearance (Maulana et al. 2023a). Typically, the higher portions of the Bogowonto watershed are among the volcanic zones susceptible to erosion (Sartohadi et al. 2018). This area is highly susceptible to erosion since it comprises weathered volcanic material with a high clay content (Pulungan & Sartohadi 2017). Upstream of Bogowonto, especially on the upper slopes of the Sumbing Volcano, is prone to gully erosion because of its thin soil and loose particles. The work by Maulana et al. (2023b) emphasises the significance of detailed scale investigations in this area due to the intensity of the gully erosion.

The study was carried out at five gully erosion spots on the upper slopes of the Sumbing Volcano, Indonesia (7027'10.05''–7024'07.69''S and 110002'29.42'' to 110003'43.73''E). The study site is constructed from volcanic material from the young Sumbing's previous eruption (Figure 1). Notably, the soil type is dominated by andosol, which is blackish brown and has a very loose to extremely loose aggregate. Gullies are clearly visible in the moorland area, which the locals also utilise for irrigation during the rainy

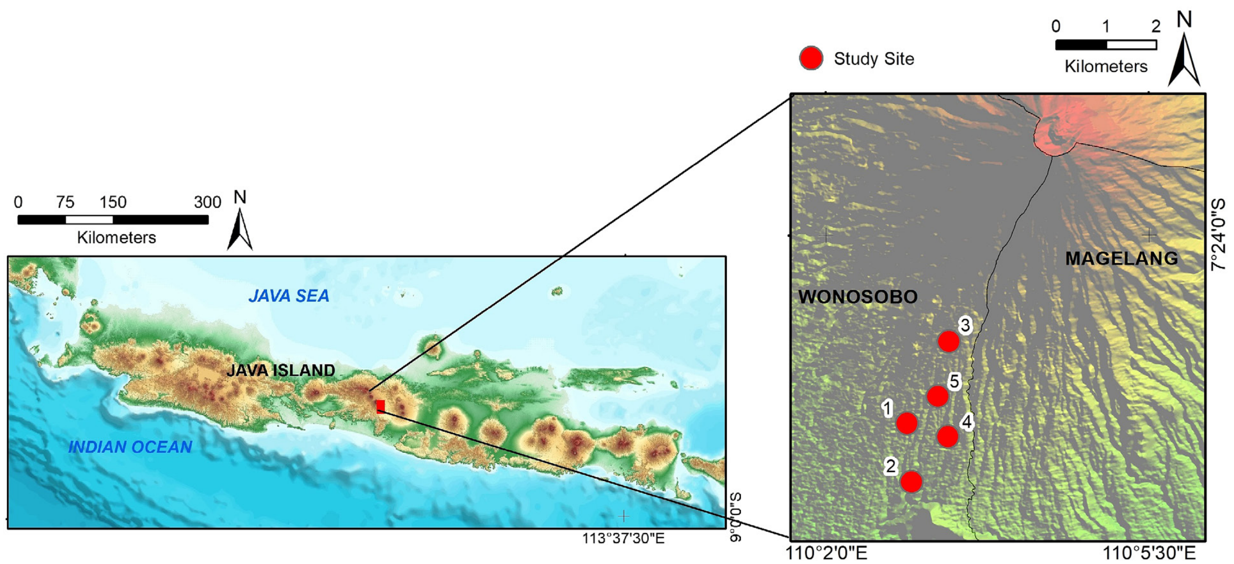

Figure 1. Study site

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season. Due to a lack of control, most gullies enlarge and deepen yearly (Maulana et al. 2025), which can become a major issue in the future.

