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Extraction and Analysis of Gully Head of Loess Plateau in China Based on Digital Elevation Model

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Abstract: In China′s Loess Plateau area, gully head is the most active zone of a drainage system in gully areas. The differentiation of loess gully head follows geospatial patterns and reflects the process of the loess landform development and evolution of its drainage system to some extent. In this study, the geomorphic meaning, basic characteristics, morphological structure and the basic types of loess gully heads were systematically analysed. Then, the loess gully head′s conceptual model was established, and an extraction method based on Digital Elevation Model (DEM) for loess gully head features and elements was proposed. Through analysing the achieved statistics of loess gully head features, loess gully heads have apparently similar and different characteristics depending on the different loess landforms where they are found. The loess head characteristics reflect their growth period and evolution tendency to a certain degree, and they indirectly represent evolutionary mechanisms. In addition, the loess gully developmental stages and the evolutionary processes can be deduced by using loess gully head characteristics. This study is of great significance for development and improvement of the theoretical system for describing loess gully landforms.

Keywords: Loess Plateau; loess gully head; Digital Elevation Model (DEM); loess landform evolution; feature extraction; statistical analysis

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1 Introduction

The Loess Plateau of China possesses a representative gully terrain area that attracts worldwide attention for its formation, geomorphological characteristics, evaluation and significance to local environment and human activities (Chu, 1956; Cheng and Jiang, 1986; Gan, 1990; Lu *et al.*, 1991; Chen *et al.*, 1998; Deng and Yuan, 2001; Liu and Li, 2003). A gully head is the apex of a loess gully. From the view point of a valley system, a loess gully head is one of the most active features in a loess gully area which controls the conflux of a watershed, influences the development of loess landforms and causes the loess of land resources. In addition, the features of a loess gully head are closely related to erosion forces and corresponding environmental factors such as loess type, topographic form, and land cover. The diversity of loess gully heads is actually a reflection of the spatial variety of the loess landform and its development stage. At the same time, the headward erosion of a loess gully head directly or potentially threatens agricultural production and people′ safety in the upriver area. Therefore, a systematic study of the geomorphic meaning and the features of loess gully heads is an important

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part of loess gully landform studies, and this study is of theoretical importance and practical value.

A gully head is a spatially limited geomorphology, and it usually lies below the divide line but is excluded from the adjacent gully system (David and William, 1988; Dietrich and Dunne, 1993; Hancock and Evans, 2006). A gully head may also be regarded as a catchment area located at the end of a gully that has not formed into a real gully yet. In other words, a gully head is considered to be an essential element of a gully system (David and William, 1992; Dietrich and Dunne, 1993; Chen *et al.*, 2004; James *et al.*, 2006). The terrain features of a gully head has been studied from the perspective of the relation between the watershed area and the slope (David and William, 1989; James *et al.*, 2006).

A gully head is a critical catchment area or located at some distance downslope from the catchments divide where channels begin to form, and this distance can be dynamic (Horton, 1945; Dunne and Aubry, 1986). The locations of gully heads are arranged according to the principles of energy minimization (Sun *et al.*, 1996). A gully head is the conflux of the stream in the watershed, and the relationship between the gully heads′ distribution and the divide lines′ spatial locality determines the basic form features and the development process of the gully landform (Qian, 2001). The amount and density of gully heads control the gullies′ basic distribution and pattern in a watershed. During the process of slope erosion, the gully head is occupied by the actual gully. Causes of gully heads′ formation, form and erosion orderliness have been studied (Luo, 1956; Jing, 1986; Lyu *et al.*, 1998; Wu and Liu, 2000; Chen *et al.*, 2009). These studies mainly focused on the description of the gully head's spatial features and the relationship analysis of the terrain index through field surveys and indoor aviation data interpretation and analysis (Luo, 1956; Jing, 1986). Based on Digital Elevation Model (DEM), a method to find gully heads had been proposed (Tribe, 1991), gully heads′ terrain parameters had been calculated and the statistics relationship among different terrain parameters had been studied (Hancock and Evans, 2006; James *et al.*, 2006; Frankl *et al.*, 2012). Based on the statistical data, the quantitative characteristics of the parameters have been discussed (David and William, 1989; Tribe, 1991; Chen *et al.*, 2012). However, up to now, there is no complete definition of a gully head or any relevant study about gully heads′ spatial variety at large scales, especially a study of causes of gully head with different spatial data.

The Loess Plateau of China presents the most extensive loess gully landforms in the world. In the loess gully-hill area, gully density is even higher than 10 km/km^2. The gully heads in this area exhibit unique characteristic with multiple forms. The features of loess gully heads in different loess landforms, such as loess tableland, loess ridge and loess hill, are shown in Fig. 1.

This research seeks to create a conceptual model derived by an extraction method based on DEM and by feature analysis of loess gully heads in different loess landforms. This paper first establishes a complete definition of a loess gully head, explains the different elements that constitute loess gully head and analyses relationships between the form and structure of loess gully head. Then, a method is proposed to extract loess gully heads by using high-resolution DEM. The spatial variety of loess gully heads and the mechanisms of loess gully head landform development and evolution are also explored.

