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A gully erosion assessment model for the Chinese Loess Plateau based on changes in gully length and area

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ABSTRACT

Gully erosion represents an important sediment source, and gully volume changes can show the contribution of gully erosion to sediment yield. On the Chinese Loess Plateau, where the gully erosion is a serious problem, valley bank gullies are the main gully types in small catchments, and the exploration of a valid method to assess the gully erosion at a large scale is needed. The objective of this study was to develop a model to assess the gully volume using linear and areal parameters that can be determined from high resolution satellite images. A 3-D scanner was used to measure the valley bank gully parameters and the two QuickBird images taken over 6 or 9 year periods in two study areas in the central Loess Plateau were used to derive historical linear and areal gully parameters. The results showed that the volume (V, m^3) of the 44 valley bank gullies calculated from a 0.15×0.15 m digital elevation model was closely related to gully length (L, m) and gully area (A_g, m^2). The power function relation between V and L was $V = 0.6529L^{2.1622}$ ($R^2 = 0.78$), indicating the high erosional vulnerability of the area. Compared with the V–L relation, the relation between V and A_g was more pronounced: $V = 0.2762A_g^{1.3971}$ ($R^2 = 0.91$). The relative error and Nash–Sutcliffe efficiency between the measured and predicted gully volumes suggested that the V–A_g relationship had a better predictive ability for gully volume. Another advantage of the V–A_g model is that the gully area can be easily measured from very high-resolution satellite images. Thus, the V–A_g relationship was suggested for modelling the gully volume on the Loess Plateau of China. The gully erosion volume during the periods of 2007 to 2013 and 2004 to 2013 in the two study areas, which was estimated based on the V–A_g relationship and parameters measured from QuickBird imagery, ranged from 0.41 to 36.76 m^3 year^{-1} and averaged 10.32 m^3 year^{-1}. This study presented a feasible model for assessing gully volume and volume changes over a large scale with high-resolution satellite images.

1. Introduction

Gully erosion is a sign of severe land degradation. Gully heads retreat because of the action of headcut migration processes (i.e., hydraulic erosion, piping, tunneling and eventually mass movement) (Poesen and Govers, 1990), which seriously interfere with the surrounding agricultural area, produce large amounts of sediment-inducing siltation of downstream reservoirs and even cause some catastrophic flooding and pollution (Poesen and Hooke, 1997; Vandekerckhove et al., 2000). Gully erosion represents an important sediment source in a range of environments (Woodward, 1999; Kompani-Zare et al., 2011). Data collected in different parts of the world show that the rates of soil loss by gully erosion represent from 10% to 94% of the total sediment yield caused by water erosion (Poesen et al., 2003), even contributing 60% to 90% to the total sediment production on agricultural land in the hilly areas of the Chinese Loess Plateau (Li et al., 2003).

Gully volume is an indicator of the contribution of the gully erosion to sediment yield (Woodward, 1999; Kompani-Zare et al., 2011). To be able to predict the future behavior of gullies, it is necessary to understand their development over time (Hessel, 2002), and the direct way of understanding their development is to measure gully volume change. Unfortunately, it is difficult to determine historical gully volume, especially on medium or large scales. Unlike ephemeral gullies, an average cross-section does not allow the calculation of historical gully volume because of continuous increases or decreases in the size over time (Frankl et al., 2013).

Current gully volume may be determined by direct field measurements with a measuring tape, erosion pins, global positioning system (GPS), total station or laser profilometers (Vandekerckhove et al., 2001; Zhu, 2012; Castillo et al., 2012). Direct field measurements are generally confined to small-scale studies because they are relatively time consuming and labor intensive. Gully volume has also been determined using a digital elevation model (DEM) (Betts and Derose, 1999; Martinez-Casasnovas, 2003; Hu et al., 2005; Parkner et al., 2006), but this method has not been widely used because of the inherent accuracy limits of DEMs. Warren et al. (2004) indicated that landforms should

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have dimensions of at least twice the DEM resolution to be defined in a grid-based model. Therefore, sufficiently high-resolution DEM is needed to accurately quantify volumes through some of the present techniques (i.e., Terrestrial laser scanner, 3D photo-reconstruction) (Castillo et al., 2012; Frankl et al., 2015). The 3-D scanner, a rapid and precise means of monitoring the dynamics of gullies, produces high resolution DEMs. It has been used successfully to assess surface landforms, including mapping and monitoring landslides and gully erosion (Bretar et al., 2009; Romanescu et al., 2012; Li et al., 2014; Zhang and Liu, 2014).

A positive correlation has been found between gully cross-sectional area and gully length (Nachtergaele and Poesen, 1999). Because the length of a gully can be easily determined from aerial photographs and satellite images (Nachtergaele and Poesen, 1999), several studies have explored the relation between the gully volume (V) and length (L) using a power equation of the form $V = aL^b$ (Nachtergaele et al., 2001a, 2001b; Capra et al., 2005; Zucca et al., 2006; Zhang et al., 2007; Muñoz-Robles et al., 2010; Kompani-Zare et al., 2011; Frankl et al., 2013). High-resolution satellite images are increasingly available and are considered to be a valuable tool for examining linear erosion (Desprats et al., 2013). QuickBird imagery has been used to map gully features over large regions (Tebebu et al., 2010; Li et al., 2015), and automatic gully identification routines have even been proposed (Vrieling et al., 2007; Shruthi et al., 2011).

