Analysis of Difference for Gully Density and the Relationship between Terrain Factors and Gully Density in the Loess Plateau Based on Google Earth and GIS

Jiangshan Zhu1* and Chenglei Hou2

1School of Geological Engineering and Geomatics, Chang’an University, Shaanxi, China
2Shandong Agriculture and Engineering University, Shandong, China

*Corresponding author e-mail: 2018126055@chd.edu.cn

Abstract. Based on ASTER GDEM V2 (30 meter) and the corresponding Google Earth high-resolution images data, small-catchments artificial interaction and random points sample method were used to estimate gully density of five selected catchments in the Loess Plateau and analysis the relationship between the difference for gully density from two methods and the areas of catchments. Besides the gully density, terrain factors such as slope, flow accumulation as well as the distribution probability of gully were calculated by using spatial analysis method. The statistical analysis method was used to analyze the correlation between gully density and terrain factors and obtain gully characteristic distribution prediction model. The results of the study indicate the following: (1) the average difference of gully density extracted by random point method and artificial interactive method is 7.86%, and the difference appears to increase first and then decrease with the watershed area. When the area of catchment is 76 km², the difference is closed to 0; when the area is 131 km², the difference is closed to maximum value, which is 0.182. The time-saving and labor-saving random point method can replace the tedious artificial interaction method. (2) The gully slope on Loess Plateau is mainly distributed at 10°~30° (74%), and the flow accumulation of gully distribution is mainly distributed at 0~0.07 km² (95%); 10°~30° and 0~0.07 km² can be used as critical reference values for, respectively. (3) The gully distribution probability showed a when slope gradient was lower than 30 degree, while a negative correlation of gully density and the flow accumulation were found in this study.

Keywords: Gully Density; Terrain Factors; Google Earth; Random Points Methods; Loess Plateau

1. Introduction

Soil erosion is one of the main environmental problems facing human development in the world today [1], and soil erosion and the resulting land degradation and sedimentation problems are serious global environmental and disaster problems [2-4]. My country is a country with very serious soil erosion, especially the soil erosion in the Loess Plateau has become the main bottleneck restricting the development of western my country [5]. The gully is a typical landform of the Loess Plateau, one of the main sources of sediment in the Loess Plateau, and also a landform type with severe soil erosion.
[6]. Relevant studies have shown that most of the sediment in the Loess Plateau comes from the erosion of slopes and gullies. Among them, small watershed-scale studies show that gully erosion and sediment yield account for about 70% of the total sediment yield [27]. Due to the high sand yield of the gully system in the Loess Plateau, scholars have carried out a series of studies on the geomorphic characteristics and the occurrence of the gully system in the Loess Plateau [8-12].

Topographic feature factors, such as slope, flow accumulation, area elevation integral, and gully density are important reference factors for studying the development and distribution of landforms. Among them, for the gully critical value extraction method, based on continuous research on gully development and distribution, the predecessors improved the extraction algorithm of related topographic factors to obtain the characteristic threshold of gully distribution. Trible [13] took into account the spatial variation of geomorphic parameters or other parameters reflecting geomorphic features, and set different thresholds for different geomorphic regions. Xiong et al. [14] derived a highly automated method for automatically extracting the catchment area of the river network based on the watershed (256 km²) based on the digital elevation model (DEM) of the watershed. Sun et al. [15] took the Yanqi River basin (with an area of 92 km²) in Beijing as the research object, extracted the river network water system, analyzed the influence of the critical support area (CSA) on the total length and average slope of the water system, and obtained the critical support area for landform development about river in the basin.

In the Loess Plateau, some scholars have used DEM data and related statistical methods to study the correlation and spatial differentiation between the basic landform types and related topographic features (such as average slope, average slope length, and undulation) of the Loess Plateau, and establish the correlation model between them [16-17]. Li et al. [18] analyzed the quantitative relationship between confluence threshold and gully density based on the characteristics of multiple landform types in the Loess Plateau of northern Shaanxi and applied DEM data with a resolution of 5m. The results showed that the model coefficients of the study area can be effectively constructed. Quantitative relationship between sink threshold and gully density. On this basis, Chen et al. [19-20] took different watersheds in the gully area of the Loess Plateau as the research object, and based on DEM data of different resolutions, set different thresholds to extract the gullies and obtain reasonable thresholds for different gully areas of the Loess Plateau. range. Recently, Yang et al. [21] proposed an efficient and comprehensive method for the distribution of flow direction and flow in flat areas. It can use algorithms related to the cumulative value and weight value of confluence in areas with large undulations and set certain catchment area threshold to extract the gully. Tang et al. [22] used Google Earth images and ASTER GDEM data to propose a large-scale gully area mapping method based on the relationship between the gully and surface runoff.

