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RESEARCH ARTICLE

Combined gully profiles for expressing surface morphology and evolution of gully landforms

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Abstract The expression of gully landforms can be regarded as an indicator of the evolutionary process of gullies. Most existing studies on the expression of gully landforms focus on plane characteristics. However, the vertical characteristics of a gully should be given considerable attention because gullies have mainly eroded the surface in the vertical direction. Current studies on vertical characteristics of gullies mainly focused on a single gully or rarely a few gullies, thereby failing to express the entire gully landform in a certain area. In this study, gully profile combination (GPC) was proposed to investigate the morphology and reveal the evolution of gully landforms. It was defined as the combination of vertical projection of all gully profiles in the entire drainage basin. Then, a gully evolution index and its statistic values were used to reveal the evolution of gully landforms based on GPC. The proposed method was applied and validated in three typical loess gully landform areas (i.e., loess tableland, ridge, and hill) in the Loess Plateau of China. Results show that GPC can effectively express gully landforms. The specific geomorphological feature (monoclinic loess tableland) can also be identified using GPC. The gully evolution index results also demonstrate different magnitudes of gully evolutionary stages in a certain area, which reflect the diversity of gullies. The average and median values of the gully evolution index increase in the three typical loess gully landforms. From loess tableland, loess ridge, and loess hill, the average values are 0.653, 0.703, and 0.763, and the median values are 0.661, 0.719, and 0.783, respectively. This method is also found to be stable with gully extraction thresholds for distinguishing different loess gully landforms. Accordingly, the evolution magnitudes of loess gully are obtained.

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1 Introduction

Gully is considered as the main factor for causing land degradation in many areas (Daba et al., 2003; Martínez-Casasnovas, 2003; Valentin et al., 2005; Taruvinga, 2009; Zhu, 2012; Castillo et al., 2014; Castillo and Gómez, 2016; Klik et al., 2016; Xu et al., 2016; Yang et al., 2018). It is an active geomorphic unit in surface evolution and is widely distributed in the world (Korzeniowska et al., 2018). Given the special position of gullies on the earth's surface, the spatial distribution, influential factor, and the evolutionary process of gully landforms have been a focus in geomorphology, hydrology, and erosion research (Oostwoud Wijdenes et al., 2000; Wu and Cheng, 2005; Willett et al., 2014; Xiong et al., 2017; Onyelowe et al., 2018). The quantitative expression of gully morphology and evolution is fundamental to achieve an improved understanding of the formation mechanism of gullies.

Many scholars have been studying the morphology and evolution of gullies and their shaped landforms for many years (Baker et al., 2015; Deng et al., 2015; Frankl et al., 2015; Zhu et al., 2018). Field method has been used by early scholars to explore the basic morphology of gullies. With the field results, the initial study on gully evolution process can be referred on the basis of certain expert knowledge assisted by limited field measured data (Di Stefano et al., 2013; Klik et al., 2016). To date, field method is still widely used in gully studies because of its excellent reliability (Casalí et al., 2006). However, this field method has two major disadvantages. First, the method is time consuming and labor intensive and is not feasible for investigating the morphology and evolution of gullies in a large area (Chang, 2015). Second, it relies heavily on knowledge from experts, which may result in subjective understanding of the gully evolution process.

The development of remote sensing (RS) and geographic information system (GIS) has made digital elevation model (DEM) a key data source in gully studies because different surface morphological features (including gullies) can be extracted from DEMs (Lv et al., 2017). Currently, different methods have been proposed to quantitatively analyze gully landforms by using DEMs (Hayakawa and Oguchi, 2006; Shruthi et al., 2011; Mararakanye and Nethengwe, 2012; Song et al., 2013; Wang et al., 2014; Wang et al., 2015; Na et al., 2017; Yang et al., 2017; Rijal et al., 2018). Among these above-mentioned gully studies, gully features should be extracted firstly using a digital terrain analysis method, such as gully network, stream knickpoint (Hayakawa and Oguchi, 2006; Wang et al., 2014), and gully boundary (Shruthi et al., 2011; Mararakanye and Nethengwe, 2012; Song et al., 2013; Wang et al., 2015; Na et al., 2017; Yang et al., 2017; Rijal et al., 2018). These studies on the extraction of gully features have profoundly enriched the understanding on the morphology of gully landforms. However, gully features are always related to a certain gully evolutionary process. The certain gully evolutionary process would vary in different environments. A simple extraction and analysis of gully features is insufficient to fully recognize the gully process.

To further analyze the morphological feature and evolutionary process of gully landforms, several interpreted or statistical indexes were proposed, such as gully width, gully density, and gully length (Kompani-Zare et al., 2011; Zhao et al., 2016; Zabihi et al., 2018). Normally, two major processes can be found in the gully evolutionary process, i.e., horizontal and headwater erosion processes. The horizontal erosion process expands the gully width, and the headwater erosion process extends the gully length. The gully density should be the representation of gully width and length formed in a specific area. The three indexes (gully density, gully width, and gully length) greatly help understand the gully formation process because they are related to the gully formation mechanism. However, these indexes mainly express the gully morphology in the plane perspective because they are obtained from the plane projections of gully features. Gully features should be the combination of plane and profile features. The profile features of gullies should be an important characteristic of gully morphology, which also indicates the gully formation process.

