GEOMORPHOMETRY 2020 PERUGIA, ITALY JUNE 22 - 26 2020

An empirical-conceptual gully evolution model using space-for-time substitution

Xiaoli Huang
College of Geographic Information and Tourism
Chuzhou University
No.1 Huifeng West Road, Chuzhou City, Anhui Province, China
xiaoliray@163.com

Guoan Tang
Key laboratory of Virtual Geographic Environment, MOE
Nanjing Normal University
No.1 Wenyuan Road, Nanjing City, Jiangsu Province, China
tangguoan@njnu.edu.cn

Abstract—**Space-for-time substitution is a concept that has been widely used in ecology and geomorphology but not strictly tested, especially in some fields of geomorphology. The objective of this study is to test whether the concept of space-for-time substitution is valid in reconstruction the evolution of a special type of gully, which called as 'Spoon-shaped Gully (SG)' in the Chinese Loess Plateau. High precision topographic data acquired by unmanned aerial vehicle (UAV) was used to analyze the morphology and morphometry of a sequence of SG ordered in terms of increasing gully length. The morphological model of gully evolution that proposed from this analysis is very similar to established models in the literature, which leads us to conclude that time can be substituted by space when reconstructing the evolution of SG of the Chinese Loess Plateau.**

I. Introduction

Due to the relatively long time scale of many geomorphic phenomena, especially some large-scale landform units, geomorphologists are generally unable to fully observe and understand landform forming processes based on existing scientific and technical conditions. Taking the loess landform as an example, although the occurrence and change of micro-topography such as rills and shallow gullies can be observed on the loess slope after heavy rainfall, the formation of the Loess Plateau takes several hundred thousand, or even millions of years. There have been various attempts to solve this problem. One approach to solve this issue has been to assume that in the modern landscape we see landforms at various stages of development and that we may therefore make inferences about changes through time based on the variety of forms we see at present. This concept is known as space-for-time substitution, which has been firstly applied in ecology to study the succession of biomes on a long time scale. The basic idea is that, in order to predict the succession process of the community, the community in the same space can be sorted according to the relative difference of the community development, under the condition that the other ecological factors, except time, are kept as stable as possible. Due to the similarity of landform evolution and community succession, this idea has been applied by some geomorphologists to the research of geomorphic evolution, such as tectonic landform, fluvial landform and estuarine and coastal landform [1], [2], [3], [4], [5], [6], [7], [8]. Despite its accepted use in the geomorphic literature, the concept of space-for-time substitution is not thoroughly tested and well proven.

We focus our study on gully system in the Chinese Loess Plateau. The landforms of the Chinese Loess Plateau have been formed through the eolian transport and accumulation of loess deposits on bedrock during the Quaternary. This unique formation mechanism and resultant landscapes attract global attention in relation to their history connected to global change, thick loess sediments, various landscape types, severe soil erosion, and the interaction between natural and human activities. Gullies caused by the water erosion are widespread in the Chinese Loess Plateau. This landform is characterized by the frequent material exchange and strong morphological changes. Among all kinds of gullies with different sizes and shapes, there exists a special type of gully, which called locally as 'Spoon-shaped Gully(SG)'. The SG is unusual because of its unique spoon like shape, unclear water confluence relationship, significant regional differences and complex erosion process.

The aims of this research are: (i) to test whether the concept of space-for-time substitution is valid in loess geomorphology, specifically in reconstructing the evolution of a special type of gully in the Chinese Loess Plateau, and (ii) to gain some new insights into the morphological evolution of gully system of the Loess Plateau.

Xiaoli Huang, Guoan Tang (2020) An empirical-conceptual gully evolution model using space-for-time substitution:

in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_69.

