Using 3D scanner to study gully evolution and its hydrological analysis in the deep weathering of southern China

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Abstract

This study integrated 3D scanner measurement techniques with hydrological analysis to study the evolution of gullies developed in the deep weathering (granite) in the subtropical climate of southern China. Two gullies were repeatedly measured using a 3D laser scanner over a 7.5-year period from 2009 to 2016. The measurements with sub-centimeter accuracy indicated that gully head retreat was the dominant process in the gully development, with a mean rate of 0.46 and 1.10 m yr⁻¹ for gully A and B respectively. To explore the relationship between gully head retreat (GHR) and hydrologic variables, rainfall with three different thresholds, rainfall erosivity and runoff depth were calculated using different methods. Statistical analysis showed a significant correlation between GHR rates and cumulative erosive rainfall depth with a daily rainfall threshold > 25 mm. Hydrological analysis and field observations suggested that gully head retreats mainly result from mass movement triggered by gravity and soil saturation, although water erosion might also play a role in destabilizing

1 the already unstable gully slopes. This study has implications for restoration of gullies in the
2 area, which requires techniques that go beyond a mere reduction of runoff contribution to
3 gully systems. Further studies are needed to gather more data on the evolution and sediment
4 delivery of gullies, to prove the hypothesis of gravity-driven gully headcut development, and
5 to explore more effective gully restoration techniques.

6 **Keywords:** Metamorphic materials; Gully head retreat; Gully wall; DEM; 3D Scanner

7

1. Introduction

Gullies are a recognized driver of landscape evolution acting at different time scales (Hancock et al., 2013). For instance, Poesen et al. (2003) classified gully evolution as short (< 5 years), medium (5-50 years) and long term (> 50 years) according to their age since the initiation of gullies. The evolution of gullies can be quantified using a set of variables, such as gully head retreat (GHR) rate, gully projected area (S) and gully volume (V) (Castillo and Gómez, 2016; Matthias et al., 2016). GHR rate is varied among different stages of gully development (Campo-Bescós et al., 2013). Therefore, it can be used as an indicator of gully evolution.

A number of studies have been conducted to measure GHR rates under different soil and climate conditions at different gully evolutionary stages. For gullies at an initial stage, or short term scale (< 5 year old), Frankl et al. (2012) reported 0.34 m yr⁻¹ of GHR rate, six of which developed in limestone colluvium, twelve in stanstone colluvium and six in Vertisols, in the northern highlands of Ethiopia, while 0.1 m yr⁻¹ of that was measured, developed in tertiary loams, marls, and calcareous sands etc in eastern Spain by Vandekerckhove et al. (2003). In comparison, greater GHR rates at an initial stage have been reported in China. For instance, Hu et al. (2007) measured GHR rates, developed in Pachic Udic Haploborolls, with a range of 0.35-7.7 m yr⁻¹ in the northeastern China, and Ma et al. (2009) reported GHR rates from 4.34 m yr⁻¹ to 12.67 m yr⁻¹ in Weiliantan of the Gonghe basin in western China, which developed in Mollisols. Regarding the medium term scale with gully age of 5-50 year, GHR rates also show a large variability. For example, Li et al. (2012) reported GHR rates of 0.36 to 0.44 m yr⁻¹ in four small catchments in the loess region of China. Also in loess-derived soils in

1 Belgium, [Nachtergaele et al. \(2002\)](#) measured an average GHR rate of 1.8 m yr^{-1} over the
2 period of 1988 to 1999. In a semi-arid catchment in Spain, [Campo-Bescós et al. \(2013\)](#)
3 documented a mean GHR rate of 0.32 m yr^{-1} from 1967 to 1982, and 0.41 m yr^{-1} in from 1982
4 to 2003, while [Avni \(2005\)](#) measured GHR rates in the range of $1.12\text{-}22.7 \text{ m yr}^{-1}$ in marine
5 sediments of the arid conditions of the Negev highlands of Israel for the period of 1990 to
6 2001. Studies have documented high GHR rates in gullies in medium term scale under other
7 circumstances, such as in a city park in Saskatchewan (Canada) where [Archibold et al. \(2003\)](#)
8 reported annual GHR rates ranged from 1.17 m yr^{-1} to 3.17 m yr^{-1} in loamy-clay-clay loam,
9 sandy clay loam-sandy loam over the period of 1994 to 2000, and in agricultural areas under
10 cultivation in Romania where an outstanding average GHR rate of 14 m yr^{-1} was measured
11 from 1961 to 1990 by [Ionita \(2006\)](#), which developed in Mollisols and argiluvissols.

12 There are comparatively few long term (with gully age > 50 years) studies on GHR
13 ([Castillo and Gómez, 2016](#)), but these studies provide a unique perspective on gully evolution
14 processes close to a mature stage of gully development. These long term GHR rates tend to
15 fall in low to medium ranges of those presented for younger gullies. For examples,
16 [Rieke-Zapp et al. \(2011\)](#) reported GHR rates of 0.35 m yr^{-1} , 1.5 m yr^{-1} and 1.26 m yr^{-1} for
17 three different gullies over the 70 years period (1935 to 2005) in the Quaternary alluvium of
18 an arid experimental basin in Arizona (USA). These values were slightly higher than those
19 measured by [Samani et al. \(2010\)](#), developed in Lithic Xerothents and Lithic Torriorthents in
20 the Hableh Rood basin in Iran, with GHR rates of 0.26 , 0.21 and 0.15 m yr^{-1} in the periods
21 1956-1967, 1967-2000 and 2000-2005, and by [Shellberg et al. \(2016\)](#) in fine-grained
22 dispersible sodic soils of Queensland (Australia), with GHR rates of 0.37 and 0.23 m yr^{-1} for

1 the periods of 1949-2005 and 2005-2010 respectively in fine-grained dispersible sodic soils.
2 The majority of gullies reported in those studies developed from readily erodible soils or
3 parent materials, such as loess soil and sedimentary rocks, while measurements on gully
4 development in the areas of metamorphic or igneous materials are scarce ([Castillo and Gómez,](#)
5 [2016](#)).

6 Some studies are conducted on the relationship between gully development or sediment
7 yield, and rainfall variables. For example, [Capra et al. \(2009\)](#) indicated that gully
8 development in a semiarid region in Sicily, Italy was mainly affected by the maximum 3-days
9 cumulative rainfall (with a threshold of 51 mm) and the maximum 1-hour rainfall intensity
10 (with a threshold of 25 mm h⁻¹). [Rieke-Zapp et al. \(2011\)](#) proved that the linear retreat of
11 gully had a strong power relationship with the product of cumulative areal precipitation and
12 contributing drainage area for a given measurement interval. For example, [Bouchnak et al.](#)
13 [\(2009\)](#) found that yearly erosive rainfall total with a threshold of daily rainfall ≥ 40 mm was
14 closely related to annual sediment yield in an arid area of Tunisia. [Castillo and Gómez \(2016\)](#)
15 analyzed the relationship between specific soil loss of studied gullies and rain depth, drainage
16 area. Although many studies were conducted on the relationship between gully development
17 and hydrological conditions, it was very scarce about the relationship between GHR rate and
18 common precipitation indicators. It also faces the similar questions in southern China.