In terms of profile features, a single gully profile can be easily extracted to investigate the vertical characteristics of gullies. The gully profile can be used to model the process of gully erosion based on knickpoint retreat (Bishop et al., 2005; Berlin and Anderson, 2007; Castillo, 2017; Martins et al., 2017), assess the evolution stage of gullies based on concavity index (Phillips and Lutz, 2008), and investigate the morphology characteristics of gullies (Tang et al., 2009; Guo et al., 2010; Zhang et al., 2011; Cao et al., 2018; Oparaku and Iwar, 2018). However, these vertical-based gully studies only focus on a single gully or rarely a few gullies in a drainage basin. Considering that considerable variations exist in different gully profiles, the entire drainage basin cannot be described using only a single gully or rarely a few gullies. In the drainage basin, many gullies are formed to a specific gully network that transports the materials and energy to the outlet in the three-dimensional space (i.e., plane and profile spaces). Thus, each gully should be linked with and even highly related to other gullies. Accordingly, all gullies should be regarded as a union or combination in analyzing the morphology and evolution of gully landforms in a drainage basin.

On the basis of the idea of combining all gullies in the drainage basin as a union, the concept of gully profile combination (GPC) was proposed first in this study. This GPC was defined as the combination of vertical projection of all gully profiles in the drainage basin. Then, a gully evolution index was used to investigate the characteristics of GPC. Three fully developed gully areas in the Loess Plateau were selected as case study areas. Their GPCs were identified through a morphological analysis of DEMs with a resolution of 5 m. Finally, the identified GPCs and their indication to the morphology and evolution of gullies were discussed in detail.

2 Study area

Three case study areas, which represent the typical loess gully landform types in the Loess Plateau of China (i.e., loess tableland, loess ridge, and loess hill), were selected in this study for GPC extraction and further gully evolution modeling. The three typical loess gully landform areas (TA1, TA2, and TA3) are located in the severe soil erosion area, which is the main part of the Loess Plateau (Fig. 1) (Xiong et al., 2016). TA1, TA2, and TA3 correspond to loess tableland, loess ridge, and loess hill, respectively. The three areas are located in the region of East Asian monsoon climate (Xiong et al., 2014). Table 1 shows the basic properties of the three areas, including elevation, area, average slope, gully depth, gully density, and landform. The landform of the three areas reflects the different gully evolution magnitudes in the Loess Plateau. The order of the gully evolution magnitude is shown as follows: loess tableland < loess ridge < loess hill.

Among the three areas, TA1 is a typical loess tableland area with the lowest magnitude of gully evolution. In this loess tableland area, the original surface of flat tableland has been reserved from gully erosion (Fig. 2(a)). The flat tableland surface has been surrounded by deep gullies, and the depth of the gully can be as high as 200 m. The density of gullies reaches 4899 m/km^2. These gully details indicate that the potential erosion force of this area

Table 1 Basic terrain information of the study area

Name	Elevation/m	Area/km^2	Average Slope	Gully depth/m	Gully density/(m·km^{-2})	Landform
TA1	761–1157	28	20.22	221.83	4899	Loess tableland
TA2	880–1186	12	29.87	133.48	5529	Loess ridge
TA3	953–1245	21	31.26	123.10	5272	Loess hill

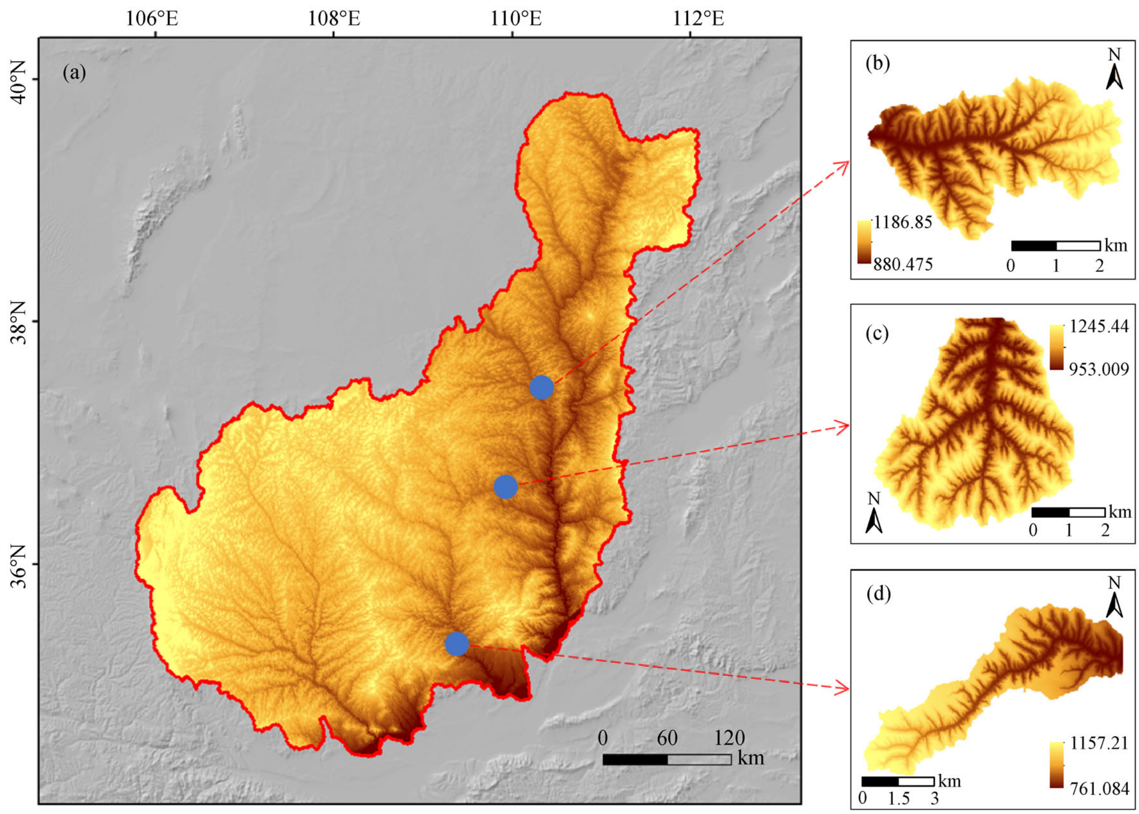

Fig. 1 Location of the study area. (a) Three test areas in the severe soil erosion area; (b) TA2, (c) TA3, (d) TA1.

should be high. The gully consists of a main gully and many other relative small gullies in this tableland area (Fig. 2(a)). An early stage of landform evolutionary process can be found in this specific loess tableland area (Xiong et al., 2017).