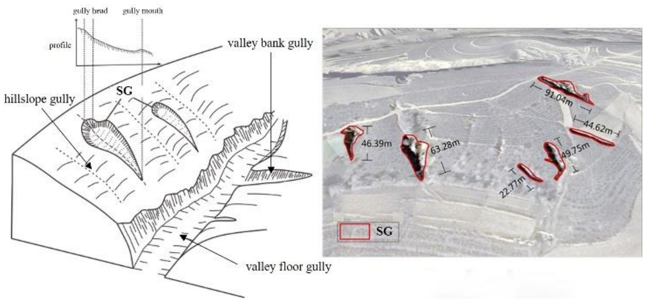


Figure 1. Sketch diagram of SG.

II. RESEARCH FOUNDATION

A. Principle of study area selection

In applications of space-for-time substitution, one should be sure that the environmental conditions are uniform across the entire study area, and there are no individual, small-scale controls (e.g. tectonics, runoff, etc.) that could affect the morphology of individual landforms. The above is fundamental to apply space-for-time substitution which is achieved by having a relative small study area or different study areas with relative same landform forming processes.

B. Regional setting

Two hillslopes situated in Xining (101°43′32″ E–101°43′39″E, 36°39′34″ N–36°39′47″N) and Yulin (108°40′23″ E–108°41′03″E, 37°23′23″ N–37°23′54″ N) of the Chinese Loess Plateau were selected as study area. Xining hillslope is located in the northwest of Xining City. The area of Xining hillslope is approximately 0.07km^2, and the difference in the elevation in this area is roughly 81m. The landform type of this area is valley plain formed by loess deposition. Yulin hillslope is located in the southwest of Jingbian County, Yulin. The area is about 0.7km^2, and the difference in the elevation in this area is roughly 98m. The area situated in the loess hilly area which are characterized by typical loess gullies and hills. Although it is likely that these 2 study areas are far away to each other which may cause other factors, such as precipitation, vegetation condition and soil texture influence SG development. However, according to previous studies [9], these 2 study areas both belong to the middle develop-ment zone (zone III) in the loess cave development density division of the Loess Plateau. The loess cave development density division comprehensively considers the geomorphological conditions, vegetation cover conditions, soil erosion modulus, rainfall and climate, etc., which affect the velopment density of loess caves. Therefore, the landform form process of these 2 areas has large similarity, which is also ma the application conditions of space-for-time substitution.

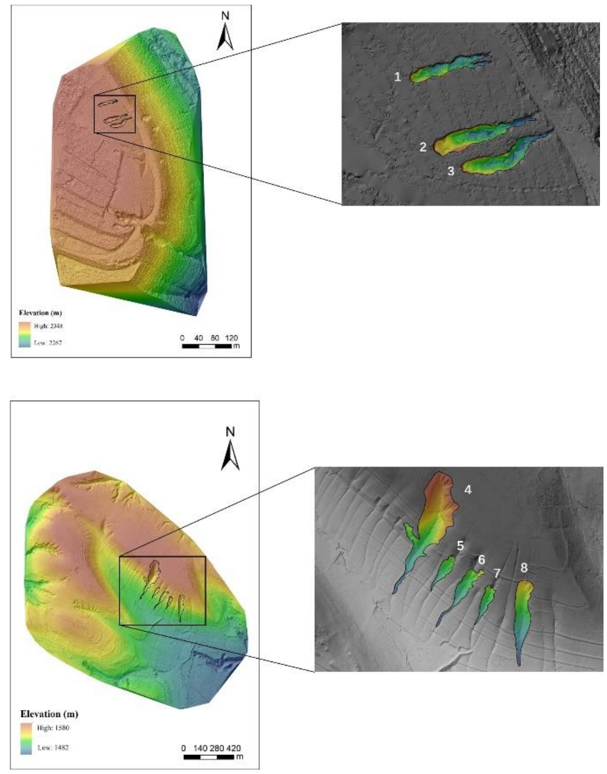


Figure 2. Distribution of SGs in study area (the upper is Xining hillslope and the lower is Yulin hillslope)

