Evolution and Development of Ephemeral Gully Erosion in Hilly and Gully Region of the Loess Plateau in China

Boyang Liu[1], Biao Zhang[1], Ziming Yin[2], Bai Hao[3], Dr. Shufang Wu[1], Hao Feng[1], and K Siddique[4]

[1]Northwest A&F University
[2]Northwest A&F University College of Natural Resources and Environment
[3]Sichuan Expressway Construction & Development Group Co Ltd
[4]The University of Western Australia

February 3, 2023

Abstract

Ephemeral gully erosion is a primary mode of soil erosion that is highly visible, affecting soil productivity and restricting land use. Watershed is the basic unit of soil erosion control; existing research has focused on several typical ephemeral gullies or slopes, which do not fully display changes in ephemeral gullies at a watershed scale. This study analyzed the spatial-temporal evolution and development rate of ephemeral gully erosion at the watershed scale on the Loess Plateau from 2009 to 2021 using remote sensing images (0.5 m resolution), unmanned aerial vehicles (UAV), and field investigations. The results revealed that: (1) most ephemeral gullies occurred in southwestern parts of the watershed, with many hills and large slope gradients; (2) average growth rates of each ephemeral gully frequency, length, density, dissection degree, and width were 2.87 km ^{2} y $^{-1}$, 1.66 m y $^{-1}$, 0.12 km km $^{-2}$ y $^{-1}$, 0.0125% y $^{-1}$, and 0.04 m y $^{-1}$, respectively; (3) ephemeral gully erosion volume (*V*) and length (*L*) had a good power function relationship: $V = 0.0842 L^{1.1932}$ ($R^2 = 0.80$). The root mean square error (RMSE) and coefficient of determination (R^2) between the measured and predicted ephemeral gully volumes suggest that the *V*–*L* relationship has a good predictive ability for ephemeral gully volume. Thus, the *V*–*L* model was used to evaluate the development rate of ephemeral gully erosion volume in small watersheds from 2009 to 2021, revealing an average value of 743.20 m ^{3} y $^{-1}$. This study proposed a feasible model for assessing ephemeral gully volume and volume changes at a watershed scale using high-resolution remote sensing images, providing a reference for understanding the development of ephemeral gully erosion in small watersheds over time.

Evolution and Development of Ephemeral Gully Erosion in Hilly and Gully Region of the Loess Plateau in China

Boyang Liu[a,b], Biao Zhang[a,b], Ziming Yin[c], Bai Hao[d], Shufang Wu[a,b]*, Hao Feng[a], Kadambot H.M. Siddique[e]

[a] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A & F University, Yangling 712100, China

[b] Institute of Water Saving Agriculture in Arid Areas of China, Northwest A & F University, Yangling 712100, China

[c] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China

[d] Sichuan Expressway Construction & Development Group Co., Ltd., Chengdu, Sichuan 610041, China

[e] The UWA Institute of Agriculture and School of Agriculture & Environment, The University of Western Australia, Perth, WA 6001, Australia

***Corresponding Author:**

Shufang Wu, College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, Shaanxi, PR China. E-mail:*wsfjs@163.com*

Highlights

- Used the SegNet model to extract ephemeral gully at the watershed scale.
- Clarified the spatial-temporal evolution of ephemeral gully from 2009–2021.
- Evaluated the development rate of ephemeral gully morphological parameters.
- Bulit an empirical model to assess ephemeral gully erosion volume.

Abstract

Ephemeral gully erosion is a primary mode of soil erosion that is highly visible, affecting soil productivity and restricting land use. Watershed is the basic unit of soil erosion control; existing research has focused on several typical ephemeral gullies or slopes, which do not fully display changes in ephemeral gullies at a watershed scale. This study analyzed the spatial-temporal evolution and development rate of ephemeral gully erosion at the watershed scale on the Loess Plateau from 2009 to 2021 using remote sensing images (0.5 m resolution), unmanned aerial vehicles (UAV), and field investigations. The results revealed that: (1) most ephemeral gullies occurred in southwestern parts of the watershed, with many hills and large slope gradients; (2) average growth rates of each ephemeral gully frequency, length, density, dissection degree, and width were 2.87 $km^2 y^{-1}$, 1.66 m y^{-1}, 0.12 km km^{-2} y^{-1}, 0.0125% y^{-1}, and 0.04 m y^{-1} , respectively; (3) ephemeral gully erosion volume (V) and length (L) had a good power function relationship:$V = 0.0842L^{1.1932}$ ($R^2 = 0.80$). The root mean square error (RMSE) and coefficient of determination (R^2) between the measured and predicted ephemeral gully volumes suggest that the V–L relationship has a good predictive ability for ephemeral gully volume. Thus, the V–L model was used to evaluate the development rate of ephemeral gully erosion volume in small watersheds from 2009 to 2021, revealing an average value of 743.20 m^3 y^{-1}. This study proposed a feasible model for assessing ephemeral gully volume and volume changes at a watershed scale using high-resolution remote sensing images, providing a reference for understanding the development of ephemeral gully erosion in small watersheds over time.

Keywords:

soil erosion, ephemeral gully, remote sensing and UAV, morphological features, development rate

1. Introduction

Soil is fundamental for life on earth, impacting global issues such as food and water security (Koch et al., 2013; McBratney et al., 2014), and is increasingly considered the main contributor to extensive ecosystem services (Dominati et al., 2010). Soil erosion is the greatest threat to soil function at the global scale (Montanarella et al., 2016) and is recognized as the most dominant land degradation process, severely damaging infrastructure, causing land degradation and water pollution in developed regions, and threatening the safety of human production and life in many developing regions (Hao et al., 2020; Mohammed et al., 2020; Pennock, 2019). Ephemeral gully erosion is a linear erosion pattern occurring on steep cultivated slope farmland, formed by the combined action of runoff erosion and human cultivation, and with a connecting role in the slope-gully system (Liu *et al.*, 1988; Poesen *et al.*, 2003; Wang *et al.*, 2003). Ephemeral gully erosion is a major contributor to soil erosion worldwide, adversely affecting water quality in the receiving water courses and impacting aquatic life (Fox et al., 2016; Gholami et al., 2019; Gupta et al., 2019; Anache et al., 2018; Devátý et al., 2019; Eekhout and de Vente, 2022; Sun et al., 2014; Tamene et al., 2020).

Research has focused on measuring ephemeral gully morphological parameters and determining their development at temporal and spatial scales. Some studies have used ground-based methods (e.g. field plots, erosion pins, tape method, volume replacement method) to garner relevant ephemeral gully data (Boardman et al., 2015; Casalí et al., 2006; Evans and Lindsay, 2010; Gómez-Gutiérrez et al. 2014; Kearney et al., 2018; Perroy et al., 2010; Romanescu et al., 2012; Shen *et al.* , 2021; Wang *et al.* , 2020a; Wang *et al.* , 2021a), but the limited data significantly impacts the reliability of the research conclusions for practical application. Further verification is needed to determine whether the conclusions under small-scale conditions can be extrapolated to larger scales. However, large-area field surveys are needed to accurately grasp the spatial distribution characteristics of ephemeral gully morphological features, requiring a large workload with low efficiency. In recent decades, the spatial resolutions, revisiting times, and detail of remote sensing data and digital elevation models (DEM) have significantly increased, providing crucial data support for accurately identifying the spatial position and morphological parameters of ephemeral gullies (Arabameri et al., 2019; Cao *et al* ., 2020; Dai *et al* ., 2020; Karydas and Panagos, 2020; King *et al* ., 2005; Liu *et al* ., 2022; Vallejo Orti et al., 2019; Yermolayev*et al* ., 2020). Ephemeral gully volume is an important morphological parameter of ephemeral gullies and an indicator of the contribution of ephemeral gully erosion to sediment yield (Kompia-Zare et al., 2011; Woodward, 1999). Understanding ephemeral gully development over time is important for predicting their future behavior, which can be done directly by measuring volume change (Li et al., 2017). Unfortunately, due to ephemeral gully characteristics and the inherent accuracy limitations of DEM, measuring ephemeral gully volume using DEM data has not been widely used. However, ephemeral gully length is the most easily obtained morphological parameter, with several studies exploring the relationship between ephemeral gully volume (V) and length (L) using the power equation $V=aL^b$ (Capra et al., 2005; Frankl et al., 2013; Kompani-Zare et al., 2011; Li et al., 2017; Muñoz-Robles et al., 2010; Zhang et al., 2007; Zucca et al., 2006).

Watershed is the basic hydrological response unit, an ideal spatial scale for studying soil and water losses, and the fundamental unit for managing ecological environments. Studies on soil erosion at the watershed scale have focused on estimating soil erosion and sediment (Cao *et al.* , 2022; Galdies *et al.* , 2022; Lufira *et al.* , 2022), assessing erosion susceptibility (Pandey *et al.* , 2021; Tahouri *et al.* , 2022; Tesema, 2022; Wang *et al.* , 2022), and analyzing the factors affecting soil erosion (Aneseyee*et al.* , 2020; Choudhury *et al.* , 2022; Guduru and Jilo, 2022; Zhao *et al.* , 2022). However, most scholars chose typically representative ephemeral gullies or slopes as research objects to analyze changes in ephemeral gullies (Capra et al., 2009; Karydas and Panagos, 2020; Li et al., 2016; Wang *et al.* 2021b; Zheng et al., 2006), but typical ephemeral gullies or slopes do not fully display changes in ephemeral gullies at a watershed scale. Therefore, clarifying the temporal and spatial development processes of ephemeral gullies at the watershed scale is valuable for determining soil and water conservation practices and understanding the characteristics of each ephemeral gully and other geomorphologic processes related to ephemeral gully erosion.

The Loess Plateau of China is a typical loess geomorphic region and one of the most serious soil erosion regions in China, if not the world (Fu*et al.* , 2011). Ephemeral gully erosion on the Loess Plateau accounts for more than 70% of its ravines, with erosion accounting for 26.60–59.20% of total slope erosion (Cheng et al., 2007; Zheng et al., 2006). Ephemeral gully erosion control has been underway on the Loess Plateau since 1999 when the Chinese government implemented 'Grain for Green Project' (Fu et al., 2017; Ran et al., 2013; Wang et al., 2014), with some areas still requiring attention. This study used 0.50 m resolution remote sensing images integrated with a deep learning image semantic segmentation model (deep learning can scientifically build high-level features from raw datasets, deliver forecasting results, and perform better than machine learning in various research areas) to identify ephemeral gullies and extract morphological features at the watershed scale, analyze the temporal and spatial distribution and evolution law of ephemeral gullies, and clarify the development processes and rate of ephemeral gully erosion at the watershed scale in the hilly and gully region of the Loess Plateau. This research will help select the most effective countermeasures to prevent and control soil erosion and provide more effective measures to protect limited land resources and ecological environments.