TA2 is a typical loess ridge area with a median magnitude of gully evolution. The original surface of this area has been eroded and divided into several ridges by gullies (Fig. 2(b)). However, the gully depth in this loess ridge area is considerably lower than that in the loess tableland area, and the gully density in loess ridge area is higher than that in the loess tableland area (Table 1). This loess ridge landform type is also called the transitional landform type between loess tableland and loess hill. TA2 is also near a settlement. Human activities also play an important role in the gully erosion process. For example, many silt dams have been constructed in this area.

TA3 is a typical loess hill area with a high magnitude of gully evolution. The original surface of this area has been largely eroded and divided into hills by gullies (Fig. 2(c)). Normally, the landform of loess hill forms on the basis of loess ridge landform because several ridge areas (especially saddle areas of the ridge) have been eroded by the gully erosion process, thereby forming independent hills. The gully depth of loess hill landform is similar to that of the loess ridge area.

As shown in Table 1, the information of gully depth and density indicates that gullies are well developed in the three areas. Therefore, these areas are suitable for the research on gully morphology and evolution by using GPC. The DEM used in this study is provided by the Bureau of Surveying and Mapping. The spatial resolution of DEM data is 5 m.

3 Methods

3.1 Concept and extraction of GPC

In this study, we proposed GPC method to investigate the

Fig. 2 Photograph of the three typical landforms in Loess Plateau (a) loess tableland, (b) loess ridge, (c) loess hill.

morphology and reveal the evolution of a drainage basin. This GPC is the combination of vertical projections of all gully profiles in a drainage basin (Fig. 3). To obtain GPC of a drainage basin, the gullies of the drainage basin were extracted first using DEM with the hydrological analysis method (Xiong et al., 2017). Then, the profiles of all gullies were extracted by attaching their corresponding elevation values from the DEM. Finally, all the gully profiles of the drainage basin were drawn into a rectangular coordinate system (Fig. 3(b)). The axis X is the horizontal distance between the gully point and the outlet point (i.e., the exit of water flow in a basin). The axis Y represents the elevation of gully point. All the profiles are linked to the outlet point of the drainage basin.

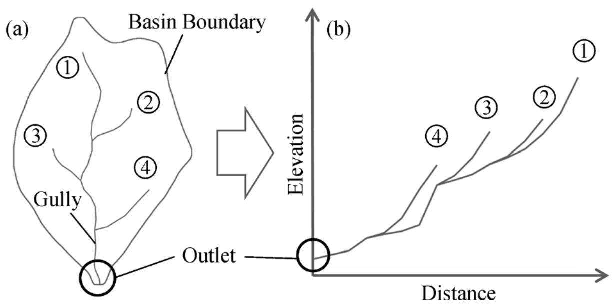

Fig. 3 Illustration of the concept of GPC. (a) Several gullies in the drainage basin, (b) GPC of the drainage basin.

3.2 Gully evolution index for GPC

The area of the upper and lower parts of topography line could represent the magnitude of evolution level (Strahler, 1952). The morphology of gully profile would vary with the change in evolution of gully (Fig. 4). On the basis of this idea, the gully evolution index was investigated to represent the magnitude of gully evolution. The gully evolution index is defined by:

$$Gully\ evolution\ index = \frac{Area(S_2)}{Area(S_1) + Area(S_2)}, \quad (1)$$

where $Area(S_1)$, $Area(S_2)$ are the areas above the gully profile (S_1) and below the gully profile (S_2) (Fig. 5), respectively. S_1 could be regarded as the preserved part from gully evolution. S_2 could be regarded as the eroded part by gully. The morphology of a gully at varying evolution stages differs. As gully evolution proceeds, the eroded part increases. As a result, the gully evolution index increases (Fig. 4).

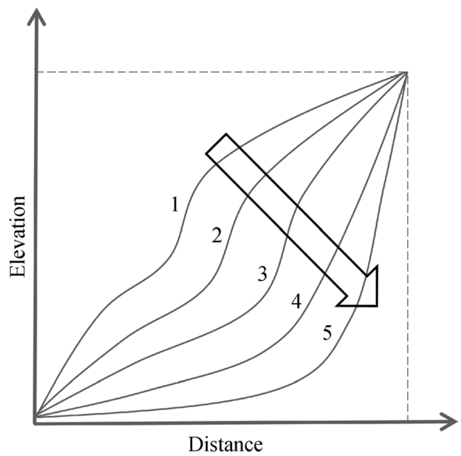

Fig. 4 Evolution of profiles of a gully. Profiles 1 to 5 represent different morphologies of gully profiles. From 1 to 5, the magnitude of gully evolution increases as the eroded part increases.

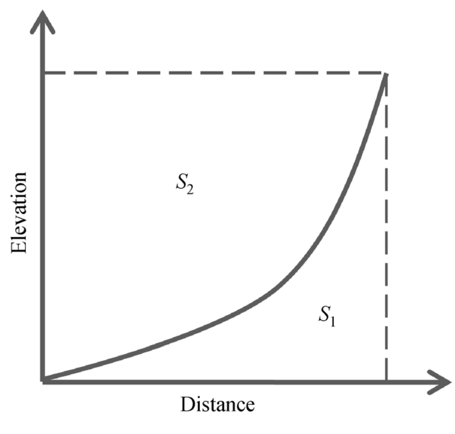

Fig. 5 Definition of the gully evolution index. The solid line represents the gully profile extracted from DEM.