2 Loess Gully Head Landform

2.1 Geomorphologic meaning

Loess gully heads, from the viewpoint of geomorphology, belong to a type of micro-topography of the loess landform. There exist two different geomorphologic interpretations of loess gully heads based on their morphology and cause of formation. Morphological interpretations insist that a loess gully head is within the negative area pitched into the land surface. The morphological characteristics of the valley area remain, even though there is little surface water flow which appears only after a rainfall. The characteristics should be very obvious at the very beginning or have a relatively stable period. Under this definition, the gully area should include the specific catchment area that ranges from the area beneath the interface of the positive and negative terrains to a surface runoff point with the highest slope variation (David and William, 1989; Hu *et al.*, 2001; Hancock and Evans, 2006; Wang *et al.*, 2008). It is in the gully head area that the surface erosion mode transitions from surface erosion to gully erosion because of the sudden increase of flow accumulation and flow speed on the loess surface. Hence, the loess gully head area is also the most active part for headward erosion in

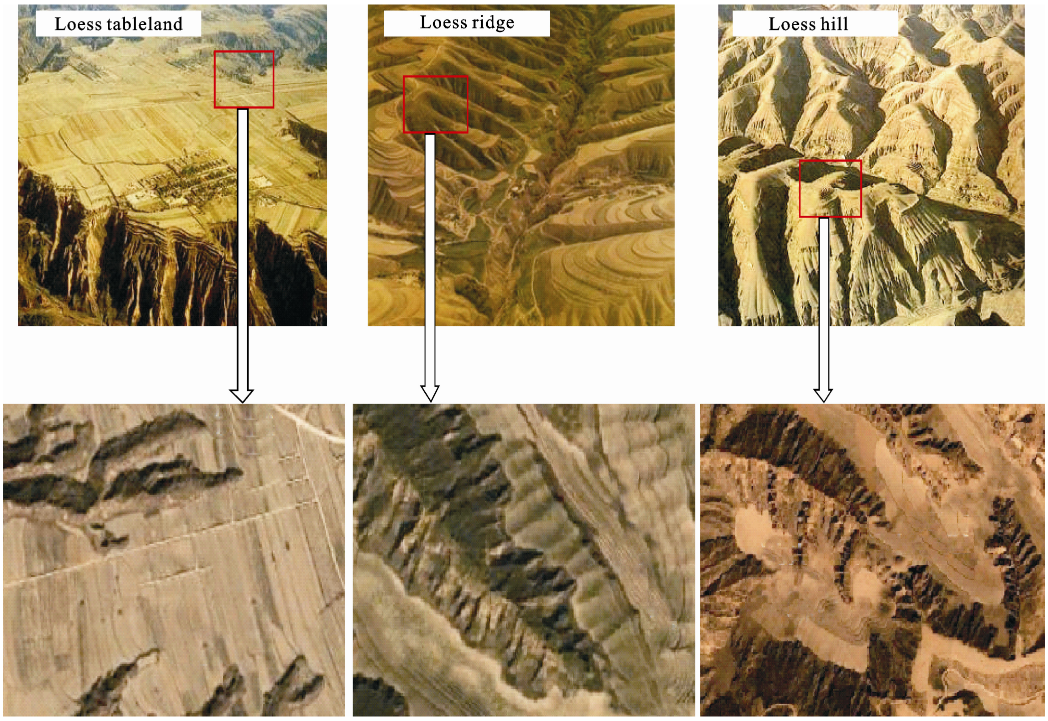


Fig. 1 Gully head in Loess Plateau, China

the Loess Plateau area. The formation of the loess gully head area is an interactive process between the stream water flow transportation and the extensive slope transportation. The factors that affect development of gully head areas are the surface runoff erosion, infiltration erosion and superficial landslide effects of the saturated slope runoffs (David and William, 1989; Lyu *et al.*, 1998; Qian, 2001). Therefore, a loess gully head possesses specific topographic features in a loess landform. The structure of a loess gully head is shown in Fig. 2. The elements of a loess gully head are watershed boundary line, gully line, gully head point, controlling area and the first watershed.

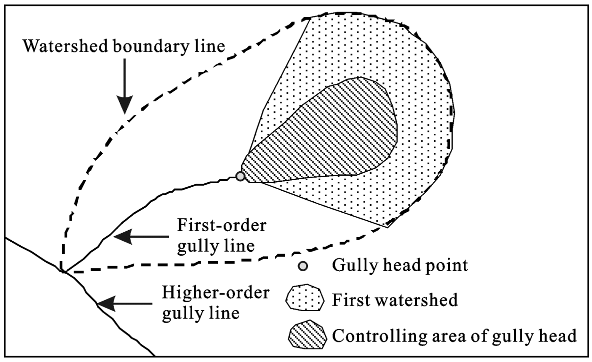


Fig. 2 Planar structure graph of loess gully head. Referring to David and William (1989)

This paper proposes that the basic feature of a gully head should be an integration of interpretations and it is virtually a reflector of all the factors influencing formation of the landform. As a real spatial entity in watershed landform of the Loess Plateau, the loess gully head is the key position which plays a significant role in material transference and energy transformation. It also supplies the power for evolution of the gully system and finally determines the speed, mode and direction of the gully's evolution. Hence, there exist some specific geomorphologic characteristics on both micro- and macro-scales.