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), a typical small watershed in the hilly and gully region of the Loess Plateau, with an average altitude of 1,235.37 m (Fig. 1 (a) and (b)). The annual average temperature is 8.80 and annual average rainfall is 550 mm (74% falls from July to Sept.). The soil type is loessial soil of the Zhoutungou watershed. The total watershed area is 33.60 km^2, with 18.70 km^2 (55.57%) of valleys (Jiang *et al.* , 1999). The ephemeral gullies are distributed mainly on slope surfaces in the southern region, accounting for about one-third of the slope area. The main measure for ephemeral gully regional governance is planting grasses and shrubs. The main valley in the watershed runs southwest to northeast, with the number of branch valleys gradually increasing from northeast to southwest. The valley and branch valley sections have a 'U' or 'V' shape, with the terrain of each valley comprising hills, slopes, and channels. In addition, we selected two slope types for field investigations to obtain measured values of ephemeral gully morphological parameters. Slope A is on sunny slopes, with an area of 22,532 m^2. Slope B is on shady slopes, with an area of 11,004 m^2 (Fig.1 (c)). We investigated 13 ephemeral gullies on slope A and six ephemeral gullies on slope B.

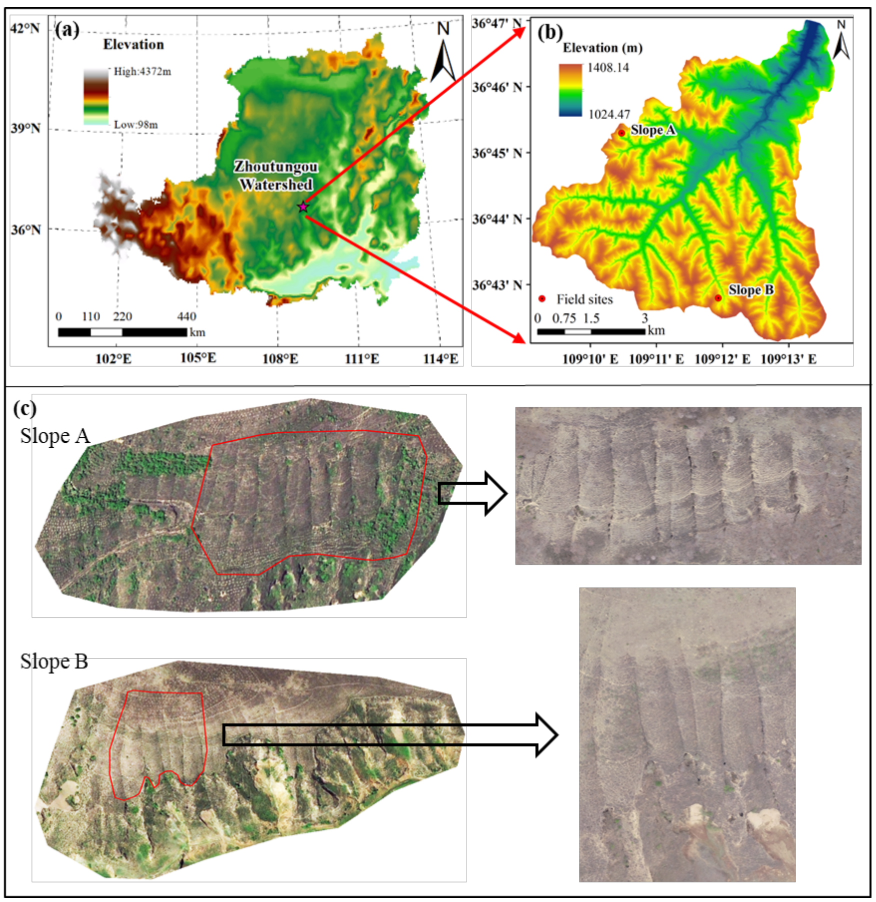


Figure 1. Location of the study area. (a) Geographical location map of the study area on the Loess Plateau. (b) Digital elevation model (DEM) of the Zhoutungou watershed. (c) Detailed information of field survey sites (Slope A located on a sunny slope, and Slope B located on a shady slope).

2.2 Data sources

This study used three different spatial scale survey methods to monitor ephemeral gully: satellite remote sensing monitoring, unmanned aerial vehicle (UAV) monitoring, and field investigations (Fig. 2). The remote sensing image data included 0.50 m high-resolution satellite images (digital orthophoto map, DOM) in 2009, 2012, and 2018 and 0.50 m high-resolution DOM images by UAV in 2021 (11,720 images). A DEM with 0.15 m resolution and DOM with 0.50 m resolution were created using Agisoft Metashape (Windows1.7.3, Agisoft, Russia). The 1:10,000 DEM data used in this study were obtained from the Shaanxi Geomatics Center of the Ministry of Natural Resources of China, and the 0.15 m resolution DEM data were obtained by the authors using UAV (Table 1). In order to avoid the influence of different DEM resolutions on the extraction accuracy of ephemeral gully morphological parameters, we changed the resolution of 0.15 m to 5 m by resampling in ArcGIS software (ArcGIS 10.2, Esri, U.S.A). The remote sensing and UAV images were obtained from April to June each year when the vegetation was not yet lush and thus had no significant impact on ephemeral gully recognition.

Table 1 Basic information on the DOM and DEM data used in this study.

Data type	Product name	Data time (year)	Spatial resolution (m)	Data source
DOM	QuickBird-02	2009	0.50	Maxar Technologies
	Pleiades	2012		CNES
	SuperView	2018		China Centre for Resources Satellite Data and Application
	PHANTOM 4 RTK	2021	0.50	Authors used UAV
DEM	1:10000 DEM	2009 and 2012	5	Shaanxi Geomatics Center of Ministry of Natural Resources of China
	0.15 m DEM	2021	0.15	Authors used UAV

Note: DOM, DEM and UAV refer to digital orthophoto map, digital elevation model and unmanned aerial vehicle, respectively,

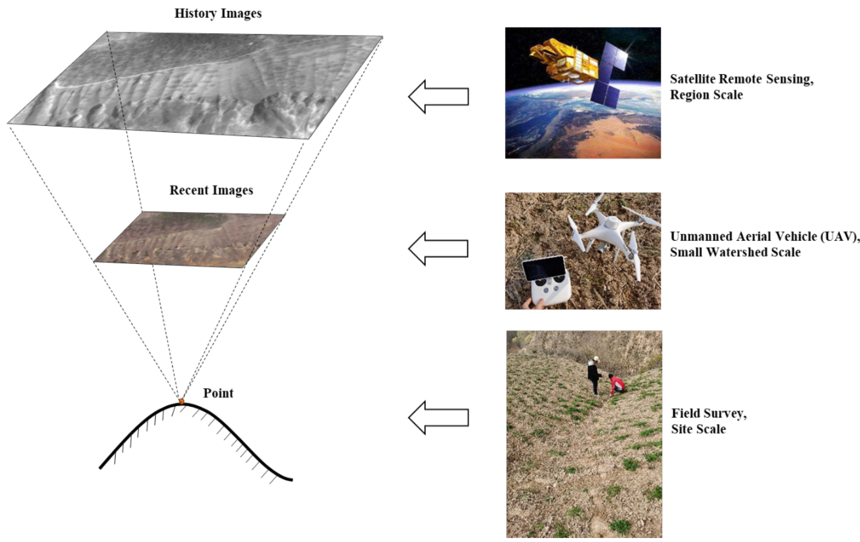


Figure 2. Three spatial scale ephemeral gully monitoring methods.

2.3 Selection of ephemeral gully identification model

The SegNet model is a convolutional neural network for pixel-level image segmentation proposed by Badrinarayanan *et al.* (2017) using end-to-end and pixel-to-pixel training to achieve image segmentation. Its core component is an encoder network and corresponding decoder network, followed by a pixel-level classifier, which outputs the probability map of the K channel, where K is the number of classification categories. Compared with other models, SegNet has fewer training parameters, smaller memory occupation, and shorter network training time (Deng et al., 2022; Jiang et al., 2020; Manickam et al., 2020). In 2021, six indexes (Accuracy, Precision, Recall, F1 value, ROC curve, and AUC) were used to compare the ephemeral gully recognition results and accuracy evaluation with U-Net, R2U-Net, and SegNet, with SegNet ranked first for ephemeral gully recognition in the hilly and gully region of the Loess Plateau, followed by R2U-Net and U-Net (Liu*et al.* , 2022). Ephemeral gully length and width between predicted and field measured values had RMSE values of 6.78 m (R^2 = 0.9817) and 0.50 m (R^2 = 0.8573), respectively, using the SegNet model, indicating its superior performance for ephemeral gully recognition and morphological feature extraction. Hence, this study used the SegNet model for ephemeral gully recognition and morphological feature extraction at the watershed scale. The process of identifying ephemeral gullies with the SegNet model was performed as follows: SegNet model carries out iterative cyclic training based on the data set until the loss value is minimum and obtains the corresponding optimal weight of the model. Based on the optimal weight and network structure of the SegNet model, ephemeral gullies were recognized using the sliding window and ignoring edge detection methods at the watershed scale (Fig. 3).

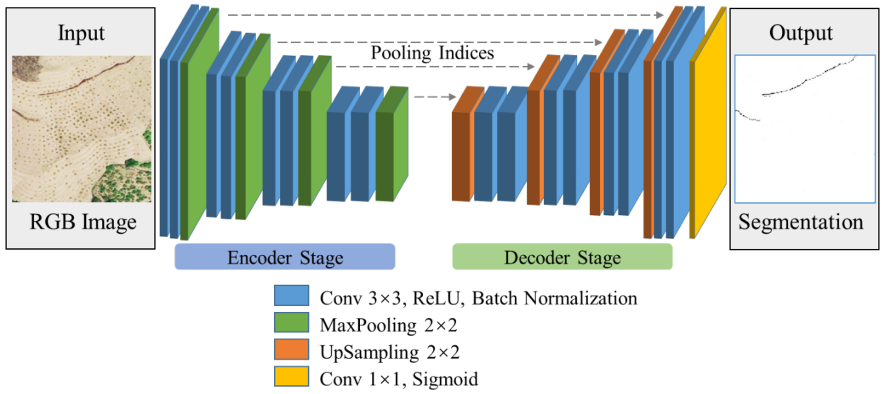


Figure 3. Network structure diagram of the SegNet model.