III. MATERIALS AND METHODS

A. Test data

In this study, the source data were composed of 19 color aerial photographs taken by UAV photogrammetry with a Matrice 210 (SZ DJI Technology Co., Ltd., Shenzhen, China), and digital aerial photogrammetry was used to generate a Digital Elevation Model (DEM) of 0.1m resolution. The processing flow is as follows. Forty-nine ground control points were obtained by the GPS-RTK (Global Positioning System Real - time kinematic) method. The geodetic datum, projection, and central meridian were WGS-84, Gauss-Kruger projection, and 111°, respectively. Aerial triangulation was performed inside a laboratory according to the control points obtained through field-work. The Digital Surface Model (DSM), including the vegetation and manmade features above the pure earth surface, was constructed using photogrammetric software (Pix4Dmapper). Editing is required to modify elevation and consequently eliminate the influences of the buildings and vegetation. Topographic features, such as contour lines, feature lines and feature points were also obtained. Finally, DEM was derived from the DSM at 0.1m resolution by using Pix4Dmapper. Besides, 0.04 m digital orthophoto maps (DOMs) were also simultaneously generated by UAV photogrammetry which served as ground truth and as reference maps.

B. *Ergodic indicator*

Choosing the suitable terrain factor as the ergodic indicator is the key to the research of landform evolution by using space-for-time substitution. Distance, location, landform dimension and complexity are generally used as ergodic indicators of landform evolution to derive the spatial sequence. According to the previous research and the basic principle of geomorphology, the most important consideration when choosing an ergodic indicator is that its main controlling factor is time (and not other factors related to lithostratigraphy, structure, exogenic controls, etc.). Therefore, combing the characteristic of the loess landform, gully length is chosen as the ergodic indicator of this research.

C. *Morphometric parameters of SGs*

To test our hypothesis that space can be substituted for time to reconstruct the evolution of SG, we used gully length as an ergodic indicator of landform evolution. We organized the eight SGs dis-tribute on the hillslopes from study area, i.e. Xining and Jingbian into a sequence of increasing gully length and labelled these SGs as ‘features 1-8’. For each feature we extracted a number of morphometric parameters from high-resolution DEM.

1. Gully length: The gully length includes the channel length (Lc) and straight length (Ls). Channel length is defined as the length of the gully from head to mouth along the stream channel, while the straight length is defined as the linear distance from the gully head to its mouth. For the same area, if the gully is much longer, there will be a larger drainage area and the gully will have experienced a much longer erosion process. At a given time, the length of each gully is fixed.
2. Gully width: The top width at any cross-section of the gully is called the gully width. A gully has many cross-sections, and thus there is more than one gully width. From the gully head to the mouth, the gully widths at 1/4, 1/2, and 3/4 of the way along the gully are marked as W1/4, W1/2 (also called middle width, Wh), and W3/4, respectively. The value obtained by dividing erosional area (A) by Lc is called the average width (Wa) or equivalent width (El Maaoui et al., 2012). The changes of gully widths along the gully and the length–width ratios can effectively describe the plane form of the gully.
3. Gully depth: The gully depth is the difference between the average elevation before the gul-ly erosion and the average elevation after the gully erosion within the gully area. The gully depth calculated in SG is the main gully depth. The change in gully depth reflects the undercut process of the valley.
4. Erosion area: The erosional area (A) refers to the area of the closed curve zone enclosed by the shoulder line, namely the area eroded away under gully erosion.
5. Erosion volume: The erosion volume refers to the change of soil volume caused by gully erosion. The calculation method is the product of the projected area of the channel and the average gully depth. The greater the amount of gully erosion per unit time, the stronger the gully erosion.
6. Opening degree: The opening degree is defined as the ratio of the average width and the av-erage depth of the gully. For deep erosion gully, the opening degree is relatively small, which is characterized by steep gully slop. For the relatively open gully, the corresponding opening degree is larger, reflecting that the gully slope is gentle, and the site conditions and land use potential are better. There are three types of gully opening degree including semi-open (1.32~2.61), open (>2.61) and deep open (<1.32).

