Soil Erosion and Profile Assessment: A Study on Left Bank of the Kangsabati River of Paschim Medinipur District in West Bengal, India

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Abstract: This paper presentation is an attempt to analyze the different geomorphological variables, measurement of soil erosion in this river bank area, hydroluic geometry, cross and long profile measurement around this Kangsabati river bank region. The present study focus on a specific site experiencing active gully erosion processes, located in the Midnapore Block of the West Medinipur District, West Bengal, India. This micro-level investigation is situated along the left bank of the Kangsabati River, a significant fluvial system that has shaped the geomorphology of the region over time.

The selected site lies within a dynamic zone where the interplay of hydrological, geomorphological, and anthropogenic factors has fostered the development of intricate gully systems. The region is characterized by an undulating topography, with soils prone to erosion due to their sandy-loamy texture, low vegetation cover, and seasonal hydrological regimes. Furthermore, the area is representative of the broader ecological and geomorphological challenges prevalent in the semi-arid tracts, making it an ideal location for a detailed investigation into gully erosion mechanisms and their associated processes.

This precise spatial delimitation provides a robust framework for the systematic collection of data, including gully cross-sections, gully longitudinal profile, slope morphology, and anthropogenic influences. The findings from this study aim to contribute valuable insights into the underlying mechanisms driving gully erosion and offer potential strategies for sustainable land management in regions experiencing similar geomorphic challenges.

Key words: Soil Erosion, Morphological Variables, Hydroluic Geometry, Profile Assessment.

1. Introduction

Schumm (1956) noted that geomorphologists have overlooked how similar different landforms can be. Researchers suggested that areas with poor land can serve as smaller models to study more complex, eroded landscapes with permanent and temporary gullies. Research on small areas facing quick erosion might help us understand erosion processes in larger regions. The sediment type can also explain how gullies change in width and depth downstream (Schumm, 1960; Kirkby and Bull, 2000). Gully erosion is a significant problem for land degradation in various environments (Valentin et al., 2005; Zucca et al., 2006; Bou Kheir et al., 2007; Conoscenti et al., 2013, 2014). Poesen et al. (2003) found that the impact of gully erosion on total sediment yield increases with the size of the study area, ranging from 10% to 95%. Gullies are formed by concentrated water flow, usually along natural drainage paths (Gyssel and Poesen, 2003). Permanent gullies are typically 0.5 to 30 meters deep (Soil Science Society of America, 2008), making them too deep to be removed by normal farming, hindering land access. Gully erosion removes soil and parent material, leading to problems like loss of nutrients, reduced soil structure, lower moisture, less vegetation, and overall land degradation that affects crop yields. Gullies connect upland areas to rivers, allowing quick water and sediment movement, which can cause off-site issues like water pollution, flooding, reduced lifespan of dams, and changes in river shape (Daba et al., 2003; Poesen et al., 2003; Capra et al., 2005; Charlton, 2008; Poesen, 2011). Studying gully erosion requires good measurement techniques, historical data, and accurate models to help prevent erosion effectively (Poesen, 2011). Gathering data on the shape and characteristics of gullies, along with factors like land use and soil type, can help land managers predict and manage erosion (Poesen et al., 2003; Valentin et al., 2005; Capra et al., 2009; Poesen, 2011). In India, about 30% of the land faces high rates of soil erosion from water, particularly in the western part of West Bengal (Chatterjee et al., 2020), where permanent gullies often form in abandoned fields and on certain soil types (Imeson and Kwaad, 1980; Poesen et al., 2003; Kirkby and Bracken, 2009). In Paschim Midnapore, severe erosion is linked to extreme environmental changes and poor land management practices. Studies on gully erosion often use simple equations to analyze their features (Nachtergaele et al., 2001a, 2001b, 2002; Capra et al., 2005, 2009; Bruno et al., 2008; Di Stefano and Ferro, 2011; Kompani-Zare et al., 2011; El Maaoui et al., 2012; Di Stefano et al., 2013; Frankl et al., 2013; Caraballo-Arias et al., 2014). Many of these equations come from studies of rills, streams, or rivers.

Regarding those question a semi-arid environment with secondary laterite gully has been take under consideration, the primary objectives of this project are to characterize the GLP morphology and understand the environmental factors controlling the morphology of GLP. The results will improve the knowledge of GLP morphology and understand the formation factors of gullies, providing a scientific basis for the prevention and treatment of gully erosion.

2. Objectives of the work

The main goals of this project work are to:

a) To describe the morphological variables (volume, length, bankfull depth, and width) of a gully system in the study gully and analyze an empirical relationship between the length of the main gully and the tributary reach and their eroded volume.

b) To assess the hydraulic geometry of the main gully and tributary reach by using a field survey.

