# The Topographic Threshold of Gully Erosion and Contributing Factors

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**Research Article**

**Keywords:** Gully erosion, Topographic threshold, Surface runoff, Powered area – slope relationship

**Posted Date:** July 12th, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-615407/v1



**Version of Record:** A version of this preprint was published at Natural Hazards on February 28th, 2022. See the published version at https://doi.org/10.1007/s11069-022-05254-6.

# Abstract

The topographic threshold is based on the power relationship between area and slope and is widely applied in gully-erosion research; however, this relationship requires further testing. Accordingly, the Alamarvdasht Lamerd and Fadagh Larestan regions in Fars Province, Iran, were selected as case studies to explore the topographic threshold for gullies. Thirty active gullies were identified in each study area during field surveys, and data describing land use and land cover, drainage areas, slope, and the physical and chemical properties of the soils were assembled. Multivariate analysis was conducted using SPSS to determine the effects of these factors. Using the power relationship between the catchment area and slope for each gully, the analyses explored critical controls for gully development.

The results showed that surface runoff was the most significant effective factor for gullies in the study areas. Sparse ground cover, fine-textured soils, and inappropriate land use all contribute to gully development. The results suggest that the relationship between slope and drainage area in the Fadagh Larestan case study is $S = 0.0192\ A^{-0.159}$ for gully headcut areas and $S = 0.0181\ A^{-0.258}$ at gully outlets. The corresponding values of the exponent β at the gully headcuts and outlets at Fadagh were − 0.15, and- 0.25, respectively. The corresponding relationships for gullies in the Alamarvdasht Lamerd area for the gully headcuts and outlets were $S = 0.0143\ A^{-0.061}$ and $S = 0.0073\ A^{-0.18}$, respectively, with β values of -0.06 and − -0.18. This study provides a basis for determining the thresholds for the initiation of gully development. Analyses of the effective factors provide clues to improve the management of bare lands to prevent the initiation of gully erosion.


# Highlights

- Considering among topographic threshold of gully erosion and contributing factors;
- Multivariate analysis was conducted to determine the effects of contributing factors;
- Determining the thresholds for the initiation of gully development;
- Using the power relationship between the catchment area and slope for each gully

# Introduction

Soil erosion remains a major problem in many regions of the world, and in many cases, the dominant source of sediment is gullies. A gully is a channel with steep sides and an active steep headcut created by fluvial erosion from periodic surface flows (usually during or immediately after heavy rain) (Poesen et al., 2003). Gully erosion is one of the most productive drivers of runoff and sediment delivery from upland areas to valley floors and permanent channels, where the consequences of erosion are manifest. Gully initiation and development is a natural process that greatly impacts natural resources, agriculture, and environmental quality by degrading land and water, disrupting ecosystems, and enhancing hazards (Gayen et al., 2019).

A common way to quantify the susceptibility of a landscape to a gully incision is to use topographical thresholds associated with specific land uses. The impacts of land management on these thresholds in agricultural settings have not been studied, although land management may significantly affect the rates of runoff and erosion (Monsieurs et al., 2016).

Determination of the key hydrological processes driving gully erosion requires evaluation of the topographic threshold. Previous studies have determined topographic thresholds for gully creation and expansion (Vandaele et al, 1996; Vandekerckhove et al, 1998; Desmet et al., 1999; Vandekerckhove et al., 2000; Nachtergaele and Poesen, 2001; Nachtergaele et al., 2002; Posen et al, 2003), there is evidence for critical thresholds related to drainage area (A) and slope (S) in the head of the gully (Posen et al., 2003.(

The idea that erosion surpassing a threshold triggers gully erosion was first introduced by Horton (1945), who argued that incision only begins in locations where the threshold of soil resistance to flow shear stress is exceeded. He defined the 'length of overland flow' as the distance over which runoff flows before concentrating into permanent drainage channels. This topographical characteristic of a drainage system can be considered a measure of the surface resistance to concentrated flow erosion. Based on this notion, Schumm (1956) defined the 'constant of channel maintenance' as the minimum area required for the development of a drainage channel.

Dietrich et al. (1993) saw the topographic threshold as the lower limits of the area and slope upstream of the gully head; when area and slope thresholds are exceeded, gullying begins. Vandekechove et al. (1998) showed that there is a topographic threshold for gully erosion that can be expressed as S = aAb. Itreflects the relationship between the drainage area and the upstream slope of the gully head. Alternatively, another formula shows the relationship between the threshold of the drainage area and the slope t > SAb. where t is the topographic threshold (Vandekechove et al., 1998). More recently, Hassel and Hatch (2003) argued that the generation of temporary gullies on the plowed land of China's Loess Plateau is controlled by a combination of topographic factors. The relationship between the drainage area and the upper slope of gullies is suggested to be an indicator of the position of the end of an emergent gully system. Morgan and Nomzolo (2003) suggested that land use and land cover, soil type, topography, and precipitation are effective factors influencing the topographic threshold for the initiation and expansion of gullies.

Soufi (2002), working in the Zangeneh, in the Fars Province region, reported that the relationship $S = aA^b$ is equal to -0.1698, concluding that the major factor in the creation of gullies is surface flow. Values for the b coefficient have been reported in several studies (Vandekechove et al., 2000; Morgan and Nomzolo, 2003, and Vandwalleghem et al., 2005).

The rates of gully development differ during the developmental stages (Bull and Kirkby, 1997). Gully formation is often very rapid during the initiation period when morphological characteristics are far from stable (Sidorchuk, 1998). The rates of gully development have been measured at several locations. Crouch and Novruzzi (1989) showed that the vertical sides, subject to undercutting, had the highest effect on erosion rate (75 mm/year), followed by vertical, fluted walls (37 mm/year).