Field assessments were conducted during the peak of the wet season, November 2023–January 2024. The data acquisition was carried out in two stages, namely: (1) the acquisition of micro watersheds and the gully appearance using a UAV (scale of 1 : 1 000); and (2) the acquisition of the gully geomorphology using the SfM technique (gully's width > 0.5 m). The tool used for the data acquisition is a Quad Copter UAV combined with a pocket camera for the SfM data acquisition. Coordinate correction is accomplished using the image-to-image method, which employs existing reference data in orthorectified high-resolution satellite images. In order to correct the coordinate accuracy, the image-to-image correction model is frequently employed in UAV data processing techniques (Ren et al. 2017). UAVs and digital cameras are used for terrestrial aerial photography acquisition. Considering the relatively tiny dimensions of the gully (< 0.5 m), it is not practical to build ground control points (GCPs) on the gully walls. We focused on accessibility when taking pictures of the gully body. An oblique technique was used to take pictures of the gully's dimensions, with each picture covering between 60–70%. The photo-taking technique used four terrestrial models, referring to the findings of Meinen and Robinson (2020).

A geomorphological technique was used to analyse the development mechanisms of the gully erosion. Geometric and morphological data are generated at the site scale from 3D and 2D data obtained from the UAV-SfM modelling. Data extraction was undertaken on specific factors, including the surface soil and gully morphometry, that affect the beginning and progression of the gully erosion (Sidorchuk 2005). Specifically, the following factors were used for identification: the soil, land cover, flow pattern, microtopography, and erosion form (Sidorchuk 2005; Ben Slimane et al. 2018). The soil and microtopography factors explain the erodibility characteristics of the material, while the erosion forms point out the actual erosion processes that occur. The land cover explains how the land cover holds back the flow of surface water, while the flow pattern factor reviews the potential strength of the flow that occurs. Finally, the exploratory descriptive analysis describes the relationship between the factors investigated, allowing inferences about the origin and progression of the gully erosion.

Typically, the gully characteristics and development are determined by dividing the body into ten segments. In addition, the segments in this study are defined as cross-sections that describe the shape and morphological characteristics of the gully. The characteristics are assessed in terms of the depth and shape, where the shape can indicate the relative age of the gully. Young gullies usually have a V shape and are relatively short, while a U shape gully is usually older. Furthermore, U gullies that have reached scars which usually indicates that the gully tends to be older. The gully development process was reviewed based on changes in the width of each segment from the SfM data. Variations in the gully width show the geomorphological development.

RESULTS

Photogrammetry processing. UAV and SfM data were collected in five micro watersheds on the upper slopes of Sumbing. The study sites were chosen based on the ease of data gathering, considering the land cover and the appearance of gully dimensions. The area of the micro watersheds studied ranged from 355.26 to 5 964.96 m^2 (Table 1). The gully dimension covers 15.91 to 154.22 m^2. Most gullies were found on agricultural land, especially moorlands with poor drainage systems and slopes > 3°.

The mosaic data reveal that there are only slight distortions. Several flaws, such as relief displacement, scale changes, and other noise, should be present in the acquisition data. The spatial resolution of the aerial photo ranges from 0.61–2.08 cm, with horizon heights varying from 30–75 m. Several features of the gully development process can be identified at a resolution of less than 2 cm, including the micro watershed boundaries, land cover details, gully body appearance, and microtopography data. Unfortunately, some significant elements that could aid in describing the gully erosion development could not be extracted from the data from the aerial photos. Critical features like gully fissures and rill erosion are skewed in the 2D and 3D aerial photo data. Due to the aerial photo limitations, crucial features like the gully depth cannot be shown. The feature extraction of gully dimensions-related issues was solved by employing SfM.

SfM is used to collect data using an instrument height ranging from 2–9 m, combining horizontal, oblique, and vertical directions. SfM data processing generates 2D and 3D data ranging from 0.11–0.57 cm

https://doi.org/10.17221/92/2024-SWR

Table 1. Recapitulation of the photogrammetric processing using the UAV-SfM approach

