

Gully Recognition and Spatial-temporal Evolution Law of Gully Based on SegNet Model

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Abstract

Gully erosion is one of the main modes of slope erosion on the Loess Plateau, which plays a connecting role in the slope gully erosion system. The Loess Plateau has wide and densely distributed gullies. The study selected a typical small watershed in the hilly and gully region of the Loess Plateau to measure the morphological characteristics and spatial-temporal distribution of gullies. A deep learning image semantic segmentation model was used to identify and extract the morphological features of gullies at the watershed scale from 2009 to 2021 based on remote sensing images (0.5 m resolution) and then analyze their temporal and spatial distribution characteristics. The results revealed that: (1) most gullies occurred in the hilly southern parts of the watershed, which has complex landforms and large slope gradients; (2) gully number increased from 1,159 in 2009 to 2,312 in 2021 (average 97 per year), with a frequency development rate of $2.87 \text{ km}^{-2} \text{ y}^{-1}$; (3) gully length generally ranged from 25–40 m, with an average growth rate is 1.66 m y^{-1} and density development rate of $0.12 \text{ km km}^{-2} \text{ y}^{-1}$; (4) gully width ranged from 0.5–1.5 m, with an average growth rate of 0.04 m y^{-1} . (5) the total gully area increased from 0.0566 km^2 in 2009 to 0.1072 km^2 in 2021, with a development rate of $4,213.39 \text{ m}^2 \text{ y}^{-1}$ and dissection degree development rate of $0.0125\% \text{ y}^{-1}$. This study provides a theoretical and scientific basis for gully erosion control and eco-environmental protection at the watershed scale on the Loess Plateau.

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Highlights

Used SegNet model to recognize gullies and extract morphological features at the watershed scale in the hilly and gully region of the Loess Plateau.

Used the spatial-temporal evolution law to clarify morphological features of gullies (e.g., number, width, area, frequency, density and dissection degree of gullies) from 2009–2021.

Abstract

Gully erosion is one of the main modes of slope erosion on the Loess Plateau, which plays a connecting role in the slope gully erosion system. The Loess Plateau has wide and densely distributed gullies. The study selected a typical small watershed in the hilly and gully region of the Loess Plateau to measure the morphological characteristics and spatial-temporal distribution of gullies. A deep learning image semantic segmentation model was used to identify and extract the morphological features of gullies at the watershed scale from 2009 to 2021 based on remote sensing images (0.5 m resolution) and then analyze their temporal and spatial distribution characteristics. The results revealed that: (1) most gullies occurred in the hilly southern parts of the watershed, which has complex landforms and large slope gradients; (2) gully number increased from 1,159 in 2009 to 2,312 in 2021 (average 97 per year), with a frequency development rate of $2.87 \text{ km}^{-2}\text{y}^{-1}$; (3) gully length generally ranged from 25–40 m, with an average growth rate is 1.66 m y^{-1} and density development rate of $0.12 \text{ km km}^{-2}\text{y}^{-1}$; (4) gully width ranged from 0.5–1.5 m, with an average growth rate of 0.04 m y^{-1} . (5) the total gully area increased from 0.0566 km^2 in 2009 to 0.1072 km^2 in 2021, with a development rate of $4,213.39 \text{ m}^2 \text{ y}^{-1}$ and dissection degree development rate of $0.0125\% \text{ y}^{-1}$. This study provides a theoretical and scientific basis for gully erosion control and eco-environmental protection at the watershed scale on the Loess Plateau.

Keywords:

Loess Plateau, morphological features of gullies, temporal and spatial distribution, returning farmland to forest, watershed scale

1. Introduction

China's Loess Plateau is the most typical loess geomorphic region in the world and one of the most serious soil erosion regions in China and perhaps the world (Fu *et al.*, 2011; Zhong *et al.*, 2022). Gully erosion is an important type of soil erosion on the Loess Plateau, with its distribution area accounting for more than 70% of the ravines and its erosion accounting for 26.6–59.2% of the total slope erosion (Zheng *et al.*, 2006). Soil erosion control on the Loess Plateau started in 1999 when the Chinese government implemented a project returning farmland to forest (Huang *et al.*, 2020; Liu *et al.*, 2019); however, gully erosion still needs attention in some areas. Watershed is the basic unit of hydrological response and an ideal spatial scale for studying soil and water losses. Clarifying the temporal and spatial evolution of gullies at the watershed scale is important for optimizing soil and water conservation measures on the Loess Plateau.

Gully erosion is a linear erosion pattern occurring on steep slope cultivated land, formed by the combined action of runoff erosion and human cultivation, and plays a connecting role in the slope gully erosion system (Liu *et al.*, 1988; Poesen *et al.*, 2003; Wang *et al.*, 2003). At present, studies on gully erosion have focused on critical topographical conditions (Daggupati *et al.*, 2014; Feng, 2022; Maignard *et al.*, 2014; Torri and Poesen, 2014), factors influencing gully formation (Feng, 2022; Gong *et al.*, 2011; Xu, 2018), mechanical processes and control measures of gully development (Guo, 2019; Xiao, 2017), flow dynamics and sediment

transport (Ban *et al.* , 2020; Kang *et al.* , 2021a; Xu *et al.* , 2021), and gully erosion models (Douglas-Mankin *et al.* , 2020; Guo *et al.* , 2019; Luquin *et al.* , 2021; Tekwa *et al.* , 2021). However, large-area field surveys are needed to accurately grasp the morphological features and spatial distribution characteristics of widely and densely distributed gullies, requiring a large workload and low efficiency. Therefore, some studies have adopted indoor model tests and field slope unit positioning tests to garner relevant gully data (Shen *et al.* , 2021; Wang *et al.* , 2020b, 2021), but the limited data significantly impacts the reliability of the research conclusions for practical application. In addition, further verification is needed to determine whether the conclusions obtained under small-scale conditions can be extrapolated to larger scales.