We could assess the evolution magnitude of all gullies in the drainage basin by using the gully evolution index. On the basis of GPC, we could easily calculate the gully evolution index of all gullies in the drainage basin. Some statistical indexes of gully evolution index based on GPC were also used to reveal the evolution of the entire drainage basin, i.e., average, median, minimum (Min), maximum (Max), standard derivation (SD).

3.3 Stability of gully evolution index

Normally, the result of extracted gullies relies on the threshold of drainage area with the flow accumulation matrix (Zhu et al., 2014), which would further affect the result of the gully evolution index. Thus, to quantitatively analyze the stability of gully evolution index and the relationship between gully extraction threshold and gully evolution index, we selected 50, 100, 150, 200, 250, 300, 350, 400, 450, and 500 as the threshold values and extracted the GPC on the basis of these gully extraction thresholds. Then, we calculated the average gully evolution index of each area and analyzed the relationship between the gully extraction threshold and the average value of gully evolution index. A linear regression model was established using the gully extraction threshold and the average value of gully evolution index. The model is shown as follows:

$$average = a_0 + a_1 \times Threshold, \tag{2}$$

where *average* is the average value of the gully evolution index in a drainage basin, *Threshold* is the value of the gully extraction threshold, and a_0 and a_1 are the parameters of the regression model.

4 Results

The gullies of each case area were extracted (Figs. 6(a), 6 (c), and 6(e)) on the basis of certain gully extraction threshold. Then, the gully profiles were calculated using DEM. To obtain GPC of the entire basin, all gullies in the area were drawn into the same coordinate system for each area (Figs. 6(b), 6(d), and 6(f)).

In terms of the morphology of GPC, the gully profile of loess tableland area (TA1) is the smoothest among the three areas (Fig. 6(b)) because the magnitude of gully evolution in this area is considerably lower than that in others. The selected loess ridge area (TA2) is close to a settlement, which indicates that the area is influenced by human activities. Some artificial buildings (e.g., terrace and dam) have been built for water and soil conservation and agriculture, which can influence the morphology of the gully profile (Ferro-Vázquez et al., 2017; Zhao et al., 2017; Kosmowski, 2018). Thus, the gully profile morphology in TA2 is considerably more complex than that in others. The morphology of some gullies may appear strange (similar to stair), especially the profile of the main gully (Fig. 6(d)). The slope gradient of profile of loess hill area (TA3) is considerably higher than that of others due to the high magnitude of gully evolution in this area (Fig. 6(f)). We find that the points of the main gully (the red line in Fig. 6) are not always lowest in the GPC. This phenomenon indicates that some of the gullies are considerably more complex and curvier than the main gully. The phenomenon is common in some areas with complex terrain.

Several statistical indexes (average, minimum, maximum, median, standard variation) of gully evolution were calculated to represent the magnitude of gully evolution in three areas (Table 2). The value of the gully evolution index in each area shows an evident trend in average and median values of gully evolution indexes (TA1 < TA2 < TA3). The trend is the same as the order of gully evolution magnitude (loess tableland < loess ridge < loess hill), which indicates that the average and median values of gully evolution indexes can reflect the magnitude of gully evolution.

The trend of the maximum value of gully evolution index is also the same as that of gully evolution magnitude. However, the difference in maximum value of different landforms is small, which indicates that the maximum index cannot assess the magnitude of gully evolution. Meanwhile, no trend of minimum and standard deviation values of gully evolution index is found, and they fail to reflect the magnitude of gully evolution. The results of statistical indexes of gully evolution indicate that the average and median values are suitable indexes for assessing the gully evolution magnitude of a drainage basin by using GPC.

5 Discussion

5.1 Morphology of GPC in loess gully landform

The gully evolution process of the Loess Plateau is a surface evolution process with an enlargement of gully area. The morphology of gully profile varies as the magnitude of gully evolution changes (Fig. 7). Figure 7(a) shows the gully profile with low magnitude of evolution (loess tableland), and Fig. 7(b) shows the gully profile with a high magnitude of evolution (loess ridge and hill). Several special features of gully profile are found in loess tableland. The most obvious one is the border of gully area (the border of inner and outer parts of a gully). The border of gully area is easily found in the gully profile in loess tableland. A dramatic change in slope can be observed at the border of gully area through gully profile (Fig. 7(a)). However, no such evident border of gully area is found in loess ridge and hill in the areas used in this study. The gully border in loess ridge and hill is considerably fuzzier than that in loess tableland (Fig. 7(b)).