	Areas (m^2)	Gully length (m)	Device height (m)	No. of photos	GSD (cm)	Land use
UAV point 1	2 829.85	20.65	75	223	2.08	moorland, shrubs
UAV point 2	5 964.17	117.7	50	253	1.29	moorland, forest
UAV point 3	3 590.96	114.39	30	352	0.61	moorland, shrubs
UAV point 4	355.26	29.78	40	194	0.98	moorland, settlement
UAV point 5	442.49	19.31	40	212	1.06	moorland
SfM point 1	19.62	20.65	3–7	51	0.24	shrubs
SfM point 2	86.64	117.7	4–9	142	0.29	bare land
SfM point 3	154.22	114.39	2–5	121	0.11	bare land, shrubs
SfM point 4	15.91	29.78	5–9	51	0.57	bare land
SfM point 5	16.85	19.31	4–9	64	0.23	bare land

GSD – ground sample distance; UAV – unmanned aerial vehicle; SfM – structure from motion

(Figure 2). Both ephemeral (≤ 30 cm) and permanent gullies (> 30 cm) can be conveniently seen at a detailed resolution of less than 0.6 cm, while rill erosion can be identified. SfM data are also accessible for assessing topographic roughness at the gully dimension. The problem is that the brush cover in some gullies might distort the results of the 3D data processing. Additional steps were required to convert the digital surface model (DSM) data into a digital terrain model (DTM) to acquire the comprehensive appearance of the gully dimensions.

SfM data were used to extract the detailed geomorphometric data processing of the gullies, while the UAV data were used to analyse the micro watershed data. Additionally, the rill erosion on the gully walls describes how the water enters the gully. Since the maximum rill breadth is only about 10 cm, the UAV data cannot accurately detect the rill distribution. Rill visualisations can be obtained from SfM data at ≤ 1 cm resolution. SfM data are more detailed than UAV data because they are acquired from multiple angles and closer to the object. The SfM revealed

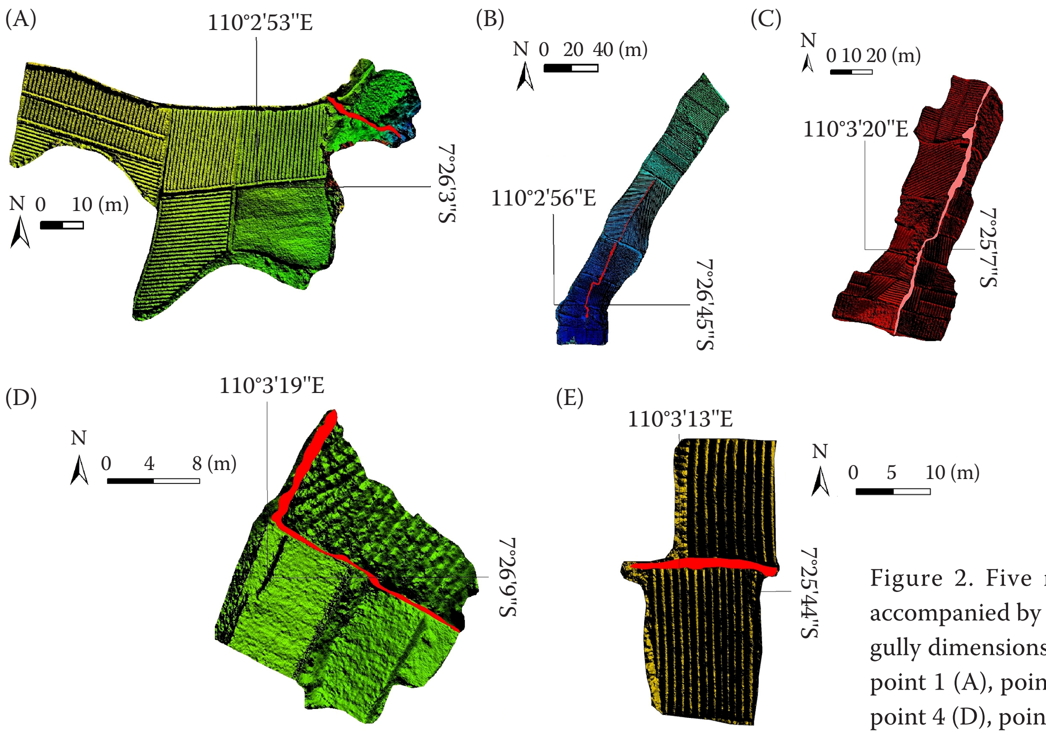

Figure 2. Five micro watersheds accompanied by a description of the gully dimensions symbolised in red: point 1 (A), point 2 (B), point 3 (C), point 4 (D), point 5 (E)