Separated by the loess shoulder-lines, the loess landform can be classified into positive and negative terrains. The relatively smooth positive terrain is just above the loess shoulder-line and erosion is dominated by sheetflood conditions, in spite of the existence of some ripples, rills and shallow gullies in this area. On the other hand, negative terrain is where gravitational erosion dominates the main geomorphological process, and the loess gully head plays a major role (as the entrance of the gully system) in absorbing the material and energy of surface flows from the upper watershed. As a result of the sudden increase of flow speed, the ability of soil transportation for flows undergoes a qualitative change, which strengthens the flows′ undercutting of land surface and headward erosion. The instability of loess gully head area may induce surface landslides and other gravitational landforms. The location and change of loess gully head depend on the balance of resistance and erosion potential, which is affected mainly by the loess type, rainfall, land cover, terrain and land use. The change of rainfall and land use will result in variation in surface erosion and sediments supplementation, which will further lead to the advance and retreat of the loess gully head. Moreover, the existence of loess material which sinks from above loess gully head may cause frequent gravitational collapse which always pushes the loess gully head forward intensively and usually forms an obvious cliff as the ending boundary of the gully head. Its location and spatial distribution are shown in Fig. 3.

2.2 Basic characteristics

The Loess Plateau covers an area of 640 000 km^2 with rich landforms, various morphology and complex evolutionary processes. Although gully heads are found in most types of landforms, the loess gully head has unique properties. Its basic characteristics are as follows:

(1) According to different classification standards, i.e. environmental condition, evolution mechanism and morphologic characteristics, loess gully heads could be classified into many types, which could construct a more comprehensive understanding of their characteristics.

(2) The formation and evolution of loess gully heads rely on several geographic factors such as the loess material, erosion power from rainfall, geomorphologic characteristics, land cover conditions and land use type. Ultimately, this could be summarized as the contradiction between erosion power and resistance of the land surface.

(3) From a careful examination of a gully head, it is apparent that the gully head is structuralized both horizontally and vertically and actually displays different features at each stage of evolution of the loess landform. As a loess gully head evolves, its structural features will continue to change quantitatively and qualitatively.

(4) The geomorphology of the Loess Plateau possesses a specific feature in that the loess terrain has a gradual change in both east-west and north-south directions. Thus, the individual and group characteristics of loess gully heads also represent an apparent regional difference.

(5) From the viewpoint of regional geomorphology, the special distribution pattern of loess gully heads′ mass could be found to have a close relationship with the evolution mode and stage of loess landforms. As the most instable section in the watershed system, a loess head could be regarded as a mirror representing loess

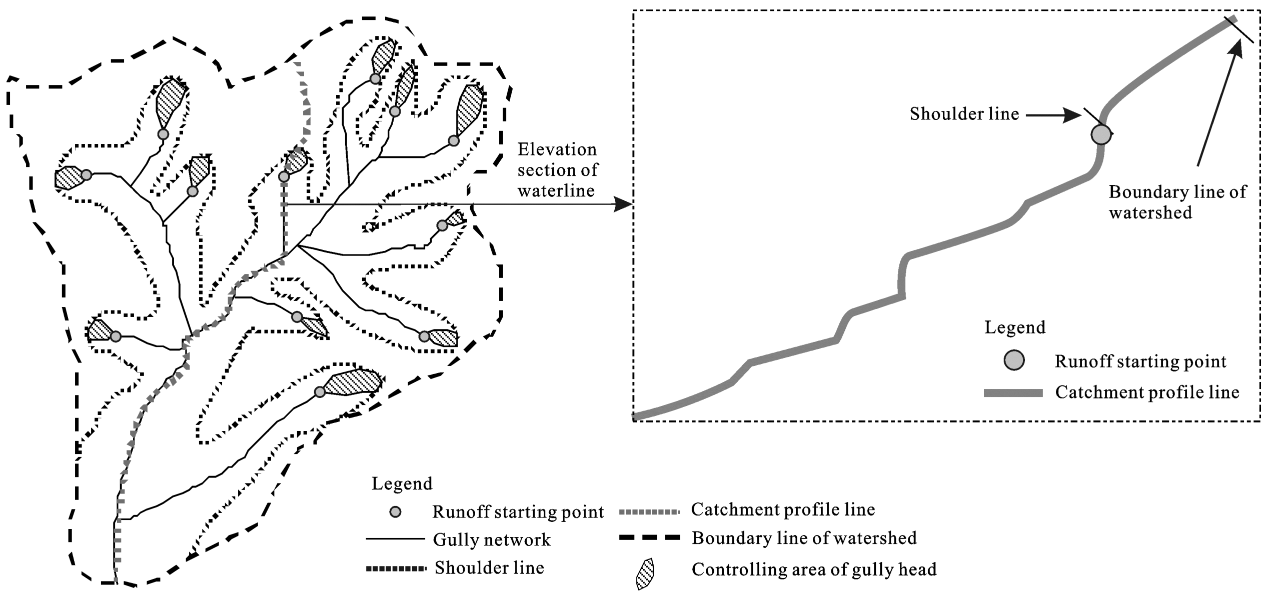


Fig. 3 Loess gully and loess gully head elements and terrain profiles of gully line map. Catchment profile line shown on the right picture is the gray dotted line on the left picture which shows the terrain surface position