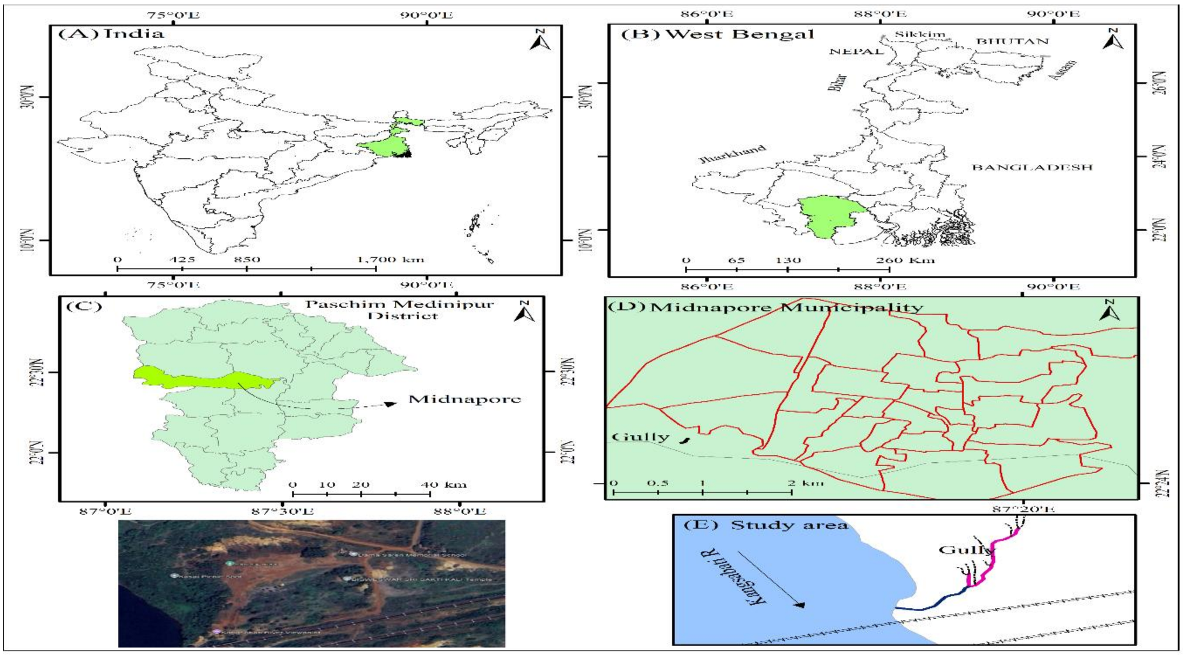
c) To assess the gully longitudinal profile (GLP) better to understand the soil erosion conditions of the study gully.

3. Study area

The present study focuses on a specific site experiencing active gully erosion processes, located in the Midnapore Block of the West Midnapore District, West Bengal, India. The study area is geographically bounded by the coordinates 87°17'46" E to 87°17'49" E and 22°24'36" N to 22°24'39" N. This micro-level investigation is situated along the left bank of the Kangsabati River, a significant fluvial system that has shaped the geomorphology of the region over time.

The selected site lies within a dynamic zone where the interplay of hydrological, geomorphological, and anthropogenic factors has fostered the development of intricate gully systems. The region is characterized by an undulating topography, with soils prone to erosion due to their sandy-loamy texture, low vegetation cover, and seasonal hydrological regimes. Furthermore, the area is representative of the broader ecological and geomorphological challenges prevalent in the semi-arid tracts of West Bengal, making it an ideal location for a detailed investigation into gully erosion mechanisms and their associated processes.

Figure 1: Study area (A) India (B) West Bengal (C) Paschim Medinipur (D) Midnapore Municipality and gully location (E) Gully location



This precise spatial delimitation provides a robust framework for the systematic collection of data, including gully cross-sections, gully longitudinal profile, slope morphology, and anthropogenic influences. The findings from this study aim to contribute valuable insights into the underlying mechanisms driving gully erosion and offer potential strategies for sustainable land management in regions experiencing similar geomorphic challenges.

4. Materials and methods

4.1 Parameters of GLP morphology

Figure 2 reveals the morphology of a typical gully along the thalweg. The GLP can be characterized by scale and shape parameters. The scale parameters include the length (Lt), height (H), and vertical erosional area (A), horizontal distance (Dh). The shape parameters comprise the vertical curvature (Cv), average gradient (Ga), concavity (Ca), gully length-gradient index (GL), and normalized gully length-gradient index (Ngl). The morphology of GLP can also be fitted via linear, exponential, logarithmic, and power functions.