Roblesa et al. (2010) studied gully erosion in Australia and reported that there is an inverse relationship between gradient, percentage of vegetation cover, and the percentage of exchangeable sodium within the gullying area. They also reported that human activities are also important in areas subjected to gully erosion. Clearly, accurate measurement of gully geomorphic parameters is very important, not only for computing the volumes of scoured sediments, but also for understanding gully erosion dynamics (Casalí et al., 2006; Frankl et al., 2013; Castillo and Gómez, 2016).

The idea of a topographic threshold for overland flow-gully erosion is a promising tool for both research and management applications. Some of the basic assumptions that were used to derive the threshold equation are also responsible for errors, including systematic ones, which introduce biases into evaluations (Rossi et al., 2015). Accordingly, we investigated the relationship between the spatial distribution of gully erosion and topographic thresholds of slope angle, position, and configuration, as well as land use changes, such as land abandonment. The aim of this study was to develop an approach for assessing whether specific topographic zones are more susceptible to gully erosion.

## Materials And Methods

This research was conducted in two areas: near Fadagh and Alamarvdasht in Fars Province, southern Iran (Fig. 1). The Fadagh, an area defined by a polygon at 27°30' to 27°43'N and 53°24' and 53°41'E, covers 430.25 $km^2$ and is located southwest of Lar City. The topography of this area comprises alluvial terraces from the Quaternary era. The average elevation is 538 m above sea level. The region's climate is hyper-dry, based on the De*Martonne* Index climatic classification (Karajii Consulting Engineers Calculations, 2007). The average annual temperature is 26°C and the average annual precipitation, based on a 22-year record, is 194.7 mm. The maximum daily rainfall was estimated to be 132 mm (Soufi, 2004).

Alamarvdasht is defined by a polygon located at 27°26' to 29°27'N and 52°52' to 53°27' E. It is also located in southern Fars Province and covers 285.82 $km^2$. This lithology comprises alluvial formations during the Quaternary era. The mean annual temperature is 24.7°C and the average annual precipitation is 235.68 mm. The maximum daily rainfall was estimated to be 47.3 mm. The average elevation is 458.7 m above sea level and the climate is classified as dry and hyper-dry based on the Demorten method (Karajii Consulting Engineers Calculations, 2007).

The key steps in our study are presented in Fig. 2.

# Gully erosion inventory map (GEIM)

To develop a GEIM, extensive field surveys were conducted in the two study areas (Figs. 3 and 4). Thirty gullies were identified in each area and subsequently mapped using ArcGIS 10.2.2. Using Nicknam and Soufi's (2009) study as a guide, gullies with cross sections of 10 m were selected for study. Field surveys measured gully depth and width. The volume of each of the 60 gullies was estimated based on their lengths, widths, and depths using GIS.

In addition to measuring gully volumes, elevations, gully catchment area, slope upstream, and aggregations of gullies were determined in the field. A digital elevation model was extracted and prepared from topographic maps of 1:25,000-scale (resolution of 10 m) in ArcGIS 102.2, to calculate gully elevations. The drainage areas at both the initiation point (Fig. 5) and the outlet of each gully were calculated after determining the elevations of these points. The gully length, width, and depth were measured manually. The slope at the headwall and outlet of each gully was measured manually using a clinometer.

A land use map was prepared from Landsat 7 satellite imagery using a support vector machine. The accuracy was estimated to be 91.5%. The main land use types in the study area are drylands, arable agriculture, pasture, forestlands, and abandoned or bare lands. The area of each land use was calculated using the ArcGIS 10.2.2. Soil samples were taken at a depth of 0–30 cm from a location near the gully head to determine the soil chemical properties. These included electrical conductivity (EC; measured using an electroconductivity meter, model 001), sodium, calcium, and magnesium content (measured using atomic absorption spectrophotometry), soil acidity (pH), and soil organic matter content (using the method of Walkley and Black, 1934). The physical properties of the soils were characterized by texture lrb% sand, % silt, 0 % clay), which was measured using the hydrometric method (Ibáñez & Ruiz-Ramos, 2006). Land cover, percentage of gravel, and amount of bare soil at each gully head were measured with a quadrat of 1m × 1m (Fig. 6).

# Results

The analysis revealed that the soils in both study areas were silty loams (Tables 1 and 2).

Table 1
The results for statistically significant variables in the Fadagh study area.

| Variables | Min | Max | Average |
|---|---|---|---|
| **Volume of sediment (m3)** | 17.03 | 5666.05 | 605.47 |
| **Vegetation cover (%)** | 0 | 27 | 4 |
| **Bare soil (%)** | 73 | 99 | 94.8 |
| **Gravel (%)** | 0 | 5 | 1.2 |
| **Slope (headcut)%** | 34 | 100 | 54 |
| **Slope (development)%** | 1 | 5 | 2 |
| **Slope (initation)%** | 1 | 8 | 3 |
| **Clay %** | 10 | 35.2 | 23.31 |
| **Silt %** | 33.1 | 63 | 53.03 |
| **Sand %** | 9 | 51.2 | 23.56 |
| **EC (ds/m)** | 5.77 | 61.1 | 19.33 |
| **pH** | 7.16 | 8.45 | 7.61 |
| **OC** | 0.034 | 0.52 | 0.20 |
| **OM** | 0.06 | 0.89 | 0.35 |
| **K** | 0.57 | 3.65 | 1.60 |
| **Na** | 23 | 256 | 85.41 |
| **Ca + Mg** | 46 | 119 | 88.26 |
| **length of gully** | 44 | 247 | 100.65 |
| **Initiation area($m^2$)** | 96.77 | 1366.34 | 394.67 |
| **Development area ($m^2$)** | 696.77 | 6655.12 | 1927.90 |
| **(km)Length of road** | 28.2 | | |
| **Landuse** | Range Land, Garden, Bare Land, Dry land | | |
| **Hydrologycal processe** | Surface runoff | | |

Table 2
The results for statistically significant variables in the Alamarvdasht study area.