The SegNet model is a symmetric structure, mainly including Encoder and Decoder stages. The Encoder stage classifies and analyzes low-level local pixel values of images through Convolution Layer, ReLU function, Batch Normalization function, and Pooling Layer to obtain high-level semantic information. The Decoder stage uses Pooling Indices, UpSampling Layer, Convolution Layer, ReLU function, and Batch Normalization function to improve the geometric shape of objects and make up for the loss of detail caused by shrinking the object in the Pooling Layer of the Encoder stage. Finally, the extracted feature image is output as a segmentation map through the Sigmoid function. This model inputs an image with three RGB channels and outputs a segmentation map with one channel.

2.4 Extraction of ephemeral gully morphological parameters

The data for ephemeral gully recognition and DEM were imported into ArcGIS software to extract the morphological features of ephemeral gullies (e.g., number, length, width, area, frequency, density, and dissection degree) using Spatial Analyst and 3D Analyst tools. For ephemeral gully length (L), the distance measurement function was used to obtain the projected ephemeral gully length, which was divided by the cosine value of the corresponding gradient to obtain the ephemeral gully length using Eq. (1). For ephemeral gully width (W), five positions were selected on the ephemeral gully length to measure ephemeral gully width, and calculate the average value of the five position widths to obtain the average ephemeral gully width using Eq. (2). Ephemeral gully area (A) is the average ephemeral gully width multiplied by the corresponding length using Eq. (3). Ephemeral gully fequency (F) is the ephemeral gully number per unit area of the watershed, reflecting the erosion intensity of ephemeral gullies in the watershed using Eq. (4). Ephemeral gully density (ρ) is the total ephemeral gully length per unit area of the watershed, reflecting ephemeral gully length characteristics in the watershed and degree of surface fragmentation using Eq. (5). Ephemeral gully dissection degree (D) is the total ephemeral gully area per unit area of the watershed, reflecting watershed ephemeral gully development using Eq. (6).

$L = \frac{L_p}{\cos\theta}$ (1)

$W = \frac{\sum_{i=1}^{5} W_i}{5}$ (2)

$A = WL$ (3)

$F = N/A_0$ (4)

$\rho = \frac{\sum_{i=1}^{n} L_i}{A_0}$ (5)

$D = \frac{\sum_{i=1}^{n} A_i}{A_0}$ (6)

where L_p is projected ephemeral gully length, θ is ephemeral gully gradient, W_i (i=1, 2, 3, 4, 5) is the five position widths of the ephemeral gully, N is ephemeral gully number, and A_0 is watershed area.

2.5 Assessing the V–L relationship and ephemeral gully erosion volume change

The data for ephemeral gully recognition and DEM (0.15 m resolution) were imported into ArcGIS software to extract each ephemeral gully erosion volume using Spatial Analyst and 3D Analyst tools. The empirical relationship between ephemeral gully volume *(V)* and length (L) was established with curve fitting analysis, which calculated the root mean square error (RMSE) and coefficient of determination (R^2) to examine the effect of ephemeral gully length on measured and predicted ephemeral gully erosion volume. Finally, we calculated ephemeral gully erosion volume in 2009 using the constructed V–L relationship and analyzed the change in ephemeral gully erosion volume from 2009 to 2021.

RMSE was calculated as Eq. (7):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i - M_i\right)^2}(7)$$

where M is measured ephemeral gully erosion volume, P is predicted ephemeral gully erosion volume, and n is the number of modeled gullies.

3. Results

3.1 Temporal and spatial changes in ephemeral gullies

The SegNet model was applied to the UAV image of the whole Zhoutungou watershed in 2021, with the sliding window and ignoring edge detection methods used to identify ephemeral gullies at the watershed scale (Fig. 4 (a)). Comparing the ephemeral gully identification results with the field survey in Fig. 4 (b), we found that the SegNet model had >91.66% accuracy for ephemeral gully number and spatial distribution accuracy.

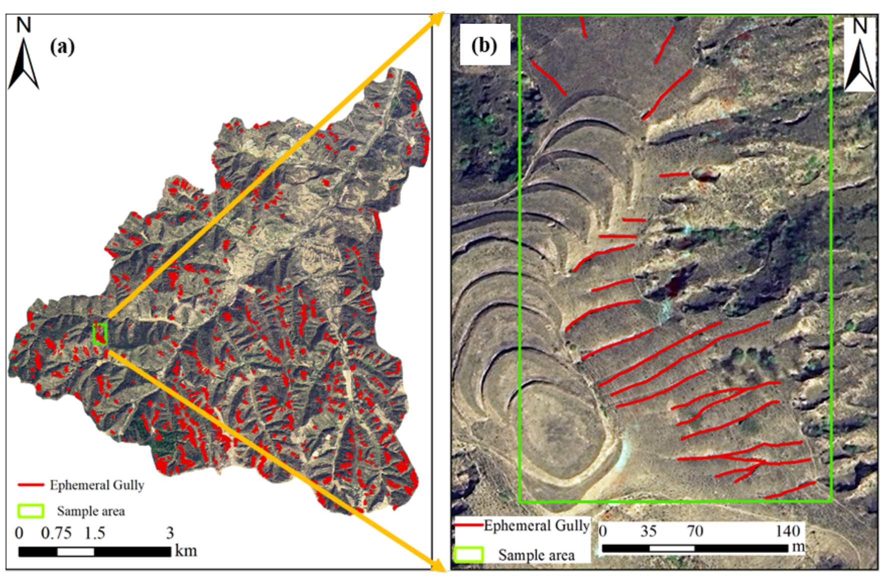


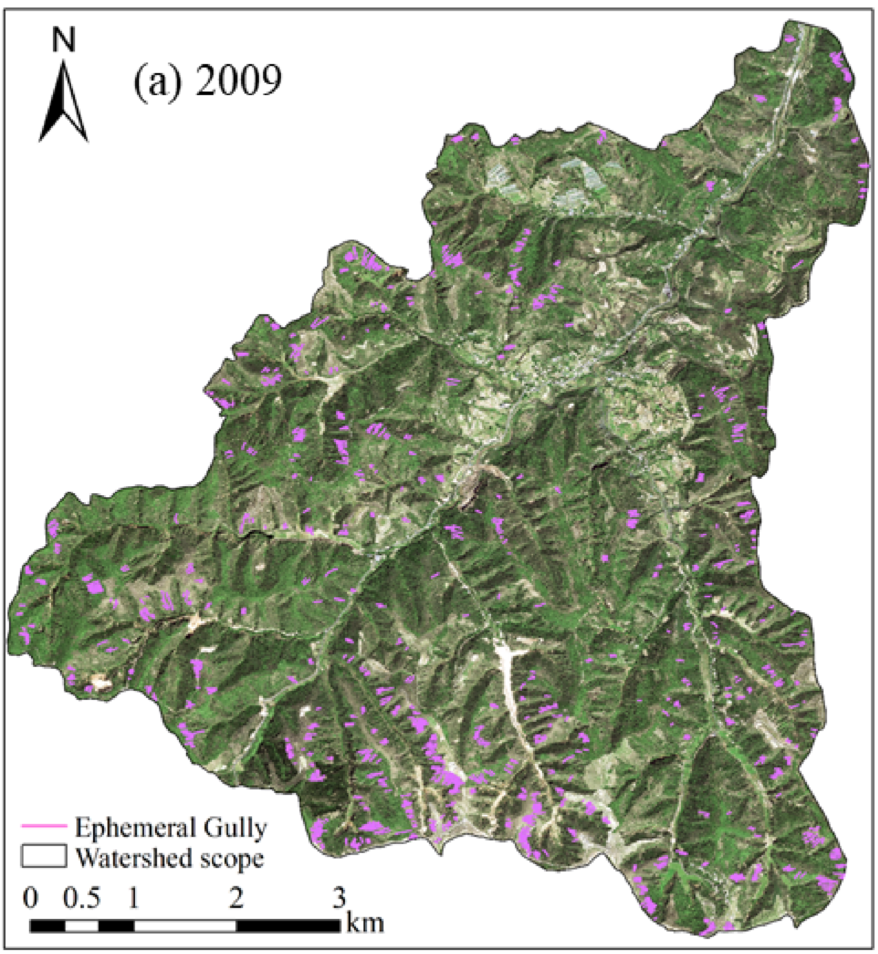
Figure 4. Recognition results of the SegNet model in the Zhoutungou watershed in 2021. Ephemeral gully recognition results at (a) the watershed scale and (b) the sampling area.

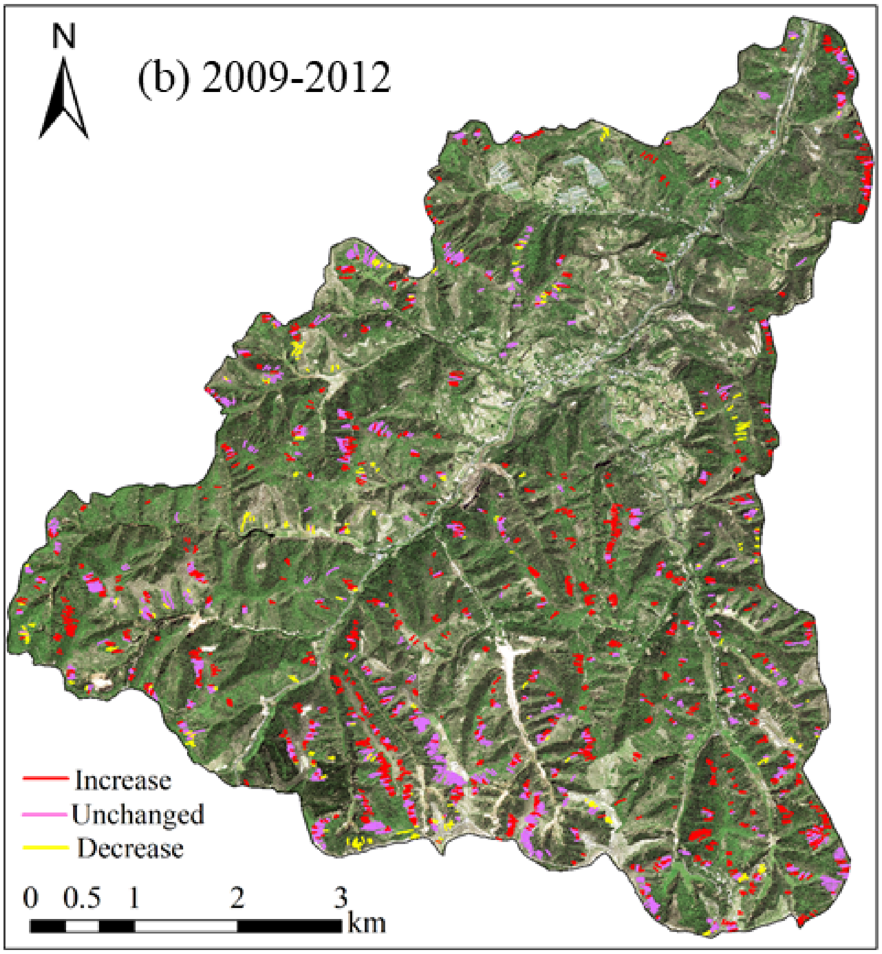
The SegNet model extracted 1,153, 2,045, 2,413, and 2,312 ephemeral gullies encompassing 34.32, 60.86, 71.82, and 68.81 km^2 in 2009, 2012, 2018, and 2021, respectively, with a frequency development rate of 2.87