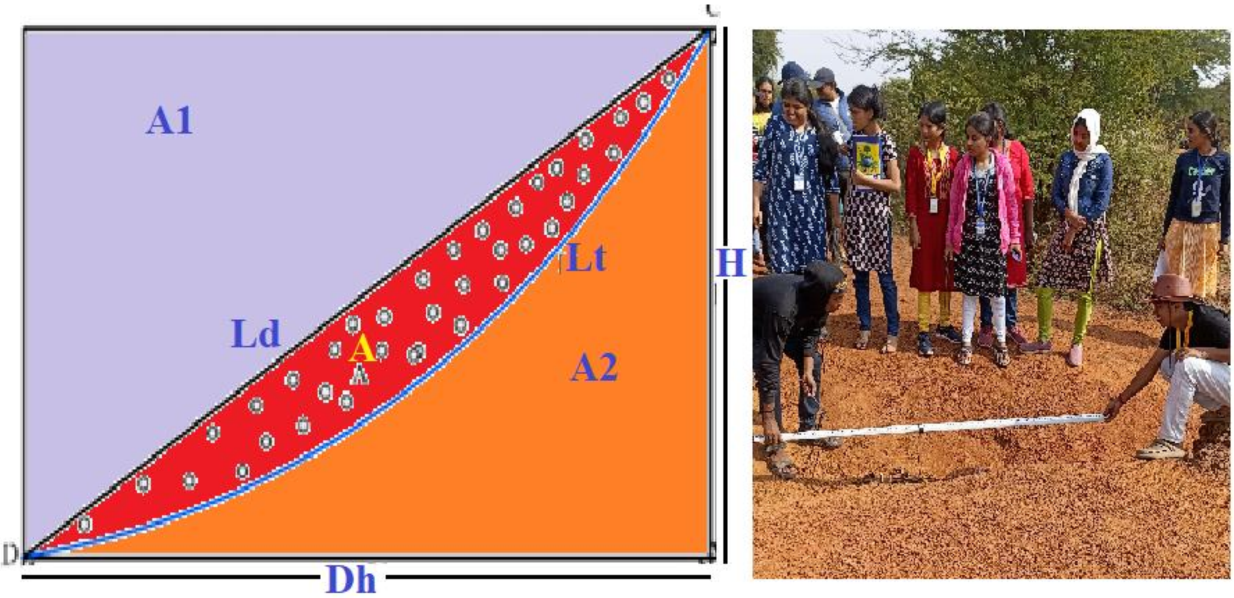


Table 1 shows the details of these parameters.

Figure 2: Scale parameters of the gully longitudinal profile (C is the gully mouth; D is the gully head)

4.2. Concavity

The concavity (Ca) refers to the concave degree of the GLP that has been used in describing alluvial river characteristics, such as downstream fining of bed material size, downstream accumulation of water and sediments from tributary inputs and river interaction with coastal boundary conditions (Hack 1957; Kesseli 1941). Ca can be calculated by using the Ivanov method (Lu et al., 1986; Ye et al., 1983) by drawing a rectangle and uniting the ends of GLP as the diagonal line of it. The rectangle is divided into the upper part

(A1) and the lower part (A2) by the GLP line according to the formula listed in Table 1. As Ca < 1, namely A1 < A2, the GLP morphology presents a convex shape; Ca = 1, namely A1 = A2, presents a straight-line shape; Ca > 1, namely A1 > A2, presents a concave shape (Lu et al., 1986; Ye et al., 1983). Generally, a convex-shaped gully has a minor erosion degree and is in a relatively active stage of gully development.

4.3. Gully length-gradient index

In 1973, Hack (1973) introduced the stream length-gradient index (SL index) to describe gradient changes of a stream longitudinal profile. It is usually sensitive to changes in stream slope and has been applied to evaluate relationships between possible tectonic activity, rock resistance, and topography (Keller et al., 1997). The equation is shown below:

H = c - k' ×= log(L)……………………………………………………………………(1) where H is the altitude of the stream longitudinal profile, c is a constant, L is the stream length measured from the drainage divide at the source of the longest stream in the drainage basin, and k' is the SL index (Chen et al., 2006). The SL index is primarily controlled by rocks and geological structures for smaller rivers; however, it mainly reflects the tectonic activity for larger rivers (Chen et al., 2003). We propose a gully length-gradient index (GL) to describe the GLP of a gully. Because a gully is smaller than a river, we did not split the gully into several segments, so that each gully only has one GL value. GL can be used to evaluate the relationship between rock resistance and gully topography. The formula is as follows:

H = c -a ×= log(Dh)……………………………………………………………………..(2) where H is the height of the GLP, C is a constant, Dh is the horizontal distance measured from the gully head to its mouth along the gully bottom, and a is the GL index.

4.4. Data acquisition

An active gully has been selected on the left bank of the Kangsabati River. Detailed point coordinates along the gully bottom were measured from the gully mouth to the head along the thalweg using GPS, prismatic compass, and dumpy level. The spacing between two neighboring points is 1.0 to 3.0 m. We also increased the spacing to 0.5–1.0 m in the part with strong topographical changes. Also recorded detailed environmental conditions, such as vegetation coverage, activity, lithology, piping erosion, and soil property for the gully in the field.