GPC provides a new perspective to view the surface of a

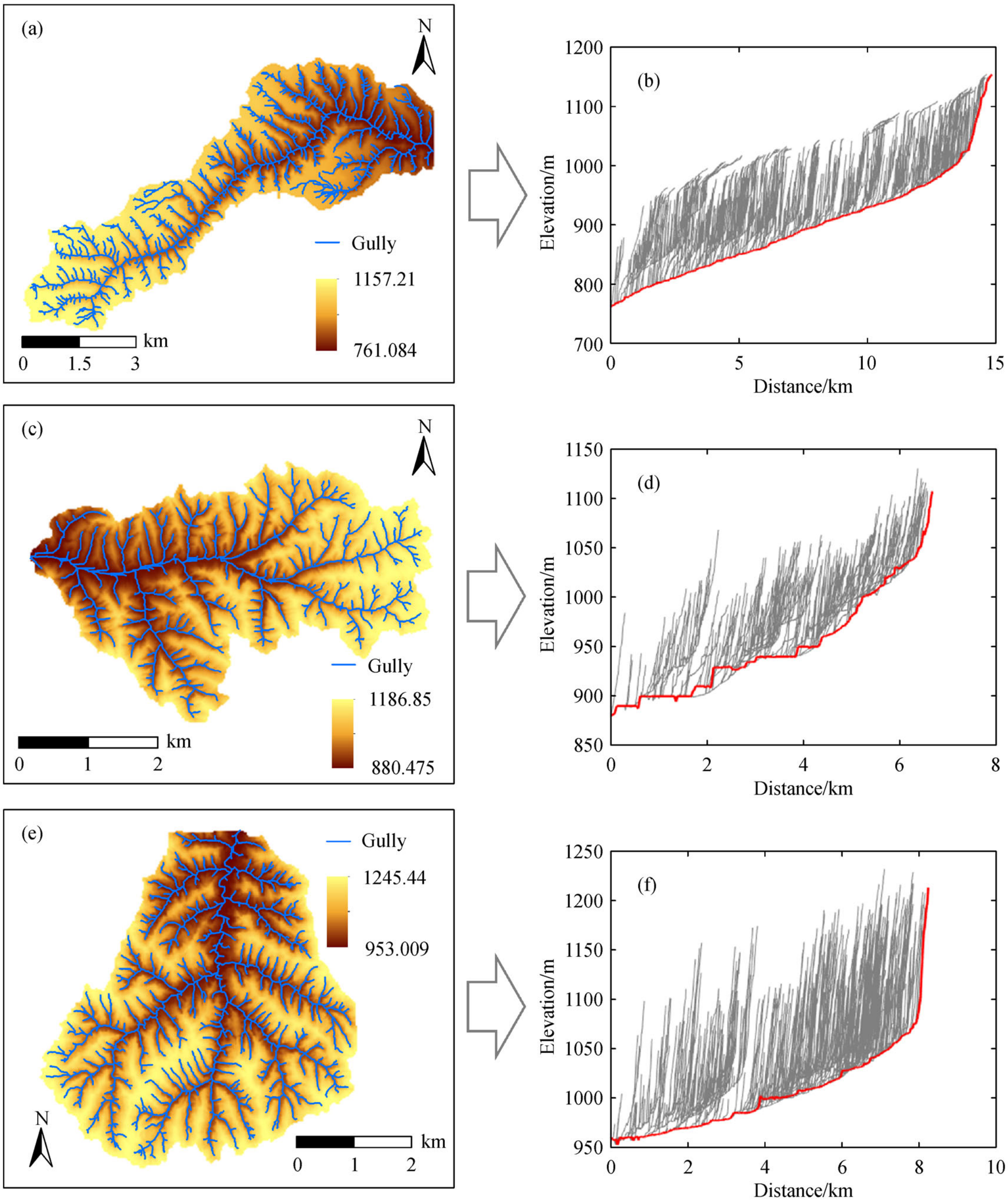

Fig. 6 Gullies and GPC of three areas. The blue line in DEM represents the gullies of the drainage basin. The red line in GPC is the main gully with the maximum length in the drainage basin. (a) Gullies in TA1; (b) GPC of TA1; (c) Gullies in TA2; (d) GPC of TA2; (e) Gullies in TA3, (f) GPC of TA3.

drainage basin. We extracted the GPCs in three case areas. The gully erosion magnitude of loess tableland is much lower than those of the two other landforms (loess ridge and hill). As a result, the morphology of gully profile is special in TA1, which is a typical loess tableland landform, compared with those in the two other areas. The border of gully area can be clearly observed in many gully profiles (Fig. 8). The original surface, which is nearly a plane, is preserved from erosion because of the low magnitude of gully evolution in loess tableland. Thus, a dynamic change is found in the gully profile in loess tableland, which is the border of gully area. However, the dynamic change is not found in all of the gully profiles in loess tableland. Therefore, not all the extracted origin points of gullies in the drainage basin are located at the original surface. This phenomenon is attributed to such factors as the morphology of surface, the value of gully extraction threshold, and the extraction algorithm.

Table 2 Gully evolution index and its statistical information

	Average	Median	Min[1)]	Max[2)]	SD[3)]
TA1	0.653	0.661	0.392	0.835	0.066
TA2	0.703	0.719	0.183	0.838	0.080
TA3	0.763	0.783	0.253	0.888	0.075

Note: 1) Min. Minimum; 2) Max: Maximum; 3) SD: Standard deviation.

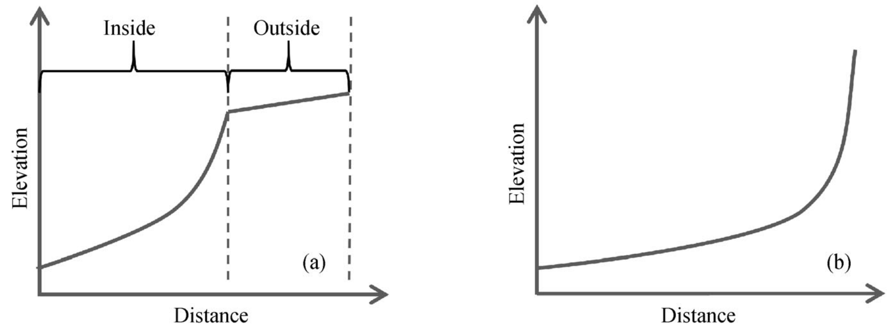

Fig. 7 Morphology of gully profiles in different landform areas. (a) Gully profile in loess tableland. The dash line represents the border of gully area; (b) gully profile in loess ridge and loess hill. The inner part is the gully area of profile. The outer part, which is nearly a plane, is the original surface preserved from gully evolution.

