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Assessment of bank gully development and vegetation coverage on the Chinese Loess Plateau

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ABSTRACT

Gully erosion is a serious environmental problem and the primary source of sediment loss on the Loess Plateau of China, yet previous research focusing on bank gullies is limited. An assessment of bank gully development is needed as a basis for predicting erosion rates under the effects of vegetation cover and land use change. To estimate bank gully retreat rates under different land uses, assess the factors leading to bank gully development and model gully area growth rate at the catchment scale, 30 catchments with an average area of 39.0 ha were selected in the southeastern part of the Loess Plateau. QuickBird images (0.61 m resolution) obtained in 2003 and 2010 were interpreted to delineate bank gully features, and a 5 m resolution digital elevation model was used to extract topographic factors. The results showed that from 2003 to 2010, the maximum retreat rates of bank gully heads in the 30 investigated catchments ranged between 0.23 and 1.08 m yr^{-1}, with an average of 0.51 m yr^{-1}. The ratio of bank gully growth area to valley area changed from 0.49 to 9.45%, depending on land use, with average increases of 3.94, 4.00 and 2.09% for the three land use types identified, i.e. mixed use, grassland and forestland, respectively. Correlation analysis indicated that the effects of topographic factors on bank gullies decreased as vegetation coverage increased in upslope drainage areas and that vegetation coverage exceeding 60% in upslope drainage areas can significantly control bank gully development. A model was built to predict the bank gully area growth rate (R_a, m^2 yr^{-1}) with upslope drainage area (A_i, m^2), local slope gradient (S, m m^{-1}) and the proportion of the area with vegetation coverage below 60% in upslope drainage areas ($\Phi_{0.6}$) at the catchment scale. The regression equation is in the form $R_a = 0.1540[(\Phi_{0.6}A_i)^{0.24}S]^{3.2588}$. Compared with previous studies, vegetation is a factor in this model, which would be helpful for assessing the influence of vegetation cover on bank gully development.

1. Introduction

Gully erosion is one of the primary manifestations of soil degradation. Gully erosion is defined as an erosion process whereby runoff water accumulates and recurs in narrow channels, removing the soil to considerable depths (Poesen et al., 2003). Data collected in different parts of the world show that soil loss rates by gully erosion represent 10 to 94% of total sediment yield caused by water erosion (Poesen et al., 2003) and contribute 60 to 90% of total sediment production on agricultural land in the hilly areas of the Chinese Loess Plateau (Li et al., 2003).

Gullying is regarded as a threshold-dependent process controlled by a wide range of factors, and it occurs only when the threshold of flow hydraulics, rainfall, topography, pedology or land use has been exceeded (Poesen et al., 2003; Valentin et al., 2005). The process is considered to be a function of the kinetic energy of concentrated overland flow (Poesen, 1986), which depends on runoff volume and velocity and, thus, is affected by topographic features (Speight, 1980). In landscapes where Hortonian overland flow dominates, runoff volume increases with catchment area (Leopold et al., 1964), and upslope drainage area has been used as a surrogate for discharge because in most cases, no runoff discharge data are available (Vandaele et al., 1996). The location and size of gullies are controlled by the generation of concentrated surface runoff of sufficient magnitude and duration to initiate and sustain erosion (Vandaele et al., 1996), and studies have focused on the relationship of upslope drainage area (A) and local slope gradient (S) to determine where gullies will develop (Patton and Schumm, 1975; Montgomery and Dietrich, 1992; Vandaele et al., 1996). The compound variable AS^2 was suggested as a suitable predictor of gully initiation (Montgomery and Dietrich, 1994; Wu and Cheng, 2005). Vandaele et al. (1996) summarized the power function $S = aA^{-b}$ to represent a critical relationship between A and S for incision. Cheng et al. (2007) defined the difference between AS^2 values at the head and the tail of ephemeral gullies as flow energy (E) and found that there was a strong linear relationship between E and the length of ephemeral gullies.

Among factors related to gully erosion, vegetation could protect the soil surface from drop impact, increasing resistance to concentrated flow erosion (Gyssels et al., 2005; De Baets et al., 2007), and decrease

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runoff discharge during a given rainfall event (Torri and Poesen, 2014). Vegetation restoration could result in a reduction of erosion-induced sediment yield in gullies (Chen and Cai, 2006; De Baets et al., 2007), and land use and vegetation were considered far more important than climatic conditions for gully processes (Poesen et al., 2003; Descroix et al., 2008). Land use change that increases vegetation cover could help control gully retreat and sediment production (Li et al., 2004). Oostwoud Wijdenes et al. (2000) indicated that land use change caused the development or reactivation of bank gullies along ephemeral streams in southeastern Spain. Consequently, vegetation and land use in a gully catchment are considered key factors for assessing gully development (Poesen et al., 2003; Galang et al., 2007; Marden et al., 2012).

Studies have attempted to predict gully area increase or gully headcut retreat with increasing drainage area and other changes in a range of environments (Seginer, 1966; Burkard and Kostaschuk, 1997; Vandekerckhove et al., 2001a). However, vegetation, which is known to favor water infiltration and to control gully development (Valentin et al., 2005), was not included in any of the reported models on gully headcut retreat.