| variables | Min | Max | Average |
|---|---|---|---|
| **Volume of sediment (m3)** | 5.4 | 836.61 | 86.78 |
| **Vegetation cover (%)** | 0 | 18 | 3.6 |
| **Bare soil (%)** | 82 | 100 | 94.97 |
| **Gravel (%)** | 0 | 7 | 1.43 |
| **Slope (headcut)%** | 8 | 50 | 26 |
| **Slope (development)%** | 1 | 3 | 2 |
| **Slope (initation)%** | 1 | 4 | 2 |
| **Clay %** | 17.2 | 38.8 | 23.63 |
| **Silt %** | 46.8 | 72 | 61.69 |
| **Sand %** | 8.8 | 30.6 | 14.66 |
| **EC (ds/m)** | 4.45 | 90.2 | 30.17 |
| **pH** | 6.61 | 7.95 | 7.22 |
| **OC** | 0.23 | 1.2 | 0.60 |
| **OM** | 0.39 | 2.06 | 1.04 |
| **K** | 0.65 | 7.7 | 3.93 |
| **Na** | 36.6 | 661 | 329.75 |
| **Ca + Mg** | 40 | 192 | 125.33 |
| **length of gully** | 13.67 | 131.4 | 47.70 |
| **Initiation area($m^2$)** | 8.03 | 338.47 | 64.32 |
| **Development area ($m^2$)** | 41.36 | 2025.68 | 303.28 |
| **(km)Length of road** | 19.1 | | |
| **Landuse** | Range Land, Bare Land, Dry land, Farmland | | |
| **Hydrologycal processe** | Surface runoff | | |

All gullies were formed on Quaternary alluvial formations. The gully densities in the Fadagh and Alamarvdasht study areas were estimated to be 8.93 and 9.4 km/km$^2$, respectively. According to the Ahmadi (1999) classification, both areas are highly susceptible to gully erosion. Morphometric data (Tables 3 and 4) showed that in the Fadagh area, gullies ranged from 44 to 247 m, with an average of 11.65 m. In Alamarvdasht, gully lengths ranged from 13.67 to 131.4 m, with an average of 47.70 m.

Table 3
Morphometric data for the study gulliesin Fadagh.

| Number of gully | Length of gully | Bottom width | | | Top width | | | Depth | | | Volume of sediment exported (m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | ave | min | Max | ave | min | max | ave | |
| **1** | 68.2 | 1.4 | 4.673 | 2.64 | 2.81 | 5.13 | 3.61 | 0.28 | 2.41 | 0.77 | 195.70 |
| **2** | 44 | 0.78 | 2.843 | 1.24 | 1.17 | 3.14 | 1.75 | 0.21 | 0.33 | 0.26 | 17.04 |
| **3** | 63.7 | 0.741 | 6.63 | 2.15 | 0.96 | 7.62 | 2.73 | 0.27 | 0.70 | 0.42 | 85.82 |
| **4** | 64.53 | 0.53 | 5.347 | 1.77 | 2.15 | 5.53 | 3.00 | 0.48 | 1.48 | 0.81 | 118.16 |
| **5** | 67 | 0.761 | 6.499 | 3.58 | 2.01 | 9.60 | 6.58 | 1.09 | 2.76 | 2.27 | 819.62 |
| **6** | 84.35 | 0.85 | 12.4 | 4.55 | 1.10 | 14.10 | 5.74 | 0.80 | 1.70 | 1.28 | 552.58 |
| **7** | 103.87 | 2.79 | 7.52 | 4.21 | 4.53 | 10.22 | 7.94 | 0.83 | 1.25 | 1.10 | 699.09 |
| **8** | 65.7 | 0.9 | 3.55 | 1.96 | 1.20 | 3.90 | 2.51 | 0.25 | 0.90 | 0.66 | 94.25 |
| **9** | 54.1 | 1.37 | 2.91 | 2.23 | 2.22 | 5.16 | 3.77 | 0.32 | 1.71 | 0.80 | 127.64 |
| **10** | 149.7 | 0.65 | 24.41 | 13.51 | 1.15 | 28.75 | 17.14 | 1.53 | 3.20 | 2.49 | 5666.05 |
| **11** | 81 | 0.84 | 2.29 | 1.51 | 1.20 | 2.97 | 2.07 | 0.70 | 1.75 | 1.24 | 198.71 |
| **12** | 94.6 | 0.54 | 1.83 | 1.00 | 0.76 | 2.51 | 1.54 | 0.34 | 1.75 | 0.96 | 132.45 |
| **13** | 116.3 | 0.33 | 2.75 | 1.38 | 0.45 | 3.49 | 1.93 | 0.28 | 1.73 | 0.94 | 221.28 |
| **14** | 92.7 | 0.53 | 2.74 | 1.56 | 0.82 | 5.21 | 2.86 | 0.63 | 3.17 | 1.63 | 425.46 |
| **15** | 117 | 1.1 | 4.41 | 2.37 | 1.37 | 5.91 | 3.57 | 1.66 | 4.37 | 2.95 | 1123.67 |
| **16** | 90.62 | 0.22 | 1.72 | 1.14 | 0.38 | 4.73 | 2.59 | 0.18 | 2.73 | 1.33 | 286.54 |
| **17** | 86.4 | 0.63 | 3.34 | 1.73 | 0.81 | 4.20 | 1.99 | 0.21 | 1.37 | 0.72 | 143.80 |
| **18** | 103.45 | 0.66 | 3.89 | 2.33 | 1.33 | 4.47 | 3.21 | 0.55 | 3.41 | 1.89 | 652.67 |
| **19** | 104.02 | 0.55 | 3.78 | 2.22 | 1.22 | 4.36 | 3.10 | 0.44 | 3.30 | 1.78 | 604.52 |
| **20** | 124.14 | 0.27 | 3.06 | 1.39 | 0.41 | 4.14 | 2.06 | 0.38 | 2.92 | 1.22 | 365.18 |
| **21** | 119.3 | 1.4 | 4.71 | 2.65 | 1.67 | 6.21 | 3.84 | 1.96 | 4.67 | 3.24 | 1354.99 |
| **22** | 137.7 | 0.52 | 3.41 | 1.41 | 0.60 | 5.96 | 2.70 | 0.31 | 2.84 | 1.35 | 539.90 |
| **23** | 93.01 | 0.43 | 1.72 | 0.89 | 0.65 | 2.40 | 1.43 | 0.23 | 1.64 | 0.86 | 109.02 |
| **24** | 87.31 | 0.52 | 3.23 | 1.62 | 0.70 | 4.09 | 1.87 | 0.11 | 1.26 | 0.60 | 121.65 |
| **25** | 247 | 0.9 | 4.22 | 2.29 | 1.67 | 4.74 | 3.24 | 0.23 | 3.41 | 1.53 | 1234.57 |
| **26** | 165 | 0.041 | 5.93 | 2.46 | 0.26 | 6.92 | 3.51 | 0.20 | 3.30 | 1.54 | 975.70 |