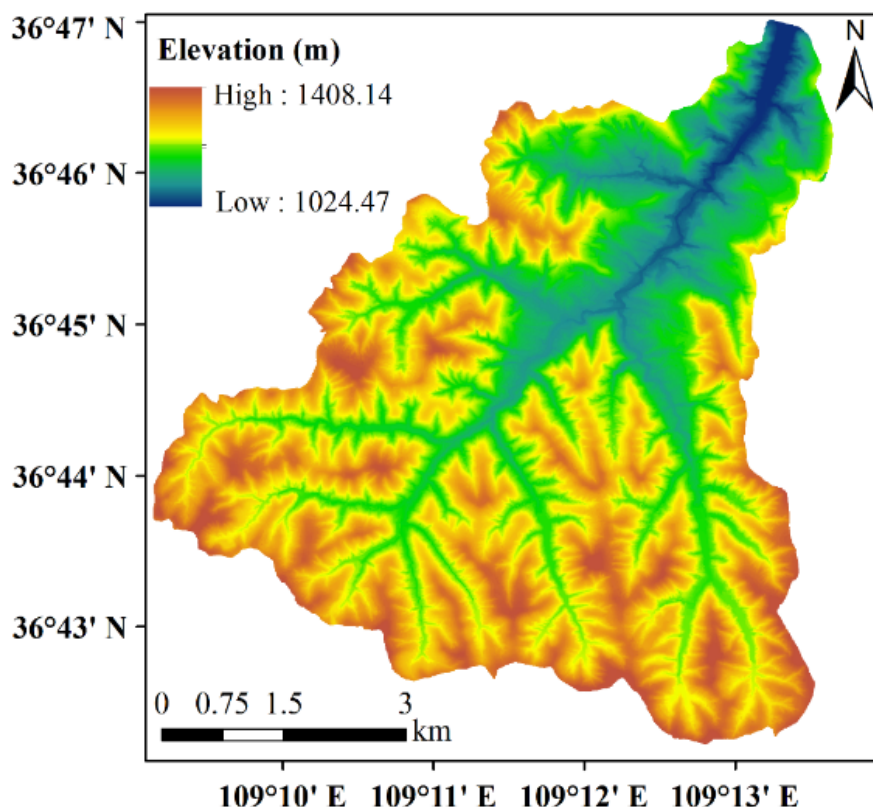
The recent rapid development of remote sensing technology has provided high-resolution remote sensing images and data for gully surveys on a large scale. Some studies have applied remote sensing images for gully recognition (Cao *et al.* , 2020; Dai *et al.* , 2020; Liu *et al.* , 2021; Yu *et al.* , 2018), determining temporal and spatial variation of gullies (Karydas and Panagos, 2020; King *et al.* , 2005; Li *et al.* , 2007; Platoncheva *et al.* , 2020; Yan *et al.* , 2005, 2006, 2010; Yermolayev *et al.* , 2020; Zhong *et al.* , 2022) and gully erosion sensitivity analyses (Amiriet *et al.* , 2019; Arabameri *et al.* , 2020; Busch *et al.* , 2021; Garosi *et al.* , 2019). On the Loess Plateau, Zhao *et al.* (2011) analyzed the correlation between land use, slope, and gully distribution using SPOT images, reporting significant differences in gully density among different land use types (grassland > forest land > hilly dry land). Zhang *et al.* (2017) extracted the lengths of 245 gullies using two QuickBird images, quantified the relationship between gully length and eroded volume, and assessed the erosion rate over six years. Qin (2009) and Qin *et al.* (2010) analyzed the topographic characteristic parameters and distribution law of gully erosion using a QuickBird image and digital elevation model (DEM), revealing that the morphological features of gullies are determined mainly by slope gradient, slope length, uphill length and confluence area in hilly and gully regions on the Loess Plateau. Wang (2020) found high gully development and large overall erosion potential in the south and north of Dongzhiyuan on the Loess Plateau and low gully development in the central region, where gully erosion is mostly caused by human activities. Liu *et al.* (2014) and Liu (2012) used ¹³⁷Cs tracer technology to study the spatial differentiation of soil erosion of typical hilly slopes in hilly and gully areas of the Loess Plateau, revealing differences in hilly slope erosion in different slope directions and an average erosion rates ranked north slope > southwest slope > northeast slope > west slope > northwest slope > south slope > southeast slope > east slope. Jiang *et al.* (1999) analyzed the distribution law of gullies in the Zhoutungou watershed in the hilly and gully region of the Loess Plateau using aerial images. They found that gullies develop mainly on slope farmland, with gullies accounting for 31.3% of the hillslope area in the watershed. Li (2011) found that the gully density in the loess area of northern Shaanxi, China changes into sunlit slope < semi-sunlit slope < sunless slope < semi-sunless slope under the same slope gradient. Tian *et al.* (2013) investigated the spatial differentiation characteristics of gullies on the Loess Plateau using 5 m resolution DEM; the results revealed clear spatial differentiation of gully density, decreasing from south to north, with gully density peaking in the Suide-Mizhi area of northern Shaanxi. The above studies were based mainly on visual interpretation and used independent slope elements in the basin as the research object. However, it is not possible to clarify the temporal and spatial distribution and evolution law of gullies at the basin scale. Few studies have identified gullies by combining deep learning and remote sensing images or investigated changes in morphological features before and after returning farmland to forests. Thus, this study used 0.5 m resolution remote sensing images integrated with a deep learning image semantic segmentation model to identify gullies and extract morphological features at the watershed scale, analyze the temporal and spatial distribution of gullies, and clarify the temporal and spatial evolution law of gullies in typical small watersheds in the hilly and gully region of the Loess Plateau to provide a theoretical and scientific basis for watershed-scale gully erosion control and ecological environment protection on the Loess Plateau.

2. Materials and Methods

2.1 Study area

The research area of this study is the Zhoutungou watershed (36°42'10" N to 36°47'10" N, 109°09'00" E to 109°13'45" E) (Liu *et al.* , 2021), a typical small watershed in the hilly and gully region of the Loess Plateau,

with an average altitude of 1,235.37 m. The total watershed area is 33.6 km², of which the valley is 18.7 km², accounting for 55.57% (Jiang *et al.*, 1999). The location of the research area is shown in Fig. 1. The climatic characteristics and soil properties of the watershed are available in Liu *et al.* (2021). The main valley in the watershed runs north to south, with the number of branch valleys gradually increasing from north to south. The main valley and branch valley sections are in ‘U’ shape, with the terrain of each valley comprising hills, slopes, and channels.



(a) (b)

Figure 1. Location of the study area. (a) Geographical location map of the study area on the Loess Plateau. (b) Digital elevation model of the Zhoutungou watershed.

2.2 Data

The remote sensing image data (Table 1) included 0.5 m high-resolution satellite images (Digital Orthophoto Map, DOM) from 2009, 2012, and 2018 and 0.07 m high-resolution DOM images from 2021 by unmanned aerial vehicle (UAV). A total of 11,720 images were obtained from UAV. A DEM with 0.15 m resolution and DOM with 0.07 m resolution were created using Agisoft Metashape (Windows1.7.3). The 1:10000 DEM data used in this study were obtained from the Shaanxi Geomatics Center of the Ministry of Natural Resources, and the 0.15 m resolution DEM data were obtained by the authors using UAV.

Table 1 Details of the DOM and DEM data used in this study

	Product name	Data time (year)	Spatial resolution (m)	Data source
DOM	QuickBird-02	2009	0.5	Maxar Technologies

	Product name	Data time (year)	Spatial resolution (m)	Data source
DEM	Pleiades	2012		CNES
	SuperView	2018		China Centre for Resources Satellite Data and Application
	PHANTOM 4 RTK	2021	0.07	Authors
	1:10000 DEM	2009 and 2012	5	Shaanxi Geomatics Center of Ministry of Natural Resources
	0.15 m DEM	2021	0.15	Authors

2.3 Model selected

Liu *et al.* (2021) used six indexes (Accuracy, Precision, Recall, F1 value, ROC curve, and AUC) to compare the gully recognition results and accuracy evaluation of the U-Net, R2U-Net, and SegNet image semantic segmentation models. The SegNet model ranked first for gully recognition in the hilly and gully region of the Loess Plateau, followed by the R2U-Net and U-Net models (Liu *et al.* , 2021). The gully length and width between predicted and measured values had RMSE values of 6.78 m and 0.50 m, respectively, using the SegNet model, indicating its superior performance for gully recognition and morphological feature extraction. Hence, this study used the SegNet model for gully recognition and morphological feature extraction at the watershed scale. Figure 2 is a network structure diagram of the SegNet model.

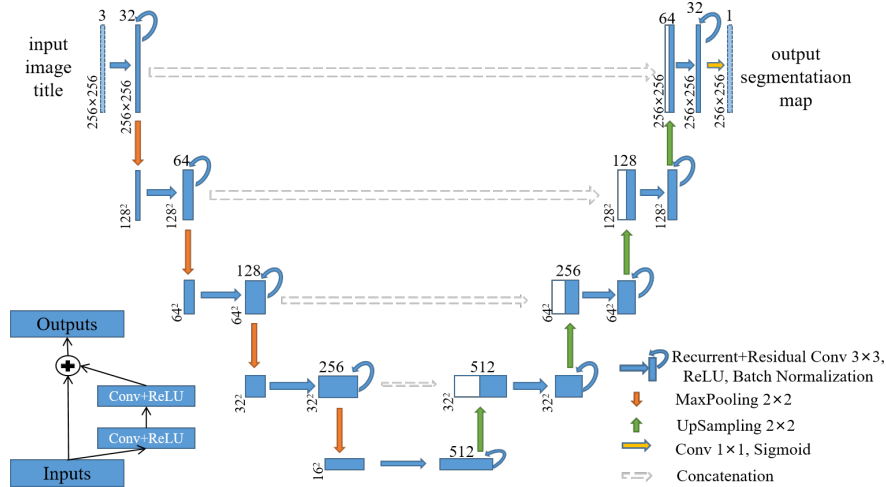


Figure 2. Network structure diagram of the SegNet model (Liu *et al.* 2021)

2.4 Extraction of morphological features of gullies

The gully recognition and DEM data were imported into ArcGIS software to extract the morphological features of gullies (e.g., number, length, width, area, frequency, density, and dissection degree) using Spatial Analyst and 3D Analyst tools. The attribute calculation function is used to obtain the projected gully length, which is divided by the cosine value of the corresponding slope to obtain the gully length. The distance measurement function is used to calculate gully width from the horizontal distance of five equally

spaced sections. The gully area is the gully width multiplied by the corresponding gully length. Gully frequency is the number of gullies per unit area of the watershed, reflecting the erosion intensity of gullies in the watershed. Gully density is the total length of gullies per unit area of the watershed, reflecting the length characteristics of gullies in the watershed and the degree of surface fragmentation. The dissection degree of gullies is the total area of gullies per unit area of the watershed, reflecting gully development in the watershed.