4.5. Measurement of gully morphology and hydraulic variables

The measurements of gully morphology and hydraulic variables were carried out by the extensive field survey. Along the gully, cross sections were individuated: along the main gully and the tributary reach. The field survey was carried out. The cross-sections were monitored using the GPS, dumpy, and prismatic compass. Each field survey allowed the reconstruction of the geometric characteristics of cross-sections by measuring (considering the bankfull stage of the channel) width (w), depth (h), cross-sectional area (A), and wetted perimeter (W). The field measurement data were analyzed using the ArcGIS 10.2 software.

4.5. Data processing

The measured data points of the gully were imported into CASS v7.1 software. Lt, Ld, A, A1, A2 could be measured directly from the GLP figure, and Cv (Lt/Ld), Ca (A1/A2) could be calculated. Dh, H, and Ga could be calculated in Excel. By using the corresponding formulas, we could calculate GL values. The skewness and kurtosis values of these parameters could reflect the statistical distribution characteristics. The GLP was fitted by linear functions. The function that minimizes the sum of squares of residuals and gives a minimum standard deviation of residuals was regarded as the best morphological fitting function (Rãdoane et al. 2002).

3.6 Gully characteristics and soil erosion assessment

Measurements of width, depth, and length of cross-section estimated the volume and surface area of the total gully system. For the measurement of erosion, a 3rd-order gully has been chosen. It is 3rd order gully system on the left bank Kangsabati River Basin. Finally, the cross-section widths and depths were measured along the gully channels. Regarding quantifying gully volumes and gully cross-section morphology, 12 cross-sections were quantified of gully segments. The maximum depths and top width of the bank's full channels were estimated. For each section, the width at the top of the cross-section, maximum scour depth, and cross-section area were measured (Fig. 3).

The eroded volume (V) of each gully segment was calculated using the cross-sectional dimensions and distance between cross-sections (Equation 3)

$$V = \sum_{i=1}^{n} LiAi \quad \ldots\ldots(3)$$

where, Li is the length of considered gully segments (m) and Ai is the respective cross-sectional area of the gully segments.

Figure 3: Example of the relief of (A) a gully cross section and (B) a view of the gully survey

5. Results

5.1. Gully characteristics (gully morphology and hydraulic variables)

The field observation (Fig. 4 and 5) results of the morphological characteristics of 12 gully profiles focus on depth variations (minimum, maximum, and average) and width (Table 1). In the case of cross-sections, 1 to 12 represents the downstream gully to the upstream gully. The result reveals that profiles 1 to 4 exhibit significant depth, with maximum depths exceeding 2 meters, making them larger and more eroded gullies. The average depths in this group range between 1.35m to 1.63m, suggesting substantial incision. Profiles 5 to 12, in contrast, have shallower depths, with maximum depths staying below 1.11m, indicating smaller and less developed gullies. The lowest minimum depths (0.06m in Profile 11) suggest incipient or developing gully formations. Based on the width and depth ratio, the gullies can be grouped into two categories: a) Deep, highly incised gullies (Profiles 1–4) and b) Shallow, less developed gullies (Profiles 5–12)

On the other hand, the width-depth relationship observed that the widest gullies are in Profiles 1 (6.00m), 2 (3.20m), and 3 (4.20m), corresponding with the deepest incisions. Conversely, Profiles 5–12, which are shallower, have widths mostly below 2.25m, reinforcing the idea that gully depth and width tend to correlate. Profile 4, despite having the highest average depth (1.63m), has a relatively narrow width (2.6m), suggesting a more vertical erosion process rather than lateral expansion. Deep gullies tend to be wider, except in cases where vertical erosion dominates (e.g., Profile 4).

Figure 4: Measurement of gully profile in different sample locations

So, the profiles 1-4 likely represent areas with high erosion rates, possibly due to factors like steep slopes, intense water flow, or soil instability. Profiles 5-12 might be in the early stages of gully formation, or in regions where erosion is less aggressive. The variability in gully widths suggests that some areas experience lateral widening, while others are more prone to vertical deepening.