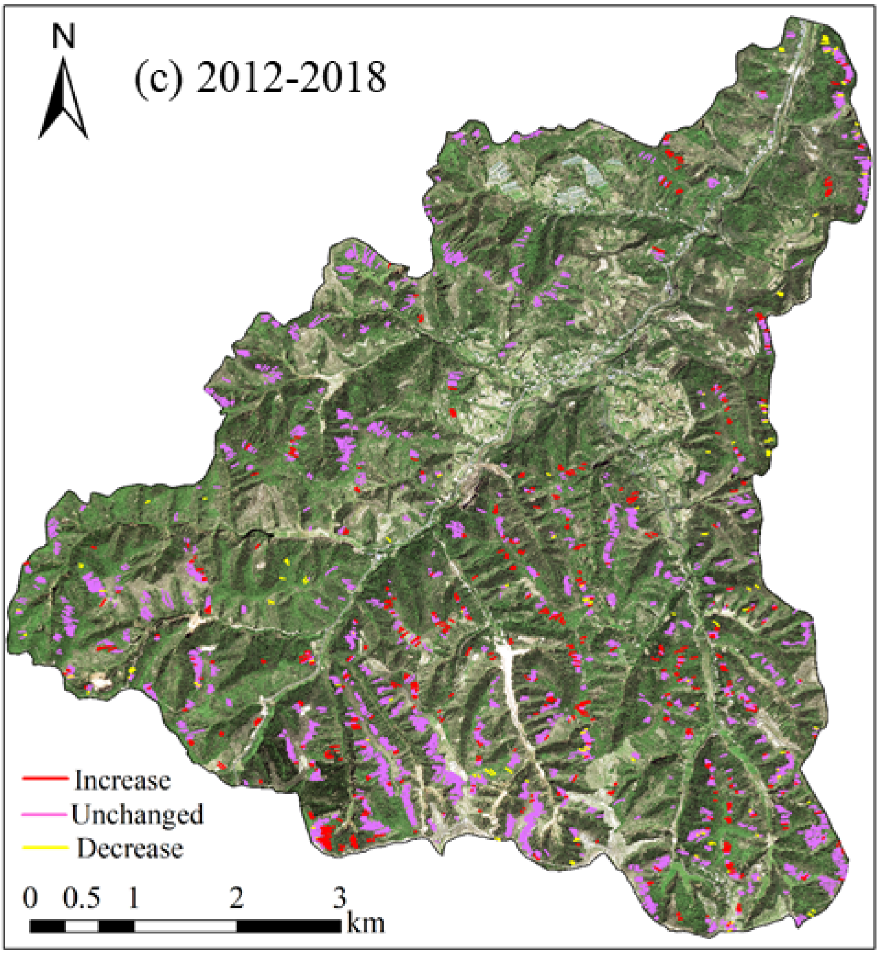
km^2y^{-1} (Table 2). Most of the ephemeral gullies were in the southern half of the Zhoutungou watershed (Fig. 5), which has complex landforms and large slope gradients. From 2009 to 2012, many new ephemeral gullies formed in the northeast and south of the watershed, but some disappeared. From 2012 to 2018, new ephemeral gullies formed in the middle south and southeast regions of the watershed, while others disappeared in the northeast and southwest regions. From 2018 to 2021, only a few regions formed new ephemeral gullies, with many disappearing in the western region.

Table 2 Statistical characteristics for ephemeral gully number and frequency in the Zhoutungou watershed from 2009–2021.

Year	Number	Total area (km^2)	Frequency (km^{-2})	Frequency development rate (km^2 y^{-1})
2009	1,153	33.60	34.32	2.87
2012	2,045		60.86	
2018	2,413		71.82	
2021	2,312		68.81	




N
(b) 2009-2012
Increase
Unchanged
Decrease
0 0.5 1 2 3
km


N
(c) 2012-2018
Increase
Unchanged
Decrease
0 0.5 1 2 3
km

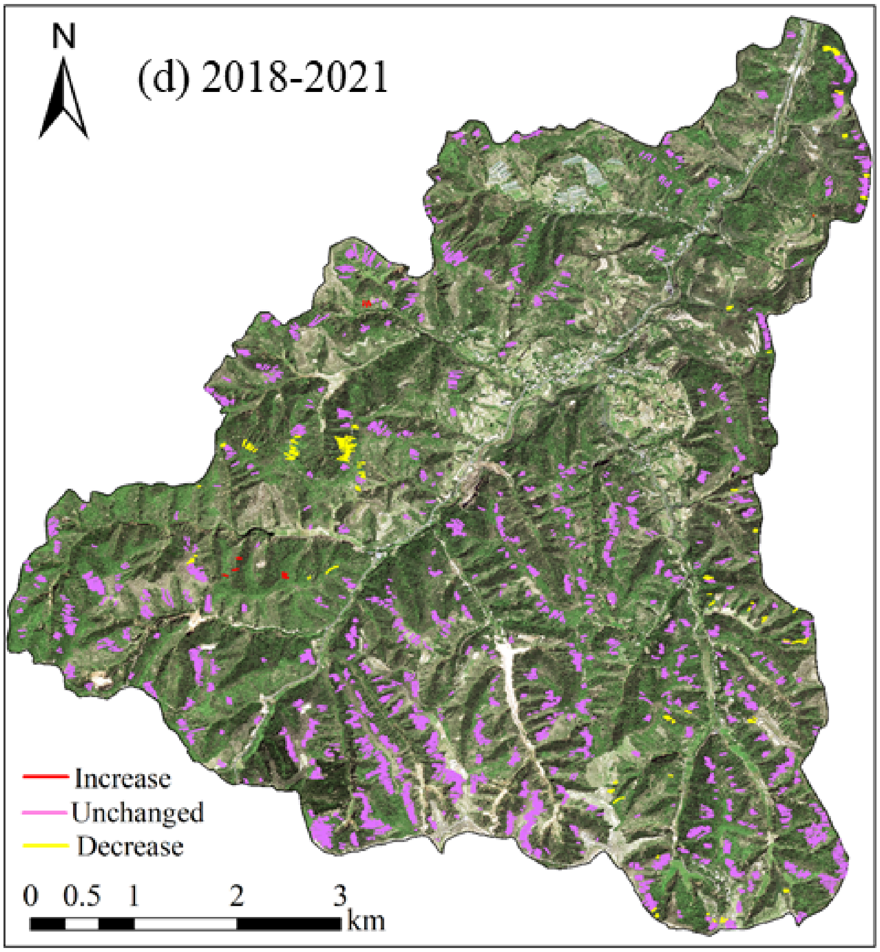


Figure 5. Spatial variation in ephemeral gully distribution from 2009–2021. (a) Ephemeral gully distribution in 2009. Spatial changes in ephemeral gully distribution from (b) 2009–2012, (c) 2012–2018, and (d) 2018–2021.

3.2 Development rate of ephemeral gully morphological features

In 2009, 2012, 2018, and 2021, ephemeral gully lengths ranged from 7.00–209.50, 5.00–228.00, 5.00–230.00, and 5.00–209.50 m (average 48.39, 46.58, 45.75, and 45.84 m) (Table 3), with total ephemeral gully lengths of 55.79, 95.26, 110.40, and 105.98 km and densities of 1.66, 2.84, 3.59, and 3.15 km km^{-2}, respectively, and development rates of 1.66 m y^{-1} (length) and 0.12 km km^{-2} y^{-1} (density). From 2009 to 2021, ephemeral gully width ranged from 0.50 to 2.50 m, with more than 99% between 0.50 and 1.50 m and an average width development rate of 0.04 m y^{-1}. The proportion of ephemeral gully widths 2.00–2.50 m decreased from 0.67% in 2009 to 0.05% in 2021. In 2009, 2012, 2018, and 2021, ephemeral gully area ranged from 6.50–230.71, 4.64–246.86, 4.64–230.00, and 5.36–209.50 m^2(average 49.12, 47.34, 46.05, and 46.36 m^2), total area was 0.0566, 0.0968, 0.1111, and 0.1072 km^2, and dissection degree was 0.17%, 0.29%, 0.33%, and 0.32%, respectively, with development rates of 4,213.39 m^{2}y^{-1} (total area) and 0.0125% y^{-1}(dissection degree). This study found that the development rate of all ephemeral gully morphological parameters gradually decreased over time.

Table 3 Ephemeral gully morphological features from 2009 to 2021 in the Zhoutungou watershed.

Morphological features	Year	Minimum	Maximum	Mean	Total
Length (m)	2009	7.00	209.50	48.39	55792.50
	2012	5.00	228.00	46.58	95295.00
	2018	2.00	230.00	45.75	110400.00
	2021	5.00	209.50	45.84	105980.00
Density (km km^{-2})	2009	2.08×10^{-4}	6.24×10^{-3}	1.44×10^{-3}	1.66
	2012	1.49×10^{-4}	6.79×10^{-3}	1.39×10^{-3}	2.84
	2018	5.95×10^{-5}	6.85×10^{-3}	1.36×10^{-3}	3.29
	2021	1.49×10^{-4}	6.24×10^{-3}	1.36×10^{-3}	3.15
Width (m)	2009	0.50	2.50	1.01	1168.21
	2012	0.50	2.00	1.01	2073.07
	2018	0.50	2.00	1.00	2423.00
	2021	0.50	2.00	1.01	2339.43
Area (m^2)	2009	6.50	230.71	49.12	56600.00
	2012	4.64	246.86	47.34	96800.00
	2018	4.64	230.00	46.05	111100.00
	2021	5.36	209.50	46.36	107200.00
Dissection degree (%)	2009	1.93×10^{-5}	6.87×10^{-4}	1.46×10^{-4}	0.17
	2012	1.38×10^{-5}	7.35×10^{-4}	1.41×10^{-4}	0.29
	2018	1.38×10^{-5}	6.85×10^{-4}	1.37×10^{-4}	0.33
	2021	1.60×10^{-5}	6.24×10^{-4}	1.38×10^{-4}	0.32

3.3 Modeling and applying the *V–L* relationship

In 2021, the total volume of 2,312 ephemeral gullies was 19,175.95 m^3 (per ephemeral gully average 8.29 ± 6.34 m^3), with 82.70% of the single ephemeral gully volume concentrated within 13.0 m^3, and only 3.46% of the single ephemeral gully volume exceeding 20 m^3. The regression model fit the following equation for ephemeral gully volume and length (Fig. 6(a)):

$V = 0.0842L^{1.1932}$ $(R^2 = 0.80,\ n = 1,594)$ (8)

where V is ephemeral gully volume (m^3) and $L$is ephemeral gully length (m).