3. Results

3.1 Extraction and analysis of the morphological features of gullies in the watershed using the SegNet model

The SegNet model was applied to the UAV images for the whole Zhoutungou watershed in 2021, using the sliding window and ignoring edge detection methods to identify gullies at the watershed scale. Figure 3 shows the gully recognition results of the Zhoutungou watershed.

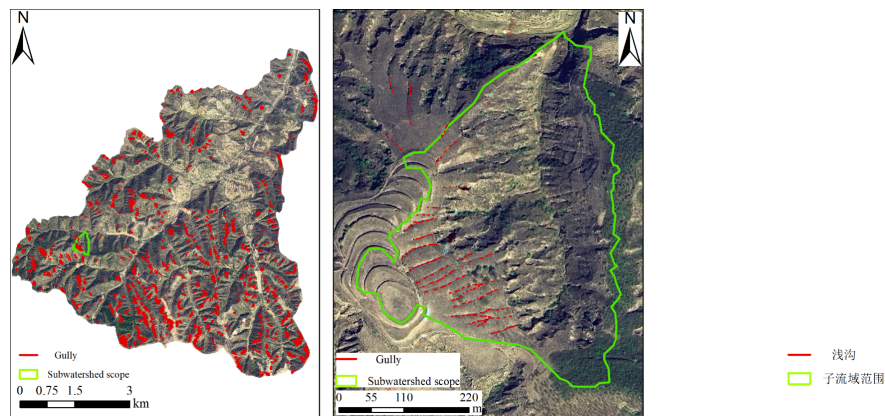


Figure 3. Recognition results of the SegNet model in the Zhoutungou watershed in 2021.

In 2021, there were 2,312 gullies in the Zhoutungou watershed, with a frequency of 68.81 per km^2 (Table 2). Gully lengths ranged from 5–209.5 m (average 45.84 m), with a total length of 105.98 km, and density of 3.15 km km^{-2} . Gully widths ranged from 0.5–2 m, with more than 85% between 1 and 1.5 m. Gully area ranged from 5.36–209.5 m^2 (average 46.36 m^2), with a total area of 0.1072 km^2 and dissection degree of 0.32%. Figure 2 and Table 2 reveal that the gullies in Zhoutungou watershed are crisscrossed and occur intensively, and some are connected in a cluster distribution. The morphological features of the gullies differ, with great uncertainty and chaotic characteristics, and no clear law of spatial distribution.

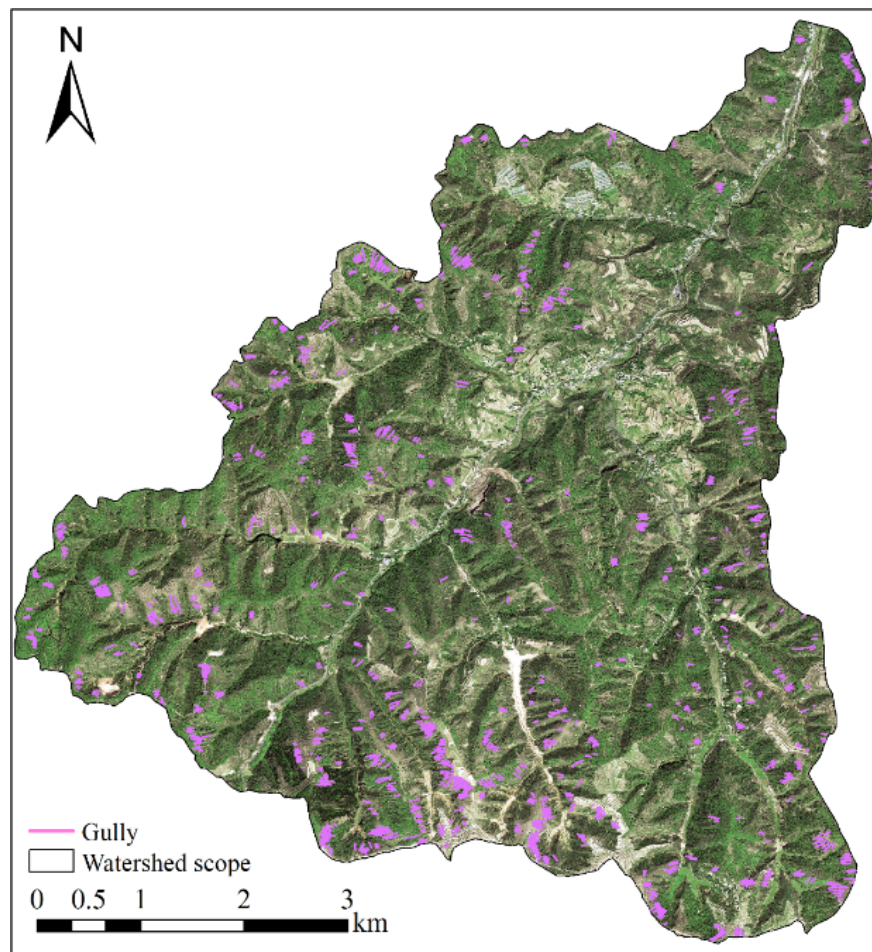
Table 2 Statistical characteristics of the morphological features of gullies in the Zhoutungou watershed in 2021

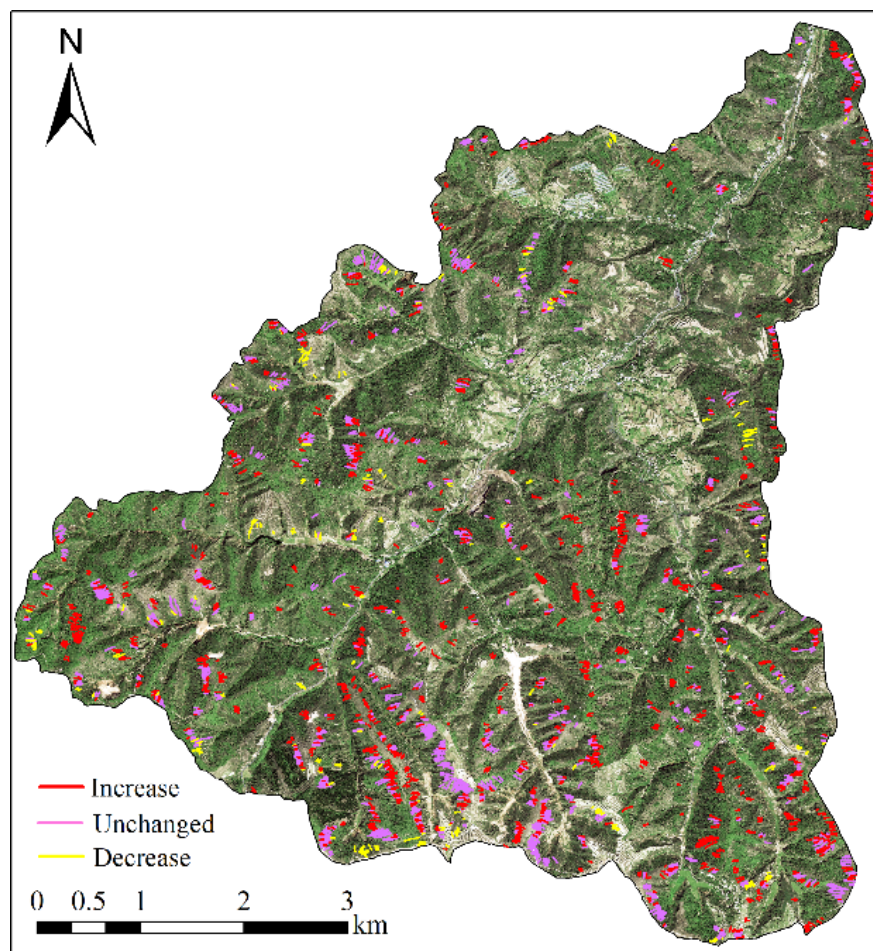
	Length (m)	Width (m)	Area (m^2)
Maximum	209.5	2	209.5
Minimum	5	0.5	5.36
Mean	45.84	1.01	46.36
Standard deviation	25.88	0.28	26.26
Coefficient of variation	56.46%	27.51%	56.65%