To sum up, although predecessors have done relevant research on the extraction of topographic factors, the correlation between basic topographic types and individual topographic factors in the Loess Plateau, the simple and high-precision gully density extraction method, gully density and multiple Research on the correlation of terrain feature factors is still rare. Therefore, by selecting five watersheds with typical gully geomorphic features in the Loess Plateau, this paper uses small-catchments artificial interaction and random points sample method to extract five regional gully samples, and analyzes the difference in gully density of the two methods, and the correlation between gully density and the two topographic factors (slope and flow accumulation, respectively), and their related critical values of the two topographic factors, as well as establishes a prediction model of gully distribution characteristics.

2. Materials and Methods

2.1. Research Area
The Loess Plateau is located in northern China, with an area of approximately 640 000 km², and is one of the four largest plateaus in China. The Loess Plateau in the narrow sense includes Longzhong, Longdong, Ningnan, Northern Shaan, and Western Shanxi[23]; the broad sense of the Loess Plateau
starts from the Qilian Mountains in the west to the Riyue Mountain in Qinghai, to the Taihang Mountain in the east, and to the Qinling and Funiu Mountains in the south Jie, north to the Great Wall [24] (Figure 1). The elevation of the Loess Plateau is between 1 000 m and 3 000 m [25]. Numerous gullies, rugged terrain and strong modern erosion are the outstanding features of typical loess landforms. The Loess Plateau is extremely fragile, and the management of the ecological environment of the Loess Plateau has always been an important and arduous task.

In order to enable the research results to represent the distribution characteristics of the Loess Plateau gully to a greater extent, this study randomly selected five typical areas in the core area of the Loess Plateau gully as the research objects, located in the north and south of Qingyang City, the junction of Qingyang and Yanan city, Yan'an City, and the northeast of Yulin City. Figure 1 is a schematic diagram of the distribution of five research sub-regions (N1-N5).

![Figure 1](image)

**Figure 1.** The Loess Plateau and the five sub-study areas of this study: N1-N5

2.2. Data Sources

This research uses ASTER GDEM V2 30m resolution figures jointly released by the National Aeronautics and Space Administration (NASA) and the Ministry of Economy Trade and Industry (METI) on January 6, 2015. The elevation data comes from the geospatial data cloud platform (http://www.gscloud.cn). From north to south, download five sceneries of typical areas of the Loess Plateau in turn, with latitude between 35°N-38°N and longitude between 107°E-110°E. The selected area has obvious characteristics of the Loess Plateau, which can meet the requirements of studying the critical value and correlation of relevant topographic factors in the valley area of the Loess Plateau.

2.3. Methods
2.3.1. **Gully extraction methods.** (1) small-catchments artificial interaction method. First, randomly select a small watershed in each of the five study areas, extract the gully of the small watershed through artificial interaction in Google Earth, vectorize the gully, count the area of the gully, and calculate the gully density of the small watershed. The formula for calculating gully density \((GD)\) is:

\[
GD = \frac{\sum A_g}{A_c}
\]  

Where, \(GD\) refers to the gully density, \(\sum A_g\) is the total area of the gully extracted from the watershed in the study area, and \(A_c(\text{km}^2)\) is the total area of the small watershed.