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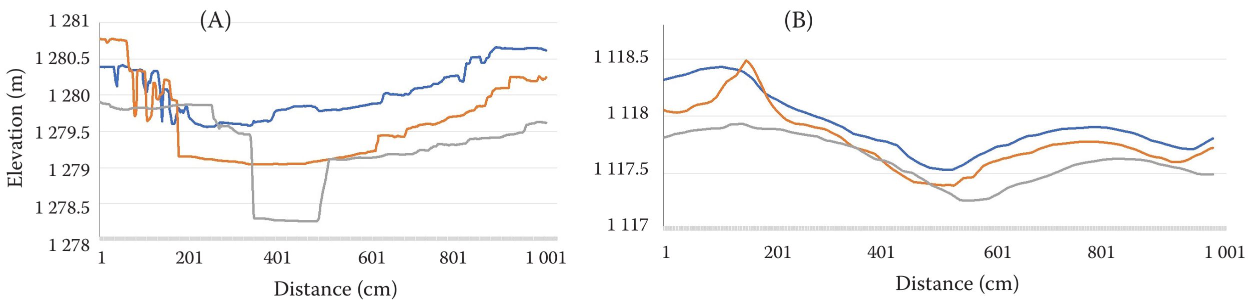

Figure 3. The cross-sectional appearance of local relief at two gully points: point 1 (A), point 2 (B)
The blue in the figure indicates the upper segment, the orange indicates the middle segment, and the grey is the lower segment

an extensive illustration of rill erosion and gully relief irregularities.

Gully erosion characteristics. The gully characteristics can provide an overview of the status of the gully development. A single sample was taken for each gully segment (upper, middle, and lower) to determine the local relief's cross-sectional appearance. The findings indicate that permanent gullies that resemble the letter U predominate in the gully erosion status (Figure 3). It was only at the fifth point, where the gully's development was still in its early stages, that a gully resembling the letter V was discovered. Specifically, the gully was still in its early stages, characterised by a narrow base (V-shape), active vertical erosion, and a tendency to be unstable. Interestingly, the three extracted pieces, the gully dimensions appear relatively constant. An anomaly was found at the first point in the gully's development, where each segment tends to have a distinct shape. This effect occurs when flow accumulates on steep slopes, causing subsidence downstream of the gully.

Gully dimension measurements were performed using SfM data, with at least ten samples taken at each gully site to acquire comprehensive gully dimensions. The gully's overall length ranges from 19.31 to 117.7 m. Segment three at point three had the widest surface (1.98 m), and segment ten at point four was the narrowest (0.22 m). Segment three at point three (1.84 m) has the widest bottom width, while segment ten at point four (0.18 m) has the narrowest. The three-point gully's surface width reaches its optimum width on the middle slope due to the steep slope bending and a sharp bend in the flow direction. This effect develops the gully erosion body and makes the gully walls more easily eroded by the flow-destructive force. The highest gully depth was found in segment four at point one (1.49 m), and the shallowest was in segment ten at point three (0.22 m) (Figure 4).

The gully is considered permanent since its average depth exceeds 0.3 m. A ground check revealed that the gully depth was less than 0.3 meters in a few places. Gullies with a depth of < 0.3 m are common in the lower slopes, where the topography softens, and sediment accumulates. This causes a shallowness in the lower slopes' section. The average gully