3.2 Temporal and spatial evolution law of morphological features of gullies

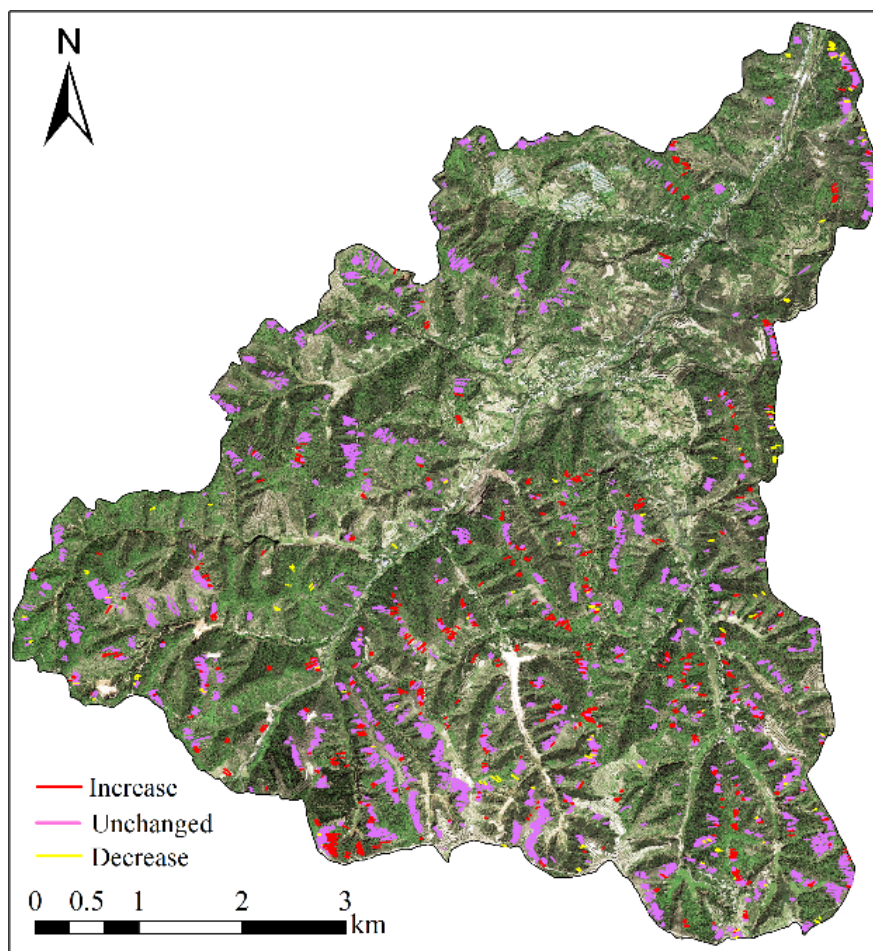
3.2.1 Number and frequency of gullies

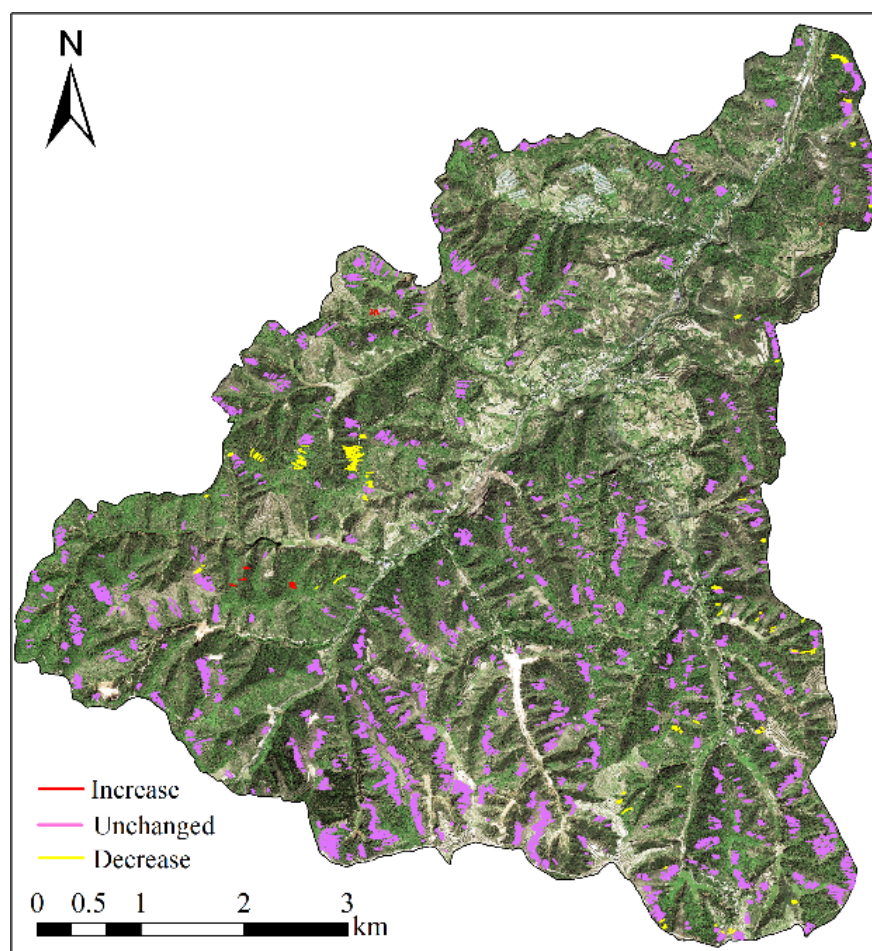
In 2009, 2012, 2018, and 2021, the number of gullies was 1,153, 2,045, 2,413, and 2,312 respectively, and the frequency of gullies is 34.32, 60.86, 71.82, and 68.81 per km^2 respectively, with a frequency development rate of $2.87 \text{ km}^{-2} \text{ y}^{-1}$. Figure 4 shows the spatial distribution evolution of gullies in Zhoutungou watershed from 2009 to 2021, mostly in the hilly southern half of the watershed, which has complex landforms and large slope gradients. From 2009 to 2012, many new gullies formed in the northeast corner and southern half of the watershed, while others disappeared. From 2012 to 2018, new gullies formed in the central south and southeast regions of the watershed, while others disappeared in the northeast corner and southwest regions. From 2018 to 2021, only a few regions formed new gullies, with many disappearing in the northeast corner, central and western regions, and southeast regions. There are three possible reasons for the disappearance of gullies: (1) In the study area, the tail of the gully generally connects with the head of the gully, and headward erosion may engulf the gully; (2) In 2011, the Chinese government implemented a gully land consolidation project on the Loess Plateau, which damaged the slope resulting in the disappearance of some gullies; (3) Returning farmland to forest on the Loess Plateau has resulted in lush vegetation, making it difficult to see some gullies in the remote sensing images.