IV. RESULTS AND DISCUSSION

A. *Gully morphometric characteristics*

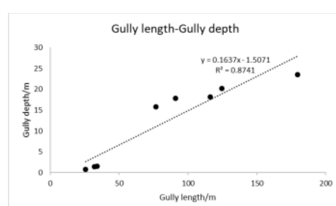
The statistical results of gully morphometric parameters show below.

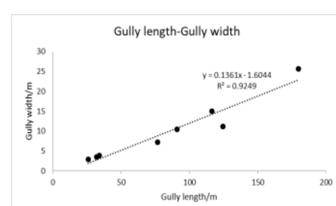
Table 1. Morphometric parameters of SG from Xining hillslope

Xining	1	2	3
Gully length(m)	25.78	34.17	32.07
Gully width(m)	2.94	3.84	3.52
Gully depth(m)	0.81	1.60	1.44
Erosion volume(m^3)	63.89	481.84	379.28
Opening degree	3.63	2.40	2.44

Table 2. Morphometric parameters of SG from Yulin hillslope

Yulin	4	5	6	7	8
Gully length(m)	179.65	91.04	116.29	76.76	124.45
Gully width(m)	25.69	10.40	14.98	7.16	11.22
Gully depth(m)	23.47	17.81	18.18	15.83	20,15
Erosion volume(m^3)	92574.36	14743.47	25082.76	7267.87	24638.01
Opening degree	1.09	0.58	0.82	0.45	0.56





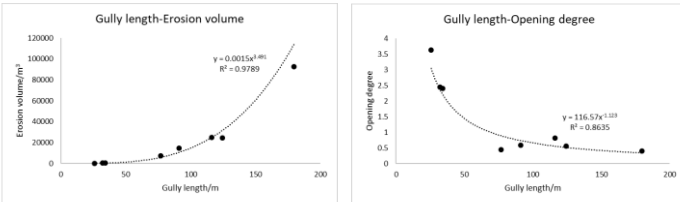


Figure 3. The variation of morphometric parameters of SG

B. Validity of space-for-time substitution model

The inferred model for the morphological evolution of SGs shows many parallels with established gully evolution models in the literature.

In terms of gully evolution in the Loess Plateau, the most distinguishing characteristics is that as the gully length increases, the width and depth of the gully are increasing simultaneously due to the lateral erosion and vertical erosion by fluviation [10]. The above process is consistent with the results obtained above.

Besides, there was a very prominent relationship of power function between erosion volume and gully length and gully area and thus the gully length and the gully area can be used to estimate the gully erosion rate at the large spatial scales because they can be easily determined from very high-resolution satellite images and DEMs [11], [12], [13]. These also show strong similarities with the results obtained.

C. SG development and tunnel erosion

4407 SGs (incomplete statistics) were marked in the Loess Plateau by visual interpretation based on Google Earth image. By using Kernel Density tool of ArcGIS 10.0, kernel density plot of SGs in the Chinese Loess Plateau was obtained. It can be seen from the plot that most of the SGs are distributed in the northwestern margin of the Loess Plateau and the Lanzhou-Dingxi area. According to previous studies [9], these areas are short of precipitation, and the loess particle is dominated by sandy loess, which has strong collapsibility and is prone to loess piping and tunnel erosion, forming a large number of loess cave systems.