19 There were vast subtropical forests in the southern China originally ([Shi et al., 2005](#)) that
20 were degraded by human activities starting at different times in different districts. There is a
21 written reference describing that collapsing gullies began to appear in 1942 in the Hetian
22 district of Fujian Province, coinciding with the start of exploitation and degradation of the

1 subtropical forests (Xu and Zeng, 1992a). We have not found documents reporting when
2 gullies began to form in Yudu county (the study site). However, similarity in soil and climate,
3 and the start of exploitation of subtropical forest in 1940's between Yudu county and Hetian
4 district suggests that development of large gullies might have started in the study region
5 around the 1940's. This agreed with the interview of an elderly farmer who said that some
6 gullies formed before 1949 when the People's Republic of China was founded. Gullies of
7 present study were probably formed in more recent decades. Until 2005, there were 239.1
8 thousand gullies in 362 counties of 7 provinces of southern China by artificial survey (Feng et
9 al., 2009), which formed in the deep red weathering granite. It was the similar geomorphology
10 with Madagascar's lavaka (Liu, 2018). Recently, some studies were also conducted on gully
11 development. For example, Du et al. (2015) utilized CORS-RTK GPS to measure the
12 elevation of 158 and 169 sample points in a gully with a projected area of 320 m² in 2011 and
13 2013 respectively. Liu and Zhang (2015) used 3D scanning technology to measure a gully
14 characteristic. However, a long series of gully measurements are also very scarce.

15 The objectives of this study are to explore dynamic evolution of gullies on the deep
16 weathering regolith in southern China by using 3D scanning techniques, and to analyze the
17 effects of rainfall, runoff on gully development. This study would enrich the global database
18 of gully development on metamorphic materials which has been much understudied, and to
19 provide a scientific basis for erosion control in southern China where gully erosion is
20 widespread and considered as one of major land degradation threats. In addition, in this study,
21 various hydrologic parameters using basic rainfall data and characterized their relationships
22 with gully head retreat rates were computed. This method may be applied to study gully

development in the regions where no direct runoff measurement is conducted.

2. Methods

2.1 Study site

The monitored gullies were located in Zuoma, a small agricultural catchment with 0.73 km² or so, about 4 kilometers north of Yudu county of Jiangxi province in southern China (115.4° N, 25.9° E) (Fig. 1). This region has a typical warm and humid subtropical monsoon climate with an average annual precipitation of 1508 mm and a mean annual temperature of 19.7 °C. The main soil type is Orthic Acrisol, with a soil depth of about 1.0 m, according to the Soil Survey Staff (Chen et al., 2004). Parent material is a weathering regolith of granite up to a depth of 20-60 m. Soil pH is about 5~6. Main crop in the catchment is rice and has two crops per year, with the first crop from April to July and the second from July to November. Land use in the catchment is a mixture of field crops (rice), tree crops, and forest lands (Fig. 1).

Fig.1. Location of the study gullies, check dam and catchment.

Based on field reconnaissance and interpretation of remote sensing images (Fig. 1), 11 collapsing gullies were identified in Zuoma catchment and more detailed information about them was described in Liu et al. (2015). Most of those gullies were located in the sloping area of the catchment, while few gullies were formed along the main channel draining of the catchment. Two of eleven gullies, hereafter referred as GA and GB, were selected for this study based on their representativeness in gully projected area (S) and gully volume (V) of gullies present in the catchment. Gully A and B, approximately 450 m apart (Fig. 1 and Fig. 2), has a distance of 20.45 m and 9.2 m from the catchment divide to gully head, and an upstream

contributing area of 1020 m² and 807 m² respectively (Fig. 1).

Gully B was present on the topographic map (with a scale of 1:10000) made in 1989 and GA was shown on Quickbird remote sensing images taken in 2005. Therefore, gully A was formed between 1989 and 2005. Although GB was already present before 1989, it is unlikely that GB formed many years further back, according to the retreat rate of GB and its distance to the valley bottom. In the period from 1989 to 2005, cultivated slopeland was converted into tree crop terraces. Since 2005, ecological restoration has been implemented with the aim of restoring the degraded forest in the catchment. Thus, our gully monitoring over the period of 2009 to 2016 represents the evolution of gullies after the catchment was converted to well-managed forest land. A check dam was constructed at the outlet of GB to prevent sediment from flowing into the river in 2012. The weathering material at the lower section of GA channel was first excavated in 2014. And later, gully A was bulldozed and repaired for construction in April, 2016 (Fig. 2).

Fig.2. Photographs of GA (a), GB (b) collapsing gullies. Note: 1. Gully wall. 2. Deposition area. 3. Gully bottom in GA (pictures taken in September, 2009).

2.2 Gully measurement and data processing

Manual measurements using measure tape, or topographic equipment such as theodolite (e.g. Chai et al., 2001; Vandekerckhove et al., 2003) are usually time consuming and of limited accuracy, particularly when used beyond small scale. An integration of GPS techniques with GIS enables to measure gully morphology with a higher accuracy in a shorter time (e.g., Hu et al., 2007) than manual methods. In recent years, 3D scanner (Rengers et al.,

1 2015) has been adopted to measure gully topographic characteristics with high accuracy and
2 efficiency. Therefore, a higher accuracy was achieved by using 3D scanner than the other
3 techniques (Gómez-Gutiérrez et al., 2014; Liu et al., 2011). Accordingly, 3D scanner has been
4 widely used to measure gully landscape (e.g. Li et al., 2017; Vinci et al., 2016; Goodwin et al.,
5 2017) and has been regarded as a benchmark technique in acquiring gully morphologic data
6 (Li et al., 2017).

7 In this study a 3D scanner (Leica HDS 3000) was used to monitor development of these
8 two gullies, with measurements carried out in September 2009, October 2011, September
9 2013, October 2014, and April 2016. Five monitoring campaigns were separated between 1 to
10 2 years, in total spanning a period of 7.5 years. A previous evaluation conducted by Liu et al.
11 (2011) validated the capability and accuracy of the equipment and data processing technology
12 for measuring gullies of such dimensions. The work procedures consisted of data collection in
13 the field and data analysis at the laboratory as follows (Fig. 3).

