Active Stage Gully Morphological Characteristics in the Loess Hilly-Gully Region Based on 3D Laser Scanning Technique

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Gully erosion plays an important role on sediment production in the Loess Hilly-gully Region. Gully morphology is strongly affected by the gully erosion process and can be used to describe the gully developmental condition. The Chabagou watershed, located in the hilly-gully region of the Loess Plateau, was selected to investigate gully morphological characteristics using a 3D laser scanning technique (LiDAR). We selected 31 representative gullies at active stages, including different watershed locations and gully orders, to quantitatively describe gully morphology and establish empirical equations for estimating gully volume based on gully length and surface area. Images and point clouds datum of the 31 gullies were collected and digital elevation models (DEMs) with 10-cm resolution were generated; then the gully fundamental morphological characteristics including gully length (L), gully width (WT) and gully depth (D), and some derivative morphological indicators including gully head curvature (C), gully width to depth ratio (w/d), gully bottom to top width ratio (WB/WT), gully surface area (Ag) and gully volume (Vg) were extracted from the DEMs using ArcGIS 10.1 (Table 1).

Table 1. Gully morphological characteristics in different watershed locations and gully orders.

Location/order	Parameters of gully morphology							
	L (m)	W_T (m)	D (m)	C (m^{-1})	w/d	W_B/W_T	A_g (m^2)	V_g (m^3)
	Different locations of watershed							
Upstream	67.4a§	20.7a	8.1a	2.0b	2.6a	0.17a	1300.5a	2042.7a
Middle-stream	59.8ab	17.9a	8.0a	3.8a	2.3a	0.13a	873.8ab	1423.6b
Downstream	53.7b	15.4a	8.4a	3.8a	2.0a	0.11a	766.7b	1346.6b
	Different gully orders							
2nd order	65.3a¶	17.4a	8.2a	2.0a	2.2a	0.14a	1315.9a	2260.8a
3rd order	57.5a	18.4a	8.5a	3.6a	2.3a	0.13a	872.1ab	1464.3b
4th order	52.0a	11.0a	6.4a	4.6a	1.8a	0.13a	622.8b	1092.1b

Note: § means that different letters in each column at different watershed locations are significantly different at $p < 0.05$ according to the LSD test. ¶ means that different letters in each column of different gully orders are significantly different at $p < 0.05$ according to the LSD test.

The results showed that gully length decreased gradually from upstream to downstream in the study watershed and gully depth was greater downstream (Table 1). A differentiation method of gully head and gully sidewalls was proposed with a mean relative error of 8.77%. Gullies in the upstream and of 2nd order were more developed with high values of gully head curvature. Gullies had more development potential from the 2nd order to the 4th order. Within the same gully orders, gullies in the downstream of the watershed were more active. U-shaped cross-sections were widely distributed in the upstream of the watershed and upper positions of a gully; while V-shaped cross-sections were widely distributed in the downstream of the watershed

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and lower positions of a gully. Gully cross-section shapes at gully scale and watershed scale were similar, namely the gully cross-sections had self-similarity. *V-L* and *V-Ag* empirical equations with acceptable accuracy established in this study could be used to estimate gully erosion degree in the study area (Figures 1 and 2). Compared with previous, the *V* increased with *L* and A_g differently, which was a result of the higher environmental variability of different region. That is to say, these empirical equations made it more convenient to estimate the gully volume but regional differences should be taken into account.