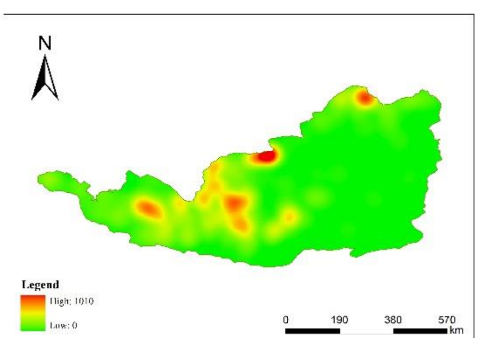


Figure 4. The kernel density plot of SG

Detailed field studies were carried out to investigate the interactions between SG development and tunnel formation processes in the selected 8 gullies. Smoke tracer method was used to investigate the SG and the associated loess cave system. The tracer method has been widely used in the fields of physics, chemistry, biology, etc. The principle is to use the radionuclide as a tracer to mark the research object to observe its trajectory and spatial distribution characteristics. Some scholars have introduced it into the study of gully erosion on the Loess Plateau, and have also obtained corresponding research results. Inspired by this, the smoke tracer method is used to roughly determine the spatial pattern of the loess cave system. The smoke generator was put into the loess cave, and blast the hole and observe the exit position of the smoke to determine the connectivity and development of the cave. The results show that the formation of SG is strongly associated with loess piping and tunnel erosion. A large number of slope surface runoff flows through the underground loess caves, resulting in the special shape of SG. The SG can be considered as a special initial form of a hillside gully widely distributed in the collapsible sandy loess area, which is dominated by piping and tunnel erosion, surface fluvial erosion and gravity erosion.

Figure 4. Tunnel outlet exploration using smoke tracer method

D. Other new insights of SG evolution in the Chinese Loess Plateau

Compared with other types of loess gullies, the amount of SG distributed in the entire Loess Plateau is small. On the one hand, because of its special development mechanism, it mostly appears in the collapsible loess area; on the other hand, because it is an intermediate form of loess gully development, its development process is sudden and accidental. The sudden collapse of the loess cave will cause SG to continue to develop in the next stage, causing SG to occupy only a short period of time throughout the development of the loess gully. Therefore, under natural conditions, it is difficult to observe a large number of SGs compared to other gullies.

References

[1] Paine A D M. 'Ergodic' reasoning in geomorphology: time for a review of the term. Progress in Physical Geography, 1985, 9(1):1-15.

[2] Kirkbride M, Matthews D. The Role of Fluvial and Glacial Erosion in Landscape Evolution: The Ben Ohau Range, New Zealand. Earth Surface Processes & Landforms, 2015, 22(3):317-327.

[3] Stolar D B, Willett S D, Montgomery D R. Characterization of topographic steady state in Taiwan. Earth & Planetary Science Letters, 2007, 261(3–4):421-431.

[4] Leyland J, Darby S E. An empirical–conceptual gully evolution model for channelled sea cliffs. Geomorphology, 2008, 102(3–4):419-434.

[5] Hilley G E, Ramón Arrowsmith J. Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California. Geology, 2008, 36(5):367-370.

[6] Fryirs K, Brierley G J, Erskine W D. Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. Earth Surface Processes & Landforms, 2012, 37(7):763–773.

[7] Micallef A, Ribó M, Canals M, et al. Space-for-time substitution and the evolution of a submarine canyon–channel system in a passive progradational margin. Geomorphology, 2014, 221(11):34-50.

[8] Ely J C, Clark C D, Spagnolo M, et al. Using the size and position of drumlins to understand how they grow, interact and evolve. Earth Surface Processes & Landforms, 2017, 43(5):1073-1087.

[9] Peng J B. Loess cave disaster. Science Press, Beijing, 2009.

[10] Liu D S. Loess and Environment. Science Press, Beijing, 1985.

[11] Li Z, Zhang Y, Zhu Q K, et al. A gully erosion assessment model for the Chinese Loess Plateau based on changes in gully length and area. Catena, 2017, 148: 195－203.

[12] Dong Y F, Xiong D H, Su Z A, et al. Critical topographic threshold of gully erosion in Yuanmou Dry-hot Valley in Southwestern Southwestern China. Physical Geography, 2013, 34(1): 50－59.

[13] Zhang T Y, Liu G, Duan X W, et al. Spatial distribution and morphologic characteristics of gullies in the Black Soil Region of Northeast China: Hebei watershed. Physical Geography, 2016, 37(3-4): 228－250.