(a) 2009 (b) 2009–2012





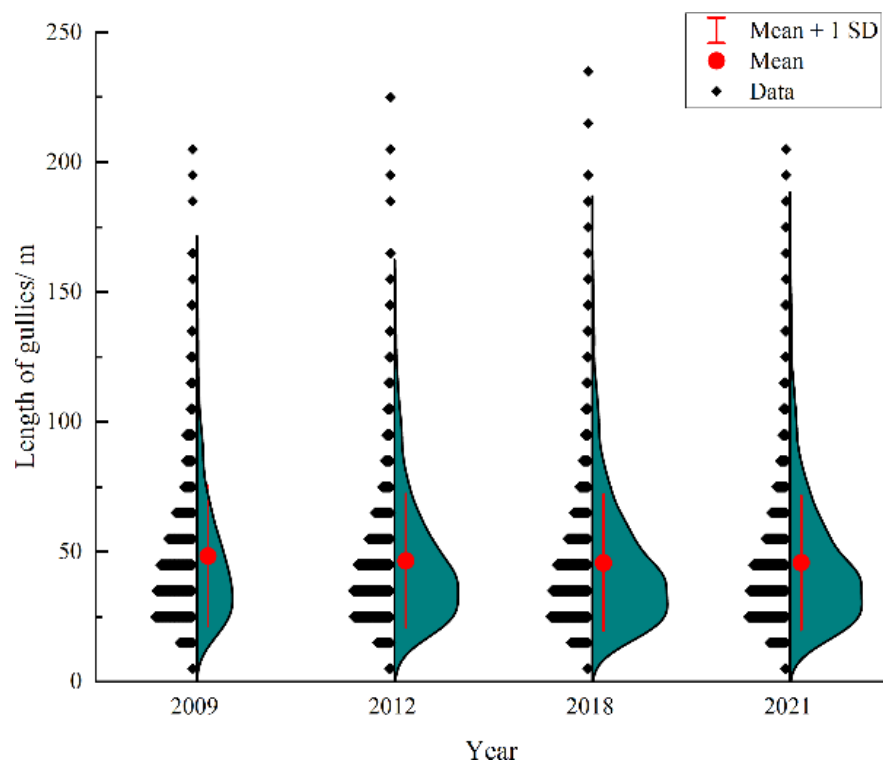
(c) 2012–2018 (d) 2018–2021

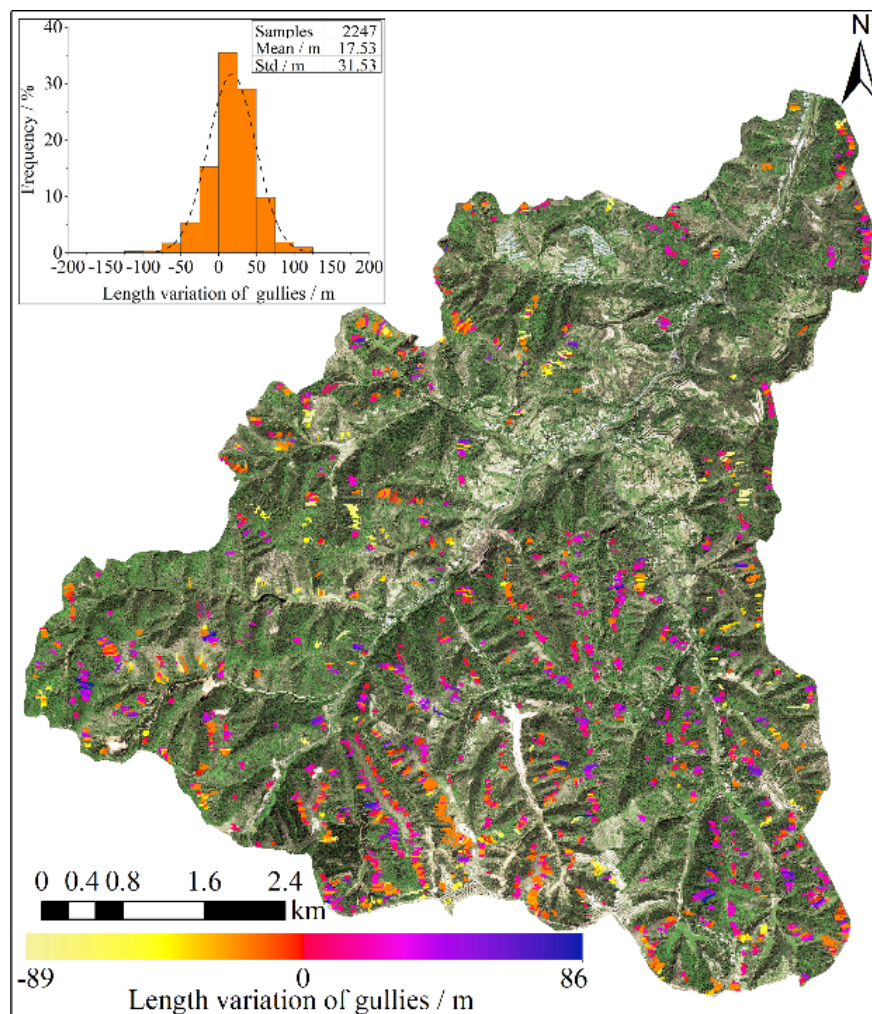
Fig. 4 Spatial variation of gully distribution from 2009–2021

3.2.2 Length and density of gullies

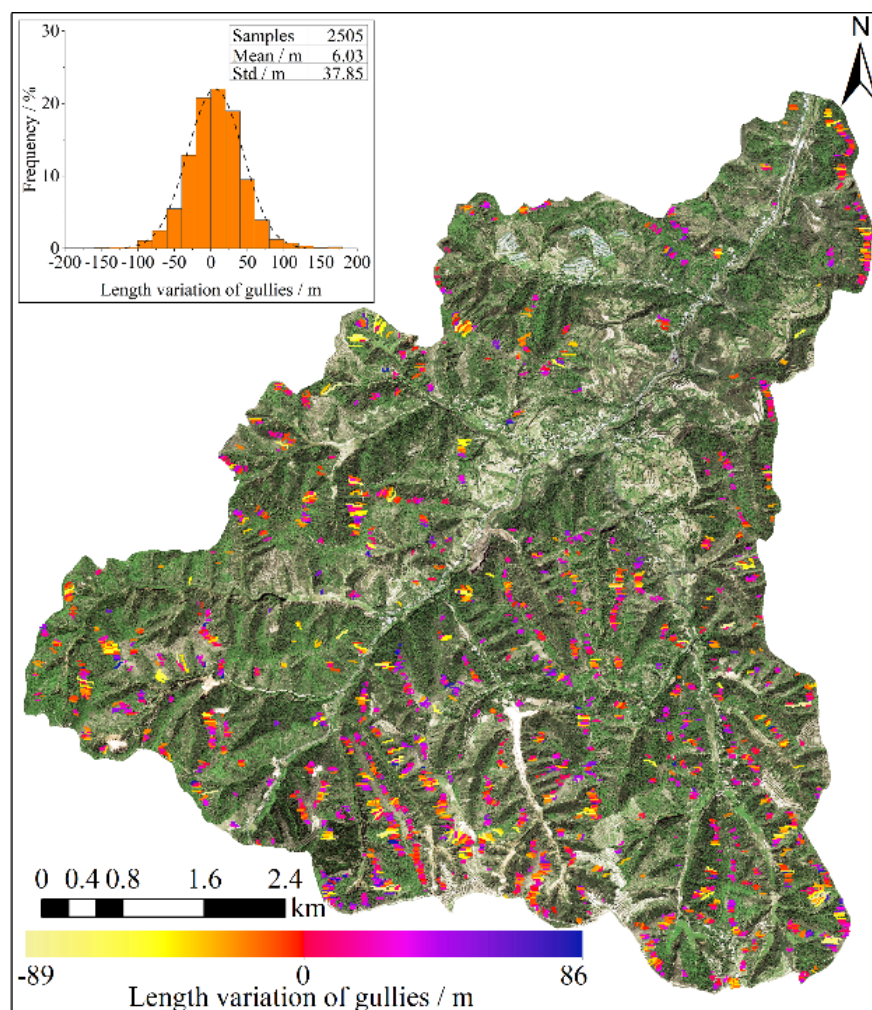
Figure 5a shows the length distribution of gullies from 2009 to 2021. In 2009, 2012, 2018, and 2021, gully lengths ranged from 7–209.5, 5–228, 5–230, and 5–209.5 m (average 48.39, 46.58, 45.75, and 45.84 m), total gully lengths were 55.79, 95.26, 110.4, and 105.98 km, and gully densities were 1.66, 2.84, 3.59, and 3.15 km^{-2} , respectively, with a length development rate of 1.66 m y^{-1} and density development rate of 0.12 $\text{km}^{-2} \text{y}^{-1}$.