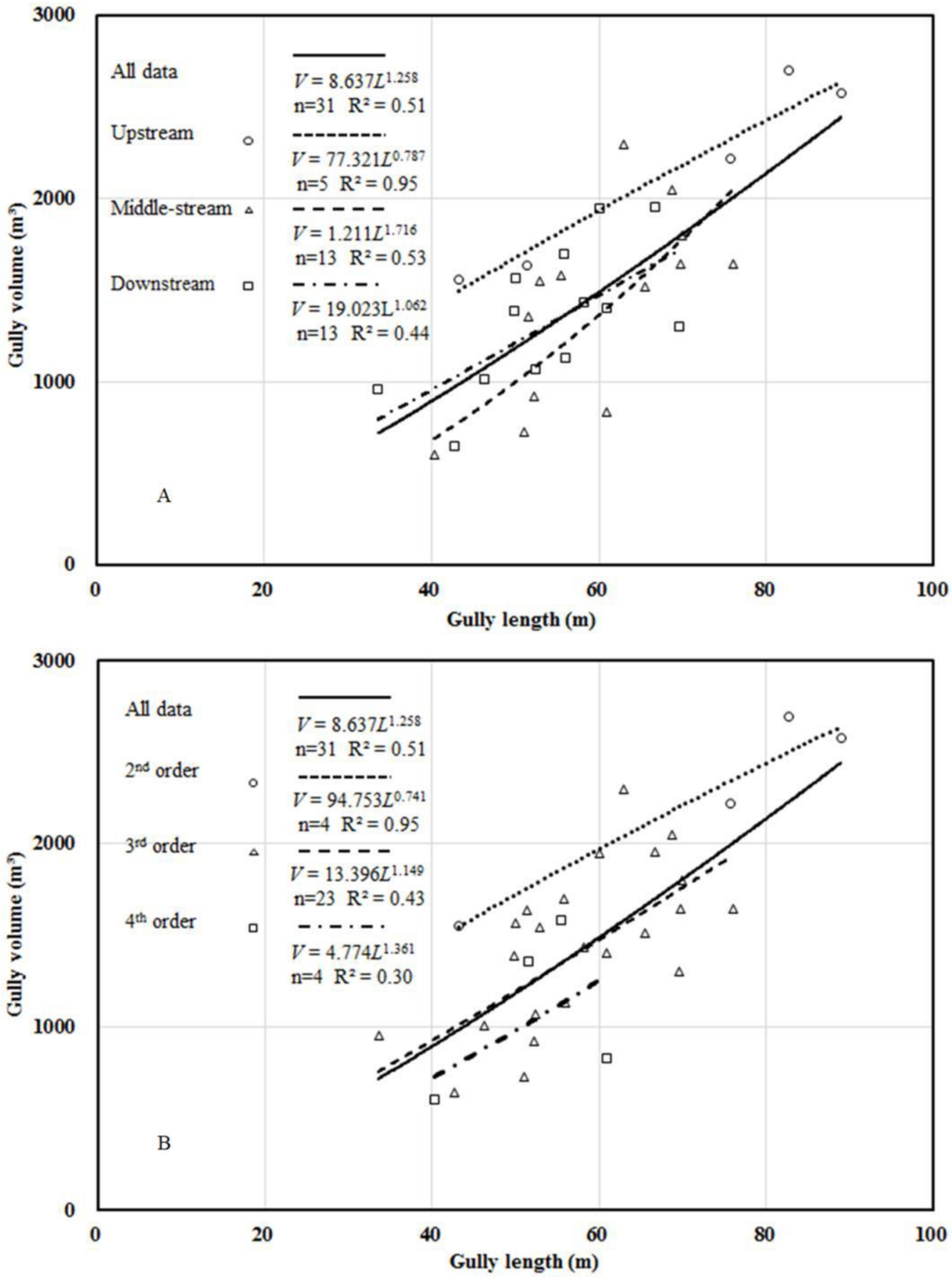

Figure 1. A.) Power relations between gully volume (*V*) and gully length (*L*) in the upstream, middle stream and downstream; B.) Power relations between gully volume (*V*) and gully length (*L*) in the second, third and fourth order of gullies (B).