Headcut advance is an essential process, and area growth rates are an important measure of gully expansion in many environments (Blong et al., 1982). Studies have used erosion pins, global positioning systems, airborne and ground-based LiDAR systems, 3-dimensional scanners, dendrochronology and aerial and satellite imagery to monitor gully headcut rate and gully area growth rate (Crouch, 1987; Burkard and Kostaschuk, 1997; Vandekerckhove et al., 2001b, 2003; Wu et al., 2008; Perroy et al., 2010; Romanescu et al., 2012). Direct field measurements and indirect measurements through dendrochronology were confined to gully studies on a small scale because they are relatively time consuming and labor intensive. The use of remote sensing data, mainly aerial photography and satellite imagery, is a favored method for assessing gully erosion (Vrieling et al., 2007). Aerial data are generally collected for smaller regions of interest and provide no multi-spectral information (Shruthi et al., 2011). Satellite imagery, by contrast, can cover large areas and be used to evaluate the importance of gully erosion at larger spatial scales (Vrieling et al., 2007). Gully features were successfully delineated by visual interpretation of aerial photography and multi-temporal comparison to monitor gully development (Daba et al., 2003; Vandekerckhove et al., 2003). High-resolution satellite images such as those from Ikonos and QuickBird are increasingly available and are considered a valuable tool for extracting the consequences of linear erosion (Desprats et al., 2013). QuickBird imagery has been used to map gully features over large regions (Tebebu et al., 2010), and automatic gully identification routines have even been proposed (Vrieling et al., 2007; Shruthi et al., 2011).

Gullies are common on the Chinese Loess Plateau and consist of three types: bank, floor and hillslope (Wu and Cheng, 2005). Bank gullies mainly occur at the boundaries between interfluves and valleys (Wu and Cheng, 2005) and can develop rapidly at or below the soil surface by hydraulic erosion, piping and, eventually, mass movement (Poesen et al., 2003). In Mediterranean environments, in addition to retreat rates, the characteristics and controlling factors of bank gullies were emphasized by Vandekerckhove et al. (2000, 2001a). Previous studies of gully erosion on the Loess Plateau mainly focused on hillslope gullies, with fewer studies dealing with bank gullies. Assessing bank gully development is important as a basis for predicting erosion rates under the effects of environmental change, especially changes in vegetation cover and land use.

The main objectives of this paper were to (1) estimate bank gully retreat rates under different land uses, (2) assess the factors leading to bank gully development, and (3) build a model for predicting gully area growth rate at the catchment scale using topography and vegetation factors.

2. Study area

The study area, the Caijiachuan basin (36°14′–36°18′ N, 110°40′–110°48′ E), is located in the southeastern part of the Loess Plateau and covers an area of 39.33 km^2. Annual average temperature is about 10 °C, and mean annual precipitation is 579.5 mm (Bi et al., 2008). During the study period of 2003–2010, annual precipitation was 525.7 mm, and rainfall from June to September accounted for 57.85% of the total annual precipitation. The study area is characterized by typical loess gullies and hills, with elevations ranging from 900 to 1590 m. Since 1999, the Restoring Farmland to Forest Project has been implemented in the study area, and vegetation coverage has been efficiently recovered. The artificial forests are mainly *Robinia pseudoacacia* and *Pinus tabuliformis*, while farmland is persistent in some small catchments. Thirty catchments in the Caijiachuan basin were selected to assess bank gully development; selection was based on land use and drainage area. Catchment area (A_c) ranges from 4.9 to 118.5 ha, with an average area of 39.0 ha (Fig. 1 and Table 1).

3. Materials and methods

3.1. QuickBird images and interpretation method

QuickBird images were acquired on October 21, 2003 and October 11, 2010. The imagery contained four multi-spectral bands with 2.4 m spatial resolution and one panchromatic band with 0.61 m spatial resolution. After the images were preprocessed, the panchromatic and multi-spectral images were fused to create a 0.61 m pan-sharpened image using the software ERDAS IMAGINE 9.2. The gully boundary line, i.e. the boundary line between ungullied hilltops and the gullies below (Hessel, 2002), is clearly distinguishable on the QuickBird images (Fig. 2). The bank gully boundary lines in 2003 and 2010 were extracted from the QuickBird images by visual interpretation (Fig. 2). All map layers were georeferenced to the UTM Zone 49N coordinate system.

3.2. Measures of bank gully growth rate

Bank gullies in the study area occurred along the boundaries of the valleys. Individual bank gully development leads to changes in the area of the entire valley. Therefore, a change in valley area was calculated as the sum of the growth area of all bank gullies on the valley boundary. Changes in valley areas from 2003 to 2010 were determined by measuring the difference of the two polygon regions transformed from the bank gully boundary lines from the two years. For each of the investigated 30 catchments, valley area in 2003 (A_v), gully area growth rate (R_a, gully growth area per year), ratio of gully growth area to valley area in 2003 (R_A), rate of change in valley perimeter per year (R_{ap}) and ratio of valley perimeter change to valley perimeter in 2003 (R_{AP}) were calculated. The maximum gully retreat rates (R_L) in each of the 30 catchments were measured using the Measure Tool in ArcGIS 9.3 (ESRI, Redlands, CA) by comparing the changes in the two valley regions extracted from the QuickBird images.

3.3. Topographic factors

A slope map was generated from the 5 m resolution digital elevation model. To calculate local slope gradients of the bank gullies, 10 m buffer polygons were created along the gully boundary of each of the 30 catchments, and the average slope gradient of each buffer polygon (S) was calculated as the local slope gradient. The inter-valley area (A_i) in each catchment was taken as the sum of the upslope drainage areas of all bank gullies in this catchment. All processes were conducted using ESRI ArcGIS 9.3 software and its extensions.

3.4. Vegetation coverage and land use

The normalized difference vegetation index (*NDVI*) provides a measure of vegetation coverage that allows comparisons of seasonal and inter-annual changes in vegetation growth and activity (Jakubauskas