| Number of gully | Length of gully | Bottom width | | | Top width | | | Depth | | | Volume of sediment exported (m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | ave | min | Max | ave | min | max | ave | |
| **27** | 74.53 | 0.03 | 4.847 | 1.12 | 1.65 | 5.03 | 2.42 | 0.43 | 1.43 | 0.81 | 98.58 |
| **28** | 79.2 | 0.5 | 3.82 | 1.97 | 1.91 | 4.34 | 2.93 | 0.19 | 2.34 | 0.87 | 224.11 |
| **29** | 144.12 | 0.38 | 3.19 | 1.71 | 0.52 | 4.25 | 2.39 | 0.49 | 3.03 | 1.53 | 601.27 |
| **30** | 97 | 0.42 | 1.92 | 1.33 | 0.58 | 4.93 | 2.79 | 0.38 | 2.93 | 1.55 | 374.29 |

Table 4
Morphometric data for the study gullies in Alamarvdasht.

| Number of gully | Length of gully | Bottom width | | | Topwidth | | | Depth | | | Volume of sediment exported (m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | ave | min | Max | ave | min | max | ave | |
| **1** | 13.67 | 0.34 | 0.35 | 0.34 | 0.27 | 0.63 | 0.47 | 0.67 | 1.56 | 1.06 | 5.47 |
| **2** | 27 | 0.24 | 1.22 | 0.70 | 1.05 | 1.85 | 1.61 | 0.82 | 1.31 | 1.08 | 35.30 |
| **3** | 25.4 | 0.36 | 0.43 | 0.38 | 0.84 | 1.03 | 0.95 | 0.47 | 0.92 | 0.70 | 11.78 |
| **4** | 38.7 | 0.37 | 1.42 | 0.84 | 0.71 | 1.88 | 1.36 | 1.10 | 2.38 | 2.03 | 91.89 |
| **5** | 26.23 | 0.52 | 0.74 | 0.63 | 0.85 | 1.32 | 1.06 | 0.52 | 1.26 | 0.86 | 19.70 |
| **6** | 29.2 | 0.16 | 0.445 | 0.31 | 0.02 | 0.93 | 0.57 | 0.37 | 0.87 | 0.53 | 6.49 |
| **7** | 21.5 | 0.22 | 0.57 | 0.37 | 0.42 | 1.62 | 0.99 | 0.37 | 1.13 | 0.73 | 12.50 |
| **8** | 30.8 | 0.04 | 0.75 | 0.47 | 0.79 | 1.32 | 1.12 | 0.34 | 1.17 | 0.77 | 19.98 |
| **9** | 29 | 0.32 | 0.625 | 0.40 | 0.73 | 1.23 | 1.07 | 0.48 | 1.27 | 0.96 | 20.92 |
| **10** | 29.4 | 0.28 | 0.47 | 0.49 | 0.54 | 0.72 | 0.60 | 0.38 | 0.86 | 0.59 | 9.78 |
| **11** | 25.7 | 0.155 | 0.44 | 0.33 | 0.23 | 0.98 | 0.66 | 0.34 | 0.58 | 0.43 | 5.44 |
| **12** | 29.6 | 0.125 | 0.44 | 0.30 | 0.23 | 0.98 | 0.68 | 0.25 | 0.41 | 0.35 | 5.41 |
| **13** | 51.3 | 0.102 | 0.85 | 0.50 | 0.28 | 2.05 | 1.06 | 0.21 | 0.89 | 0.55 | 25.79 |
| **14** | 61.7 | 0.2 | 0.54 | 0.39 | 0.35 | 2.20 | 1.21 | 0.22 | 0.78 | 0.46 | 26.09 |
| **15** | 21 | 0.27 | 0.3 | 0.29 | 0.65 | 1.02 | 0.82 | 0.35 | 0.66 | 0.50 | 6.10 |
| **16** | 32.45 | 0.35 | 0.68 | 0.51 | 0.53 | 1.50 | 0.97 | 0.22 | 0.81 | 0.53 | 14.84 |
| **17** | 55.1 | 0.25 | 2.1 | 0.83 | 0.46 | 3.15 | 1.62 | 0.20 | 1.10 | 0.66 | 54.04 |
| **18** | 96.2 | 0.3 | 1.79 | 1.08 | 0.54 | 3.40 | 1.92 | 0.13 | 1.79 | 0.66 | 115.01 |
| **19** | 43.9 | 0.15 | 0.76 | 0.43 | 0.46 | 2.01 | 1.22 | 0.32 | 0.68 | 0.46 | 17.62 |
| **20** | 44.3 | 0.12 | 1.17 | 0.54 | 0.50 | 1.72 | 1.06 | 0.28 | 0.45 | 0.40 | 13.53 |
| **21** | 44.1 | 0.65 | 1.6 | 1.29 | 1.15 | 2.31 | 2.02 | 0.56 | 1.11 | 0.78 | 58.20 |
| **22** | 57.56 | 0.37 | 1.03 | 0.75 | 0.62 | 2.21 | 1.60 | 0.75 | 2.11 | 1.64 | 120.09 |
| **23** | 45.6 | 0.52 | 1.35 | 1.01 | 0.67 | 1.86 | 1.32 | 0.17 | 0.66 | 0.45 | 26.31 |
| **24** | 48.3 | 0.43 | 1.12 | 0.82 | 0.87 | 2.00 | 1.39 | 0.29 | 1.06 | 0.66 | 33.97 |
| **25** | 78.4 | 1.26 | 5.72 | 3.51 | 1.04 | 6.31 | 3.92 | 0.45 | 3.94 | 2.24 | 836.61 |
| **26** | 112 | 0.4 | 3.3 | 1.42 | 0.65 | 3.15 | 2.15 | 0.28 | 1.42 | 0.91 | 197.14 |