The above regression function indicated a power function relationship between ephemeral gully volume and ephemeral gully length (R^2 = 0.80). Previous studies also used a power function of the form $V{=}aL^b$ to reveal the relationship between ephemeral gully volume (V) and ephemeral gully length (L), where the values of constant a ranged from 0.0082–2.94 and exponent b ranged from 1.12–2.1622 (Capra et al., 2005; Frankl et al., 2013; Li et al., 2017; Muñoz-Robles et al., 2010; Zucca et al., 2006). In this study, constant a (0.0842) and exponent b (1.1932) were within the corresponding intervals reported in previous studies, and ephemeral gully length can be accurately and conveniently extracted based on large-scale DOM or DEM. Moreover, the volumes of the ephemeral gullies were modeled using Eq. (8) and compared to measured ephemeral gully volumes. Linear regression between the predicted and measured ephemeral gully volumes produced R^2 and RMSE values of 0.97 and 0.85 m^3, respectively (Fig. 5(b)). There was no observable systematic bias between the predicted and measured ephemeral gully volumes using the *V–L* relationship. Therefore, the *V–L*model can be used to assess ephemeral gully volume in the hilly and gully region of the Loess Plateau.

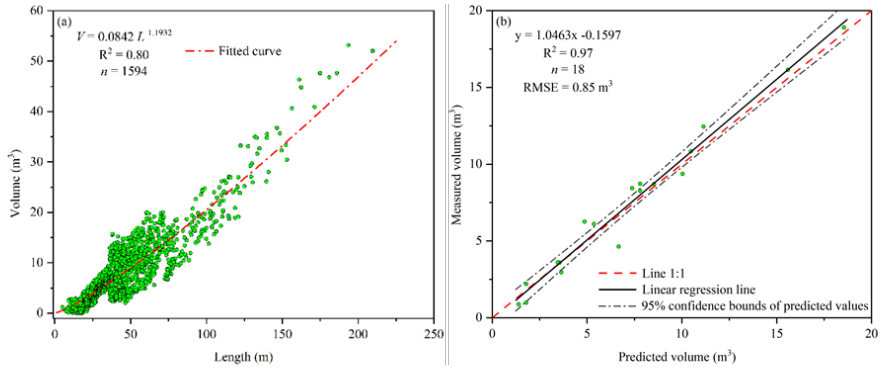


Figure 6. Establishment and verification of the V–L model. (a) Power relationshi between ephemeral gully volume (V) and ephemeral gully length (L). (b) Comparison of predicted ephemeral gully volume with measured ephemeral gully volume.

3.4 Estimation of ephemeral gully erosion volume and erosion rate

Ephemeral gully erosion volume was calculated based on the V–Lmodel using the length of 1,153 ephemeral gullies interpreted by remote sensing images in 2009, with the ephemeral gully erosion volumes in 2009 and 2012 summarized in Table 4. In 2009, the total erosion volume of 1,153 ephemeral gullies was 10,257.60 m^3, with an average erosion volume of each ephemeral gully of 8.90 m^3. In 2021, the total erosion volume of 2,312 ephemeral gullies was 19,175.95 m^3, with an average erosion volume of each ephemeral gully of 8.29 m^3. From 2009 to 2021, the ephemeral gully erosion volume change was mainly in the south of the watershed (Fig. 7), where the terrain is broken and has many steep slopes. In addition, the slope area has damaged soil structure and less vegetation coverage after the gully land consolidation project, so soil erosion can easily occur under extreme rainfall. The average erosion volume of each ephemeral gully increased by 3.54 m^3 or 0.29 m^3y^{-1}, and the total erosion volume of all ephemeral gullies (except for those that disappeared) increased by 8,918.35 m^3 or 743.20 m^3y^{-1} from 2009 to 2021.

Table 4 Ephemeral gully volume from 2009 to 2021 in the Zhoutungou watershed.

Year	Number	Minimum (m^3)	Maximum (m^3)	Mean (m^3)	Total (m^3)	Average annual development rate ($m^3\ y^{-1}$)
2009	1153	0.86	49.54	8.90	10257.60	743.20
2012	2045	0.57	54.80	8.50	17376.93	
2018	2413	0.57	55.38	8.33	20110.76	
2021	2312	0.01	53.16	8.29	19175.95	

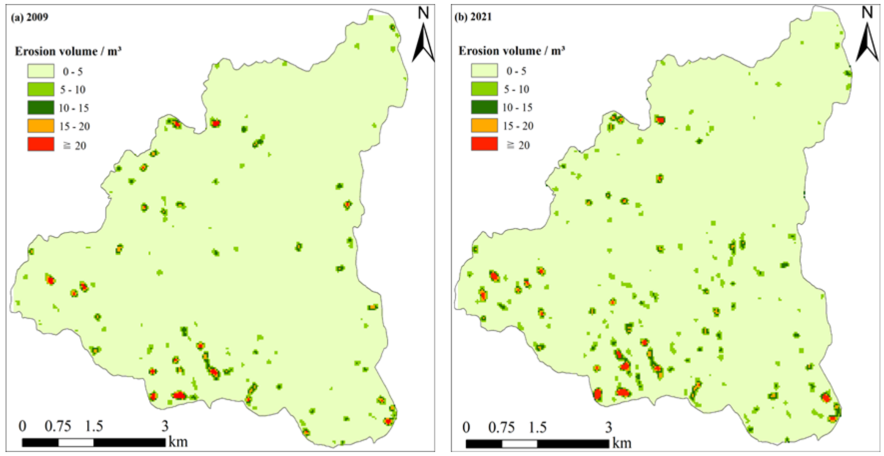


Figure 7. Spatial distribution of ephemeral gully erosion volume in (a) 2009 and (b) 2021.

4. Discussion

4.1 Ephemeral gully morphological parameters

This study combined remote sensing imagery and the SegNet model to analyze temporal and spatial changes of ephemeral gully morphological features at a watershed scale. In 1999, Jiang *et al.* (1999) analyzed the distribution characteristics of ephemeral gullies using W-B (White-Black) aerial photographs, identifying 4,495 ephemeral gullies in the Zhoutungou watershed. We found that the ephemeral gully numbers in the watershed decreased from 4,495 in 1999 to 1,153 in 2009 due to the 'Grain for Green Project' significantly improving vegetation coverage on the Loess Plateau, reducing slope soil erosion and inhibiting the formation and development of slope ephemeral gullies (Chen *et al.* , 2019; Dou *et al.* , 2020; Liang *et al.* , 2019). However, ephemeral gully numbers changed after 2009 due to (1) the frequent occurrence of extreme rainfall on the Loess Plateau increasing soil erosion (Hu *et al.* , 2019; Li *et al.* , 2022; Wang*et al.* , 2020b; Zhao *et al.* , 2021); (2) the gully land consolidation project (implemented in 2011 to increase arable land by excavating soil from the slopes on both sides of gullies, combined with simultaneous comprehensive gully prevention and control measures); despite reducing watershed erosion to a certain extent (Chen *et al.* , 2020; Han *et al.* , 2018; Jin, 2014; Jin *et al.* , 2019; Kang *et al.* , 2021), its associated engineering involving topsoil stripping and ridge construction damaged the slope vegetation (increased slope) and soil environment (loosened soil structure), forming new ephemeral gullies on the slope.

This study found that ephemeral gully lengths ranged from 5 to 230 m (average 48.39 m)—more than 82.35% ranged from 15 to 70 m—with an average growth rate of 1.66 m y^{-1} from 2009 to 2021. However, other studies reported ephemeral gully lengths ranging from 7.71 to 237 m (average 56.50 m), with 60% from 30 to 60 m (Cheng et al., 2006; Cheng et al., 2007; Jiang *et al.,* 1999). The hilly and gully region of the Loess Plateau has a unique and large undulating terrain, prone to developing long ephemeral gullies. Compared with previous studies, our study revealed shorter ephemeral gully lengths, which may be due to ephemeral gullies being: (1) buried or cut off by road construction and the gully land consolidation project, or (2) greatly eroded by headward gully erosion or vertical wall collapse under the influence of extreme rainfall.

4.2 *V*–*L* relationship

The V–L relationship was best described by a power equation $V{=}aL^b$, with Eq. 8 revealing an R^2 value of 0.80, constant a of 0.0842, and exponent b of 1.1932, all within the corresponding intervals reported in previous studies (Capra et al., 2005; Frankl et al., 2013; Li et al., 2017; Muñoz-Robles et al., 2010; Zucca et al., 2006) and indicating that ephemeral gully length was a good predictor of ephemeral gully erosion volume. However, Li et al. (2017) showed that the relationship between gully volume and gully area had a larger Nash-Sutcliffe efficiency (Ens) and coefficient of determination (R^2) and smaller relative error (Er) than the relationship between gully volume and gully length, indicating that the V–Ag prediction model performed better than the V–Lrelationship.

Ephemeral gullies are those transitioning from rill to gully. Due to the characteristics of ephemeral gullies and the limitation of DOM/DEM resolution, it is difficult to accurately obtain ephemeral gully areas. Ephemeral gully length is the most easily and accurately obtained morphological parameter from high-resolution remote sensing images, with good R^2 and RMSE between the V–L models established in this study, and thus has great application potential for estimating ephemeral gully erosion volume in the hilly and gully region of the Loess Plateau in China.

4.3 Ephemeral gully erosion rate

The world is under serious threat of soil erosion. The ephemeral gully erosion rate in Europe and America is 90–6,490 t km^{-2} y^{-1} (Capra et al., 2009; Li et al., 2016; Maetens et al., 2012; Panagos et al., 2015; Valcárcel et al., 2003). On the Loess Plateau, the ephemeral gully erosion rate without vegetation coverage is about 1,000–12,000 t km^{-2} y^{-1}, and with vegetation coverage is 215 t km^{-2} y^{-1} in the Loess Plateau (Zhang et al., 2017; Zheng, 2006). This study estimated an ephemeral gully erosion rate of 22.12 m^{3}km^{-2} y^{-1} or 28.75 t km^{-2} y^{-1} (average soil bulk density is 1.3 g cm^{-3}) based on high-resolution remote sensing images in the watershed from 2009 to 2021, considerably lower than previous results but attributed to the improved vegetation coverage in the watershed since the Chinese government implemented the 'Grain for Green Project' in 1999.