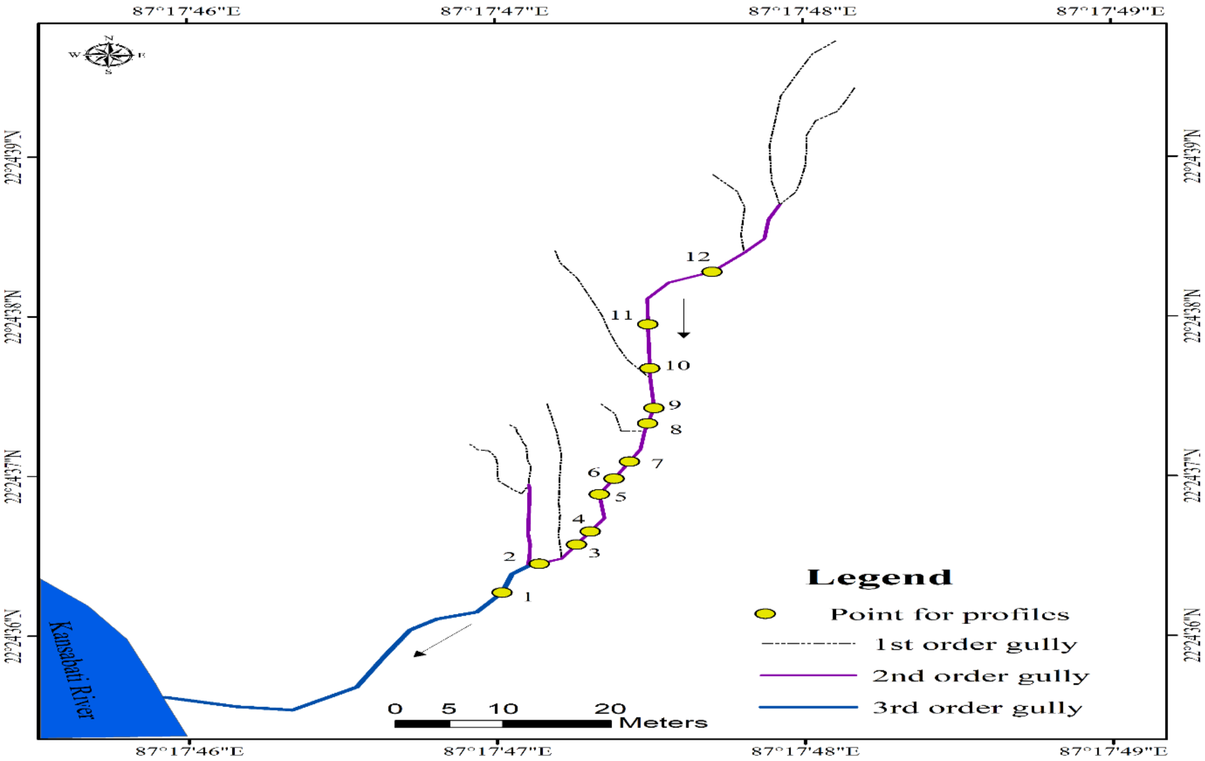


Figure 5: The gully network and cross-sections survey locations map generated by handheld GPS

Table 1: Gully cross-sectional width and depth data sets

Gully characteristics	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7
	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)
Minimum	0.26	0.63	0.50	0.84	0.13	0.31	0.17
Maximum	2.12	2.05	1.99	2.08	0.71	0.59	0.93
Average	1.35	1.40	1.38	1.63	0.44	0.45	0.64
Width	6.00	3.20	4.20	2.6	1.10	1.00	1.30
Gully Characteristics	Profile 8	Profile 9	Profile 10	Profile 11	Profile 12		
	Depth (m)	Depth (m)	Depth (m)	Depth (m)	Depth (m)		
Minimum	0.13	0.10	0.11	0.06	0.20		
Maximum	0.98	1.00	1.00	0.97	1.11		
Average	0.37	0.60	0.51	0.49	0.61		
Width	1.30	2.25	1.82	1.70	1.25		