| Number of gully | Length of gully | Bottom width | | | Topwidth | | | Depth | | | Volume of sediment exported (m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | ave | min | Max | ave | min | max | ave | |
| **27** | 48.3 | 0.35 | 1.76 | 1.00 | 0.70 | 2.17 | 1.45 | 0.30 | 0.71 | 0.49 | 32.72 |
| **28** | 42.7 | 0.42 | 1.99 | 1.18 | 1.20 | 5.28 | 3.41 | 0.66 | 2.30 | 1.60 | 185.63 |
| **29** | 131.4 | 0.35 | 2.52 | 1.69 | 0.80 | 4.35 | 2.63 | 0.22 | 2.71 | 1.33 | 448.65 |
| **30** | 90.6 | 0.23 | 2.27 | 0.94 | 0.45 | 3.01 | 1.60 | 0.24 | 1.94 | 0.92 | 146.58 |

Table 3. Morphometric data for the study gulliesin Fadagh. Analysis of gully-depth estimates indicate that the average depths in Fadagh and Alamarvdasht were 1.31 m and 0.84 m, respectively, which are typically regarded as deep (depths > 0.8 m) gullies (Nachtergaele et al., 2002). Land use and land cover are among the most important factors for gully erosion, and the results indicate that gullies in the study areas primarily form on poor pasturelands or on dry lands.

Soil type, geological formation, and vegetation cover were the factors affecting threshold topography. The average percentages of bare soil upslope of the target gullies of Fadagh and Alamarvdasht were 94.8% and 94.97%, respectively (Tables 1 and 2). Gully erosion and runoff rates are related to the amounts of bare soil and vegetation-free areas on the slopes above the gullies. Quaternary formations in the study areas contain fine-grained and loose material prone to erosion and gully formation. The grain size distributions ( average percentages of clay, silt, and sand) of the soils in Fadagh and Alamarvdasht were 23.31%, 53.03%, 23.66%, 23.64%, 61.69%, and 14.67%, respectively. Previous studies have noted that Quaternary formations are susceptible to erosion in other study areas (Posen et al., 2003; Vanwalleghem et al., 2003).

The average EC and pH in the Fadagh area were 19.3 ds/m and 7.61. In the Alamarvdasht area, EC and pH were 30.17 ds/m and 7.22. According to Evans (1980), these values imply soil instability. The organic matter contents in Fadagh and Alamarvdasht were 0.35% and 1.04%, respectively. Morgan (1995) indicated that the threshold for organic matter content to resist erosion was 3.5%. Based on our organic content measures, soils in both areas are unlikely to be erosion-resistant.

Despite being smaller in area, Fadagh has a greater volume of gully erosion. The primary reason for this was land use. Rangeland, shrubs, and natural forests have lower Fadagh than Alamarvdasht. Th points to the significant erosion impacts caused by deforestation and intensive land use. Vegetation change and overall degradation of natural ecosystems tend to increase runoff and gully erosion.

The ranges of spatial coverage of drainages near gully head cuts and outlets in Fadagh were 0.00007–0.2648 ha and 0.0696–0.6655 ha, respectively (Table 5). The slopes of these two zones in Fadagh ranged from 0.01 to 0.08% and 0.01 to 0.05%, respectively. Gully number 19 had the largest gully head drainage area among the 30 gullies in the Fadagh area (Table 5), and 99% of this area was bare soil; the remaining 1% was stone and gravel at the surface. The Alamarvdasht zone exhibited gully head and outlet drainage areas from 0.0008 to 0.338 ha and 0.0041 to 0.2025 ha, respectively (Table 6). The slopes of these areas ranged from 0.01 to 0.04% and 0.01

to 0.03%. The maximum head cut drainage area was found at gully number 29. It also had a high proportion of bare soil (99%). The data indicate that larger head-cut drainage areas and less area covered by vegetation decrease the topographic threshold of gully erosion.

Table 5
Summary characteristics of the study gullies in Fadagh.