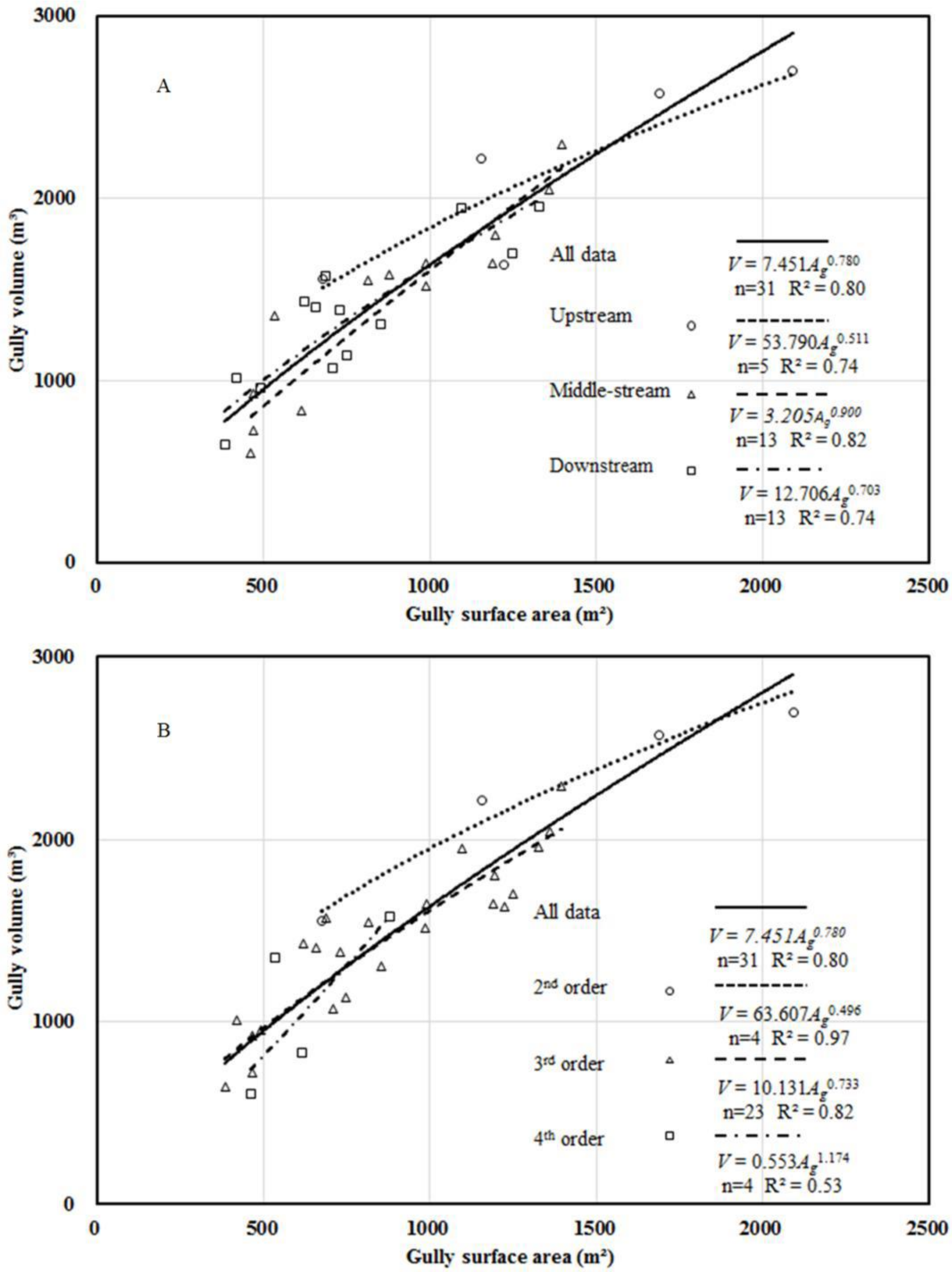

Figure 2. Power relations between gully volume (*V*) and gully surface area (A_g) in the upstream, middle stream and downstream (A); Power relations between gully volume (*V*) and gully surface area (A_g) in the second, third and fourth order of gullies (B).

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