(2) Random points sample method. Artificial interaction can accurately extract the gully density, but due to the large workload, it is only suitable for small-scale research. In order to study the distribution characteristics of the gully density at a larger scale, this paper uses a Random points sample method to extract the gully density of the area. Zhao et al [7] used the Random points sample method for the first time to estimate the gully density of 46 watersheds in the Loess Plateau. The basic steps of this method are as follows: Firstly, randomly distribute several samples in the selected study area, import them into Google Earth, and judge whether the sample points fall in the gully system through artificial identification. Finally, the gully density of the watershed area is calculated as: the ratio of the sample points \((S_g)\) falling into the gully system to the total sample points \((S_t)\):

\[
GD = \frac{S_g}{S_t}
\]  

Figure 2.a is the total number of samples randomly distributed in a certain watershed, Figure 2.b is the non-ditch samples, and Figure 2.c is the gully samples.

Zhao et al [7] found through error analysis that for small watersheds \((\text{area} < 1000 \text{ km}^2)\), it is economical to have a sample point of about 100, that is, considering random sample extraction errors and artificial time-consuming. In order to improve the accuracy of random sample extraction, this study also compared with artificial interactive extraction of gully density, generated 200 total samples in each research object, and analyzed the difference between Random points sample method and artificial interactive method to extract gully density.
2.3.2. Terrain feature factor extraction. On the basis of selecting watersheds in each study area and using two methods to extract gully information, further study the geomorphic features and related critical values of the gully. Based on the 30m resolution digital elevation data of ASTER GDEM V2, this paper extracts and calculates the terrain feature factors of each study area and gully respectively. Based on the previous research and the research purpose of this article, the slope and flow accumulation [26] and two main topographic factors are selected to analyze the geomorphological characteristics of the gully. The extraction and calculation methods of geomorphic factors are mainly based on ArcGIS related models, among which:

1. Slope calculation
   Use the slope calculation function of the raster surface in the 3D analysis tool to extract the slope of the DEM raster data.

2. Calculation of flow accumulation
   Flow accumulation refers to how many grids of water flow converge to a certain point. According to the flow direction raster layer, the tracking accumulation calculation of the raster is performed, and the grid of the accumulation amount of the confluence is established. The principle of flow statistics is to count the total number of grids flowing through the pixel point in the flow direction grid. Use the hydrology analysis tool in the spatial analysis function to calculate the flow accumulation.

2.3.3. Spatial analysis and statistical analysis. On the basis of extracting the gully density and related topographic factors, the frequency distribution of the topographic factors of the gully is analyzed, and the distribution probability of the related topographic factors of the gully is calculated. At the same time, compare the distribution probability of gully topography factors in different regions. Finally, based on the correlation analysis between gully density and topographic factors in the five research areas, a gully density distribution model based on topographic factors is established.
(1) Analysis of the geomorphic characteristics of the gully
The extracted gully and the above-mentioned extracted slope and flow accumulation are superimposed and analyzed, and the corresponding topographic factor characteristic value of each gully is calculated. Analyze the probability of gully distribution and topographic factor characteristics in different regions.

(2) Gully distribution feature prediction model
Based on the extraction of gully density and corresponding terrain feature factors, the correlation between gully distribution and terrain factors is analyzed, and a prediction model of gully density distribution and related terrain factors is established based on the regression statistical model.

3. Results and Analysis

3.1. Gully Density
Table 1 shows the results of gully density extraction using two methods: small watershed artificial interaction method and random sampling method. Among them, the watershed area is the total area of the watershed (km²); the sample watershed area is the area of the small watershed where the artificial interactive extraction gully is located (km²); the random sample gully density is, in the entire watershed area, the ratio of the number of points to the total number of randomly scattered points (%); the artificial gully density is the ratio (%) of the gully area extracted artificially and the sample watershed area. Figure 3.a shows the relationship between the difference between the random sample gully density and the artificial gully density and the watershed area.

| Watershed | Watershed area /km² | Sample watershed area /km² | Sample watershed area / Watershed area (%) | Random sample GD (%) | Artificial GD (%) |
|-----------|---------------------|----------------------------|---------------------------------------------|----------------------|------------------|
| N1        | 154.76              | 41.84                      | 27.04                                       | 35.00                | 20.67            |
| N2        | 165.04              | 22.27                      | 13.49                                       | 33.00                | 24.96            |
| N3        | 119.27              | 46.46                      | 38.95                                       | 58.00                | 41.67            |
| N4        | 57.28               | 14.00                      | 24.44                                       | 50.50                | 64.80            |
| N5        | 112.66              | 6.01                       | 5.34                                        | 45.50                | 30.57            |
Figure 3. Relationship between gully density difference and watershed area

It can be seen from Table 1 that when the selected watershed area is different, the difference between the random sample gully density and the artificial gully density is different. The N4 watershed area is 57.28 km², and the artificial gully density is about 15% higher than the random sample gully density; the N1, N2, N3 and N5 watershed area is larger than the N4 watershed area, between 100-200 km², the random sample gully density is higher than the artificial gully density. Overall, the gully density of the five watersheds is between 20% and 60%, and the average gully density is 36%.