| Number Of gully | Initiation Area (ha) | Development Area (ha) | Slope (initiation) m/m | Slope (Development) m/m | Bare soil (%) | Vegetation (%) |
|---|---|---|---|---|---|---|
| **1** | 0.020161 | 0.138672 | 0.05 | 0.03 | 93 | 2 |
| **2** | 0.009677 | 0.069677 | 0.08 | 0.05 | 94 | 5 |
| **3** | 0.023572 | 0.143808 | 0.05 | 0.01 | 97 | 3 |
| **4** | 0.019318 | 0.165637 | 0.05 | 0.03 | 98 | 1 |
| **5** | 0.014101 | 0.120423 | 0.01 | 0.02 | 98 | 2 |
| **6** | 0.028374 | 0.123864 | 0.01 | 0.02 | 95 | 1 |
| **7** | 0.017982 | 0.14905 | 0.02 | 0.03 | 97 | 3 |
| **8** | 0.014709 | 0.097612 | 0.01 | 0.03 | 98 | 0 |
| **9** | 0.017188 | 0.12847 | 0.02 | 0.03 | 98 | 2 |
| **10** | 0.069047 | 0.665512 | 0.02 | 0.02 | 97 | 1 |
| **11** | 0.011524 | 0.077017 | 0.05 | 0.03 | 95 | 0 |
| **12** | 0.027375 | 0.129382 | 0.04 | 0.02 | 97 | 0 |
| **13** | 0.024783 | 0.114933 | 0.05 | 0.03 | 98 | 1 |
| **14** | 0.013496 | 0.087161 | 0.05 | 0.01 | 97 | 0 |
| **15** | 0.068084 | 0.268056 | 0.02 | 0.03 | 95 | 5 |
| **16** | 0.048262 | 0.164131 | 0.03 | 0.02 | 96 | 4 |
| **17** | 0.018396 | 0.082481 | 0.03 | 0.01 | 91 | 7 |
| **18** | 0.04437 | 0.19498 | 0.03 | 0.02 | 94 | 6 |
| **19** | 0.038824 | 0.227974 | 0.03 | 0.01 | 99 | 0 |
| **20** | 0.022407 | 0.164159 | 0.03 | 0.02 | 73 | 27 |
| **21** | 0.04007 | 0.129203 | 0.04 | 0.03 | 92 | 8 |
| **22** | 0.045521 | 0.243911 | 0.04 | 0.02 | 96 | 3 |
| **23** | 0.016004 | 0.166542 | 0.04 | 0.01 | 89 | 11 |
| **24** | 0.024486 | 0.088631 | 0.03 | 0.03 | 97 | 3 |
| **25** | 0.136634 | 0.64456 | 0.04 | 0.03 | 92 | 8 |
| **26** | 0.073096 | 0.309611 | 0.05 | 0.01 | 98 | 1 |

| Number Of gully | Initiation Area (ha) | Development Area (ha) | Slope (initiation) m/m | Slope (Development) m/m | Bare soil (%) | Vegetation (%) |
|---|---|---|---|---|---|---|
| **27** | 0.049898 | 0.167202 | 0.02 | 0.01 | 97 | 1 |
| **28** | 0.021489 | 0.103571 | 0.05 | 0.03 | 89 | 9 |
| **29** | 0.059917 | 0.417725 | 0.02 | 0.03 | 97 | 3 |
| **30** | 0.030258 | 0.199762 | 0.03 | 0.02 | 97 | 3 |

Table 6
Summary characteristics of the study gullies in Alamarvdasht.

| Number Of gully | Initiation Area(ha) | Development Area (ha) | Slope (initiation) m/m | Slope (Development) m/m | Bare soil (%) | Vegetation (%) |
|---|---|---|---|---|---|---|
| 1 | 0.001214 | 0.004136 | 0.02 | 0.02 | 97 | 3 |
| 2 | 0.005897 | 0.021394 | 0.04 | 0.03 | 95 | 2 |
| 3 | 0.003298 | 0.012775 | 0.04 | 0.01 | 98 | 2 |
| 4 | 0.00823 | 0.039635 | 0.01 | 0.03 | 93 | 7 |
| 5 | 0.00194 | 0.012166 | 0.01 | 0.02 | 91 | 6 |
| 6 | 0.008175 | 0.023316 | 0.02 | 0.01 | 100 | 0 |
| 7 | 0.000803 | 0.005725 | 0.02 | 0.01 | 92 | 7 |
| 8 | 0.009063 | 0.025736 | 0.01 | 0.01 | 83 | 11 |
| 9 | 0.001795 | 0.006321 | 0.04 | 0.03 | 93 | 7 |
| 10 | 0.003913 | 0.011815 | 0.04 | 0.02 | 85 | 11 |
| 11 | 0.003376 | 0.012058 | 0.04 | 0.02 | 98 | 1 |
| 12 | 0.003111 | 0.022027 | 0.02 | 0.01 | 98 | 2 |
| 13 | 0.005545 | 0.028152 | 0.04 | 0.01 | 97 | 0 |
| 14 | 0.00649 | 0.045 | 0.01 | 0.02 | 96 | 4 |
| 15 | 0.003478 | 0.015545 | 0.02 | 0.02 | 92 | 8 |
| 16 | 0.004167 | 0.028765 | 0.01 | 0.03 | 99 | 0 |
| 17 | 0.005662 | 0.017706 | 0.01 | 0.01 | 82 | 18 |
| 18 | 0.011061 | 0.044357 | 0.01 | 0.02 | 89 | 10 |
| 19 | 0.003654 | 0.0149 | 0.03 | 0.02 | 97 | 0 |
| 20 | 0.002364 | 0.01142 | 0.02 | 0.01 | 99 | 0 |
| 21 | 0.006552 | 0.022415 | 0.01 | 0.01 | 94 | 6 |
| 22 | 0.005167 | 0.025487 | 0.02 | 0.02 | 98 | 0 |
| 23 | 0.007168 | 0.038469 | 0.03 | 0.02 | 96 | 1 |
| 24 | 0.006643 | 0.031441 | 0.01 | 0.02 | 99 | 0 |
| 25 | 0.007741 | 0.04752 | 0.04 | 0.03 | 98 | 2 |
| 26 | 0.012528 | 0.080396 | 0.04 | 0.01 | 98 | 0 |

| Number Of gully | Initiation Area(ha) | Development Area (ha) | Slope (initiation) m/m | Slope (Development) m/m | Bare soil (%) | Vegetation (%) |
|---|---|---|---|---|---|---|
| **27** | 0.002612 | 0.012899 | 0.01 | 0.02 | 99 | 1 |
| **28** | 0.033847 | 0.202586 | 0.03 | 0.01 | 98 | 2 |
| **29** | 0.004329 | 0.018802 | 0.04 | 0.01 | 99 | 0 |
| **30** | 0.013159 | 0.026903 | 0.01 | 0.02 | 96 | 0 |

# Comparison Of Coefficients For The Topographic Threshold

Extremely low coefficient b values (Table 7) indicate that the slope did not have a significant effect on promoting gullying. It seems that vegetation cover has a more profound effect on gully development. The relationship for deep gullies located at the heads of gullies in the Fadagh area is $S = 0.0192A^{-0.15}$. In Alamarvdasht, $S = 0.0143A^{-0.06}$. These equations representing areas near gully outlets in Fadagh and Alamarvdasht were $S = 0.0181A^{-0.25}$ and $S = 0.0073A^{-0.18}$, respectively.