14 (1) According to micro-relief and vegetation cover around the gullies, three target points
15 were established by using the differential GPS. A concrete foundation was laid out 0.5 m deep
16 at each target point so as to maintain its fixed position throughout the monitoring period. The
17 target points were used to ensure the accuracy of point cloud data and their overlapping in
18 consecutive campaigns. Gully A was scanned with one station throughout the entire
19 monitoring period, while GB required one station from 2009 to 2013, but two stations from
20 2014 to 2016 due to the enlargement of gully. Fig. 2 shows the change of gully walls over
21 time.

22 (2) The scanner was positioned about 5 m in the front of gully outlet. It was run by the

1 proprietary software, Leica Cyclone 5.1. Horizontal interval of scanning points was 10 mm,
2 with a vertical accuracy of ± 2 mm. After a gully was scanned, all the point cloud data
3 corresponding to the same gully were merged into a single cloud by using Leica Cyclone 5.1,
4 in which the data coordinate system was transformed into the geodetic coordinate system, and
5 the data interference coming from elements such as trees or grass was eliminated using the
6 filtering and editing function of the software. The processed point cloud data was then
7 exported into ArcGIS software (version 10.2). [Romanescu et al. \(2012\)](#) had indicated the
8 effect of vegetation on the accuracy of Digital Elevation Model (DEM) derived from the
9 scanned point data because the filtering function deletes measurement points of vegetated
10 areas. Those blank areas need to be interpolated, which therefore affects the accuracy of DEM.
11 Nevertheless, vegetation growth within gullies of the present study was very limited. Thus the
12 blank spaces caused by filtering were very small and their effect on DEM should be
13 negligible.

14 (3) Digital Elevation Model derived from point cloud data had a grid spacing of $0.05 \text{ m} \times$
15 0.05 m . The gully boundary line and three types of areas (gully wall, deposition area, gully
16 bottom) for both gullies were extracted from the DEMs to represent the landforms. Gully
17 projected area (S) and volume (V) were calculated using the Functional Surface Module, and
18 slope gradient was computed by the Slope Module in ArcGIS 10.2. The area and position of
19 two gullies were compared with a previous survey conducted in 2005 using laser
20 distancimeter to ensure their accuracy ([Liu et al., 2015](#)).

21 (4) Multi-temporal DEMs were used to determine the changes of elevations over time, and
22 to calculate the gully S and V, as well as their temporal changes. The evolution of the gully

boundary line along the principal direction of gully (Fig. 8) was used to determine GHR rates (gully head retreat rate) for evaluation of gully development stage.

Fig.3 Flow chart of gully data collection and processing.

2.3 Computation of rainfall erosivity and surface runoff

The cumulative precipitation for four monitoring intervals (Sep/2009 - Oct/2011, Oct/2011 - Sep/2013, Sep/2013 - Oct/2014, and Oct/2014 - Apr/2016) was 3608.7, 3826.3, 1667.9, and 3988.8 mm respectively. Wischmeier and Smith (1978) suggested daily rainfall of 12 mm as a threshold of erosive rainfall. In the study region, 24-hour accumulative rainfall ranging 25-50 mm is classified as rainstorm, and if exceeding 50 mm, as heavy rainstorm (Xie et al., 2016). Accordingly, rainfall erosivity using three thresholds of 12, 25, 50 mm to determine which one corresponds best to gully evolution was calculated. The rainfall erosivity was calculated from daily rainfall using Eq. 1 which was developed by Zhang et al. (2002), and calibrated for China's conditions using the data collected by the First National Water and Soil Conservation Survey in China.

$$RE_i = \rho \sum_{j=1}^k (D_j)^\sigma \quad \text{Eq. (1)}$$

Where RE_i is the rainfall erosivity of the i th half-month of the year, $\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$; it is noted that each month is divided into two half months: days 1-15 and day 16 to the end of the month and one year comprises 24 half months; k is the number of days in the i th half-month; D_j is the effective rainfall for day j in one half-month, mm; D_j is the actual rainfall if the daily rainfall total is greater than 12 mm; otherwise, D_j is considered as 0. The

terms ρ and σ are empirical coefficients determined by the following formulas:

$$\sigma = 0.8363 + 18.144P_{d12}^{-1} + 24.455P_{y12}^{-1} \quad \text{Eq. (2)}$$

$$\rho = 21.586\sigma^{-7.1891} \quad \text{Eq. (3)}$$

Where P_{d12} and P_{y12} are the average daily and annual rainfall for days with rainfall > 12 mm, respectively. In this study, P_{d25} and P_{y25} , and P_{d50} and P_{y50} were also applied in Eq. 2 to calculate the ρ parameter using daily rainfall threshold of 25 and 50 mm, respectively.

The erosive rainfall with a threshold of daily rainfall total greater than 12 mm and rainfall erosivity were showed in Fig. 4 according to rainfall record at local meteorological station. The average annual erosive rainfall and rainfall erosivity were respectively 1233.6 mm and 8696.3 MJ mm ha⁻¹ h⁻¹ yr⁻¹ for the period from 1989 to 2005. Rainfall data record indicated that rainfall conditions from 1989 to 2005 were not significantly different from those after 2005 (Fig. 4).

Fig.4. Daily erosive rainfall and rainfall erosivity since 1988 to 2016.

The SCS-CN (curve number) method developed by the USDA SCS (Soil Conservation Service, 1972) was used to calculate the daily surface runoff (Q_{surf}) from daily rainfall:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad \text{Eq. (4)}$$

Where Q_{surf} is daily surface runoff in mm, R_{day} is daily rainfall in mm, I_a is initial abstraction in mm, S is potential maximum retention of water by soil in mm.

The potential maximum retention, S , is calculated from Eq. 5,

$$S = \left(\frac{25400}{CN} \right) - 254 \quad \text{Eq. (5)}$$

1 Where CN is the curve number. Since initial abstractions, I_a , is usually approximated as
 2 0.2S, Eq. 4 can be rewritten as:

$$3 \quad Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad \text{Eq. (6)}$$

4 CN values are tabulated for different hydrological soil group, land use and antecedent
 5 moisture conditions (Table 1). In the study area, according to the characteristics of infiltration
 6 (Wei et al., 2013), soil in the gully catchment areas is classified in-between group A and group
 7 B, and land use is woodland with good conditions. Thus the value of CN_2 , corresponding to
 8 average Antecedent Moisture Condition (AMC II), is 42.5 according to Table 1.