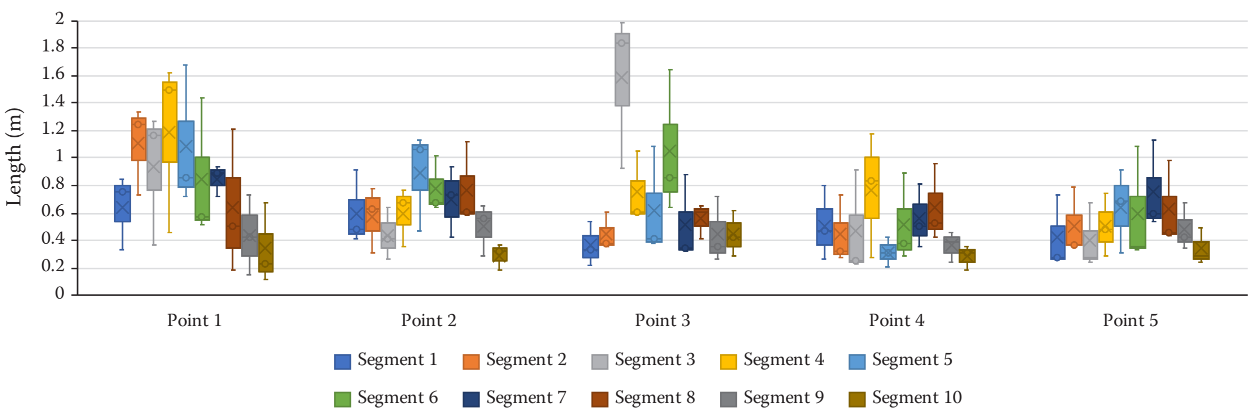

Figure 4. Descriptive statistics of the gully dimensions

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depth value for the entire length is 0.33–0.74 m. The highest average gully depth was at point two, in the most significant catchment (5 964.17 m^2), increasing the surface runoff potential. In addition, large watersheds tend to have longer and steeper slopes, which can increase the flow energy and carry more soil material. A higher destructive force is exerted on the gully dimensions by the combination of the flow and the results of the surface soil erosion.

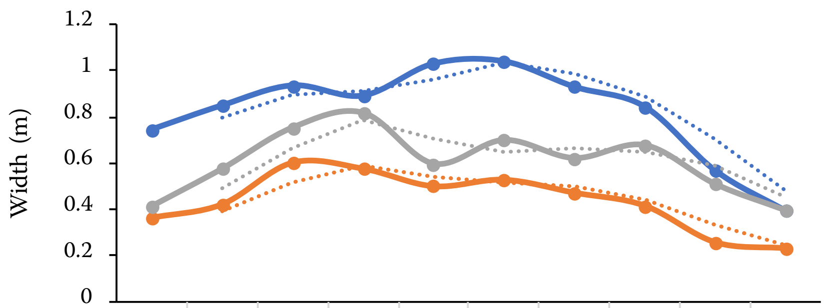
Gully erosion development process. Gully erosion develops and emerges through an assortment of characteristics and sophisticated processes. There are three phases to the chronology of gully formation: initiation, development, and stabilisation. Considering that the current gully was previously formed, the initiation stage at the study site is presently complete. Furthermore, only some of the gully bottom has reached the rock or parent material, indicating incomplete stabilisation. A few spots have made it to the parent material and are only found on the middle slopes. In summary, the gully formation is in the development stage.

The pattern of gully formation is complex. This viewpoint is confirmed by the variable (rather than linear) description of the width and depth of the gully. The gully's body develops vertically and laterally in an irregular manner. In order to find development patterns, the natural break approach is used to divide the gully body into ten pieces. It can be shown that there is a trend toward lateral development in segments two through six and that this trend starts to reduce in segments seven through ten (Figure 5). At the bottom of the gully, segments two to four demonstrate a lateral development, which begins to decline in segments five to ten. This phenomenon indicates that soil mass movement is more likely to occur in the upper and middle slopes. Ideally, the runoff rate is lower on the upper slope, which makes the erosion smaller. This pattern suggests that additional factors influence the material mobility on the upper slope. The gravitational forces and steep slope make the upper slope more susceptible to material movement.