The increased vegetation coverage and biomass results in a dense vegetation canopy that can intercept and redistribute rainwater and reduce the kinetic energy of raindrops, and the grassland cover and plant litter can reduce runoff erosion by avoiding the direct impact of raindrops on soil, increasing soil infiltration capacity and runoff resistance and decreasing runoff velocity (Hayas et al., 2017; Mukai, 2017; Sun et al., 2016; Vanmaercke et al., 2016). In addition, the well-developed root systems have great physical and chemical binding effects for combining soil particles and soil aggregates to improve soil cohesion and the shear strength and tensile strength of the soil–root matrix, significantly enhancing soil resistance to erosion (Allen et al., 2018; Barthès and Roose, 2002; De Baets and Poesen, 2015; Guo et al., 2019; Khan and Lateh, 2015; Wang et al., 2021c; Zegeye et al., 2018; Zhao et al., 2013). In summary, vegetation restoration has improved soil erosion conditions and enhanced regional water and soil conservation benefits.

5. Conclusion

The SegNet model was used to recognize ephemeral gullies and extract their morphological features at a watershed scale from 2009 to 2021 to analyze temporal and spatial distribution characteristics of ephemeral gullies in the hilly and gully region of the Loess Plateau. This study showed that ephemeral gullies are mainly located in the southern part of the watershed, where there are complex landforms and steep slopes. The increase in ephemeral gully number, length, width, total area, frequency, density, dissection degree, and erosion volume was 97 y^{-1}, 1.66 m y^{-1}, 0.04 m y^{-1}, 4,213.39 m^{2}y^{-1}, 2.87 km^{2}y^{-1}, 0.12 km km^{-2}y^{-1}, 0.0125% y^{-1}, and 22.12 m^3 km^{-2} y^{-1}, respectively. The regression analysis revealed a power function relationship between ephemeral gully erosion volume and length:$V = 0.0842L^{1.1932}$ ($R^2 = 0.80,\ n = 1,594$). Indeed, The regression analysis revealed ephemeral gully length can be measured accurately and easily from high-resolution satellite images. This study demonstrated that assessing ephemeral gully erosion volume and volume rate is feasible using a regression model of ephemeral gully erosion volume and length from historical high-resolution remote sensing images in the hilly and gully region of the Loess Plateau in China.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (41977064), National Key R&D Program of China (2021YFD1900700), Fundamental Research Funds for the Central Universities (2452021158; 2452021036), and 111 Project of the Ministry of Education and the State Administration of Foreign Experts Affairs (B12007). The authors express their gratitude to colleagues in their research group for their help with the experiments.

References

Allen, P.M., Arnold, J.G., Auguste, L., White, J., Dunbar, J., 2018. Application of a simple headcut advance model for gullies. Earth Surface Processes and Landforms, 43, 202-217.*https://doi.org/10.1002/esp.4233*.

Anache, J.A.A., Flanagan, D.C., Srivastava, A., Wendland, E.C., 2018. Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado. Science of The Total Environment, 622-623, 140-151.*https://doi.org/10.1016/j.scitotenv.2017.11.257*.

Aneseyee, A.B., Elias, E., Soromessa, T., Feyisa, G.L., 2020. Land use/land cover change effect on soil erosion and sediment delivery in the Winike watershed, Omo Gibe Basin, Ethiopia. Science of The Total Environment, 728, 138776.*https://doi.org/10.1016/j.scitotenv.2020.138776*.

Arabameri, A., Pradhan, B., Rezaei, K., 2019. Spatial prediction of gully erosion using ALOS PALSAR data and ensemble bivariate and data mining models. Geosciences Journal, 1, 1-18. *https://doi org/10.1007/s12303-018-0067-3*.

Badrinarayanan, V., Kendall, A., Cipolla, R., 2017. SegNet: a deep convolutional encoder-decoder architecture for image segmentation. IEEE Transactions on Pattern Analysis and Machine Intelligence, 39, 2481-2495.*https://doi.org/10.1109/TPAMI.2016.2644615*.

Barthès, B., Roose, E., 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena, 47, 133-149.*https://doi.org/10.1016/S0341-8162(01)00180-1*.

Boardman, J., Favis-Mortlock, D., Foster, I., 2015. A 13-year record of erosion on badland sites in the Karoo, South Africa. Earth Surface Processes and Landforms, 40, 1964-1981.*https://doi.org/10.1002/esp.3775*.

Cao, J.J., Tang, G.A., Fang, X., Liu, Y.J., Zhu, Y., Li, J.L., Wagner, W., 2020. Identification of active gully erosion sites in the Loess Plateau of China using MF-DFA. Remote Sensing, 12, 589.*https://doi.org/10.3390/rs12030589*.

Cao, Z.H., Ke, Q.H., Zhang, K.L., Zhang, Z.D., Liu, Y.N., Xiao, S.Z., Wei, M.Y., 2022. Millennial scale erosion and sedimentation investigation in karst watersheds using dating and palynology. Catena, 217, 106526.*https://doi.org/10.1016/j.catena.2022.106526*.

Capra, A., Mazzara, L.M., Scicolone, B., 2005. Application of the EGEM model to predict ephemeral gully erosion in Sicily, Italy. Catena, 59, 133-146.*https://doi.org/10.1016/j.catena.2004.07.001*.

Capra, A., Porto, P., Scicolone, B., 2009. Relationships between rainfall characteristics and ephemeral gully erosion in a cultivated catchment in Sicily (Italy). Soil and Tillage Research, 105, 77-87.*https://doi.org/10.1016/j.still.2009.05.009*.

Casalí, J., Loizu, J., Campo, M.A., De Santisteban, L.M., Álvarez-Mozos, J., 2006. Accuracy of methods for field assessment of rill and ephemeral gully erosion. Catena, 67, 128-138.*https://doi.org/10.1016/j.catena.2006.03.005*.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. Nature Sustainability, 2, 122-129.*https://doi.org/10.1038/s41893-019-0220-7*.

Chen, W.L., Xu, Q., Zhao, K.Y., Zhou, X.P., Li, S.L., Wang, J., Wang, X.C., Xu, J.Q., 2020. Spatial analysis of land-use management for gully land consolidation on the Loess Plateau in China. Ecological Indicators, 117, 106633.*https://doi.org/10.1016/j.ecolind.2020.106633*.

Cheng, H., Wu, Y.Q., Zou, X.Y., Si, H., Zhao, Y.Z., Liu, D.G., Yue, X.L., 2006. Study of ephemeral gully erosion in a small upland catchment on the Inner-Mongolian Plateau. Soil and Tillage Research, 90, 184-193.*https://doi.org/10.1016/j.still.2005.09.006*.

Cheng, H., Zou, X.Y., Wu, Y.Q., Zhang, C.L., Zheng, Q.H., Jiang, Z.Y., 2007. Morphology parameters of ephemeral gully in characteristics hillslopes on the Loess Plateau of China. Soil and Tillage Research, 94, 4-14.*https://doi.org/10.1016/j.still.2006.06.007*.

Choudhury, B.U., Nengzouzam, G., Islam, A., 2022. Evaluation of climate change impact on soil erosion in the integrated farming system based hilly micro-watersheds using Revised Universal Soil Loss Equation. Catena, 214, 106306.*https://doi.org/10.1016/j.catena.2022.106306*.

Dai, W., Hu, G.H., Yang, X., Yang, X.W., Cheng, Y.H., Xiong, L.Y., Strobl, J., Tang, G.A., 2020. Identifying ephemeral gullies from high-resolution images and DEMs using flow-directional detection. Journal of Mountain Science, 17, 3024-3038.*https://doi.org/10.1007/s11629-020-6084-5*.

De Baets, S., Poesen, J., 2010. Empirical models for predicting the erosion-reducing effects of plant roots during concentrated flow erosion. Geomorphology, 118, 425-432.*https://doi.org/10.1016/j.geomorph.2010.02.011*.

Deng, T.F., Fu, B.L., Liu, M., He, H.C., Fan, D.L., Li, L.L., Huang, L.K., Gao, E.T., 2022. Comparison of multi-class and fusion of multiple single-class SegNet model for mapping karst wetland vegetation using UAV images. Scientific Reports, 12, 13270.*https://doi.org/10.1038/s41598-022-17620-2*.

Devátý, J., Dostál, T., Hösl, R., Krása, J., Strauss, P., 2019. Effects of historical land use and land pattern changes on soil erosion – Case studies from Lower Austria and Central Bohemia. Land Use Policy, 82, 674-685.*https://doi.org/10.1016/j.landusepol.2018.11.058*.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics, 69, 1858-1868.*https://doi.org/10.1016/j.ecolecon.2010.05.002*.

Dou, Y.X., Yang, Y., An, S.S., Zhu, Z.L., 2020. Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. Catena, 185, 104294.*https://doi.org/10.1016/j.catena.2019.104294*.

Eekhout, J.P.C., de Vente, J., 2022. Global impact of climate change on soil erosion and potential for adaptation through soil conservation. Earth-Science Reviews, 226, 103921.*https://doi.org/10.1016/j.earscirev.2022.103921*.

Evans, M., Lindsay, J., 2010. High resolution quantification of gully erosion in upland peatlands at the landscape scale. Earth Surface Processes and Landforms, 35, 876-886.*https://doi.org/10.1002/esp.1918*.

Fox, G.A., Sheshukov, A., Cruse, R., Kolar, R.L., Guertault, L., Gesch, K.R., Dutnell, R.C., 2016. Reservoir sedimentation and upstream sediment sources: perspectives and future research needs on streambank and gully erosion. Environmental Management, 57, 945-955.*https://doi.org/10.1007/s00267-016-0671-9* .

Frankl, A., Poesen, J., Scholiers, N., Jacob, M., Haile, M., Deckers, J., Nyssen, J., 2013. Factors controlling the morphology and volume (V)–length (L) relations of permanent gullies in the northern Ethiopian Highlands. Earth Surface Processes and Landforms, 38, 1672-1684.*https://doi.org/10.1002/esp.3405*.

Fu, B.J., Liu, Y., Lü, Y.H., He, C.S., Zeng, Y., Wu, B.F., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecological Complexity, 8, 284-293.*https://doi.org/10.1016/j.ecocom.2011.07.003*.

Fu, B.J., Wang, S., Liu, Y., Liu, J.B., Liang, W., Miao, C.Y., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annual Review of Earth and Planetary Sciences, 45, 223-243.*https://doi.org/10.1146/annurev-earth-063016-020552*.