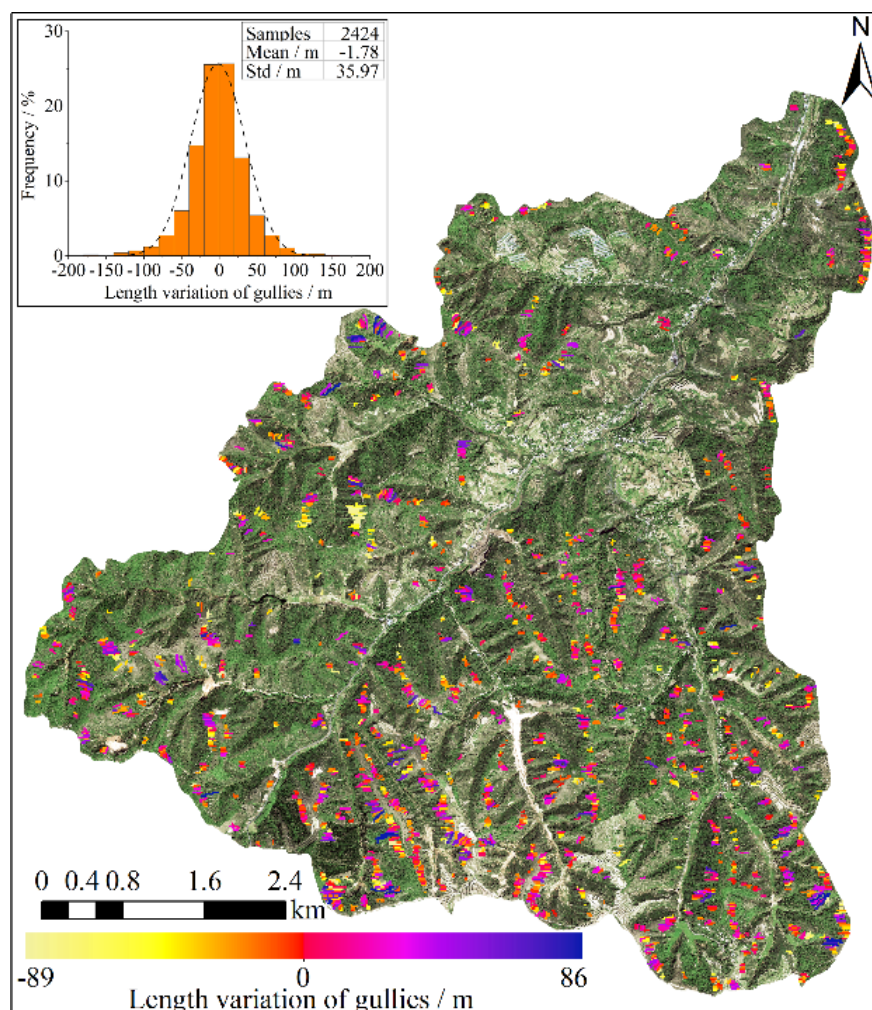
The length variation in gullies is clear and normally distributed. From 2009 to 2012, 65.82% of gullies increased in length, 22.86% decreased, and 11.32% did not change, with >64% of the length changes between 0 and 50 m. From 2012 to 2018, 56.49% of gullies increased in length, and 43.07% decreased, with >62% of the length changes between –20 and 40 m. From 2018 to 2021, 47.81% of the gullies increased in length, and 51.40% decreased, with >52% of the length changes between –20 and 20 m. From 2009 to 2021, the proportion of length decreases gradually increased, and the proportion of the length increases gradually decreased, indicating that gully development is under control.





(a) Length distribution of gullies (b) Length variation from 2009–2012





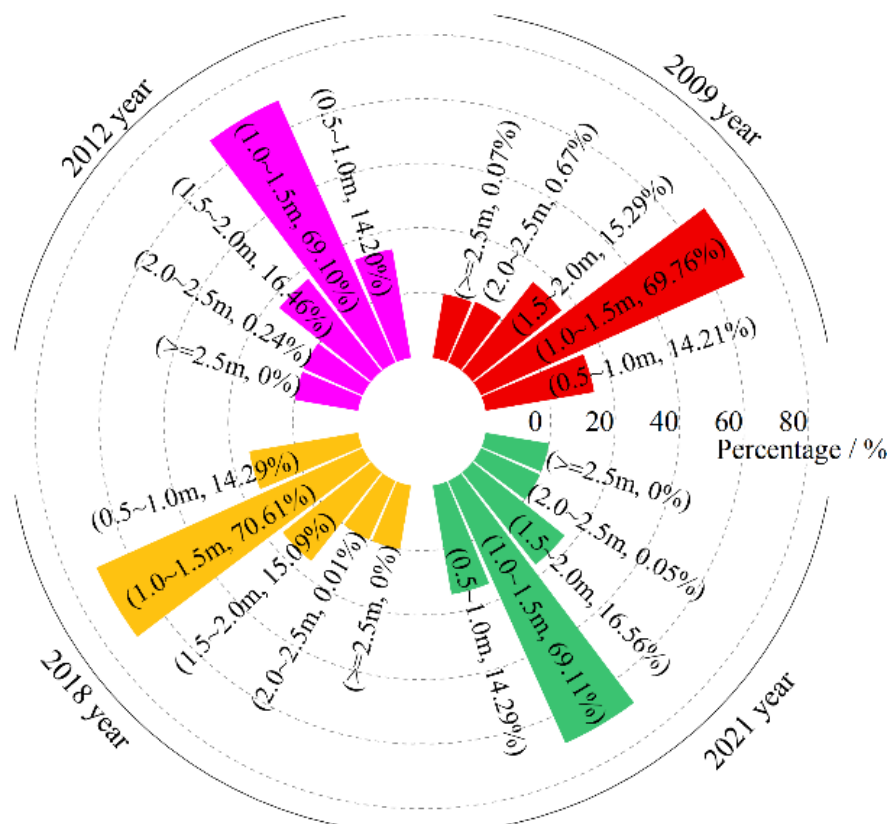
(c) Length variation from 2012–2018 (d) Length variation from 2018–2021

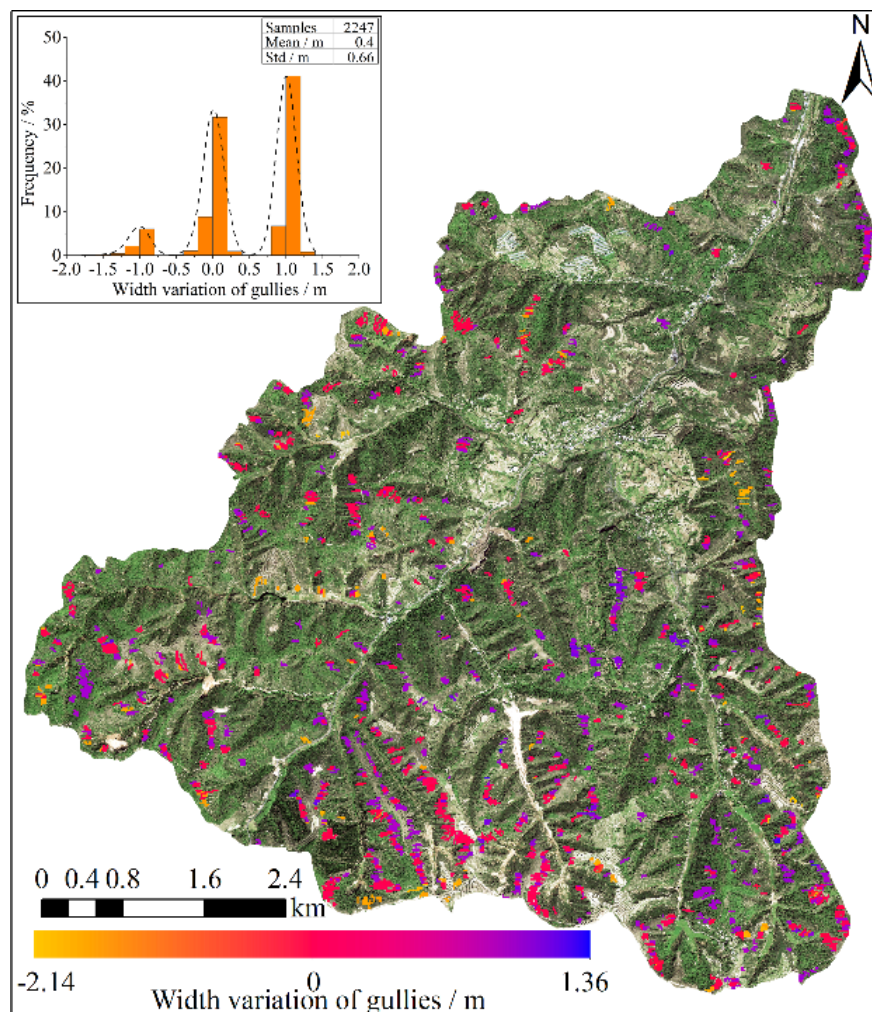
Figure 5. Length spatial-temporal evolution of gullies from 2009 to 2021