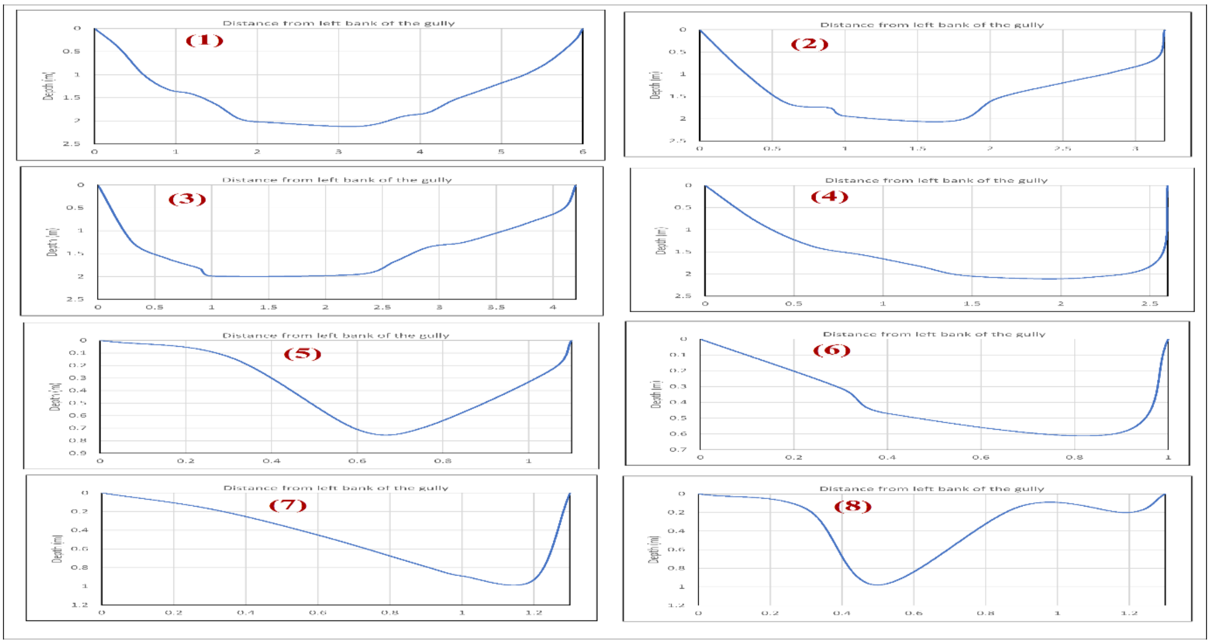


Figure 6: Gully cross-profile with width and depth in meters

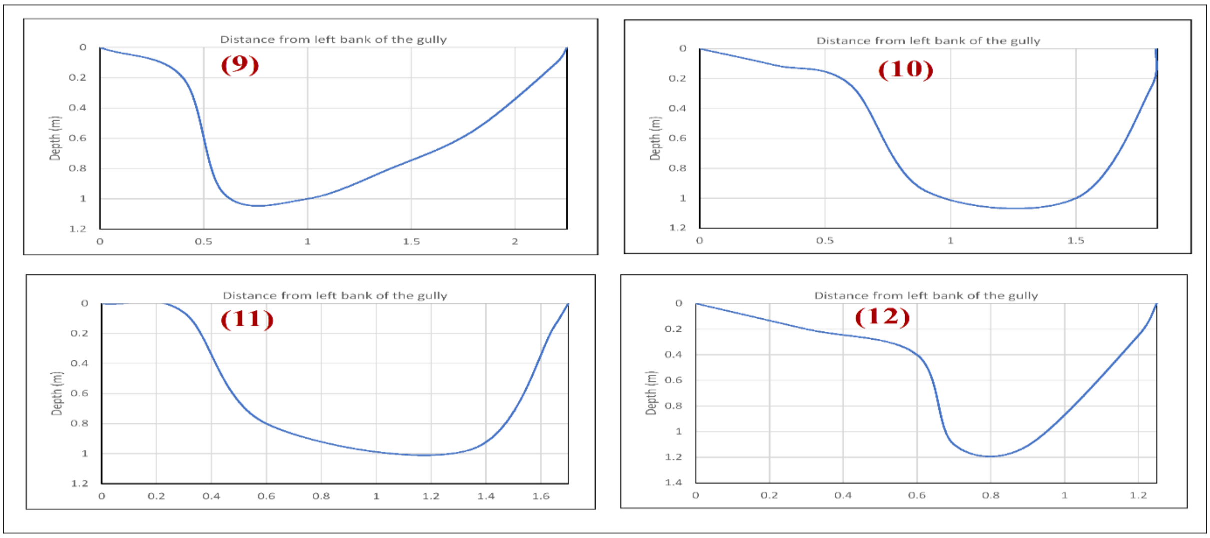


Figure 6: Continued

5.2. Gully erosional processes in the study area

Gully erosion is the result of the combination of different processes including head-cut erosion, sidewall sloughing, tunneling, micro-piping, slaking piping, and sapping (Knapen et al., 2007; Shit et al., 2016). This study area shows that runoff rates were the principal causes of gully development because of toppling, knickpoints, and subsidence processes' effect on gully sidewalls.

Field observation study revealed that channels widening and extended through sidewall sloughing and headward erosion processes (Fig. 7). The valley lengthening is considerable due to the high intensity of energy available from intensive rain that acts on steep slopes. The increase rate of gully length of gully area is not evenly everywhere, which varies according to upslope contributing area, slope gradient, slope aspect, length, and texture. Valley widening is mainly developed by basal erosion along valley sides and the subsequent slab failure. Continuous removal of eroded materials from the base of valley sides is to be maintained for active valley widening. During the field survey shows the extent of widening increases manifold after the junction with a tributary. Table 1 shows that the volume was increased with increasing gully order. Some parts of the gully where the result reveals that reverse manner due to toppling, knickpoints, and subsidence processes affect gully sidewalls. The volume of the gully increased from upward to downward but in the 3rd point site of the gully, volume increased in the 2nd point site and 6th point gully to the 7th point gully due to side toppling (Fig. 6). So, the concentrated energy along the channels was responsible for the valley deepening.