landform development. With the evolution of the loess landform going from young to youth and middle stages, *etc*., the density of loess gully heads is continually increasing and their position is approaching the divide line of a watershed. For instance, while the loess gully heads on both sides of the divide line touch each other, this could represent a symbol indicating that the loess terrain is entering its middle age evolutionary stage. Hence, a gully head-based research on loess terrain is of critical significance regarding the regional geomorphology of the Loess Plateau.

2.3 Characteristic elements of structure

As shown in Fig. 2 and Fig. 3, a loess gully head, as a micro-landform in loess gully landforms, is a multidimensional spatial object. Its dimensional spatial structure can be divided into a feature point, a feature line and a polygon based on the shape of the loess gully head. The feature point, i.e. gully head point, is the intersection of the controlling area of gully head with the gully line. It is also the outlet of the gully head-controlled area which shares the same position with the runoff starting point (Fig. 2 and Fig. 3). The feature line includes the gully head boundary which usually takes the approximate shape of a leaf with the gully head point at the tip. Actually, the polygon, i.e. the controlling area of the gully head indicates the controlling area within the feature line. Besides the constituent elements of the gully head, there are other gully head related spatial objects, i.e. the tips of the gully line, shoulder-lines and runoff starting points, whose feature elements and structure are shown in Fig. 2 and Fig. 3.

2.4 Classification of loess gully head

Although the Loess Plateau area has a variety of gully heads, there is not a commonly accepted standard or rule for their classification. At present, the main classification scheme is mainly based on their shapes. Gully heads, as a part of a drainage system within a watershed area, possesses specific characteristic shapes, combination states and formation causes, which lead to the following classification schemes:

(1) By shapes: wedge-shaped gully heads, arc-shaped gully heads, ring-shaped gully heads, bisected-type gully heads, spindle-shape gully head and dendritic-shape gully head.

(2) By combination states: single gully heads and combined gully heads. Single gully heads control a separate area corresponding to only one head. And combined gully heads are areas where one or more adjacent single heads form a structural flow-accumulation contribution region.

(3) By formation causes：gravitational collapse-based gully heads, water erosion-based gully heads and mixture erosion forces-based gully heads. Generally, a gravitational collapse-based gully head extends straight ahead with a heavy gradient. Most of them are single gully heads. Once they run into resistance to their development, the gully head usually takes a perpendicular turn or bifurcates to form a more complex form. The single gully heads or combined gully heads exist in a relatively flat area, with diverse shapes and dispersive main orientation, and could usually be found to be formed by water erosion. However in the loess area, the majority of gully heads are caused by mixture erosion forces. In the process, gravitational collapse initiates the shapes of gully heads and then water erosion produces carving in detail. Those gully heads usually keep a main orientation of extension (David and William, 1988; 1989; Xiao *et al.*, 2004; James *et al.*, 2006; Frankl *et al.*, 2012).

Based on loess gully heads′ shapes and combined loess gully heads′ combination states and formation causes, a brief classification of loess gully heads is listed in Table 1.

3 Materials and Methods

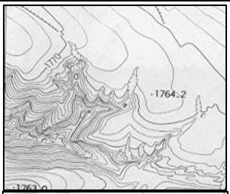
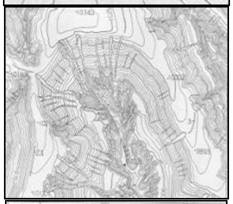
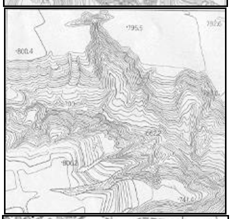
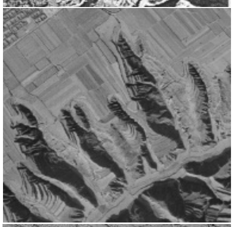
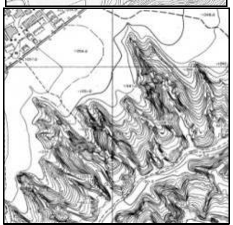
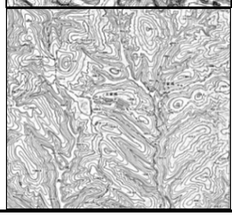
3.1 Study area

Shaanxi Province are marked from TA-1 to TA-5, and located in Chunhua County, Yijun County, Ganquan County, Yan′an County and Suide County, respectively, each test area covering a total area of 100 km^2 and with full watersheds large enough to study (Fig. 4). These test areas can typically and reasonably represent different loess landform types, namely loess tableland, loess flat-topped ridge, loess ridge, loess hill ridge and loess hill. These test areas are within a cold temperate continental monsoon climate, and their elevation ranges between 750 m and 1100 m above sea level and their terrain reliefs are listed in Table 2.