It can be seen from Figure 3.a that the difference in gully density extracted by the two methods is correlated with the size of the watershed area, and the average difference in gully density extracted by the two methods is 7.86%. Analyzing the gully errors of the five watersheds and the two methods, it can be seen that the error value first increases and then decreases with the watershed area, that is, as the watershed area represented by a random sample increases, the larger the error, the larger the error reaches a certain limit. After the value, the error gradually decreases. When the watershed area is 76 km², the error is close to 0, that is, the gully density extracted by the Random points sample method is consistent with the artificial interaction method; when the watershed area is 131 km², the error is close to the maximum value, which is 0.182. Therefore, the random sample point method can effectively estimate the gully density of a certain watershed area.

Figure 4 is extraction gully density map of five watersheds. Among them, the dark red dots are randomly scattered sample points, and the area enclosed by thin red lines is the gully sample extracted artificially.
3.2. Distribution Characteristics of Slope

In order to analyze the gully slope distribution characteristics of the Loess Plateau, the gully area extracted by the Random points sample method and the slope of the study area are superimposed and analyzed to obtain the gully slope distribution characteristics. Table 2 shows the slope probability statistics of the five watersheds, and Figure 5 shows the slope frequency statistics of the five watersheds.

| Slope(°) | N1  | N2  | N3  | N4  | N5  | ALL |
|---------|-----|-----|-----|-----|-----|-----|
| 0-10    | 0.11| 0.11| 0.09| 0.09| 0.23| 0.13|
| 10-20   | 0.47| 0.29| 0.36| 0.38| 0.50| 0.40|
| 20-30   | 0.31| 0.44| 0.36| 0.39| 0.24| 0.34|
| 30-40   | 0.11| 0.14| 0.16| 0.12| 0.03| 0.12|
| >40     | 0.00| 0.02| 0.03| 0.02| 0.00| 0.01|

Table 2. Probability statistics of slopes in five watersheds
It can be seen from Table 2 that the gully slopes of the Loess Plateau are widely distributed, but mainly distributed between 10° and 30°. It can be seen from Figure 5 that the gully samples in this slope interval accounted for 74.0% of the total samples: among them, the gully samples with a slope in the interval of 10°-20° accounted for 40% of the total samples; the gully samples with a slope in the interval of 20°-30° Road samples accounted for 34% of the total samples. When the slope is greater than 40°, the gully probability is less than 1%.

3.3. Distribution Characteristics of Flow Accumulation

In the same way, the extracted gully area and the study area's confluence cumulant are layered and analyzed to obtain the distribution characteristics of the confluence cumulant of the gully sample points. Table 3 shows the statistical results of the probability statistics of the cumulants of the five river basins, and Figure 5 shows the statistical results of the cumulants of the five river basins.

| flow accumulation (km²) | N1  | N2  | N3  | N4  | N5  | ALL |
|-------------------------|-----|-----|-----|-----|-----|-----|
| 0                       | 0.29| 0.18| 0.30| 0.31| 0.35| 0.29|
| 0-0.005                 | 0.42| 0.42| 0.45| 0.39| 0.38| 0.41|
| 0.005-0.01              | 0.11| 0.17| 0.09| 0.10| 0.09| 0.11|
| 0.01-0.07               | 0.10| 0.22| 0.14| 0.14| 0.13| 0.14|
| >0.07                   | 0.08| 0.01| 0.02| 0.06| 0.05| 0.05|

**Figure 5. Statistical analysis diagram of gully slope**

![Figure 5. Statistical analysis diagram of gully slope](image)
It can be seen from Table 3 that the flow accumulation of the sample points is mainly concentrated between 0 and 0.07 km². It can be seen from Fig. 5 that the gully samples in this flow accumulation interval account for 95% of the total samples in the gully region. Among them: the gully samples with cumulative confluence in the interval of 0~0.01 km² accounted for 81% of the total samples; the gully samples with cumulative confluence in the interval of 0.01~0.07 km² accounted for 14% of the total samples. When the flow accumulation is greater than 0.07 km², the gully probability is less than 5%.