Table 7
The comparison of correlation coefficient of topographic threshold relationship in two climates

| **Alamarvdasht** | | | | **Fadagh** | | | |
|---|---|---|---|---|---|---|---|
| $R^2$ | | b | Variable | $R^2$ | | b | Variable |
| 0.006 | negetive | 0.06 | Initiation | 0.26 | negetive | 0.15 | Initiation |
| 0.13 | negetive | 0.18 | Development | 0.06 | negetive | 0.25 | Development |

The topographic thresholds for gully erosion in the Fadagh and Alamarvdasht study areas (Figs. 7 to 10) were lower than those reported by Vandekerckhov and Poesen (1998) in study areas in Spain and Portugal. This divergence most likely reflects differences in vegetation cover in drainages upstream of the gullies. However, these results are generally in line with those of Vandekerckhov and Poesen (1998) and Poesen et al. (2003).

The topographic threshold of gully erosion has been studied in various areas around the world. Vanwalleghem et al. (2005) indicated that the topographic thresholds for deep and shallow gullies in Belgium were 0.0578 and 0.02, respectively. Posen and Vandekerckhov et al. (1998) concluded that the topographic threshold is a function of environmental conditions (soil type, topography, land use, and climate). They reported values of exponent b to be -0.266 in Portugal and − 0.133 in Spain, and estimated topographic thresholds for Portugal and Spain were 0.102 and 0.157, respectively. Posen and Vandekerckhov (1998) found topographic thresholds in Belgium, France, and the UK, ranging from 0.025 to 0.09.

### Exponent b of topographic threshold of at head and outlet of gullies in Fadagh

To determine the factors that affect the exponent b of the topography threshold, a stepwise regression was conducted on the relationship between b of the head-cut topographic threshold (the dependent variable) and the set of factors compiled (features of soil, slope, percentages of bare soil, gravel, vegetation cover, areas of headward and outlet drainage, and the lengths and depths of gullies (independent variables) for the Fadagh study area using SPSS. The topographic threshold at the gully head was significantly related to nine variables at the 1% confidence level, with a determination coefficient of 78.4%. These nine variables are: headward gully drainage area, percentage of bare soil, pH, OM, EC, percentage of clay content, Mg, percentage of silt content, and elongation coefficient (Table 8).

Table 8
The final equation using stepwise regression

| Standardized coefficients | Coefficient $R^2$ | The significant level |
|---|---|---|
| Y=-.013 + 0.231pH-0.220Ec-0.337Om-0.176Silt + 0.484Clay + 0.455Mg-0.689Area1 + 0.388sk-0.198 percentage of bare soil | 78.4% | 1% |

The standard coefficients and the resulting linear equation suggest that each unit of pH (0.231), Mg (0.455), elongation coefficient-sk (0.388), and clay (0.484) magnify b, and each unit of Om (0.337), Ec (0.220), Silt (0.176), area of headward drainage area (0.689), and percentage of bare soil (0.198) attenuate b.

A similar regression was run on the relationship between the topographic threshold and the independent variables at the gully outlet in Fadagh. The topographic threshold of the gully outlet is statistically related to nine variables at a significance level of 1%; the determination coefficient was 97% (Table 9). The standard coefficients and linear equation indicate that for each unit of k (0.107), Ca (0.61), gully outlet drainage area (0.989), percentage of bare soil (0.06), percentage of gravel (0.05), and compression ratio (0.63) magnify the threshold and each unit of clay (0.115) and Ec (0.137) attenuate it.

Table 9
The final equation using stepwise regression

| Standardized coefficients | Coefficient | The significant level |
|---|---|---|
| Y=-0.007 + 0.107k -0.137Ec + 0.61Ca -0.115Clay + 0.989Area2 + 0. 060 percentage of bare soil + 0.053 percentage of gravel + 0.063 compression ratio | 97 % | 1% |

### xponent b of topographic threshold of at head and outlet of gullies in Alamarvdasht

The same variables were regressed for data from Alamarvdasht. At the heads of the gullies in Alamarvdasht, the exponent b of the topographic threshold was significantly related to 12 of the independent variables at the 1% confidence level and had a 90.8 % determination coefficient (Table 10).

Table 10
The final equation using stepwise regression and the coefficients

| Standardized coefficients | Coefficient | The significant level |
|---|---|---|
| Y = 0.17 + 0.410k + 0.926ph + 0.20Ec + 0.218om + 1.42mg + 1.28ca -7.03na -0.793Area1 – 1.09 vegetation cover- 0.944 percentage of bare soil – 0.898sk – 1.13L | 90.8% | 1% |

Table 11
The final equation using stepwise regression and the coefficients

| Standardized coefficients | Coefficient | The significant level |
|---|---|---|
| Y=-0.249sedm – 0.291k -0.807ph -0.174Ec- 0.199om – 1.04mg + 5.08na + 1.42Area2 + 0.813vegetation cover + 0.653 percentage of bare soil + 0.685sk + 0.854L | 93.4% | 1% |

Each unit of k (0.410), Ca (1.28), pH (0.926), Ec (0.20), Om (0.218), and Mg (1.42) amplify b and each unit of the percentages of bare soil (0.944), vegetation cover (1.09) and Sk, elongation coefficient (0.898), headward drainage area (0.793), Na (7.03), and length of the gully (1.13) attenuated it.