3.2.3 Width of gullies

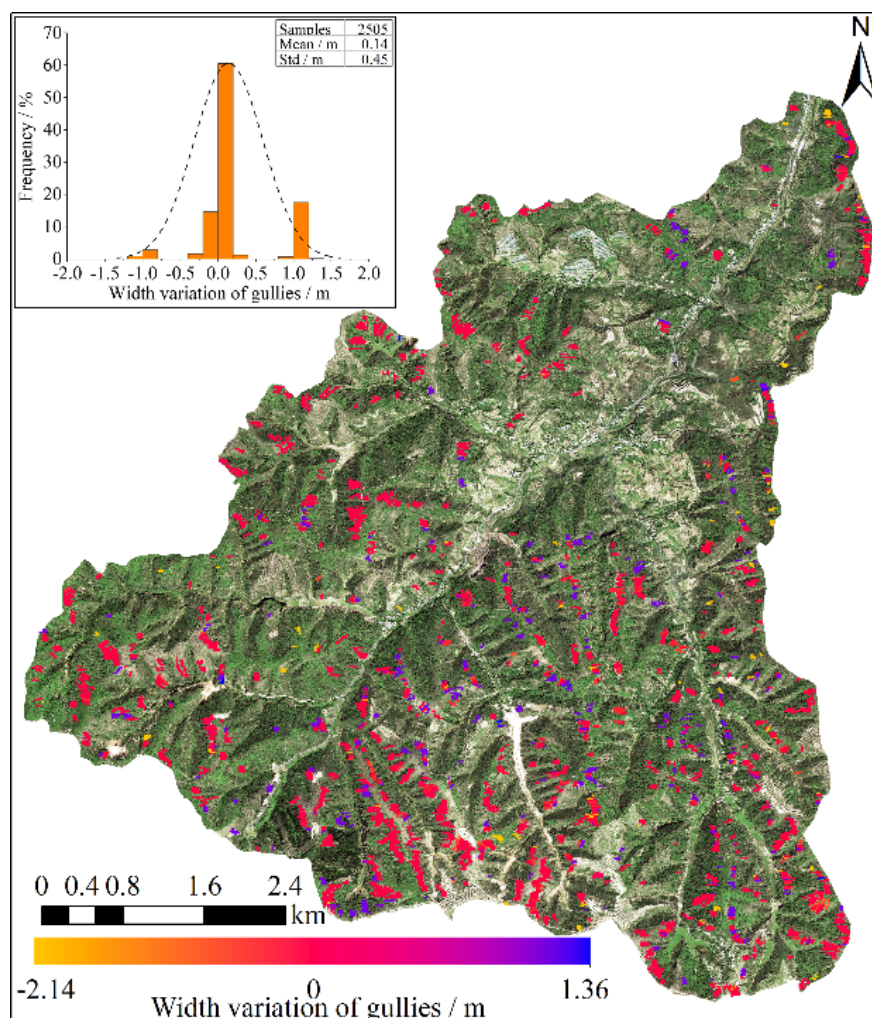
From 2009 to 2021, gully width ranged from 0.5 to 2.5 m, with more than 99% between 0.5 and 1.5 m (Fig. 6a). The proportion of gully widths 2.0–2.5 m decreased from 0.67% in 2009 to 0.05% in 2021. From 2009 to 2021, the gullies had an average width development rate of 0.04 m y^{-1} .

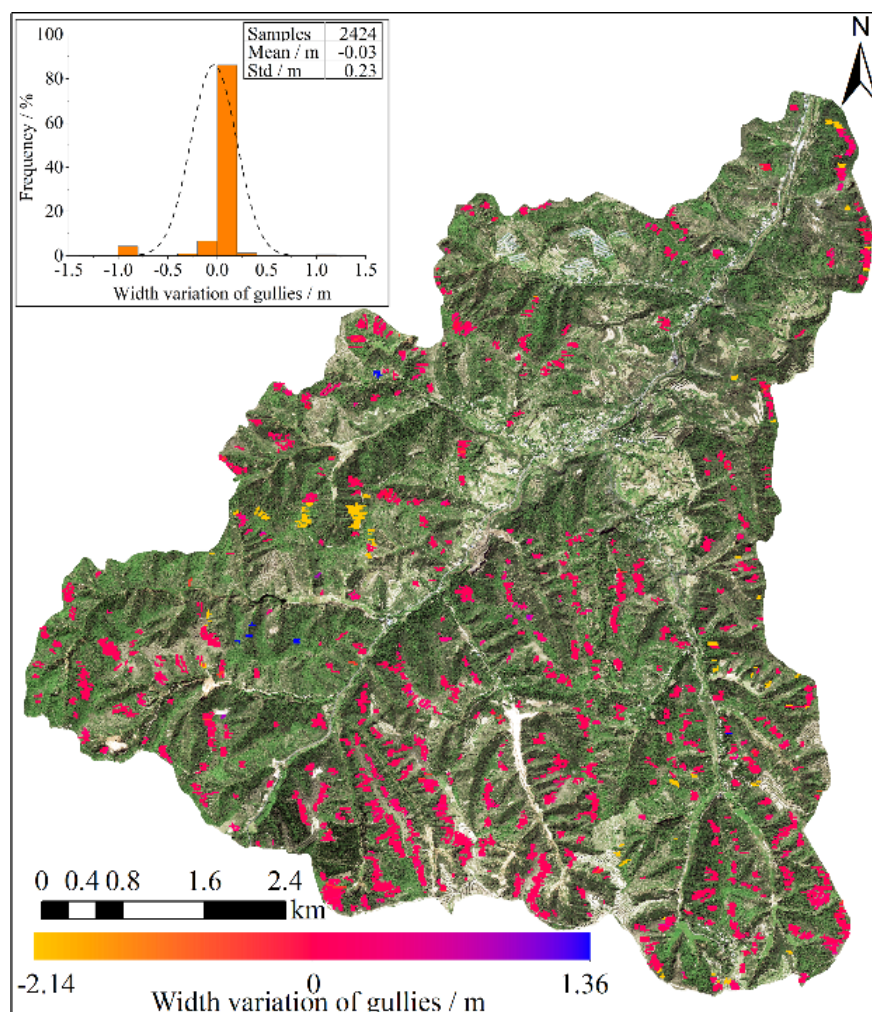
From 2009 to 2012, 63.73% of gullies increased in width, 18.81% decreased, and 17.47% did not change, with about 32% changing by 0–0.2 m and about 41% changing by 1–1.2 m (Fig. 6b). From 2012 to 2018, 29.14% of gullies increased in width, 19.84% decreased, 51.02% did not change, with about 61% changing by 0–0.2 m (Fig. 6c). From 2018 to 2021, 17% of gullies increased in width, 12.21% decreased, and 70.79% did not change, with more than 86% changing by 0–0.2 m (Fig. 6d). The average width variation range of gullies gradually decreased from 2009 to 2021.