3.4. Gully Distribution Feature Prediction Model

Based on the statistical analysis of slope and flow accumulation, using multiple regression statistical analysis method, a prediction model of gully distribution characteristics is established:

\[ GD = 0.0146 \times S' - 71.4233 \times A' + 0.9269 \] (3)

Where, GD refers to the gully density, \( S' \) is the weighted average value of the slope distribution in the watershed, and \( A' \) is the weighted average value of the flow accumulation distribution in the watershed. among them,

\[ S' = \sum (S \times P_s) \] (4)

\[ A' = \sum (a \times P_a) \] (5)

Where, \( S \) is the slope value, \( P_s \) is the probability corresponding to the slope value, and \( a \) is the value of the flow accumulation, \( P_a \) which refers to the probability corresponding to the value of the flow accumulation.

According to the prediction model of gully distribution characteristics, for a certain range of slopes, as the slope increases, surface runoff is easier to form, the ability of surface erosion is greater, and the probability of developing into a gully is greater. Therefore, the gully density in this area is larger, the gully distribution and slope show positive correlation; the greater the flow accumulation, the stronger the erosion capacity of the area, the less likely to form surface runoff, the less probable it will develop into a gully, and the greater the probability of being located in the river gully, so the gully density in this area is relatively small, and the gully distribution and the flow accumulation show a negative correlation.
4. Discussion
Gully is one of the main landform types in the Loess Plateau, and it is also the main source of sediment in this area. Recently, a large number of studies have been conducted on the gully distribution and topographic characteristics of the Loess Plateau. Due to the complex distribution and formation mechanism of gully landforms in the Loess Plateau, its distribution is wide and uneven, it is difficult to carry out quantitative research and spatial distribution extraction. At present, in the small-scale range, part of the research is based on high-resolution remote sensing data, using a relatively time-consuming artificial interaction method to extract the gully range and estimate the gully density. At the same time, some scholars use a relatively efficient Random points sample method to estimate the gully in small watersheds, and use this method as verification data to test the accuracy of the gully based on remote sensing and digital elevation model estimation. The comparative study in this paper shows that the results of the Random points sample method have a certain accuracy and relatively high efficiency. However, compared with the artificial interaction method with higher accuracy, this method often underestimates the gully density of the watershed, and the error is different from the experimental results. It is related to the size of the basin area. Therefore, when using this method to estimate the gully density, attention should be paid to the watershed area limitation of its application.

At the same time, the characteristics of the spatial distribution of the geomorphic factors of the gully density in the Loess Plateau have received extensive attention. Based on DEM, the predecessors conducted extensive research on the terrain complexity of the Loess Plateau and the structural characteristics of the gully network [29]. Based on five typical regions of the Loess Plateau, this study studies the distribution of the two main factors, the slope of the gully distribution and the flow accumulation. This study shows that the slopes of the gullies collected based on random samples are mainly concentrated between 10° and 30°, accounting for 74% of the total samples. This shows that the gullies of the Loess Plateau are mainly distributed in the valley areas with larger slopes. The results of previous studies are consistent. Flow accumulation is another important geomorphological factor, describing the ability of surface erosion from another aspect. The confluence threshold is an important parameter extracted from the valley network [20]. This study shows that the flow accumulation in the gully of the Loess Plateau is mainly concentrated in 0–0.07 km² (accounting for 94% of the sample). This shows that the Loess Plateau gully is mainly distributed in the upper reaches of the basin. Runoff has a strong ability to damage the stability of surface materials, making it easier to transport surface materials. The upstream area has a large slope and strong surface erosion ability, and soil erosion is relatively easy to occur. Therefore, the probability of gully development is greater. In the gully region, this flow accumulation range occupies the largest proportion. When the flow accumulation is greater than a certain threshold (>0.07 km²), the water flow is rapid and the water flow is large, and the ability to wash the surface is too strong, so that the surface develops beyond the intermediate state of the gully and quickly develops into a river gully.