3.2 Test data

The test data include DEM, Digital Orthophoto Map (DOM) and Digital Line Graph (DLG). The DEM and DLG used in this study are both obtained from topog-

Table 1 Classification of loess gully head

No.	Name	Maps of loess gully head		Classification basis	
		Digital Orthophoto Map (DOM)	Digital Line Graph (DLG)	Shape and combination state	Formation cause
1	Wedge-shaped gully head			Gully head is combined, and its main direction is obvious	Mixture erosion forces
2	Arc-shaped gully head			Gully head is arc-shaped (palmate) and combined, and its main direction is not obvious	Mainly water erosion
3	Ring-shaped gully head			Gully head is ring-shaped and combined, and its main direction is not obvious	Mainly water erosion
4	Bisected-type gully head			Gully head is bisected-type and individual, and its main direction is obvious	Mainly gravitational collapse
5	Spindle-shape gully head			Gully head is linear shape and individual, and its main direction is obvious	Mainly gravitational collapse
6	Dendritic-shape gully head			Gully head is messy, and it contains many ending gully heads. Its main direction is not obvious and confusing	Mainly water erosion

Note: DLG maps refers to ′Atlas of China landform′ (′Atlas of China landform′ Editing Group, 1985)

raphic maps at the scale of 1 ∶ 10 000. The DEM has a resolution of 5-m. The DOM with 1-m resolution from aerial images is chosen to provide more information of micro-geomorphologic features. In order to obtain a result from integrated watersheds, this study extracts one full watershed from each test area. The major geomorphologic features of the five watersheds are shown in Table 2. The gully level refers to the highest gully level in the experimental watershed, and its meanings refer to Horton (1945).

3.3 Data extraction and statistical methods

The loess gully heads are extracted by using DEM, DOM and DLG data. The shoulder lines are extracted based on DOM, DLG and DEM data. Other elements such as watershed divide lines, gully networks, runoff starting points and controlling areas of gully heads are mainly extracted from DEM. The extraction scheme is

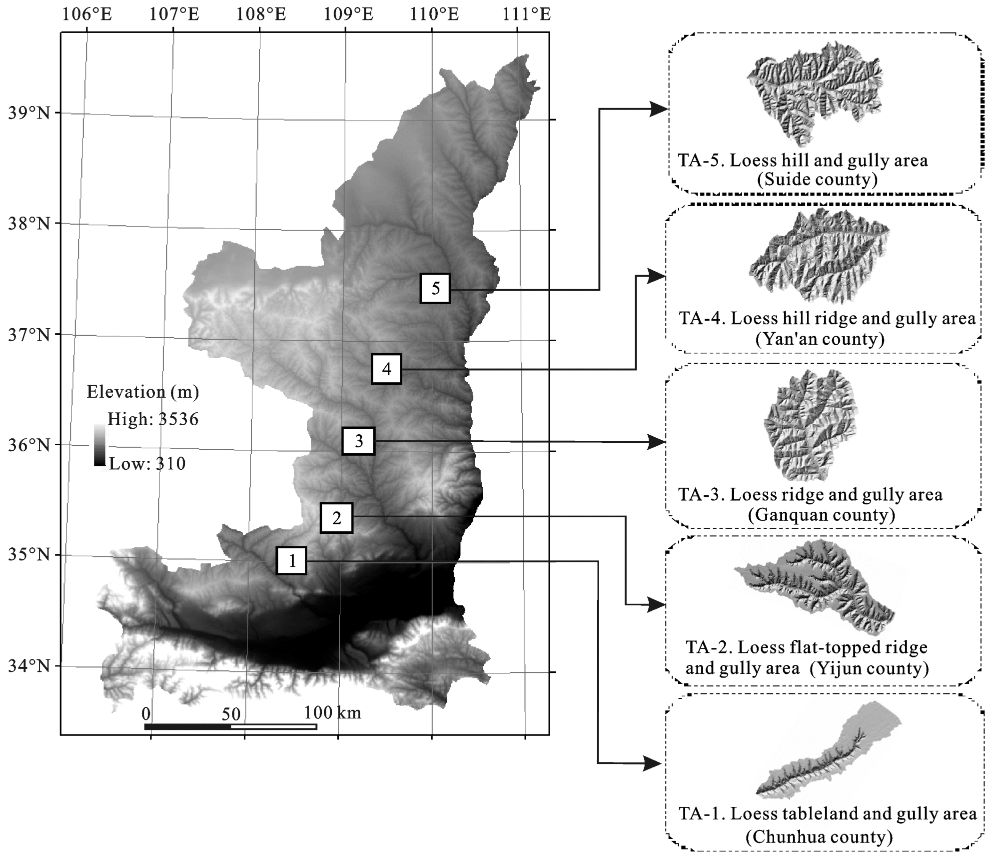


Fig. 4 Distribution of five test areas in Shaanxi Province, China

Table 2 Major geomorphologic features of five watersheds extracted from five test areas in Shaanxi Province, China

Test area	Location	Loess landform type	Feature parameter			
			Catchment area (km^2)	Gully density (km/km^2)	Gully level	Relief (m)
TA-1	Chunhua	Loess tableland	13.50	1.60	3	349.90
TA-2	Yijun	Loess flat-topped ridge	19.50	2.99	5	336.14
TA-3	Ganquan	Loess ridge	19.32	3.55	5	283.72
TA-4	Yan′an	Loess hill ridge	18.35	4.37	5	337.12
TA-5	Suide	Loess hill	12.33	4.56	4	317.52

shown in the following flowchart (Fig. 5).