Vertical development occurs frequently in segments two to four. Vertical development is generally steady in segments five to eight and decreases in segments eight to ten. Vertically, the upper slope (segments one to four) is highly susceptible to erosion, whereas the middle slope (segments five to eight) is moderately susceptible. The lower slope (segments eight to ten) has the shallowest gully depth. This susceptibility pattern supports a theoretical framework that identifies the middle slope as a transportation zone, the lower slope as a sedimentation zone, and the upper slope as an erosion zone.

DISCUSSION

Several factors influence the propensity of gully dimensions to become narrower on the lower slopes, including the slope, conservation, hydrology, geomorphic processes, and soil. The slope can influence the water flow and geomorphic processes on a buckling slope (Luo et al. 2023). Flow acceleration occurs on the middle slope due to the steep slope morphology. This consequence causes a larger lateral and vertical development. The middle slopes are also susceptible to geomorphic processes such as subsidence because



Segment	1	2	3	4	5	6	7	8	9	10
Surface	0.746	0.85	0.936	0.892	1.03	1.04	0.93	0.844	0.568	0.394
Bottom	0.364	0.422	0.602	0.576	0.5	0.528	0.472	0.416	0.258	0.232
Depth	0.414	0.576	0.754	0.818	0.598	0.7	0.622	0.678	0.51	0.396

Segment

Figure 5. The average gully width trend at the study site

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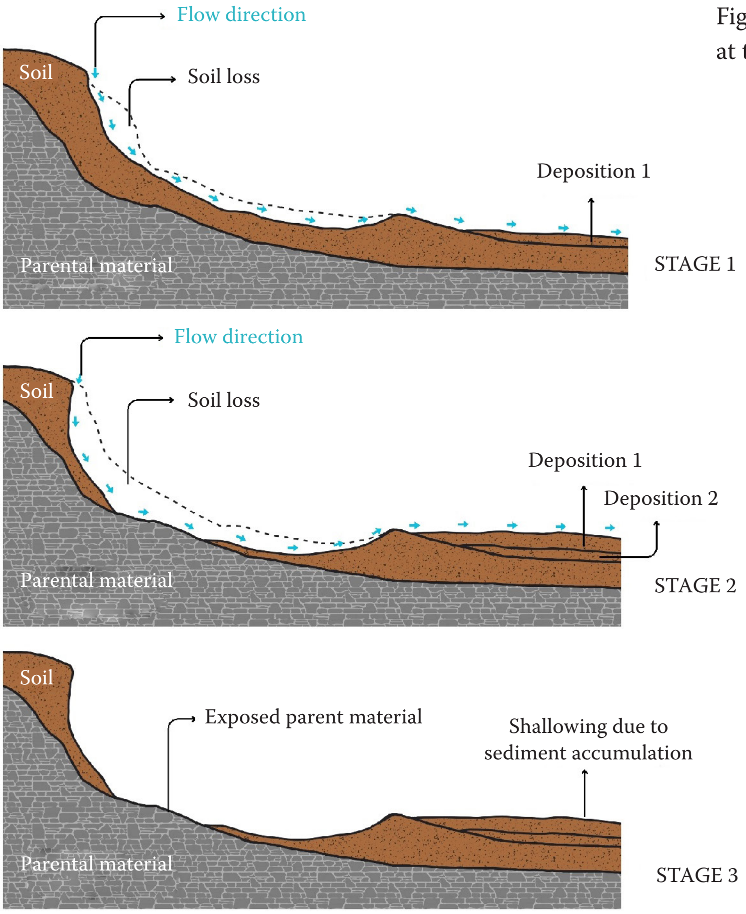

Figure 6. Scheme of the gully development process at the study site

robust flows can create instability in the lower gully walls, leading to sinking in the higher gully walls (Stage 2). Due to the surface soil movement at the bottom of the gully, the intermediate slope denudes. This stage causes scars on the middle slope.