Although there are many studies on the geomorphological characteristics of the Loess Plateau gully, there is currently a lack of large-scale studies on the density distribution of the Loess Plateau gully. Based on DEM data with medium-scale resolution and Google Earth high-resolution images, this paper conducts a preliminary study on the two geomorphic factors of gully distribution in the Loess Plateau, namely slope and flow accumulation, and obtains the critical values of the two factors of gully distribution. This value can be used as a critical reference value for large-scale gully density estimation.

5. Conclusion
By selecting five regions with typical geomorphological features in the Loess Plateau, based on 30m resolution ASTER GDEM V2 and Google Earth high-resolution image data, small-catchments artificial interaction and random points sample method were used to estimate gully density of five selected catchments in the Losses Plateau and analysis the relationship between the difference for gully density from two methods and the areas of catchments. The correlation between gully density and the two topographic factors (slope and flow accumulation, respectively) were analysis. The related
critical values of the two topographic factors were calculated. And a prediction model of gully distribution characteristics was established.

1) The average difference between the gully density value extracted by the Random points sample method and the gully density value extracted artificially is 7.86% and the size of the difference first increases and then decreases with the watershed area. When the watershed area is 76 km², the error is close to 0; when the basin area is 131 km², the error is close to the maximum value, which is 0.182. Therefore, the random sample point method can effectively estimate the gully density of a certain area of watershed basin, and its applicability and accuracy are limited by the watershed area.

2) Through geo-statistical analysis, the distribution characteristics of the slope of the Loess Plateau gully and the flow accumulation are obtained: Among them, the gully slope of the Loess Plateau is mainly distributed between 10° and 30°, accounting for 74% of the total sample. The gully flow accumulation is mainly concentrated in 0-0.07 km², accounting for 95% of the total sample. The above values can be used as critical reference values for geomorphological factors related to gully distribution in the Loess Plateau.

3) Based on the gully prediction linear model, when the slope is below 30°, the gully distribution and the slope are positively correlated, when the slope is above 30°, the gully distribution and the slope are negatively correlated; gully distribution and confluence The cumulative amount shows a negative correlation.

4) Based on the above-mentioned study on the difference between the random sampling method and the artificial interaction method for extracting gully density and the preliminary results of the two geomorphic factors of slope and flow accumulation, it is necessary to increase the range and number of typical geomorphic areas of the Loess Plateau in the future. Random points sample method and artificial interaction method are used to extract the difference of gully density and related geomorphological factors for further research, and provide reference for the estimation of large-scale gully density.

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References

[1] Zheng S.F. Discussion on soil erosion prevention and protection strategies and measures[J]. Water Conservancy Science and Cold Region Engineering, 2019, 2(5): 135-138.
[2] Zhang Y.T., Xiao H.B., Nie X.D., et al. Research progress of soil erosion at home and abroad in the past 30 years based on bibliometric analysis[J]. Acta Pedologica Sinica, 2020, 57(4): 797-810.
[3] Bao W. Analysis of soil erosion and soil erosion[J]. Hunan Water Resources and Hydropower, 2010, 1: 42-43.
[4] Dai Y.J. Discussion on Soil Erosion and Ecological Environment[J]. Groundwater, 2014, 36(4): 109-110.
[5] Zhang Y. Research on the ground slope spectrum of the Loess Plateau[D]. Northwest University, 2003.
[6] Xu X.Z. Model test study on sediment interception effect of dam system in the Loess Plateau [D]. Tsinghua University, 2005.
[7] Zhao J.L., Vanmaercke M, Chen L.Q, et al. Vegetation cover and topography rather than human disturbance control gully density and sediment production on the Chinese Loess Plateau[J]. Geomorphology, 2016, 274(dec.1): 92-105.
[8] He L.H. Evaluation and Model Research on the Renovation Potential of the Loess Plateau Gully[D]. Nanjing University, 2014.
[9] Guo W.Z. Experimental Study on Gravity Erosion and Sediment Yield Process of Loess Gully[D]. Dalian University of Technology, 2018.
[10] Wang L.L. Water-sediment coupling mechanism of different spatial scales in the loess hilly and gully area[D]. Northwest Sci-Tech University of Agriculture and Forestry, 2017.