ArcGIS 10.0 with public domain spatial analysis, hydrologic analysis and spatial statistics models were used to derive slope, slope length, drainage area, *etc*. Excel and SPSS are the tools used for statistical analysis of loess gully head features.

4 Experiment Results and Analyses

4.1 Slope analysis

The loess gully heads of five test areas are extracted under the scheme shown in Fig. 5. Then, a series of statistics have been obtained, and they are applied to investigate the geomorphological features of loess gully heads (Table 3).

Comparing the slope condition of gully heads, we find that the mean slopes are similar to each other and their coefficients of variation values support this result as well. Figure 6a shows a consistent distribution in the five different test areas. In addition, the minimum value of the mean slope is 32.03° in TA-3, and the other areas are approximately 35° with a variation of less than 2°. Moreover, mean slope ratios show great differences ranging from 1.30 to 6.73 in the five test areas, present-

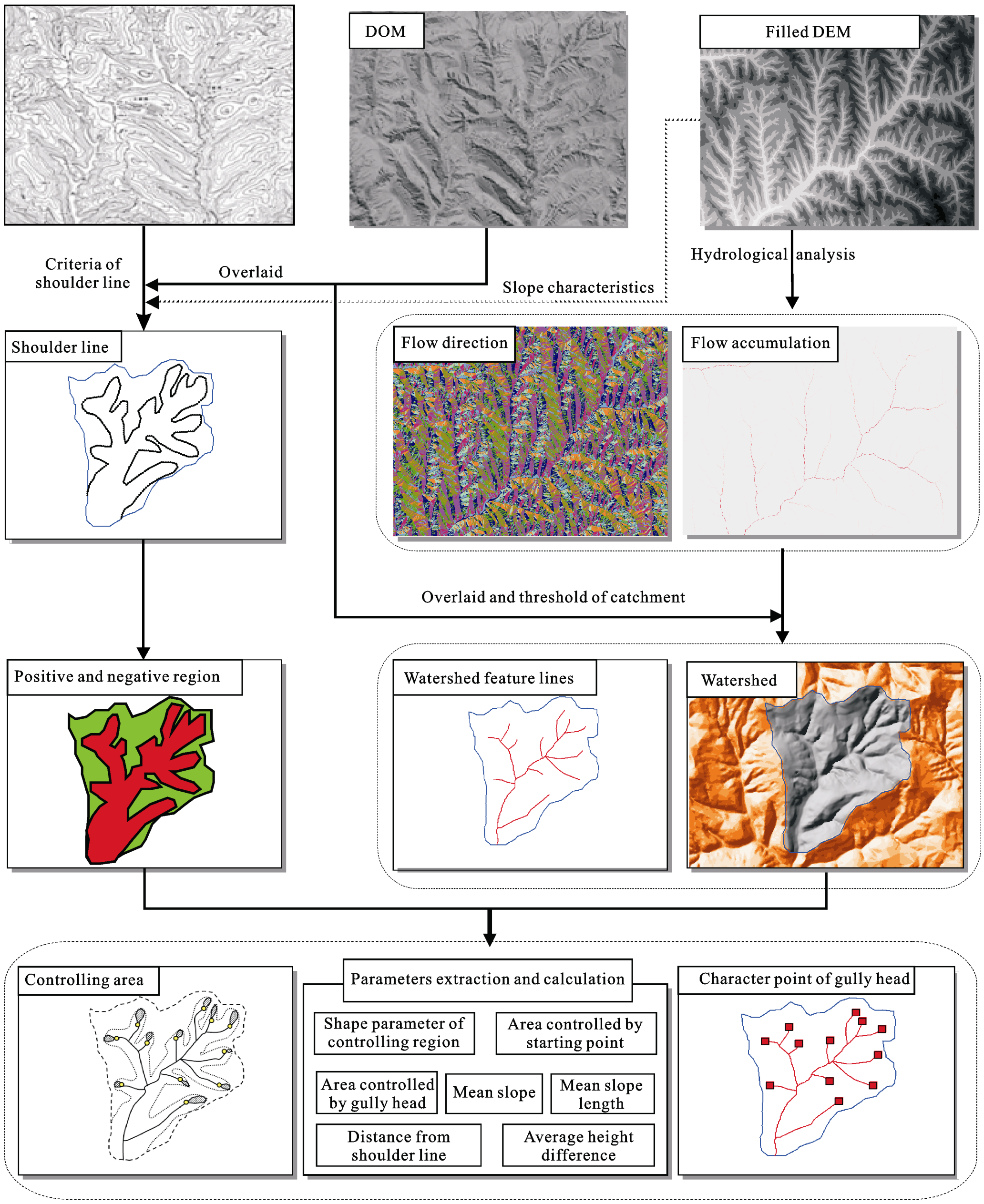


Fig. 5 Extraction scheme of loess gully heads and their features

Table 3 Statistics of loess gully head features

Test area	Number of gully head samples	Area ratio		Mean slope			Mean slope length	
		Mean	Coefficient of variation	Mean (°)	Coefficient of variation	Mean slope ratio	Mean (m)	Coefficient of variation
TA-1	39	12.57	1.37	35.78	0.16	6.73	142.12	0.97
TA-2	137	13.55	0.72	36.70	0.16	4.33	103.12	0.51
TA-3	189	9.54	0.74	32.03	0.19	2.45	102.78	0.35
TA-4	243	24.16	0.63	36.14	0.18	1.48	65.11	0.38
TA-5	141	33.14	0.51	34.16	0.17	1.30	49.18	0.54

Note: Area ratio means controlling area by gully head against corresponding controlling area by starting points

ing a rough logarithmic distribution, as shown in Fig. 6b. This result shows that the slope values of loess gully heads have similar characteristics in different loess landform areas.

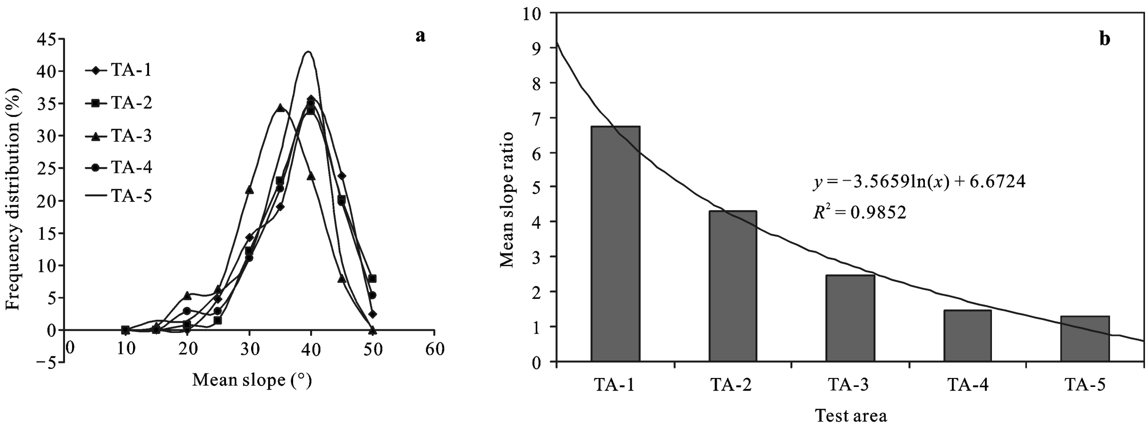


Fig. 6 Mean slope (a) and mean slope ratio (b) of loess gully heads in five test areas

4.2 Slope length condition of loess gully head