Sedimentation happens because the lower slopes typically have a softer shape. Furthermore, sediment accumulation forms several layers, ultimately making the lower slope tend to be flatter (Stage 3). Interestingly, the lower slope tends to have narrower dimensions due to the sedimentation. Subsidence may be precipitated by the narrowing of the gully dimensions on the lower slope if the gully capacity is insufficient for handling surface flow. The sediment on the lower slope typically hardens during the dry season and is covered in grass. This phenomenon can be a bottleneck that causes subsidence on the lower slope (Maulana et al. 2025). Figure 6 shows a schematic of how the gully erosion process has developed.

Conservation and soil characteristics influence the gully development. It is clear how planting plants contributes to natural conservation by changing the gully's dimensions (Maulana et al. 2023b). The lower slopes are all densely vegetated compared to others. When the surface flows strike soil aggregates, vegetation roots can bind together to make the soil more stable and resistant to slipping off (Fattet et al. 2011; Maulana et al. 2023b). In addition to increasing the water infiltration into the soil through their roots, vegetation overhangs stop splash erosion. Furthermore, vegetation on the inner gully walls can minimise the rill erosion by the flow dispersion mechanism. Sun et al. (2024) found that vegetation can slow down surface runoff, which is linked to our findings.

Morphologically, the U-shaped gully has progressed to the development stage. At points one, four, and five, the gullies feature scars that look like little depressions caused by the surface flow with a slight discharge over a long period. The existence of scars suggests inequalities in the soil resistance near the gully's bottom. Scars may occur in shallow gullies (≤ 30 cm) with steep slopes (16–35°). Furthermore, the scars suggest that the gully's relative age has shifted from the mature to the old phase (Maulana et al. 2023a). According to the logic of the rule of superposition,

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a gully is considered old if it has encountered rock or parent material.

Gully scars may occasionally penetrate deeper and halt once they come into contact with parent material or rock. Since the gully flow has an axial pattern that encourages flow build-up, these features likewise impact the presence of scars. Frontal gullying begins on the upper slopes and turns into axial gullying on the middle and lower slopes. This means that the frontal pattern can also lead to flow accumulation. Scars may also generate subsidence that leads to lateral erosion and indirectly indicates a vertical erosion process. During the dry season, the piping phenomena can be seen at point one, where tiny fissures could allow water to escape beneath the gully when the first rainstorm occurs.

CONCLUSION

Gully erosion monitoring was performed to identify the sensitivity and development of gully erosion. Five gully sites were examined using the geomorphology approach. The data acquisition findings revealed variations in the data resolution of 0.11–0.57 cm (SfM) and 0.61–2.08 cm (UAV). According to the findings, particularly susceptible gullies have steep slopes (> 16°) and are relatively mature for their age. Scars at the bottom indicate that the gully is relatively old as the parent material begins to become apparent. Additionally, practically every gully already has a shape that resembles a jug or the letter U, suggesting that the gully's earliest stages of growth have been completed. Gullies with centralised, axial flow types are typically more susceptible than others. Every segment has a slightly unique gully development, and the segment with high flow accumulation always has the deepest point. Vertical erosion most frequently occurs on the middle slope of the gully. Since silt from the middle and upper slopes is carried by water downstream, the flow speed drops, making the middle slope more susceptible to flow accumulation.

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REFERENCES

Ben Slimane A., Raclot D., Rebai H., Le Bissonnais Y., Planchon O., Bouksila F. (2018): Combining field monitoring and aerial imagery to evaluate the role of gully erosion in a Mediterranean catchment (Tunisia). Catena, 170: 73–83.

Dai W., Qian W., Liu A., Wang C., Yang X., Hu G., Tang G. (2022): Monitoring and modeling sediment transport in space in small loess catchments using UAV-SfM photogrammetry. Catena, 214: 106244.

Fashae O., Obateru R., Olusola A., Dragovich D. (2022): Factors controlling gully morphology on the quartzite ridges of Ibadan, Nigeria. Catena, 212: 106127.

Fattet M., Fu Y., Ghestem M., Ma W., Foulonneau M., Nespoulous J., Le Bissonnais Y., Stokes A. (2011): Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. Catena, 87: 60–69.