Finally, consulate that the down-cutting and associated wasting helped in the removal of both lateral and basal support of the materials at the source, and thus an overhanging slope development. This slope, thus, retreated by the dislodgement of the overhanging materials which led to valley lengthening. Intense overland flow erosion in the form of rills can wreck barren land and generate environmental tribulations. The present study examined the lateral expansion of channel banks and the deepening of channels under the condition of shallow overland flow. However, further experiment is needed at a large scale to assess the rill development of its management practices in the study site.

Figure 7: Schematic diagram showing gully erosion processes and example of gully bank failures

5.3. Assessment of gully longitudinal profile (GLP) in this study area

For a long period, it was widely observed that farmers exhibited minimal awareness of soil erosion and demonstrated little to no inclination toward implementing preventive measures (Pretty and Shah, 1999). However, in more recent years, developmental agencies and scientific researchers have identified that farmers have, in fact, recognized soil erosion as a significant concern and have adopted various methods to mitigate its effects (Reij and Critchley, 1996). During on-site field investigations, it was evident that while local inhabitants displayed awareness of rill erosion, their understanding of sheet erosion remained relatively limited. Additionally, the economic constraints prevalent among the tribal populations residing in the region have contributed to widespread deforestation, as these communities have been compelled to clear vegetation for subsistence and livelihood purposes.

To comprehensively analyze the prevailing soil erosion conditions in conjunction with settlement locations within deforested regions, the morphological characteristics of the gully longitudinal profile (GLP) were examined. The GLP morphology is notably influenced by the extent of vegetation cover present in the area. A denser plant cover in gully-prone regions plays a crucial role in reinforcing soil resistance against erosion and diminishing the impact of hydrodynamic forces. Consequently, vegetation helps to regulate sediment yield, control the rate of soil erosion, and inhibit the expansion of gullies, thereby maintaining them in a relatively stable state over an extended period (Ding et al., 2016). As a result, the GLP morphology tends to exhibit a prolonged and smooth curvature with a greater length (Lt) and a lower vertical curvature (Cv) value. This morphological characteristic serves as a vital topographic parameter for assessing gullies in correlation with their basal structures (Patel et al., 2021). This index is instrumental in estimating the extent of erosion, projecting gully development trends, and evaluating soil degradation rates.

To achieve a more precise assessment of GLP morphology, gully formations in this study area have been systematically analyzed (Fig. 8). A set of seven fundamental parameters—including gully length, horizontal distance, height, vertical erosion area, vertical curvature, concavity, and the gully length-gradient index—were measured using primary field data (Table 2 and Fig. 8). The maximum recorded gully length (Lt) in the study area was 115.3 meters. In this specific gully, negative values of parameter 'A' indicate ongoing active gully formation. The concavity index ('Ca') was measured at 0.139, classifying the gully as having a convex shape, given that gullies are categorized as convex when Ca <1, slightly concave when Ca ranges from 1 to 2, and highly concave when Ca exceeds 2. Additionally, the vertical curvature ('Cv') was found to be 1.16, indicating that the gully falls within the slightly curved category. This classification is based on the convention that a quasi-straight GLP has a Cv value of <1.1, while a Cv value exceeding 1.1 represents a slightly curved shape.

Furthermore, the gully length-gradient index (GL) was calculated at 30.65. This index provides insights into the lithological variations and the degree of erosion affecting gullies in the region. Based on the observed GL values, it can be inferred that the study area exhibits moderate erosion resistance. As a result, the lithological characteristics of the terrain make it susceptible to soil particle detachment, thereby influencing the ongoing soil erosion processes in this landscape.

Table 2: Parameters results of gully longitudinal profile

Gully channel	Lt (m)	Dh (m)	H (m)	A (m2)	Cv	Ca	GL
2nd	143.77	115.3	8.60	-59.21	1.16	0.139	30.65