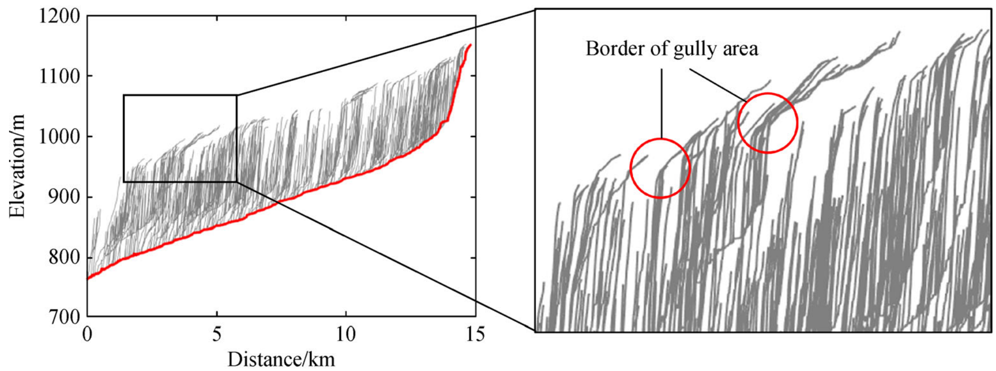

Fig. 8 GPC of loess tableland test area.

GPC also offers a new way to identify some global features of a drainage basin. The most essential characteristic, a monoclinic plane, can be easily identified in the GPC (Fig. 9). The monoclinic plane reflects the morphology of the original surface preserved from gully evolution. A large number of gully origin points are located in the loess tableland plane. As a result, the origin point of gullies is collinear in the GPC. Moreover, the line is not horizontal but inclined, which indicates that the original surface is a monoclinic plane. This monoclinic plane appears nearly parallel to the main channel (Fig. 9), which supports the inheritance view of loess landform evolution process (Xiong et al., 2014; Xiong et al., 2016)

The landform of TA2 is loess ridge. The magnitude of gully evolution is considerably more than that of loess tableland, and the original surface has been eroded and divided into several ridges by gullies. The original surface plane nearly disappears. The border of gully area completely disappears from the gully profile. Given that the original surface plane is eroded by gullies, the origin point is non-collinear in GPC. The typical loess hill area (TA3) is the most serious area eroded by gullies. Similar to TA2, no evident gully border is found in the gully profile and collinear origin point. The morphologies of most gullies are also similar to one another, and finding a knickpoint from the GPC is difficult. This phenomenon indicates that the evolution of gullies in TA3 is nearly complete. The diversity of gully morphology in the area is considerably lower than those in other areas.

5.2 Influence of gully extraction threshold

During the process of gully extraction, the selection of gully extraction threshold value is a key issue in related

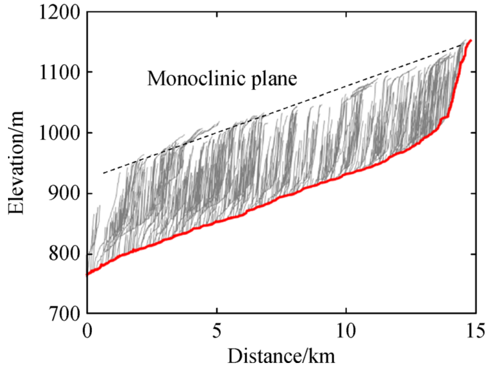

Fig. 9 GPC in loess tableland. The dash line represents the monoclinic plane.

study and will influence the result of gully extraction. Many works have been conducted to analyze the gully extraction threshold problem (Gyasi-Agyei et al., 1995; Bhowmik et al., 2015; Reddy et al., 2018). To assess the impact of the gully extraction threshold on the stability of GPC, different gully profiles with dissimilar gully extraction thresholds are examined in this section.

Three models were established on the basis of a series of gully extraction thresholds to quantitatively analyze the relationship between gully extraction threshold and gully evolution index. We found that a strong linear relationship exists between the gully extraction threshold and the average value of gully evolution index (Fig. 10). The results show that the gully extraction threshold influences the value of the gully evolution index. The average value of the gully evolution index in a drainage basin will decrease as the gully extraction threshold increases. Two parameters a_0 and also reflect some properties of the influence.

The parameter a_0 is the intercept of the line and reflects the average gully evolution index with a very low gully extraction threshold. The value of a_0 is lowest in TA1 (a_0= 0.65), followed by that in TA2 (a_0= 0.70). The highest value of intercept is found in TA3 (a_0= 0.76). The influence of gully extraction threshold is different in loess tableland (TA1), loess ridge (TA2), and loess hill (TA3). We could estimate the magnitude of the influence through the slope gradient (a_1) of linear regression. In loess tableland (a_1= 1.9×10^{-5}), gully extraction threshold has the least influence on gully evolution index. The effect in loess ridge comes second (a_1= 3.8×10^{-5}). Gully evolution index is most easily influenced by gully extraction threshold in loess hill (a_1= 4.1×10^{-5}).