Galdies, C., Azzopardi, D., Sacco, A., 2022. Estimates of soil erosion rates in a principal watershed in Gozo, Malta under current and future climatic conditions. Catena, 210, 105900.*https://doi.org/10.1016/j.catena.2021.105900*.

Gholami, A., Bonakdari, H., Mohammadian, M., Zaji, A.H., Gharabaghi, B., 2019. Assessment of geomorphological bank evolution of the alluvial threshold rivers based on entropy concept parameters. Hydrological Sciences Journal, 64, 856-872.*https://doi.org/10.1080/02626667.2019.1608995*.

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.*https://doi.org/10.1016/j.catena.2014.04.004*.

Guduru, J.U., Jilo, N.B., 2022. Assessment of rainfall-induced soil erosion rate and severity analysis for prioritization of conservation measures using RUSLE and Multi-Criteria Evaluations Technique at Gidabo watershed, Rift Valley Basin, Ethiopia. Ecohydrology & Hydrobiology.*https://doi.org/10.1016/j.ecohyd.2022.09.002*.

Guo, M.M., Wang, W.L., Shi, Q.H., Chen, T.D., Kang, H.L., Li, J.M., 2019. An experimental study on the effects of grass root density on gully headcut erosion in the gully region of China's Loess Plateau. Land Degradation & Development, 30, 2107-2125.*https://doi.org/10.1002/ldr.3404*.

Gupta, A.K., Rudra, R.P., Gharabaghi, B., Daggupati, P., Goel, P.K., Shukla, R., 2019. CoBAGNPS: A toolbox for simulating water and sediment control basin, WASCoB through AGNPS model. Catena, 179, 49-65.*https://doi.org/10.1016/j.catena.2019.02.003*.

Han, X.L., Lv, P.Y., Zhao, S., Sun, Y., Yan, S.Y., Wang, M.H., Han, X.N., Wang, X.R., 2018. The effect of the gully land consolidation project on soil erosion and crop production on a typical watershed in the Loess Plateau. Land, 7, 113.*https://doi.org/10.3390/land7040113*.

Hao, H.X., Cheng, L., Guo, Z.L., Wang, L., Shi, Z.H., 2020. Plant community characteristics and functional traits as drivers of soil erodibility mitigation along a land degradation gradient. Land Degradation & Development, 31, 1851-1863.*https://doi.org/10.1002/ldr.3579*.

Hayas, A., Poesen, J., Vanwalleghem, T., 2017. Rainfall and vegetation effects on temporal variation of topographic thresholds for gully initiation in Mediterranean Cropland and Olive Groves. Land Degradation & Development, 28, 2540-2552.*https://doi.org/10.1002/ldr.2805*.

Hu, J.F., Gao, P., Mu, X.M., Zhao, G.J., Sun, W.Y., Li, P.F., Zhang, L.M., 2019. Runoff-sediment dynamics under different flood patterns in a Loess Plateau catchment, China. Catena, 173, 234-245.*https://doi.org/10.1016/j.catena.2018.10.023*.

Jiang, J., Lyu, C.J., Liu, S.Y., He, Y.Q., Hao, X.T., 2020. RWSNet: a semantic segmentation network based on SegNet combined with random walk for remote sensing. International Journal of Remote Sensing, 41, 487-505.*https://doi.org/10.1080/01431161.2019.1643937*.

Jiang, Y.Q., Wang, Z.L., Hu, G.R., Hao, X.P., 1999. Distribution features of shallow gully. Research of Soil and Water Conservation, 6, 182-185.*https://doi.org/10.3969/j.issn.1005-3409.1999.02.037*. (in Chinese with English abstract)

Jin, Z., 2014. The creation of farmland by gully filling on the Loess Plateau: a double-edged sword. Environment Science & Technology, 48, 883-4.*https://doi.org/10.1021/es405392c*.

Jin, Z., Guo, L., Wang, Y.Q., Yu, Y.L., Lin, H., Chen, Y.P., Chu, G.C., Zhang, J., Zhang, N.P., 2019. Valley reshaping and damming induce water table rise and soil salinization on the Chinese Loess Plateau. Geoderma, 339, 115-125.

https://doi.org/10.1016/j.geoderma.2018.12.048.

Kang, Y.C., Gao, J.E., Shao, H., Zhang, Y.Y., Li, J., Gao, Z., 2021. Evaluating the flow and sediment effects of gully land consolidation on the Loess Plateau, China. Journal of Hydrology, 600, 126535.*https://doi.org/10.1016/j.jhydrol.2021.126535*.

Karydas, C., Panagos, P., 2020. Towards an assessment of the ephemeral gully erosion potential in Greece using google earth. Water, 12, 603.*https://doi.org/10.3390/w12020603*.

Kearney, S.P., Fonte, S.J., García, E., Smukler, S.M., 2018. Improving the utility of erosion pins: absolute value of pin height change as an indicator of relative erosion. Catena, 163, 427-432.*https://doi.org/10.1016/j.catena.2017.12.008*.

Khan, Y.A., Lateh, H., 2015. Plant Root Reinforcement Against Local Failure Mechanism of Natural Slope. in: Lollino, G., Giordan, D., Crosta, G.B., Corominas, J., Azzam, R., Wasowski, J., Sciarra, N. (Eds.), Engineering Geology for Society and Territory - Volume 2. Springer International Publishing, Cham, pp. 1275-1280.

King, C., Baghdadi, N., Lecomte, V., Cerdan, O., 2005. The application of remote-sensing data to monitoring and modelling of soil erosion. Catena, 62, 79-93.*https://doi.org/10.1016/j.catena.2005.05.007*.

Koch, A., McBratney, A., Adams, M., Field, D., Hill, R., Crawford, J., Minasny, B., Lal, R., Abbott, L., O'Donnell, A., Angers, D., Baldock, J., Barbier, E., Binkley, D., Parton, W., Wall, D.H., Bird, M., Bouma, J., Chenu, C., Flora, C.B., Goulding, K., Grunwald, S., Hempel, J., Jastrow, J., Lehmann, J., Lorenz, K., Morgan, C.L., Rice, C.W., Whitehead, D., Young, I., Zimmermann, M., 2013. Soil security: Solving the global soil crisis. Global Policy, 4, 434-441.*https://doi.org/10.1111/1758-5899.12096*.

Kompani-Zare, M., Soufi, M., Hamzehzarghani, H., Dehghani, M., 2011. The effect of some watershed, soil characteristics and morphometric factors on the relationship between the gully volume and length in Fars Province, Iran. Catena, 86, 150-159.*https://doi.org/10.1016/j.catena.2011.03.008*.

Li, H., Cruse, R.M., Bingner, R.L., Gesch, K.R., Zhang, X.Y., 2016. Evaluating ephemeral gully erosion impact on Zea mays L. yield and economics using AnnAGNPS. Soil and Tillage Research, 155, 157-165.*https://doi.org/10.1016/j.still.2015.07.018*.

Li, P.F., Chen, J.N., Zhao, G.J., Holden, J., Liu, B.T., Chan, F.K.S., Hu, J.F., Wu, P.L., Mu, X.M., 2022. Determining the drivers and rates of soil erosion on the Loess Plateau since 1901. Science of The Total Environment, 823, 153674.*https://doi.org/10.1016/j.scitotenv.2022.153674*.

Li, Z., Zhang, Y., Zhu, Q.K., Yang, S., Li, H.J., Ma, H., 2017. A gully erosion assessment model for the Chinese Loess Plateau based on changes in gully length and area. Catena, 148, 195-203.*https://doi.org/10.1016/j.catena.2016.04.018*.

Liang, W., Fu, B.J., Wang, S., Zhang, W.B., Jin, Z., Feng, X.M., Yan, J.W., Liu, Y., Zhou, S., 2019. Quantification of the ecosystem carrying capacity on China's Loess Plateau. Ecological Indicators, 101, 192-202.*https://doi.org/10.1016/j.ecolind.2019.01.020*.

Liu, B.Y., Zhang, B., Feng, H., Wu, S.F., Yang, J.T., Zou, Y.F., Siddique, K.H.M., 2022. Ephemeral gully recognition and accuracy evaluation using deep learning in the hilly and gully region of the Loess Plateau in China. International Soil and Water Conservation Research, 10, 371-381.*https://doi.org/10.1016/j.iswcr.2021.10.004*.

Liu, Y.B., Zhu, X.M., Zhou, P.H., Tang, K.L., 1988. The laws of hillslope channel erosion occurence and development on Loess Plateau. Memoir of NISWC, Academia Sinica, 7, 9-18. (in Chinese with English abstract)

Lufira, R.D., Andawayanti, U., Cahya, E.N., Dianasari, Q., 2022. Land conservation based on erosion and sedimentation rate (case study of Genting Watershed Ponorogo Regency). Physics and Chemistry of the Earth, Parts A/B/C, 126, 103143.*https://doi.org/10.1016/j.pce.2022.103143*.

Maetens, W., Vanmaercke, M., Poesen, J., Jankauskas, B., Jankauskiene, G., Ionita, I., 2012. Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data. Progress in Physical Geography, 36, 599-653.*https://doi.org/10.1177/0309133312451303*.

Manickam, R., Kumar Rajan, S., Subramanian, C., Xavi, A., Eanoch, G.J., Yesudhas, H.R., 2020. Person identification with aerial imaginary using SegNet based semantic segmentation. Earth Science Informatics, 13, 1293-1304.*https://doi,org/10.1007/s12145-020-00516-y.*

McBratney, A., Field, D.J., Koch, A., 2014. The dimensions of soil security. Geoderma, 213, 203-213.*https://doi.org/10.1016/j.geoderma.2013.08.013.*

Mohammed, S., Al-Ebraheem, A., Imre, H., Alsafadi, K., Dikkeh, M., Pham, Q., Linh, N., Szabo, S., 2020. Soil management effects on soil water erosion and runoff in central Syria-A comparative evaluation of General Linear Model and Random Forest Regression. Water, 2529.*https://doi.org/10.3390/w12092529.*

Montanarella, L., Pennock, D., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Aulakh, M., Yagi, K., Hong, S.Y., Vijarnsorn, P., Zhang, G.L., Arrouays, D., Black, H., Krasilnikov, P., Sobocká, J., Alegre, J., Henríquez, C., Vargas, R., 2016. World's soils are under threat. Soil, 2, 79-82.*https://doi.org/10.5194/soil-2-79-2016.*

Mukai, S., 2017. Gully erosion rates and analysis of determining factors: A case study from the semi-arid main Ethiopian Rift Valley. Land Degradation & Development, 28, 602-615.*https://doi.org/10.1002/ldr.2532.*

Muñoz-Robles, C., Reid, N., Frazier, P., Tighe, M., Briggs, S.V., Wilson, B., 2010. Factors related to gully erosion in woody encroachment in south-eastern Australia. Catena, 83, 148-157.*https://doi.org/10.1016/j.catena.2010.08.002.*

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environmental Science & Policy, 54, 438-447.*https://doi.org/10.1016/j.envsci.2015.08.012.*

Pandey, S., Kumar, P., Zlatic, M., Nautiyal, R., Panwar, V.P., 2021. Recent advances in assessment of soil erosion vulnerability in a watershed. International Soil and Water Conservation Research, 9, 305-318.*https://doi.org/10.1016/j.iswcr.2021.03.001.*

Pennock, D., 2019. Soil Erosion: The Greatest Challenge for Sustainable Soil Management. FAO–Food and Agriculture Organization of the United Nations, Rome.