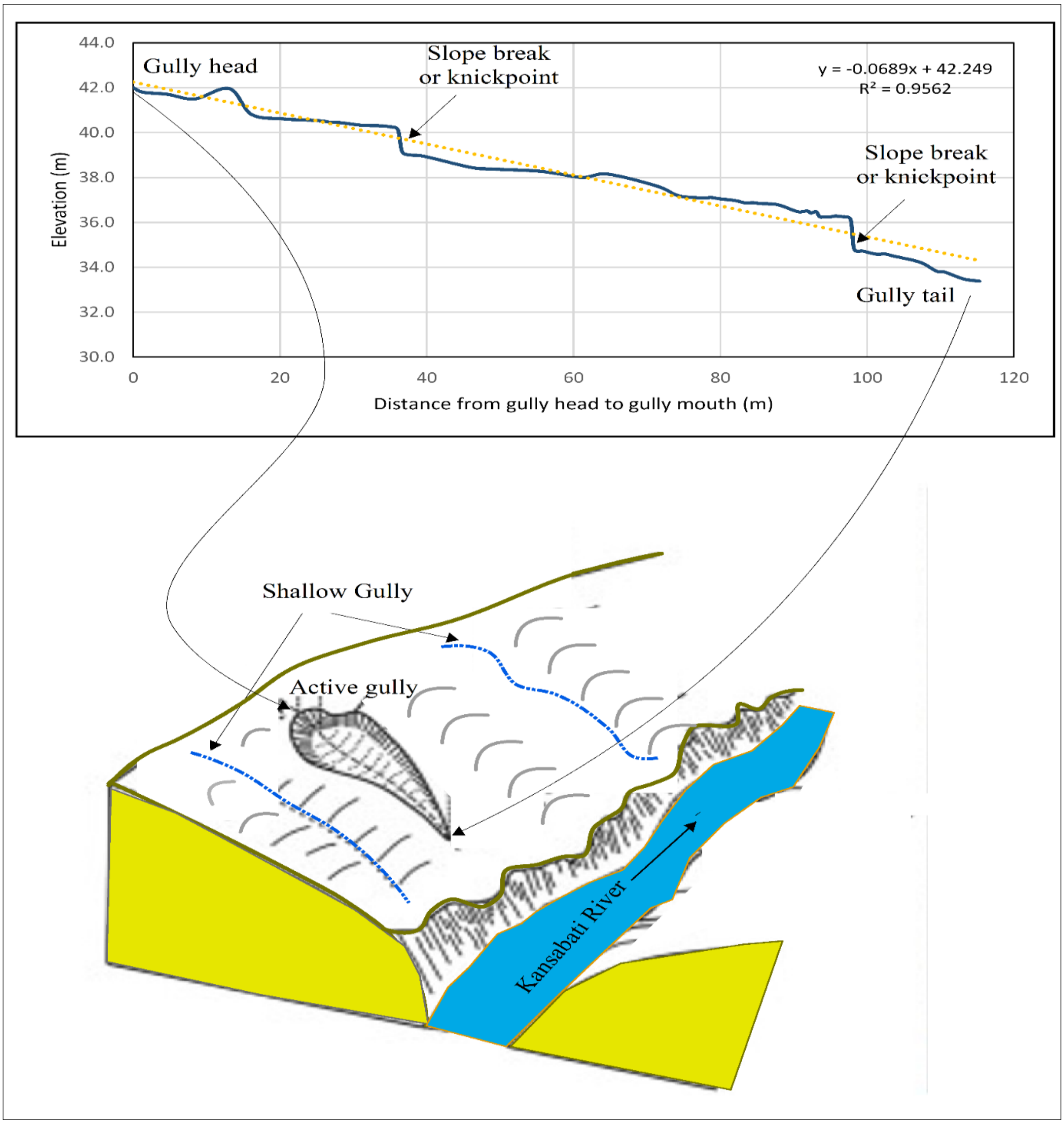


Figure 8: Longitudinal profile of the selected gully

Table 3: Parameters to describe the morphological characteristics of gully longitudinal profile

Parameters	Equation and significance
Length (m) Lt	The total distance of the gully thalweg between the gully mouth and gully head.
Horizontal distance (m) Dh	The total horizontal distance from the gully mouth to its head. Dh also denotes the degree of erosion and gully development time.
Height (m) H	H represents the vertical distance between gully mouth and gully head.
The vertical erosional area (m^2) A	The area covered by the straight line between the gully mouth (Ld) and Lt.
Vertical curvature (Cv)	Cv=Lt/Ld; to denotes the gully longitudinal profile (GLP) curvature.
Concavity (Ca)	Ca=A1/A2; it denpotes the change characteristics of the GLP and concave degree of the GLP.
Gully length-gradient index (GL)	GL $=(e_1-e_2)/\ln(D_2)-\ln(D_1)$; where e represent elevation, D is distance, 1 is first point from the source, and 2 is the second point from the source.

6. Results and discussion

The overall analysis of gully cross-sectional characteristics, erosional processes, and longitudinal profiles offers a comprehensive view of the gully dynamics in the study area. The deep, highly incised gullies reflect zones of intense erosional activity, while the shallower gullies indicate areas at an earlier stage of development or subject to less aggressive forces. The observed morphological patterns, combined with the detailed GLP analysis, underscore the importance of both hydraulic energy and vegetation cover in controlling soil erosion.

The results suggest that active gully erosion in the study area is a multifaceted process influenced by hydrological forces, slope dynamics, and land-use practices. To a certain extent, few parameters and mathematical fitting functions can reflect the GLP morphology and the stability of the gully. Soil properties, vegetation, piping erosion, and topography are important to control the local GLP morphology. This study enables improving knowledge of GLP morphology and understanding of the formation factors of gullies. The insights gained from the morphological and process-based assessments provide valuable guidance for developing targeted soil conservation and gully management strategies, which are essential for mitigating further land degradation in this region.

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