Comparing slope lengths of loess gully heads as listed in Table 3, we find that mean slope length obviously differs specifically in the loess tableland (TA-1), loess ridge (TA-3) and loess hill (TA-5). But in the loess flat-topped ridge (TA-2) and loess ridge (TA-3), mean slope length is similar but TA-2 has a relatively large coefficient of variation. Similarly, the loess hill (TA-5) has a mean slope length value similar to loess ridge (TA-4) while its value of coefficient of variation is relatively larger.

Mean slope length of loess gully heads present differences in different loess landform areas and show a strong relationship with the coarseness of the land surface. Mean slope length statistically presents a regular exponential distribution from the loess tableland to the loess hill. In the loess ridge area, the lowest coefficient of variation of loess gully heads indicates that slope length is homogeneous, but it is relatively discrete in other loess landform types with higher coefficients of variation. It is proven that the features of loess gully heads in different loess landform types exhibit significantly different characteristics based on their spatial distributions.

4.3 Area ratio condition of loess gully head

This study classifies area ratio to determine the frequency distribution of loess gully heads in the five test areas (Fig. 7). In the test areas TA-1, TA-2 and TA-3, the frequency curves peak deviation are skewed to their left sides. Their peaks appear at the classification sections of 2.5–5.0 and 5.0–7.5, respectively. Along with the increase of surface roughness, i.e. TA-4 and TA-5, the peaks move from the low area ratio to a higher one as their frequency values decrease. This statistical law indicates that in the loess tableland and the loess ridge, the controlling area of a loess gully head is small but its variation of area ratio is relatively high (Table 3), which suggests that loess gully heads are developing strongly and the gully system is in a growing stage. While in the more rough loess hill area, the controlling area of loess gully heads is relatively large with small variation and its area ratio frequency value changes smoothly, which shows that the gully heads have developed into a stable stage. Thus, in different loess landform types, the distribution law of area ratio of loess gully heads indicates the apparent differences among the areas studied. Therefore, the area ratio value could be applied to reveal the stage of loess gully head evolution, as well as to show the potential in retrieving details of the loess landform evolution.