9

10 **Table 1** Runoff curve number values for average moisture condition, CN_2

11

12 The CN values for antecedent dry (CN_1) and wet (CN_3) conditions can be calculated using
 13 daily rainfall and Eq.7-8. AMC I (dry) is defined as when the cumulative rainfall in the
 14 previous five days is less than 13 mm, and AMC III (wet) is defined as when cumulative
 15 rainfall for the previous five days is more than 28 mm. When the cumulative rainfall is
 16 between 13 and 28 mm, it is considered as AMC II (average). The curve number for AMC I
 17 and AMC III can be calculated from CN_2 using the following relations (USDA, 1986):

$$18 \quad CN_1 = \frac{4.2CN_2}{10 - 0.0584CN_2} \quad \text{Eq. (7)}$$

$$19 \quad CN_3 = \frac{23CN_2}{10 + 0.13CN_2} \quad \text{Eq. (8)}$$

20 Where CN_1 is curve number of AMC I, CN_2 is curve number for AMC II, CN_3 is curve
 21 number for AMC III.

1 Given the small contributing area for both gullies, we assume a negligible concentration
2 time and a homogeneous soil type.

3 *2.4 Assessing GHR relationship with hydrologic parameters*

4 The relationships between gully evolution and hydrological variables were analyzed using
5 Origin software version 8.1. Firstly, the linear relations between gully head retreat of GA, GB
6 and ≥ 12 mm, ≥ 25 mm, ≥ 50 mm rainfall depth, rainfall erosivity was estimated. The best
7 linear relation was known. Secondly, gully head retreat of GA, GB was divided by the
8 maximum of every gully for normalized value. Thirdly, the linear regression between the
9 normalized gully head retreat of both gullies and the best rainfall depth, rainfall erosivity was
10 fitted.

11 **3. Results**

12 *3.1 Gully development processes*

13 [Fig. 5](#) displays the change of gully elevation over 7.5-year monitoring period for GA and
14 GB respectively. A few points deserve further comments here: (1) Both gullies presented a
15 significant upslope retreat, with gully depth, which is defined as the difference in elevation
16 between gully head and gully outlet, changed from 27.54 m to 30.77 m for GA, and from
17 13.89 m to 17.15 m for GB. In other words, gully depth increased by 3.26 m and 3.23 m
18 during 7.5 years period for GA and GB, respectively. This represents an increase rate of about
19 0.43 m yr^{-1} for both gullies. (2) The change in elevation was the highest in gully head area,
20 moderate in gully side walls, and the lowest in gully bottom. This reflects that gullies changed
21 mainly in the longitudinal direction of gully axis towards the catchment divide, while the
22 elevation of gully depositional area changed moderately, with an increase due to deposition of
23 sediment coming from gully wall collapse and gully head retreat. Field observations of both

gully heads show the signs of water erosion (rills) and mass movement, suggesting that gully erosion was still active.

Fig.5. Elevation changes of GA (a) and GB (b) during the study period.

[Fig. 6](#) shows the changes in slope gradient of different parts of gullies during the study period. Slope gradient was above 60°, in some cases even up to 80° in gully walls, while it ranged from 20° to 60° at gully bottom, and 0° to 40° in the depositional area. It is noticeable in [Fig. 6](#) development of rills and small ephemeral gullies in gully bottom of GB over the period of 2009 to 2014, reflected by a drastic change of slope gradients, even exceeding 60° at some points. Slope gradient of gully walls measured in this study is in a similar range, above 60°, to those described by [Zhang and Liu \(2014\)](#) in a study of collapsing gully walls in the weathering parent material in Guangdong Province, also in southern China. [Fig. 7](#) summarizes the mean slope gradient of three areas of each gully during the study period. It can be seen that the mean slope gradient of gully walls was about 65° and 70° for GA and GB respectively, while that of the depositional area in both gullies was about 50°, and that of the bottom area decreased from 35-50° at the beginning of the study period to 20° at the end of the study period for both gullies. The average slope gradient at the exit of both gullies was about 20°, reflecting the deposition of the eroded sediment as the overland flow lost energy for transport. The change in slope gradient for GA from 2014 to 2016 was not due to natural processes, but due to reshaping of gully bottom area for construction.

[Fig. 8](#) demonstrates the evolution of gully walls over time. It can be clearly seen that widening of one of the walls (left side looking downhill) in GA was so dramatic, with a

1 magnitude even comparable to that of gully head retreat. However, the retreat of gully wall
2 was caused by construction work performed there, instead of natural collapse processes.

3
4 **Fig.6.** Changes of slope gradient of GA (a), GB (b) during the study period. 1. Gully wall. 2.
5 Deposition area. 3. Gully bottom.

6 **Fig.7.** Changes of mean slope gradient of GA (a), GB (b) during the study period.

7 **Fig.8.** Spatial retreat of GA, GB gully wall in the study period.

8 9 *3.2 Dynamic evolution of gully head*

10 [Fig. 9](#) displays the gully retreat distance of both gullies during the study period. It is
11 apparent that both gullies were still active at the end of this study period. Gully head retreat of
12 GB was faster than that of GA. And also it moved upslope at a less variable retreat rate than
13 that of GA, though GA accelerated its retreat rate after 2011.

14 [Fig. 9](#) and [Table 2](#) present the cumulative gully head retreat (GHR) distance and GHR rate
15 for GA and GB during the study period. Total retreat distance was 3.24 m for GA and 8.28 m
16 for GB. The mean retreat rate of GA in 2009-2016 was 0.46 m yr^{-1} , while that of GB was 1.10
17 m yr^{-1} , more than twice as much than that of GA. The yearly GHR rate among the different
18 measurement intervals ranged from 0.03 m yr^{-1} to 1.37 m yr^{-1} for GA, while it ranged from
19 0.09 m yr^{-1} to 2.51 m yr^{-1} for GB. During the entire monitoring period, GA developed at a
20 lower rate than GB, with the exception of the first two years (2009-2011).

21 **Fig.9.** Cumulative retreat distance of both gullies with time.

22 **Table 2** Gully retreat (GH) and gully retreat rate (GHR) during the different intervals
23

24 *3.3 The relationships between gully development and hydrologic variables*

25 [Table 3](#) summarizes the results of different erosive rainfall depths and rainfall erosivity
26 over all the measurement intervals of the study period by using three different rainfall

thresholds (>12, >25, >50 mm). Among all the intervals between measurements, the first one (2009-2011) clearly had smaller erosive rainfall depths with the threshold of > 50 or 25 mm day⁻¹ than other ones. This translated into a lower rainfall erosivity for large rainstorms during this interval as compared to the other three ones. If the threshold with daily rainfall of 12 mm was used, a moderate increase in erosive rainfall depth and rainfall erosivity during the last interval was only observed.