Perroy, R.L., Bookhagen, B., Asner, G.P., Chadwick, O.A., 2010. Comparison of gully erosion estimates using airborne and ground-based LiDAR on Santa Cruz Island, California. Geomorphology, 118, 288-300.*https://doi.org/10.1016/j.geomorph.2010.01.009.*

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena, 50, 91-133.*https://doi.org/10.1016/S0341-8162(02)00143-1.*

Ran, L.S., Lu, X.X., Xu, J.C., 2013. Effects of vegetation restoration on soil conservation and sediment loads in China: A critical review. Critical Reviews in Environmental Science and Technology, 43, 1384-1415.*https://doi.org/10.1080/10643389.2011.644225.*

Romanescu, G., Cotiuga, V., Asandulesei, A., Stoleriu, C., 2012. Use of the 3-D scanner in mapping and monitoring the dynamic degradation of soils: case study of the Cucuteni-Baiceni Gully on the Moldavian Plateau (Romania). Hydrology and Earth System Sciences, 16, 953-966.*https://doi.org/10.5194/hess-16-953-2012.*

Shen, H.O., Feng, J., Wang, D.L., Li, H.L., Wang, Y., 2021. Characteristics of soil erosion and sediment size distribution for different land uses in the Chinese Mollisol region. Journal of Mountain Science, 18, 1295-1306.*https://doi.org/10.1007/s11629-020-6553-x.*

Sun, L., Zhang, G.H., Liu, F., Luan, L.L., 2016. Effects of incorporated plant litter on soil resistance to flowing water erosion in the Loess Plateau of China. Biosystems Engineering, 147, 238-247.*https://doi.org/10.1016/j.biosystemseng.2016.04.017.*

Sun, W.Y., Shao, Q.Q., Liu, J.Y., Zhai, J., 2014. Assessing the effects of land use and topography on soil erosion on the Loess Plateau in China. Catena, 121, 151-163.*https://doi.org/10.1016/j.catena.2014.05.009*.

Tahouri, J., Sadiki, A., Karrat, L.h., Johnson, V.C., Chan, N.W., Fei, Z., Kung, H.T., 2022. Using a modified PAP/RAC model and GIS-for mapping water erosion and causal risk factors: Case study of the Asfalou watershed, Morocco. International Soil and Water Conservation Research, 10, 254-272.*https://doi.org/10.1016/j.iswcr.2021.07.003*.

Tamene, G.M., Adiss, H.K., Alemu, M.Y., 2020. Effect of slope aspect and land use types on selected soil physicochemical properties in north western Ethiopian highlands. Applied and Environmental Soil Science, 2020, 8463259.*https://doi.org/10.1155/2020/8463259*.

Tesema, T.A., 2022. Erosion hotspot mapping using integrated morphometric parameters and Land use/land cover of Jigjiga Watershed, Ethiopia. Heliyon, 8, e09780.*https://doi.org/10.1016/j.heliyon.2022.e09780*.

Valcárcel, M., Taboada, M.T., Paz, A., Dafonte, J., 2003. Ephemeral gully erosion in northwestern Spain. Catena, 50, 199-216.*https://doi.org/10.1016/S0341-8162(02)00139-X*.

Vallejo Orti, M., Negussie, K., Corral-Pazos-de-Provens, E., Höfle, B., Bubenzer, O., 2019. Comparison of three algorithms for the evaluation of TanDEM-X data for gully detection in Krumhuk farm (Namibia). Remote Sensing, 11, 1327.*https://doi.org/10.3390/rs11111327*.

Vanmaercke, M., Poesen, J., Van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., Bezerra, J.F.R., Bolysov, S., Dvinskih, A., Frankl, A., Fuseina, Y., Guerra, A.J.T., Haregeweyn, N., Ionita, I., Makanzu Imwangana, F., Moeyersons, J., Moshe, I., Nazari Samani, A., Niacsu, L., Nyssen, J., Otsuki, Y., Radoane, M., Rysin, I., Ryzhov, Y.V., Yermolaev, O., 2016. How fast do gully headcuts retreat? Earth-Science Reviews, 154, 336-355.*https://doi.org/10.1016/j.earscirev.2016.01.009*.

Wang, B., Zhang, G.H., Shi, Y.Y., Zhang, X.C., 2014. Soil detachment by overland flow under different vegetation restoration models in the Loess Plateau of China. Catena, 116, 51-59.*https://doi.org/10.1016/j.catena.2013.12.010*.

Wang, D.D., Yuan, Z.J., Cai, Y.T., Jing, D.W., Liu, F., Tang, Y., Song, N.N., Li, Y.Y., Zhao, C.Y., Fu, X.Y., 2021c. Characterisation of soil erosion and overland flow on vegetation-growing slopes in fragile ecological regions: A review. Journal of Environmental Management, 285, 112165.*https://doi.org/10.1016/j.jenvman.2021.112165*.

Wang, J.X., Zhang, Y., Deng, J.Y., Yu, S.W., Zhao, Y.Y., 2021b. Long-term gully erosion and its response to human intervention in the tableland region of the Chinese Loess Plateau. Remote Sensing, 13, 5053.*https://doi.org/10.3390/rs13245053*.

Wang, L., Zheng, F.L., Liu, G., Zhang, X.C.J., Wilson, G.V., Shi, H.Q., Liu, X.J., 2021a. Seasonal changes of soil erosion and its spatial distribution on a long gentle hillslope in the Chinese Mollisol region. International Soil and Water Conservation Research, 9, 394-404.*https://doi.org/10.1016/j.iswcr.2021.02.001*.

Wang, N., Jiao, J.Y., Bai, L.C., Zhang, Y.F., Chen, Y.X., Tang, B.Z., Liang, Y., Zhao, C.J., Wang, H.L., 2020b. Magnitude of soil erosion in small catchments with different land use patterns under an extreme rainstorm event over the Northern Loess Plateau, China. Catena, 195, 104780.*https://doi.org/10.1016/j.catena.2020.104780*.

Wang, W.L., Lei, A.L., Li, Z.B., Tang, K.L., 2003. Study on dynamic mechanism of rills, shallow furrows and gully in the soil erosion chain. Advances in Water Science, 371-375.*https://doi.org/10.3321/j.issn:1001-6791.2003.04.015*.

Wang, Y.Z., Dong, Y.F., Su, Z.A., Mudd, S.M., Zheng, Q.H., Hu, G., Yan, D., 2020a. Spatial distribution of water and wind erosion and their influence on the soil quality at the agropastoral ecotone of North China. International Soil and Water Conservation Research, 8, 253-265.*https://doi.org/10.1016/j.iswcr.2020.05.001*.

Wang, Z.G., Zhang, G.H., Wang, C.S., Xing, S.K., 2022. Assessment of the gully erosion susceptibility using three hybrid models in one small watershed on the Loess Plateau. Soil and Tillage Research, 223, 105481.*https://doi.org/10.1016/j.still.2022.105481.*

Woodward, D.E., 1999. Method to predict cropland ephemeral gully erosion. Catena, 37, 393-399.*https://doi.org/10.1016/S0341-8162(99)00028-4.*

Yermolayev, O., Platoncheva, E., Essuman-Quainoo, B., 2020. Spatial-temporal dynamics of the ephemeral gully belt on the plowed slopes of river basins in natural and anthropogenic landscapes of the east of the Russian plain. Geosciences, 10, 167.*https://doi.org/10.3390/geosciences10050167.*

Zegeye, A.D., Langendoen, E.J., Tilahun, S.A., Mekuria, W., Poesen, J., Steenhuis, T.S., 2018. Root reinforcement to soils provided by common Ethiopian highland plants for gully erosion control. Ecohydrology, 11, e1940.*https://doi.org/10.1002/eco.1940.*

Zhang, Y., Fan, C.H., Gong, Y.H., Zhang, J.H., 2017. Investigation on ephemeral gully erosion rate based on QuickBird images in Loess Hilly region. Transactions of the Chinese Society for Agricultural Machinery, 48, 239-244.*https://doi.org/10.6041/j.issn.1000-1298.2017.08.027.* (in Chinese with English abstract)

Zhang, Y.G., Wu, Y.Q., Liu, B.Y., Zheng, Q.H., Yin, J.Y., 2007. Characteristics and factors controlling the development of ephemeral gullies in cultivated catchments of black soil region, Northeast China. Soil and Tillage Research, 96, 28-41.*https://doi.org/10.1016/j.still.2007.02.010.*

Zhao, L.S., Fang, Q., Hou, R., Wu, F.Q., 2021. Effect of rainfall intensity and duration on soil erosion on slopes with different microrelief patterns. Geoderma, 396, 115085.*https://doi.org/10.1016/j.geoderma.2021.115085.*

Zhao, W.J., Wang, H.Y., Zhang, Z.Y., Feng, S.W., Zheng, Y.K., Li, S., Luo, Y., Liu, H.Y., 2022. Discrimination of soil magnetism enhanced by land use and its implications for inferring alterations in sediment sources and soil erosion in a homogeneous watershed: An example from the Guizhou Plateau, SW China. Catena, 217, 106476.*https://doi.org/10.1016/j.catena.2022.106476.*

Zhao, Y.G., Wu, P.T., Zhao, S.W., Feng, H., 2013. Variation of soil infiltrability across a 79-year chronosequence of naturally restored grassland on the Loess Plateau, China. Journal of Hydrology, 504, 94-103.*https://doi.org/10.1016/j.jhydrol.2013.09.039.*

Zheng, F.L., Jiang, Z.S., Wu, M., 2006. Ephemeral gully erosion process and modeling in the Loess Plateau of China, PROCEEDINGS of the Eighth Federal Interagency Sedimentation Conference (8thFISC), Reno, NV, USA, pp. 689-697.

Zucca, C., Canu, A., Della Peruta, R., 2006. Effects of land use and landscape on spatial distribution and morphological features of gullies in an agropastoral area in Sardinia (Italy). Catena, 68, 87-95.*https://doi.org/10.1016/j.catena.2006.03.015.*