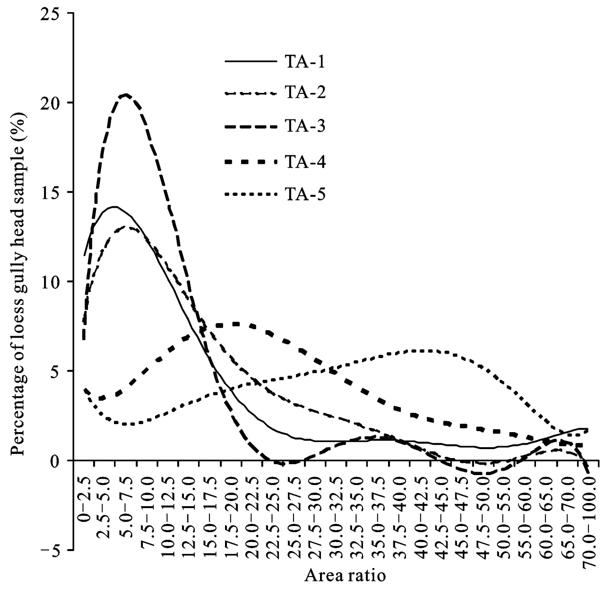


Fig. 7 Frequency fitted curves of area ratio in different test areas

5 Discussion

Regarding the analysis of the statistical results, the mean slope and mean slope length values show characteristics of similarity and discrepancy in different loess landform areas, which proved that they have a strong relationship with the coarseness of the land surface as discussed in 4.1 and 4.2. There exists an apparent difference in the area ratio values of the various loess gully heads. Through analysis of the frequency curves of the area ratio classification, area ratio of the loess gully heads becomes stable with the landform evolution, which is consistent with the erosion acceleration rate of the landform area. With the results in 4.2 and the erosion law of the loess gully landform evolution, it can be concluded that the loess ridge area possesses a higher potential for further erosion where the mean area ratio is small (Table 3). In the loess tableland, loess gully heads, dominated by gravitational collapse and deep undercutting, show relatively weak fluvial erosion to the land surface. Furthermore, the evolution process of loess gully heads in the loess hill area has passed its strongest erosion stage, and the erosion acceleration rate is becoming stable or even decreasing.

Furthermore, the above analyses highlight the characteristics of the stages and formation causes in the development of loess gully heads. On the basis of above results, we recognize that loess gully heads may reflect not only the obvious similarities and discrepancies in different loess landform areas, but also the evolutionary stages and formation causes of loess landforms. Further supported from the interpretation result of the DOM and the contours from DLG, we recognize that the gully network in the loess tableland evolves from the ripples present on the slope surface. Moreover, under fluvial erosion, loess gully heads extend and finally form different shapes which are mainly of wedge shaped and bisected types, and a fewer number have an arc shape. However, loess gully heads in the loess ridge, dominated by fluvial erosion, still evolve so strongly that they will expand further and eventually form the arc-shaped pattern. With the same erosion condition as the loess ridge, gully heads in the loess hill remain relatively stable. Their controlling areas and patterns, typically in ring shape and bisected type, appear to change slightly.

In the same landform area, the direction of a single gully head is not apparent in contrast to the direction of combined gully heads that is highly apparent. The statistical characteristics of combined gully heads may reflect the evolution period of loess landforms and represent better stability on certain watershed scales (usually containing five level gullies). The peak value and frequency of classification curves of the area ratio also represent the evolution period of loess landforms. While analysed samples are fewer, variations of mean slope ratio and mean slope length have better statistic fitted values and can reflect spatial difference patterns of loess gully heads more accurately.

6 Conclusions

In this paper, the loess gully head landform′s concept model, classification scheme and extracting method based on DEM are analysed and established. Some important loess gully head features are achieved based on DEM, DLG and DOM. Statistics of loess gully head features, such as slope, slope length and area ratio parameters, are achieved and analysed in depth. Finally, based on the analysis of statistical results, we arrive at some conclusions regarding the features of loess gully heads. The slope values of loess gully heads have similarity in different loess landform areas, while mean slope length and area ratio of loess gully heads present an apparent difference in different loess landform areas. Thus, we recognize that the loess gully heads reflect obvious similarities and discrepancies in different loess landform areas. These characteristics reflect the growth period and evolution tendency of loess landforms to a certain degree, and they may indirectly represent evolutionary mechanisms as well. So, we can conclude that the loess ridge landform development is strong, but the loess hill landform development is stable. While the less tableland landform by gravitational erosion and fluvial erosion is in early developmental period.

Because this study is based on multi-spatial data and lacks measured data of loess gully heads, the reliability of the extraction method and the precision of quantitative factors need further verification. At the same time, regional differences of characteristics and formation mechanisms of loess gully heads will continue to be the focuses for further researches.

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