Fig. 10-11 demonstrates the Change of GA, GB GHR rate with yearly rainfall depth and rainfall erosivity. It is evident that the GHR rate of GB presents a higher (statistically significant) correlation with erosive rainfall depths and rainfall erosivity than that of GA. The best of three daily rainfall thresholds was 25 mm for calculating hydrological variables correlating with GHR rate. Gully A has a weaker correlation (statistically insignificant) with erosive rainfall and rainfall erosivity, which was largely due to the low retreat rate measured in the interval of 2011-2013.

Table 3 Erosive rainfall and rainfall erosivity in the different intervals

Fig.10. Change of GA, GB GHR rate with yearly rainfall depth and rainfall erosivity.

Fig.11. The relationships between GHR rates (GA and GB) and runoff depth, runoff amount.

Furthermore, we calculated the normalized gully head retreat rate (GHR*) by dividing GHR rate with the maximum retreat rate measured in each gully, and plotted GHR* against rainfall depth and rainfall erosivity calculated with the threshold of 25 mm (Fig. 12). The linear regression model indicated a significant correlation of GHR* with hydrological variables at a p=0.05 using an F test.

Fig.12. Correlation between normalized gully retreat rate (dividing by the maximum retreat rate measured at each gully) vs. rainfall depth (left) and rainfall erosivity (right) using 25 mm as the threshold to include these events.

4. Discussion

4.1 Dynamic evolution of gully head retreat

Table 3 showed the low runoff coefficient calculated for the contributing area of both gullies, with a mean value of about 1.4% over the entire study period. This low runoff coefficient is in the same range of those measured from the experimental runoff plots with similar forest and soil type in Fujian province according to the study by Bu et al. (2017). Prior to land use change, the study area was covered by cropland. Model analysis by using a CN value of 72 for cropland (Table 1) indicates a much higher runoff coefficient (approximately 9%), which might be largely responsible for rill erosion and gully formation, given the greater erosive rainfall in the region (approximately 135 mm yr⁻¹) during the earlier years. Even at the relatively low runoff rate presently, there is ample evidence of rill initiation in the unprotected slopes even from small contributing areas (Fig. 13).

Fig.13. Rill initiation on steep unprotected slope in the same soil with a small contributing area.

Gully head was the more active retreat area than gully walls for both gullies, with an average retreat rate of 0.46 m yr⁻¹, ranging from 0.03 to 2.59 m yr⁻¹. This is greater than the 0.1 m yr⁻¹ in a gully system within tertiary loams, marls, calcareous sands etc in Eastern Spain (Vandekerckhove et al., 2003), and the 0.34 m yr⁻¹ in limestone colluvium, stanstone colluvium, Vertisols of the semi-arid highlands, Northern Ethiopia (Frankl et al., 2012), as well as the 0.36-0.44 m yr⁻¹ in loess region in China (Li et al., 2012). However, it is smaller

1 than many other retreat rates in the literature, such as the 1.12-22.7 m yr⁻¹ in marine sediments
 2 of the Negev highlands of Israel by Avni (2005), the 1.17-1.5 m yr⁻¹ in Saskatoon (Archibold
 3 et al., 2003), the 1.8 m yr⁻¹ within loess-derived soils in southwest of Leuven, Belgium
 4 (Nachtergaele et al., 2002), 2-3 m yr⁻¹ developed in Cambisols or Fluvisols with mainly
 5 silt-loam textures in Baringo district, Kenya (Oostwoud Wijdenes and Bryan, 2001), and the
 6 6.2 m yr⁻¹ in the Pachic Udic Haploborolls, northeast China (Hu et al., 2007). It is possible
 7 that the low runoff rate (due to soil properties) as well as the relatively small contributing area
 8 might have contributed to this medium retreat rate despite the high rainfall present in the
 9 study area. When compared with gully head retreat rates in other regions of the world, the one
 10 measured in this study was within the median normal range reported in the literature. The
 11 projected surface area of both gullies showed an increase over time as well, with 16.57 m² yr⁻¹
 12 and 25.52 m² yr⁻¹ for GA and GB respectively (Table 4 and 5). It expanded at an increasing
 13 rate after 2013, which was associated with a period of greater rainfall depth and erosivity. The
 14 difference in increase of gully volume between two gullies was much greater than that of
 15 surface area, with an average change rate of 34.61 m³ yr⁻¹ and 330.72 m³ yr⁻¹ for GA and GB,
 16 respectively. The greater difference in volume between two gullies arises mostly from gully
 17 dimension and location, with GB developing towards a higher slope angle which results in a
 18 much greater gully depth as compared to GA (Fig. 3).

19

20 **Table 4.** Changes of Gully surface (S) area during the different intervals

21

22 **Table 5.** Changes of Gully volume (V) during the different intervals

23

1 There are several classifications about gully development stages. For instance, [Zhang and](#)
2 [Liu \(2011\)](#) proposed the evolution of a gully in two stages: formation and development, and
3 the development stage is further divided into three sub-stages: young stage, mature stage, and
4 old stage. The classification is based on the ratio of gradational erosion from gully wall to
5 yearly sediment delivery at the exit of gully. In this study, it is difficult to differentiate those
6 stages because of the scarce quantitative data on gully wall collapses and sediment transport
7 in the gully system, but active retreat of gully heads suggests that gullies have not reached an
8 old stage, but still in a mature stage instead. A continuous monitoring of these gullies,
9 including sediment delivery from the gully to streams, could provide a comprehensive
10 characterization of gully development stages.

11

12 *4.2 The relationship between gully head retreat and hydrologic variables*

13 This study showed a significant correlation of GHR rates with the cumulative erosive
14 rainfall depth and erosivity with a threshold $> 25 \text{ mm day}^{-1}$, particularly for GB which had
15 been evolving for at least 17 years (since 1989) with limited human intervention. The
16 threshold for erosive rainfall triggering gully development varies in the literature. [Bouchnak](#)
17 [et al. \(2009\)](#) found that yearly erosive rainfall total with a threshold of daily rainfall $\geq 40 \text{ mm}$
18 was closely related to annual sediment yield produced by head cutting in an arid area of
19 Tunisia. [Capra et al. \(2009\)](#) indicated that gully development in a semiarid region in Sicily
20 (Italy) was mainly affected by two hydrological variables, the maximum 3-days cumulative
21 rainfall (with a threshold of 51 mm) and the maximum 1-hour rainfall intensity (with a
22 threshold of 25 mm h^{-1}). A comparison of rainfall thresholds for gully development among

different regions comes to an interesting finding: while subtropical climate in this study has much greater annual precipitation than the arid and semiarid climates in the aforementioned studies, a lower erosive rainfall threshold for gully head retreat is required in the former than in the latter. It is also interesting to note that active headcut retreat of gullies in present study is associated with a small runoff volume, resulting from small contributing area and low runoff coefficient. This, in combination with field observations suggests that mass movement triggered by soil saturation and the high slope angle of gully head might be the dominant process in gully development (Fig. 14). Although scarce, only happening four times during one year observation period, Xu (1992b) reported that hyperconcentrated flows developed on bare surfaces of the same soil type as the study catchment in rainfall events with an intensity greater than 0.5 mm min^{-1} . This might explain why rainfall threshold for gully retreat in our region is lower than those observed in other arid and semiarid areas, and also provided indications that control of gully erosion in this area should not solely rely on reduction of runoff generated from gully catchment after gully is initiated. Nevertheless, this does not discount the role of water erosion in gully development, which can initiate rills on bare gully surfaces that in turn further destabilize the slope.