Therefore, it is possible to assess the gully volume over large areas using field data or 3-D scanning data to establish a regression model between the gully volume and other geometric variables, from which a historical gully volume model could be estimated and some easily measured gully geometric variables quantified using historical aerial photographs and satellite images. Thus, the gully volume change and gully erosion could be assessed.

The Loess Plateau of China was selected as a typical area to examine the possibility of accessing the gully volume change. The reason for choosing this area was that gully erosion is an important process and a major contributor to sediment yields (Wu and Cheng, 2005); however, the relationships between the gully volume and other geometric variables of gullies are unclear. The specific objectives of this study were to (1) investigate the relationships between the morphologic characteristics of the gullies obtained by 3-D scanning, (2) build a model to assess the gully volume using linear and areal gully parameters, and (3) estimate the gully volume change using the morphology parameters, which are easily determined using two Quickbird images over 6 or 9 year periods.

2. Study area and gully types

Three main gully types exist on the Loess Plateau of China: valley bank gullies, floor gullies and hill slope gullies (Wu and Cheng, 2005). Valley bank gullies occur at the boundaries between interfluves and valleys as shown in Fig. 1. Valley bank gullies in two selected study areas were investigated in this study because they are the most important sources of sediment yield and the main threat to inter-valley land quality, and they are easily measured with a 3-D scanner.

Both selected study areas are located in the northern Shaanxi Province (Fig. 1). One area is a part of the Hegou catchment in Wuqi County covering an area of 0.50 km^2 (108°13′16″–108°13′41″E, 36°53′25″–36°53′57″N). The annual average temperature is approximately 8 °C, and the annual average precipitation is 467.6 mm, according to the records from 1957 to 2012, with 60.7% of total annual precipitation falling from June through September. This study area is characterized by typical loess gullies and hills with elevations ranging from 1290 to 1590 m. Cropping and grazing have been prohibited in this area since 1998 to allow for the vegetation restoration. Today, herbaceous species, including *Artemisia sacrorum*, *Artemisia giraldii*, *Stipa capillata*, *Lespedeza davurica*, *Artemisia frigida*, *Potentilla acaulis*, *Potentilla chinensis* and *Leymus secalinus*, are dominant (Zhu et al., 2011).

The second study area Qiaogou, located in Suide County on the hilly and gully Loess Plateau (110°17′22″–110°17′49″E, 37°29′36″–37°30′15″N) spreads over 0.45 km^2. The elevations in the Qiaogou area range from 810 to 960 m. The annual average temperature is 9.9 °C and the annual average precipitation is 446.1 mm according to the records from 1957 through 2012, with 61.4% of total annual precipitation falling from June through September. Cropland in the Qiaogou catchment has been returned to grassland or woodland since 2001 (Cheng et al., 2007), and the dominant species include *Ziziphus sativa*, *Atemisia gmelini*, *Atemisia grandii*, *Stipa bungeana*, *Heteropappus altaicus* and *Lespedeza davurica*.

3. Materials and methods

3.1. Field measurements with a 3-D scanner

Morphological parameters of the valley bank gullies were measured using a TOPCON 3-D scanner (Imaging Station IS) with a position accuracy of 2 mm ± 2 ppm, which obtains 3-D data by automatically scanning at a specified pitch.

The use of 3-D scanning, particularly when studying large gullies with irregular surfaces like those found on the Loess Plateau, requires increased attention during the selection of scanning positions. Defective field deployment can cause the omission of some parts within the targeted area and low accuracy, which implicitly leads to major flaws of the final 3-D model (Romanescu et al., 2012). In our study area, the valley bank gullies are located at the boundaries between the interfluves and the valleys in the catchment. The 3-D scanner was set on a hill slope facing the valley bank gully across the valley, with <200 m between the scanner and the valley bank gully head. 3-D data were obtained by automatic scanning on a 15 × 15 cm grid. Measurements were taken in July 2013 in the Hegou catchment (24 gullies) and in September 2013 in the Qiaogou catchment (20 gullies).

3.2. Data processing

The DEM for each gully (DEM$_g$) was derived from the DEMs created using the 3-D scanner data with a pixel size of 0.15 × 0.15 m (Fig. 2). The gully boundary line for each gully was extracted from the DEM$_g$ to represent the landforms before gully erosion, and the gully volume (V, m^3) was calculated using the Polygon Volume Module in ArcGIS 10.1. The gully volume represents the volume below the polygon formed by gully boundary line and above DEM$_g$ surface of each gully.

Gully length (L, m) and gully area (A_g, m^2) were calculated based on the gully boundary line using ArcGIS 10.1. A total of 129 gully cross-sections were generated and measured from DEM$_g$ using ArcGIS 10.1, 56 in the Hegou catchment and 73 in the Qiaogou catchment. In addition, the maximum depth (D, m), top width (TW, m) and bottom width (BW, m) of each gully were calculated. The ratio between gully bottom width and top width (BW/TW) and the ratio between gully top width and depth (TW/D) were calculated to represent the shape of a gully cross-section, and finally $[(TW + BW) / 2] \times D$ gave the cross-sectional area (CSA, m^2). Gullies displaying large TW/D ratios are much wider then they are deep and vice versa (Frankl et al., 2013). All map layers were georeferenced to the UTM Zone 49 N coordinate system.

Variance analysis (ANOVA, $\alpha = 0.05$) of the logarithm values of morphological parameters was performed to compare the differences between the two study areas. A two-sample Kolmogorov–Smirnov test ($\alpha = 0.05$) was performed on the logarithm of morphological characteristics to test whether the two samples come from the same distribution. Normality of the distributions was tested with a one-sample Kolmogorov–Smirnov test ($\alpha = 0.05$).