Fernández T., Gómez-Lopez J.M., Pérez-García J.L., Cardenal J., Delgado J., Mata E., Sánchez-Gómez M., Calero J., Tovar-Pescador J., Moya F. (2020): Analysis of gully erosion in a catchment area in olive groves using UAS photogrammetry techniques. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives, 43(B2): 1057–1064.

Gómez-Gutiérrez Á., Schnabel S., Berenguer-Sempere F., Lavado-Contador F., Rubio-Delgado J. (2014): Using 3D photo-reconstruction methods to estimate gully headcut erosion. Catena, 120: 91–101.

He T., Yang Y., Shi Y., Liang X., Fu S., Xie G., Liu B., Liu Y. (2022): Quantifying spatial distribution of interrill and rill erosion in a loess at different slopes using structure from motion (SfM) photogrammetry. International Soil and Water Conservation Research, 10: 393–406.

Kariminejad N., Pourghasemi H.R., Hosseinalizadeh M., Rossi M., Mondini A. (2023): Evaluating land degradation by gully erosion through soil erosion indices and rainfall thresholds. Natural Hazards, 117: 3353–3369.

Luo J., Yang P., Pei X., Li J., Shan S., Duan Y., Huang Y. (2023): Impact of rock fragment shapes and soil cohesion on runoff generation and sediment yield of steep cut slopes under heavy rainfall conditions. Sustainability (Switzerland), 15: 10841.

Maulana E., Sartohadi J., Setiawan M.A. (2023a): AHP GIS-based gully erosion susceptibility modelling in tropical volcano environment. Journal of Hunan University Natural Sciences 50: 190–200.

Maulana E., Sartohadi J., Setiawan M.A. (2023b): Soil conservation at the gully plot scale in the tropical volcanic landscape of Sumbing. AIMS Environment 10: 832–846.

https://doi.org/10.17221/92/2024-SWR

Maulana E., Sartohadi J., Setiawan M.A. (2025): Landscape design for gully erosion control on the upper slopes of Mount Sumbing, Central Java, Indonesia. Journal of Degraded and Mining Lands Management, 12: 7037–7047.

Meinen B.U., Robinson D.T. (2020): Mapping erosion and deposition in an agricultural landscape: Optimization of UAV image acquisition schemes for SfM-MVS. Remote Sensing of Environment, 239: 111666.

Pulungan N.A., Sartohadi J. (2017): Variability of soil development in hilly region, Bogowonto Catchment, Java, Indonesia. International Journal of Soil Science, 13: 1–8.

Ren X., Sun M., Zhang X., Liu L. (2017): A simplified method for UAV multispectral images mosaicking. Remote Sensing, 9: 962.

Sartohadi J., Pulungan N.A.H.J., Nurudin M., Wahyudi W. (2018): The ecological perspective of landslides at soils with high clay content in the middle Bogowonto watershed, Central Java, Indonesia. Applied and Environmental Soil Science, 2018: 648185.

Sidorchuk A. (2005): Stochastic components in the gully erosion modelling. Catena, 63: 299–317.

Sun H., Luo L., Guo W., Hu X., Xu Y., Wang W. (2024): Exploring rational vegetation configuration to relative increase runoff, reduce erosion and soil organic carbon loss in gully-slopes on the Chinese Loess Plateau. Journal of Hydrology, 640: 131678.

Wang R., Sun H., Yang J., Zhang S., Fu H., Wang N., Liu Q. (2022): Quantitative evaluation of gully erosion using multitemporal UAV data in the Southern Black Soil Region of Northeast China: A Case Study. Remote Sensing, 14: 1479.

Wasson R.J., Caitcheon G., Murray A.S., McCulloch M., Quade J. (2002): Sourcing sediment using multiple tracers in the catchment of Lake Argyle, Northwestern Australia. Environmental Management, 29: 634–646.

Yang Y., Shi Y., Liang X., Huang T., Fu S., Liu B. (2021): Evaluation of structure from motion (SfM) photogrammetry on the measurement of rill and interrill erosion in a typical loess. Geomorphology, 385: 107734.

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