Fig.14. Example of mass movement in headcut of GB.

5. Conclusions

This research has provided insight into the evolution of gullies on metamorphic material (granite) in southern China by monitoring two gullies using 3D scanner from 2009 to 2016. Our results indicate that gully head retreat is the major process of gully development in this

1 region, with a mean rate of 0.46 and 1.10 m yr⁻¹ for gully A and B respectively, and that this
2 process remains active once activated even with a small runoff contribution area of
3 subtropical forest. The explanation for this is that the major mechanism for gully head retreat
4 is the displacement by mass movement of gully head due to a combination of steep slopes and
5 soil saturation. This might explain the good correlation between GHR rates and erosive
6 rainfall and erosivity with a daily rainfall threshold of 25 mm which is lower than those
7 observed in arid and semiarid areas. It also has implications for restoration of gullies in the
8 area, which requires techniques that go beyond a mere reduction of runoff contribution to
9 gullies. Further studies are needed to gather more data on evolution and sediment delivery of
10 gullies, to prove the hypothesis of a gravity-driven gully headcut development, and to explore
11 more effective gully restoration techniques.

12

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19

20 **References**

21 Archibold, O. W., Levesque, L. M. J., de Boer, D. H., Aitken, A. E., Delanoy, L., 2003. Gully
22 retreat in a semi-urban catchment in Saskatoon, Saskatchewan. *Applied Geography* 23:

1 261-279. DOI: 10.1016/j.apgeog.2003.08.005.

2 Avni, Y., 2005. Gully incision as a key factor in desertification in an arid environment, the

3 Negev highlands, Israel. CATENA 63: 185-220. DOI: 10.1016/j.catena.2005.06.004.

4 Ballesteros Cánovas, J. A., Stoffel, M., Martín-Duque, J. F., Corona, C., Lucía, A., Bodoque, J.

5 M., Montgomery, D. R., 2017. Gully evolution and geomorphic adjustments of badlands

6 to reforestation. Scientific Repo 7: 1-8.

7 Bouchnak, H., M. S. Felfoul, M. R. Boussema, Snane, M. H., 2009. Slope and rainfall effects

8 on the volume of sediment yield by gully erosion in the Souar lithologic formation

9 (Tunisia). CATENA 78(2): 170-177.

10 Bu, J., Ye, G., L., Y., X., F., Li D., 2017. Characteristics of Runoff and Sediment Yield of

11 Different Land Use Patterns in Changting County, Fujian Province. Research of Soil and

12 Water Conservation 24(4): 1-5. (in chinese)

13 Campo-Bescós, M. A., Flores-Cervantes, J. H., Bras, R. L., Casalí, J., Giráldez, J. V., 2013.

14 Evaluation of a gully headcut retreat model using multitemporal aerial photographs and

15 digital elevation models. Journal of Geophysical Research-Earth Surface 118: 2159-2173.

16 DOI:10.1002/jgrf.20147.

17 Capra, A., Porto, P., Scicolone, B., 2009. Relationships between rainfall characteristics and

18 ephemeral gully erosion in a cultivated catchment in Sicily (Italy). Soil and Tillage

19 Research 105(1): 77-87.

20 Castillo, C., Gómez, J. A., 2016. A century of gully erosion research: Urgency, complexity

21 and study approaches. Earth-Science Reviews 160: 300-319. DOI:

22 10.1016/j.earscirev.2016.07.009.

1 Chai, Z., Fan, J., Liu, S., 2001. Analysis on development characteristics and process of gully
2 in Yuanmon basin on lower reaches of Jiasha river. *Scientia Geographica Sinica* 04:
3 339-343. (In Chinese)

4 Chaplot, V., Brown, J., Dlamini, P., Eustice, T., Janeau, J. L., Jewitt, G., Lorentz, S., Martin, L.,
5 Nontokozo-Mchunu, C., Oakes, E., Podwojewski, P., Revil, S., Rumpel, C., Zondi, N.,
6 2011. Rainfall simulation to identify the storm-scale mechanisms of gully bank retreat.
7 *Agricultural Water Management* 98(11): 1704-1710.

8 Chen, Z. C., Gong Z. T., Zhang, G. L., Zhao, W. J., 2004. Correlation of soil taxa between
9 Chinese soil genetic classification and Chinese soil taxonomy on various scales. *Soil* 36
10 (6): 584-595.

11 Du, Y., Li, S. X., Ding, S. W., He, Y. J., Deng, Y. S., 2015. Study of CORS-RTK combined
12 with GIS in collapsing gully monitoring of southeast Hubei Province. *Yangtze River*
13 46(12): 87-89. (in Chinese)

14 Feng, M. H., Liao, C. Y., Li S. X., Lu, S. L., 2009. Investigation on status of hill collapsing
15 and soil erosion in southern China. *Yangtze River* 40(8): 66-68, 75. (In Chinese)

16 Frankl, A., Poesen, J., Declercq, J., et al. 2012. Gully head retreat rates in the semi-arid
17 highlands of Northern Ethiopia. *Geomorphology* 173: 185-195. DOI:
18 10.1016/j.geomorph.2012.06.011.

19 Gómez-Gutiérrez, Á., Schnabel, S., Berenguer-Sempere, F., Lavado-Contador, F.,
20 Rubio-Delgado, J., 2014. Using 3D photo-reconstruction methods to estimate gully
21 headcut erosion. *CATENA* 120: 91-101.

22 Goodwin, N. R., Armston, J. D., Muir, J., Stiller, I., 2017. Monitoring gully change: A

1 comparison of airborne and terrestrial laser scanning using a case study from Aratula,
2 Queensland. *Geomorphology* 282: 195-208.

3 Gulam, V., Gajski, D., Podolszki, L., 2018. Photogrammetric measurement methods of the
4 gully rock wall retreat in Istrian badlands. *CATENA* 160: 298-309. DOI:
5 10.1016/j.catena.2017.09.024.