(a) Width distribution of gullies (b) Width variation from 2009–2012





(c) Width variation from 2012–2018 (d) Width variation from 2018–2021

Figure 6. Width spatial-temporal evolution of gullies from 2009 to 2021

3.2.4 Area and dissection degree of gullies

Table 3 shows the area distribution of gullies from 2009 to 2021. In 2009, 2012, 2018, and 2021, gully area ranged from 6.5–230.71, 4.64–246.86, 4.64–230, and 5.36–209.5 m² (average 49.12, 47.34, 46.05, and 46.36 m²), total area was 0.0566, 0.0968, 0.1111, and 0.1072 km², and dissection degree was 0.17%, 0.29%, 0.33%, and 0.32%, respectively, with a total area development rate of 4,213.39 m² y⁻¹ and dissection degree development rate of 0.0125% y⁻¹. From 2009 to 2012, 70.36% of gully areas increased, and 23.85% decreased. From 2012 to 2018, 56.29% of gully areas increased, and 43.31% decreased. From 2018 to 2021, 48.43% of gully areas increased, and 51.03% decreased. The area variation range in gullies gradually decreased from 2009 to 2021.

Table 3 Area distribution of gullies from 2009 to 2021

Year	Minimum (m ²)	Maximum (m ²)	Mean (m ²)	Total area (km ²)	Dissection degree (%)	Growth ratio (%)	De
2009	6.5	230.71	49.12	0.0566	0.17		
2012	4.64	246.86	47.34	0.0968	0.29	70.36	23

Year	Minimum (m ²)	Maximum (m ²)	Mean (m ²)	Total area (km ²)	Dissection degree (%)	Growth ratio (%)	De
2018	4.64	230	46.05	0.1111	0.33	56.29	43
2021	5.36	209.5	46.36	0.1072	0.32	48.43	51

4. Discussion

This study combined remote sensing imagery and the SegNet model to analyze the morphological features of temporal and spatial distribution law in gullies at a watershed scale. Jiang *et al.* (1999) analyzed the distribution characteristics of gullies using W-B aerial photographs to identify 4,495 gullies in the Zhoutungou watershed in 1999. We found that the number of gullies in the watershed decreased sharply from 4,495 in 1999 to 1,153 in 2009 (Fig. 7) due to China's returning farmland to forest project that has significantly improved vegetation coverage on the Loess Plateau and reduced the occurrence of slope soil erosion (Chen *et al.*, 2019; Dou *et al.*, 2020; Liang *et al.*, 2019), inhibiting the formation and development of slope gullies. However, the number of gullies increased slightly after 2009 due to (1) extreme rainfall on the Loess Plateau, increasing soil erosion (Huet *et al.*, 2019; Li *et al.*, 2022; Wang *et al.*, 2020a; Zhao *et al.*, 2021); (2) the gully land consolidation project implemented in 2011 increasing the cultivated land area and, despite reducing watershed erosion to a certain extent (Chen *et al.*, 2020; Han *et al.*, 2018; Kang *et al.*, 2021b; Li *et al.*, 2016; Zhao, 2014; Zhao *et al.*, 2019), its associated engineering involving topsoil stripping and ridge construction has damaged the slope vegetation (increased slope) and soil environment (loosened soil structure), forming new gullies on the slope; (3) returning farmland to forest on the Loess Plateau has resulted in lush vegetation, making it difficult to see some gullies in the remote sensing images. Soil erosion on the Loess Plateau will gradually decline to achieve the strategic goal of protecting and controlling the ecological environment of the Loess Plateau, and 'green water and green mountains are golden mountains and silver mountains'.

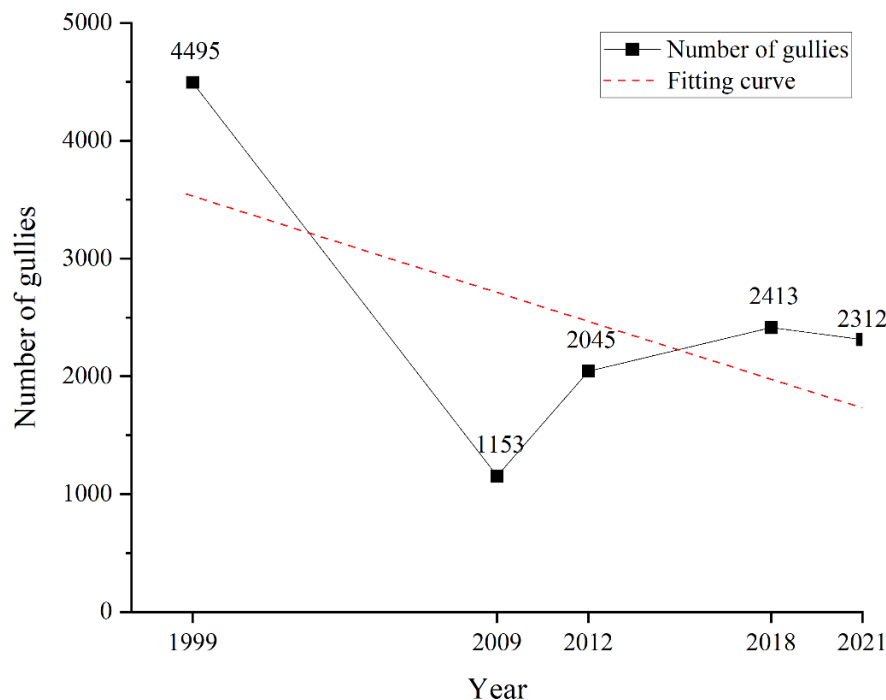


Figure 7. Changes in the number of gullies before and after the project returning farmland to forest in the Zhoutungou watershed

Numerous studies have analyzed the temporal and spatial distribution of gullies on the Loess Plateau (Chen, 1984; Guo and Wang, 2019; Kanget al. , 2016; Zheng et al. , 2016; Zhong et al. , 2022). This study found that the gully number increased by 1,159 from 2009 to 2021, with an average growth rate of 97 per year, mostly in the hilly southern part of the watershed, which has complex landforms and large slope gradients. From 2009 to 2021, gully lengths ranged from 5 to 230 m (average 48.39 m), of which 55% ranged from 25 to 40 m, with an average growth rate of 1.66 m y⁻¹. However, other studies reported gully lengths ranging from 7.71 to 237 m (average 56.5 m), of which 60% ranged from 30 to 60 m (Jiang et al., 1999; Li, 2011; Qin et al., 2010; Zhang et al. 2017; Zhong et al. 2022). The shorter gully lengths in this study may be related to the more recent conversion of farmland to forest, inhibiting the development of gullies.

In terms of length, this study found that more than 99% of the gullies are 0.5–1.5 m wide, with an average growth rate of 0.04 m y⁻¹. Similarly, Liu et al. (1988, 2018) reported gully widths in loess hilly and gully areas of around 0.3–0.5 m, sometimes 1–2 m. The total area of gullies ranged from 0.0566–0.1111 km², accounting for 0.17–0.33% of the total watershed area. However, Jiang et al. (1999) reported a much higher value for the total Zhoutungou watershed area in 1999 (4.0 km² or 11.89% vs. 0.0566 km² or 0.17%).

To sum up, while some research results are based on the temporal and spatial distribution characteristics of gullies on the slope of the Loess Plateau, and the project returning farmland to forest has controlled the gully development, the frequent occurrence of uncertain extreme rainfall events and poor consolidation of the results of returning farmland to forest are the main reasons for the increased gully erosion on the Loess Plateau in recent years. Soil erosion control and innovative erosion control strategies need further investigation.

5. Conclusion

In this study, the SegNet model was used to recognize gullies and extract their morphological features at a watershed scale from 2009 to 2021 to analyze the temporal and spatial distribution and evolution law of gullies. The number of gullies increased by 1,159 from 2009 to 2021 (average 97 per year), with a frequency development rate of 2.87 km² y⁻¹, mainly in the hilly southern part of the watershed, with complex landforms and large slope gradients. Gully lengths ranged from 5 to 230 m (average 48.39 m), with an average growth rate of 1.66 m y⁻¹ and density development rate of 0.12 km km⁻² y⁻¹. More than 99% of the gullies are 0.5–1.5 m wide, with an average growth rate of 0.04 m year⁻¹. The total gully area increased from 0.0566 km² in 2009 to 0.1072 km² in 2021, with a total area development rate of 4,213.39 m² y⁻¹ and dissection degree development rate of 0.0125% y⁻¹. Future soil erosion control should strengthen the erosion strategy caused by extreme rainfall events. Persisting with the returning farmland to forest project should realize ecological environmental protection of the Loess Plateau, and the strategic goal of ‘green water and green mountain is golden mountain and silver mountain’.

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