[11] Wang L. Spatial frequency spectrum analysis of erosion gullies in small watersheds of the Loess Plateau[D]. Graduate School of Chinese Academy of Sciences (Research Center for Soil and Water Conservation and Ecological Environment, Ministry of Education), 2013.

[12] Yang T. Research and Application of Two-scale Runoff and Sediment Yield Mathematical Models Based on GIS in Loess Gully Region[D]. Nanjing Normal University, 2006.

[13] Tribe A. Automated recognition of valley lines drainage networks from grid digital elevation models: a review and a new method---Comment[J]. Journal of Hydrology, 1992, 139(1-4): 263-293.

[14] Xiong L.H, Guo S.L. Discussion on DEM-based digital river network generation method [J]. Journal of Yangtze River Scientific Research Institute, 2003, 20(4): 14-17.

[15] Sun Y.B, Gong H.L, Zhao W.J, et al. Discussion on DEM-based digital river network generation method[J]. Journal of Capital Normal University (Natural Science Edition), 2005, 26(2): 106-111.

[16] Zhang T. Research on the spatial correlation characteristics of multiple topographic factors in the Loess Plateau of northern Shaanxi based on DEM [D]. Northwest University, 2005.

[17] Zhu H.C, Liu H.Y, Tang G.A, et al. Simulation of the quantitative relationship between DEM terrain information factors—taking the experiment on the Loess Plateau in northern Shaanxi as an example[J]. Journal of Shandong University of Science and Technology (Natural Science Edition), 2006, 25(2): 16-19.

[18] Li J., Tang G.A, Zhang T., et al. Using DEM to extract the confluence threshold of the valley network of the Loess Plateau in northern Shaanxi[J]. Bulletin of Soil and Water Conservation, 2007, 27(2): 75-78.

[19] Chen T, Zhu J.Z, Ma H., et al. Research on the threshold range for gully extraction in the gully area of the Loess Plateau[J]. Journal of Yangtze River Scientific Research Institute. 2008, 25(3): 28-30.

[20] An Y.C. Research on the distribution characteristics of valley systems and site types in the Loess Plateau[D]. Beijing Forestry University, 2009.

[21] Zhang H.M, Yao Z.H, Yang Q.K., et al. An integrated algorithm to evaluate flow direction and flow accumulation in flat regions of hydrologically corrected DEMs[J]. Catena, 2017, 151: 174-181.

[22] Liu K., Hu D., Tang G.A., et al. Large-scale mapping of gully-affected areas: An approach integrating Google Earth images and terrain skeleton information[J]. Geomorphology, 2018, 314(AUG.1): 13-26.

[23] Luo L.X. Divide the gully land and gully type landform types in the loess regions of western Shanxi, northern Shaanxi, and eastern Gansu[J]. Acta Geographica Sinica, 1956, 23(3): 201-222.

[24] Zhang B.S, Zhang R.H. The natural boundary of the Loess Plateau[J]. Journal of Northwest University, 1984(4): 67-85.

[25] Editorial Committee of "Chinese Natural Geography", Chinese Academy of Sciences: "Chinese Natural Geography and Geomorphology", Science Press, 1980.

[26] Yang J.L. Research on watershed feature extraction based on multi-scale DEM [D]. Fuzhou University, 2010.

[27] Tang G.A, Zhu S.J, Li F.Y., et al. Study on the area elevation integral of the Loess Plateau based on DEM[J]. Acta Geographica Sinica, 2013, 68(7): 921-932.

[28] Pike R J, Wilson S E. Elevation-Relief Ratio, Hypsometric Integral, and Geomorphic Area-Altitude Analysis[J]. Geological Society of America Bulletin, 1971, 82(4): 1079-1084.

[29] Liu G., Li Sh.D, Zhang Liang. Overview of gully extraction algorithms based on DEM[J]. Geography and Geo-Information Science, 2003, 19(5): 11-14.