6 Hancock, G. R., Willgoose, G. R., Lowry, J., 2013. Transient landscapes: gully development
7 and evolution using a landscape evolution model. *Stochastic Environmental Research*
8 *and Risk Assessment* 28(1): 83-98.

9 Hu, G., Wu, Y., Liu, B., Yu, Z., You, Z., 2007. Short-term gully retreat rates over rolling hill
10 areas in black soil of Northeast China. *Catena* 71: 321-329.
11 DOI:10.1016/j.catena.2007.02.004.

12 Ionita, I., 2006. Gully development in the Moldavian Plateau of Romania. *CATENA* 68:
13 133-140. DOI: 10.1016/j.catena.2006.04.008.

14 Li, Z., Zhang, Y., Yao, W., Zhu, Q., 2012. Estimating gully development rates in Hilly Loess
15 Region of Western Shanxi province based on QuickBird images. *Transactions of the*
16 *Chinese Society of Agricultural Engineering* 22:141-148. (In Chinese)

17 Li, Z., Zhang, Y., Zhu, Q. K., Song, L., Ma, H., 2017. A gully erosion assessment model for
18 the Chinese Loess Plateau based on changes in gully length and area. *CATENA* 148:
19 195-203.

20 Liu, H., Liu, X., Zhang, P., Wang, Y., 2011. Characteristics of slope collapse and its
21 monitoring technology in Southern China. *Science of Soil and Water Conservation* 9(2):
22 19-23. (In Chinese)

1 Liu, H., Qin, F., Chen, J., Liu, Z., Ding, W., 2015. Accuracy of slope collapse data collected
2 by artificial survey. *Journal of Yangtze River Scientific Research Institute* 3: 117-120. (In
3 Chinese)

4 Liu, X., 2018. Benggang erosion landform and research progress in a global perspective.
5 *Progress in Geography* 37(3): 342-351. (In Chinese)

6 Liu, X., Zhang, D., 2015. Temporal-spatial analyses of collapsed gully erosion based on
7 three-dimensional laser scanning. *Transactions of the Chinese Society of Agricultural*
8 *Engineering* 31 (4) :204-211. (In Chinese)

9 Ma, Y., Yan, P., Wang, G., Song, Y., Wang, Y., Yang, H., Zhu, M., 2009. Preliminary results of
10 gully erosion by remote sensing monitoring in Weiliantan, Gonghe basin, Qinghai
11 province. *Research of Soil and Water Conservation* 16(2): 1-5. (In Chinese)

12 Matthias, V., Poesen, J., Bert, V. M., et al. 2016. How fast do gully headcuts retreat?
13 *Earth-Science Reviews* 154: 336-355. DOI: 10.1016/j.earscirev.2016.01.009.

14 Nachtergaele, J., Poesen, J., Oostwoud Wijdenes, D., Vandekerckhove, L., 2002.
15 Medium-term evolution of a gully developed in a loess-derived soil. *Geomorphology* 46:
16 223-239. DOI:10.1016/S0169-555X(02)00075-2.

17 Nichols, M. H., Nearing, M., Hernandez, M., Polyalcov, V. O., 2016. Monitoring channel
18 head erosion processes in response to an artificially induced abrupt base level change
19 using time-lapse photography. *Geomorphology* 265:107-116. DOI:
20 10.1016/j.geomorph.2016.05.001.

21 Oostwoud Wijdenes, D. J., Bryan, R., 2001. Gully-head erosion processes on a semi-arid
22 valley floor in Kenya: a case study into temporal variation and sediment budgeting. *Earth*

1 Surface Processes and Landforms 26: 911-933. DOI: 10.1002/esp.225.

2 Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and
 3 environmental change: importance and research needs. CATENA 50: 91-133.
 4 [https://doi.org/10.1016/S0341-8162\(02\)00143-1](https://doi.org/10.1016/S0341-8162(02)00143-1)

5 Rengers, F. K., Tucker, G. E., 2015. The evolution of gully headcut morphology: a case study
 6 using terrestrial laser scanning and hydrological monitoring. Earth Surface Processes and
 7 Landforms 40: 1304-1317. DOI: 10.1002/esp.3721.

8 Rielke-Zapp, D. H., Nichols, M. H., 2011. Headcut retreat in a semiarid watershed in the
 9 southwestern United States since 1935. CATENA 87: 1-10. DOI:
 10 [10.1016/j.catena.2011.04.002](https://doi.org/10.1016/j.catena.2011.04.002).

11 Romanescu, G., Cotiuga, V., Asandulesei, A., Stoleriu, C., 2012. Use of the 3-D scanner in
 12 mapping and monitoring the dynamic degradation of soils. Case study of the
 13 Cucuteni-Baiceni Gully on the Moldavian Plateau (Romania). Hydrol. Earth Syst. Sci.
 14 16: 953–966.

15 Samani, A. N., Ahmadi, H., Mohammadi, A., Ghoddousi, J., Salajegheh, A., Boggs, G.,
 16 Pishyar, R., 2010. Factors Controlling Gully Advancement and Models Evaluation
 17 (Hableh Rood Basin, Iran). Water Resour Manage 24: 1531-1549. DOI:
 18 [10.1007/s11269-009-9512-4](https://doi.org/10.1007/s11269-009-9512-4).

19 Shi, D. M., Shi, X. Z., Liang, Y., Yu, D. S., 2005. Soil erosion and conservation issue in the
 20 subtropical China. Subtropical soil and water conservation 17(3): 1-5.

21 Shellberg, J. G., Spencer, J., Brooks, A. P., Pietsch, T. J., 2016. Degradation of the Mitchell
 22 River fluvial megafan by alluvial gully erosion increased by post-European land use

1 change, Queensland, Australia. *Geomorphology* 266: 105-120. DOI:
2 10.1016/j.geomorph.2016.04.021.

3 Soil Conservation Service. 1972. National engineering handbook, Section 4: Hydrology.
4 Washington D C: US Department of Agriculture Soil Conservation Service.

5 USDA, 1986. Urban hydrology for small Watersheds, TR-55, United States Department of
6 Agriculture, 210-VI-TR-55, 2nd edition.

7 Vandekerckhove, L., Poesen, J., Govers, G., 2003. Medium-term gully headcut retreat rates in
8 Southeast Spain determined from aerial photographs and ground measurements. *Catena*
9 50: 329-352. DOI: 10.1016/S0341-8162(02)00132-7.

10 Vanmaercke, M., J. Poesen, B. V. Mele, Demuzere, M., Bruynseels, A., Golosov, V., et al.
11 2016. How fast do gully headcuts retreat? *Earth-Science Reviews* 154: 336-355.