The intercept of linear regression (a_0) reflects the average gully evolution index with a very low gully extraction threshold. The slope of the linear (a_1) model reflects the magnitude of the influence of gully extraction threshold on gully evolution index. We found that the order of two parameters is the same as gully evolution magnitude (loess tableland < loess ridge < loess hill) in three areas. We can conclude that the average of gully evolution index can still correctly reflect the magnitude of gully evolution

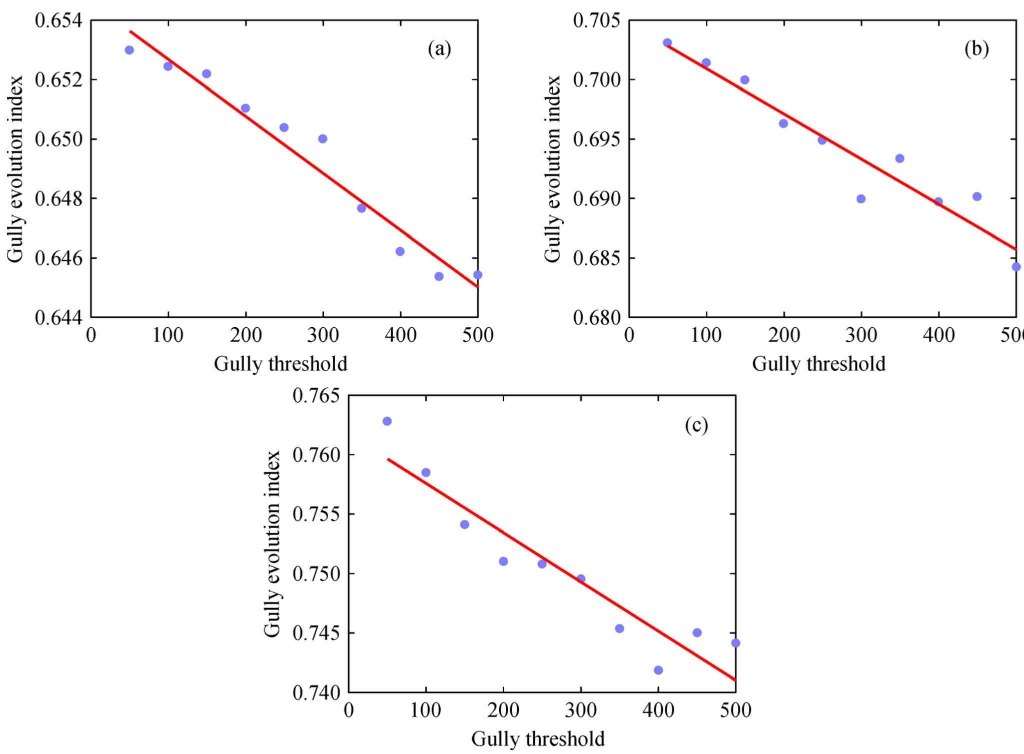

Fig. 10 Relationship between the gully extraction threshold and the average value of gully evolution index. (a) TA1; (b) TA2; (c) TA3.

(loess tableland < loess ridge < loess hill) in different landforms as the gully extraction threshold varies.

We also notice that is negative in the three areas, and this finding indicates that gully evolution index decreases as gully extraction threshold increases. Figure 11 represents the gully profile with high and low gully extraction thresholds. The two types of gullies are drawn into the same coordinate (Fig. 11(b)). As the gully extraction threshold decreases, the top part of the gully disappears. The remaining parts (blue line in Fig. 11(b)) are close to a straight line, which indicates a low gully evolution index. Therefore, a high gully extraction threshold corresponds to a low gully evolution index.

5.3 Distribution of gully evolution index in a drainage basin

A drainage basin can be recognized as a union composed of numerous gullies. The process of gully evolution can be recognized as the process in which young gullies increasingly age. On the basis of GPC, we could easily calculate the histogram of gully evolution indexes in a drainage basin. With the evolution of gullies in a drainage basin, the histogram of gully evolution index will change. During the evolution of gullies in the drainage basin, the young gully with low gully evolution index will age. Its gully evolution index value will also increase. As a result, the gully evolution index of the entire drainage basin will increase, and the histogram of gully evolution index will move to the right (Fig. 12). Meanwhile, some young gullies will appear and start to develop.

We calculated the evolution indexes of gullies in the above-mentioned three areas on the basis of GPC. Their histograms were calculated using gully evolution indexes. To compare the differences among histograms, we illustrated the histogram of the three areas into the same coordinate system (Fig. 13). The proportion of young gullies in TA1 is considerably more than those in others. Therefore, TA1 is the youngest drainage basin among the three areas. The gully evolution index of most gullies is between 0.6 and 0.8 in TA2. The value of gully evolution index in TA3 is the highest in three areas. The value of many gullies in TA3 is more than 0.8.

The distribution of gully evolution index in the drainage basin reflects the trend of gully evolution magnitude (TA1 < TA2 < TA3) in three areas. High gully evolution magnitude indicates high proportion of old gullies. As a result, the histogram of gully evolution index will move to the right. On the contrary, the proportion of old gullies is low and the gully evolution magnitude is low, which indicates that the drainage basin is young. The histogram of gully evolution index will also move to the left.

Regardless whether in loess tableland, ridge, or hill, some gullies with low evolution index are found. This phenomenon implies that many young gullies (gullies with low magnitude of evolution) still exist regardless of the type of landform. Not all gullies of old drainage basin are old. Many young gullies are found in the old drainage basin, although its proportion is considerably lower than those in the young drainage basin.

The evolution of a drainage basin depends not only on its property but also on the property of adjacent drainage basin. TA1, with the highest proportion of young gullies, is a typical young drainage basin. A low proportion of gullies are found around the drainage basin. Sufficient room to develop young gullies is available, which results in high proportion of young gullies. However, compared to TA1, the room for young gullies is much less than that in TA2. The proportion of young gullies is much lower than that in TA1. Given that TA3 is a typical loess hill, its surface is filled with gullies. Little room for development of young gullies is available. As a result, the proportion of young gullies in TA3 is the lowest in three areas.