12 Vinci, A., Todisco, F., Mannocchi, F., 2016. Calibration of manual measurements of rills using
13 Terrestrial Laser Scanning. *CATENA* 140: 164-168.

14 Wei, L. N., Chen, X., Cheng, Q. B., Huang, Y. Y., 2013. Soil permeability and effects of
15 vegetation in the red soil hilly region. *CHINA SCIENCEPAPER* 8(5): 377-380. (In
16 Chinese)

17 Wischmeier, W. H., Smith, D. D., 1978. Predicting Rainfall Erosion Losses: A Guide to
18 Conservation Planning. Agric. Handbook No. 537. Washington, D.C: USDA.

19 Xie, Y., Yin, S. Q., Liu, B. Y., Nearing, M. A., Zhao, Y., 2016. Models for estimating daily
20 rainfall erosivity in China. *Journal of Hydrology* 535: 547-558.

21 Xu, J. X., Zeng, G. H., 1992a. Benggang erosion in sub-tropical granite weathering crust
22 geo-ecosystems: an example from Guangdong province. *Erosion, Debris Flows and*

1 Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992).
2 IAHS Publ. no 209.

3 Xu, J. X., 1992b. Hyperconcentrated flow in southern China granite region and the
4 implications in geomorphology. *Journal of Sediment Research* 2: 14-21. (In Chinese)

5 Zhang, D., Liu, X., 2011. Evolution and phases division of collapsed gully erosion landform.
6 *Journal of Subtropical Resources & Environment* 6: 23-28. (In Chinese)

7 Zhang, D., Liu, X., 2014. Application of 3D Laser Scanning to monitoring the landform
8 changes of collapsing hill and gully: A case study of Liantanggang collapsing hill and
9 gully in the Wuhua county of Guangdong. *Tropical geography* 34(2): 133-140. (In
10 Chinese)

11 Zhang, W. B., Xie, Y., Liu, B. Y., 2002. Rainfall erosivity estimation using daily rainfall
12 amounts. *Sci. Geogr. Sin.* 22, 705-711. (In Chinese).
13

Fig.1. Location of the mentioned gullies, check dam and their situated catchment.

Fig.2. Daily erosive rainfall and rainfall erosivity since 1988 to 2016.

1

a.

GA-Sep/2009

GA-May/2013

GA-Apr/2016

b.

GB-Sep/2009

GB-May/2013

GB-Apr/2016

Fig.3. Photographs of GA (a), GB (b) collapsing gullies. Note: 1. Gully wall. 2. Deposition area. 3. Gully bottom in GA (pictures taken in September, 2009).

2

3

Fig.4 Flow chart of gully data collection and processing.

Fig.5. Elevation changes of GA (a) and GB (b) during the study period.

Fig.6. Evolution of slope gradient of GA (a), GB (b) during the study period. 1. Gully wall. 2. Deposition area. 3. Gully bottom.

Fig.7. Evolution of mean slope gradient of GA (a), GB (b) during the study period.

Fig.8. Spatial retreat of GA (a), GB (b) gully wall in the study period and indication of the three lines used to measure retreat rates in Fig.9.

g.9. Cumulative Retreat distance of both gullies with time.

Fi

Fig.10. Change of GA, GB GHR rate with yearly rainfall depth and rainfall erosivity

Fig.11. The relationship between GA, GB GHR rate and runoff depth, runoff amount.

Fig. 12. Correlation between normalized gully retreat rate (dividing by the maximum retreat rate measured at each gully) vs. rainfall depth (left) and rainfall erosivity (right) using 25 mm as the threshold to include these events.

Fig. 13. Rill initiation on steep unprotected slope in the same soil with a small contributing area.

Fig. 14. Example of mass movement in headcut of GB.

Table 1 Runoff curve number values for average moisture condition, CN2.

Description of Land use	Hydrologic Soil Group			
	A	B	C	D
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, >75% ground cover)	30	48	65	73
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

Source: USDA, 1986

Table 2 Gully retreat (GH) and gully retreat rate (GHR) during the different intervals

Time interval	GA gully		GB gully	
	GH (m)	GHR rate (m yr ⁻¹)	GH (m)	GHR rate (m yr ⁻¹)
Sep/2009-Oct/2011	0.90	0.45	0.17	0.09
Oct/2011-Sep/2013	0.06	0.03	2.01	1.00
Sep/2013-Oct/2014	1.37	1.37	2.51	2.51
Oct/2014-Apr/2016	1.09	0.73	3.59	2.39
Total	3.42	0.46	8.28	1.10

Table 3. Erosive rainfall and rainfall erosivity in the different intervals

Time intervals	Rainfall amount (mm)	Runoff (mm)	Erosive rainfall (mm yr ⁻¹)			Rainfall erosivity (MJ·mm·ha ⁻¹ ·h ⁻¹ yr ⁻¹)		
			≥ 12mm	≥ 25mm	≥ 50mm	≥ 12mm	≥ 25mm	≥ 50mm
Sep/2009-Oct/2011	2855.89	1.78	1107.95	705.4	71.05	7703.1	5563.6	717.05
Oct/2011-Sep/2013	2978.86	10.08	1095.8	792.85	272.4	8358.35	6759.85	2881.35
Sep/2013-Oct/2014	1514.8	8.10	1169.2	910.9	294.9	9253.1	7942.2	3028.7
Oct/2014-Apr/2016	2689.07	10.29	1338.3	948.1	212.5	9706.9	7653.4	2281.8

Table 4 Gully surface (S) change during the different intervals.

Time interval	GA gully		GB gully	
	S change (m ²)	Yearly S change (m ² yr ⁻¹)	S change (m ²)	Yearly S change (m ² yr ⁻¹)
Sep/2009-Oct/2011 (2 yr)	13.36	6.68	25.05	12.56
Oct/2011-Sep/2013 (2 yr)	1.68	0.84	27.83	13.92
Sep/2013-Oct/2014 (1 yr)	53.1	53.1	49.73	49.73
Oct/2014-Apr/2016 (1.5 yr)	56.15	37.43	88.82	59.21
Total (7.5 yr)	124.29	16.57	191.43	25.52

Table 5 Gully volume (V) change during the different intervals

Time intervals	GA gully		GB gully	
	V change (m ³)	Yearly V change (m ³ yr ⁻¹)	V change (m ³)	Yearly V change (m ³ yr ⁻¹)
Sep/2009-Oct/2011	57.42	28.71	457.74	228.87
Oct/2011-Sep/2013	30.59	15.295	450.28	225.14
Sep/2013-Oct/2014	419.75	419.75	426.37	426.37
Oct/2014-Apr/2016	-248.15	-165.433	1145.99	763.99
Total	259.61	34.61	2480.38	330.72