5.4 Implications of GPC for other landform areas

Gullies, as vessels of material and energy transportation

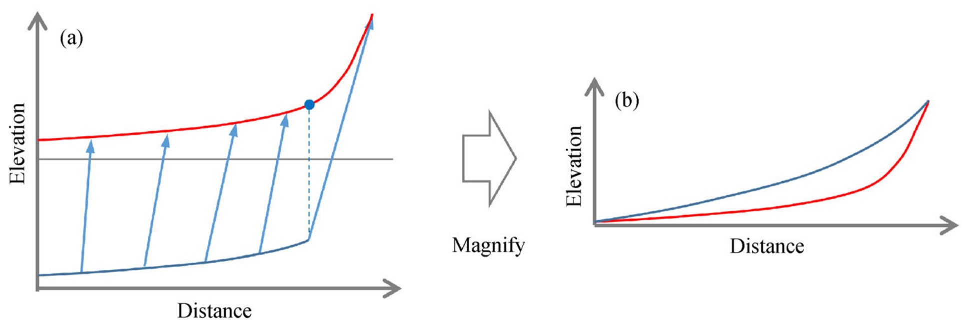

Fig. 11 Gully profiles with different gully extraction thresholds. (a) Gully profiles with low extraction threshold (red one) and high extraction threshold (blue one); (b) morphology of gully profile influenced by gully extraction threshold. The red line represents the gully profile with low extraction threshold. The blue line, magnified to the same scale as the red line, represents the gully profile with high extraction threshold.

Fig. 12 Histogram of gully evolution index. The left part is the histogram of young drainage basin, and the right part is that of old drainage basin. The left part will gradually become right part during the evolution of gullies in a drainage basin.

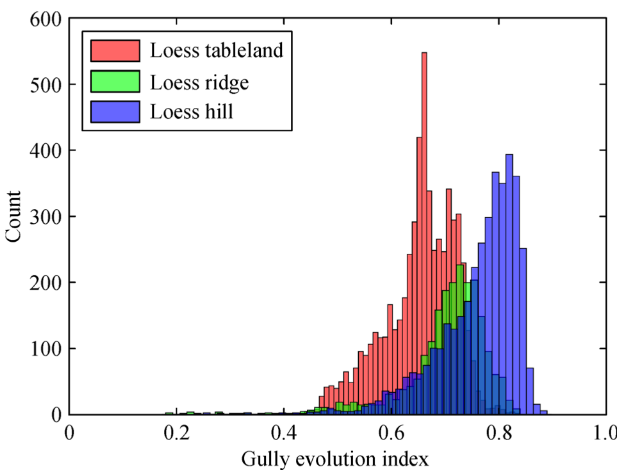

Fig. 13 Distribution of gully evolution index in three areas. The red, green, and blue parts refer to TA1, TA2, and TA3.

during the earth's surface processes, are widely distributed in different landform areas (Perron et al., 2009; Willett et al., 2014; Xiong et al., 2017). Thus, the understanding of gully evolutionary process should be critical for geomorphologists and hydrologists. The GPC provides a new understanding of the morphology and evolution in gully landforms. We believe that each gully in a gully landform area should be linked with and even highly related to other gullies. Thus, all gullies should be considered and can be regarded as a combination in analyzing the morphology and evolution of gully landforms. Accordingly, the potential global feature of an area can be achieved. In this research, three typical gully landform areas in the Loess Plateau have been selected to validate the proposed GPC method. However, this method is not limited only to loess areas. The selected different loess gully landforms only provide knowledge of landform evolution stages, which inversely help demonstrate the capability of GPC for gully evolution modeling. Under the similar geographical background of loess depositional and gully erosion processes (Xiong et al., 2016), the selected three loess gully landforms can be compared with one another, and the result should be reliable. When this GPC method is adopted in other gully landform areas, GPC can also be extracted from a DEM directly. The morphologies of GPC vary in different gully landforms. Thus, the gully morphology can be expressed. When conducting comparative analysis of gully evolution index for gully evolution, this index should be discussed with the same geographical background (e.g., loess tableland, ridge, and hill in the loess area in different gully evolution stages). GPC can help further understand the morphology and evolution of gully landforms because it provides a comprehensive view to explore the gullies of a gully landform.

6 Conclusions

A combined gully profile method was proposed to investigate the morphology and reveal the evolution of gully landforms. In this method, the concept of GPC was defined as the combination of vertical projections of all gully profiles in a drainage basin. Based on GPC, a gully evolution index was proposed in this study to reveal the magnitude of gully evolution in a drainage basin. Three typical loess gully landform areas, namely, loess tableland, ridge, and hill, were selected as case areas. The GPCs of the three areas were extracted using DEM with a resolution of 5 m. We found that GPC can be a reliable method to reflect the morphology of loess tableland, ridge, and hill. Several features (e.g., border of gully area and loess tableland plane) can be easily identified in GPC. The differences in GPCs of the three areas also reflect the diversity of morphology in different landforms. The gully evolution indexes of all the gullies in the drainage basin were extracted on the basis of GPCs in the three areas. We found that the average and median values of gully evolution index can reflect the gully evolution magnitude of the entire drainage basin. The average values of the three areas are 0.653, 0.703, and 0.763, respectively. The median values are 0.661, 0.719, and 0.783. The average value of gully evolution index serves as a reliable index to estimate the magnitude of gully evolution in a drainage basin. It still can correctly reflect the gully evolution magnitude as the gully extraction threshold varies. The gully evolution index of each gully in the drainage basin was calculated to obtain the histogram of gully evolution indexes. The histogram of gully evolution index in a drainage basin reflects the distribution of gully evolution magnitude. High magnitude of gully evolution corresponds to high proportion of old gullies, whereas low magnitude indicates high proportion of young gullies.

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