The exponent b correlated with 13 of the independent variables based on data from the gully outlets in Alamarvdasht. These relationships were significant at the 1% level and had a 93.4 % determination coefficient (Table 10). The standard coefficients suggest that each unit of Na (5.08), L (0.854), sk (685), vegetation cover (0.813), percentage of bare soil (2.653), and gully outlet drainage area (1.42) augment b and Ca (0.94), Mg (1.04), Om (0.199), Ec (0.174), pH (0.807), k (0.291), and sedimentation volume (0.249).

## Discussion

The results show that components of soil characteristics (e.g., textures, especially clay and sand) have different relationships with topographic thresholds. Higher amounts of clay combined with high densities of sodium (or high sodium absorption) may reduce topographic thresholds (e.g., gully no. 4 in Fadagh and no. 23 in Alamarvdasht). Therefore, destroying the soil structure decreases the permeability and prepares soil for more erosion. However, we believe that increasing concentrations of calcium and magnesium may cause aggregation of soil colloids, improve soil structure, increase soil permeability, and make the soil more resistant to erosion. The sand component will occasionally increase or decrease topographic thresholds, the reason for which may be the size of the sand particles. Increasing sand may reduce the initiation and expansion of gullies' thresholds because of the presence of fine sand. Increasing the percentage of silt may reduce the topographic thresholds. Increases in salinity concurrent with higher densities (compared to sodium) of calcium and magnesium may increase the topographic threshold. However, if the density of sodium is higher than that of calcium and magnesium, the threshold is reduced. Increased topographic thresholds of gullies may also be due to increased percentages of organic content in soils. However, this is seldom associated with gullying, as the effect of organic matter on topographic threshold is difficult to measure. Increases in organic material and increased depth of gullies can lead to increases in topographic threshold. Soil acidity has the least effect on threshold, and it can also be said that it was essentially ineffective. In areas where the relationship between gullying and soil acidity is negative, surface flow is the primary cause of gully erosion.

An increased form coefficient reduced the topographic threshold. This relationship indicates that with greater curvature of the surface, discharge increases speed, has less opportunity to penetrate to the lower layers, and less potential for subsurface erosion.Increased gully width to gully depth ratios suggest that surface flow has a greater role and may reduce thresholds. In regions where surface flow is the dominant process, more convex upstream areas may reduce the topographic threshold. Furthermore, elongation of the gully may increase its topographic threshold.

Increases in the percentages of clay and silt decrease and increase the topographic threshold, respectively, because clay increases the erosion resistance of soil surfaces. This study shows that increased sodium absorption decreases vegetation and decreases the threshold. Furthermore, the organic matter in the soil increases the topographic threshold. Other scholars have pointed out the roles of these elements in gully erosion expansion (e.g., Oostwoud and Bryan (1991) studied the Njemp Plateau of Baringo, Kenya, Kukal et al. (2002) conducted a study in India, Descroix et al. (2008) worked in tropical areas, Svoray and Markovitch (2009) in Israel, Oliveira-Filho (1994) in Brazil, Vandwalleghem et al. (2005) in Belgium, and Vandekerckhove et al. (2003) in Spain).

Previous research in Belgium has shown that b tends to be negative, exemplified by the effect of surface runoff on loess and alluvial sediments, particularly those of the Quaternary. However, this demonstrates the dominance of surface runoff in the initiation and expansion of gullies. Our research draws conclusions similar to those of Vanwalleghem (2005). The differences in some of our results are likely due to the types and densities of vegetation, geology, and drainage characteristics. Morgan and Mngomezulu (2003) determined that the correlation coefficients of the topographic threshold at the heads of gullies in Switzerland ranged from 0.072 to 0.496. Our measures were 0.54 for Fadagh and 0.13 for Alamarvdasht, respectively. Other topographic thresholds for gully erosion in other regions of the world are as follows: Desmet et al. (1999), from 2.8 to 6.3 in Belgium, Vanwalleghem et al. (2005), from 2 to 5.78, in France, England, and Vandekechove et al. (1998) in Belgium, from 6 to 9 in southern Spain, 1.57, and in northern Portugal 1.02.

The topographic thresholds of gully erosion in the two study areas in Iran were lower than those obtained by others (Posen et al., 2003, Vandekerckhove et al., 2003, Vanwalleghem et al., 2005). This could be due to the different coverage of vegetation coverage upstream of gullies. As in some of the aforementioned studies, good pasture and soils can be other factors for lower topographic thresholds for gully erosion. Comparisons of land use and thresholds indicate that agricultural lands in our study regions have lower thresholds (Fig. 11). In central Belgium, the critical slope of the soil surface and drainage area (after Poesen et al., 1998). It seems that soil properties, land use, and discharge of the flow are effective on the topographic threshold of gully erosion (Fig. 12).

Figure 11. The relationship between slope and land use of the gully drainage areas. Note: Dashed lines show the use of agricultural land and bold lines show the forest, prairie, and woodland settings. The numbers refer to (1) central Belgium (Poesen, unpublished data); (2) central Belgium (Vandaele et al., 1996); (3) Portugal (Vandaele et al., 1996); (4) France (Vandaele et al., 1996); (5) South Downs, United Kingdom (Boardman, 1992). (6) Colorado, USA (Patton and Schumm, 1975); (7) Sierra Nevada, California, USA (Montgomery and Dietrich, 1988); (8) California, USA (Montgomery and Dietrich, 1988); (9) Oregon, USA: (Montgomery and Dietrich, 1988); and (10) New South Wales, Australia (Nanson and Erskine, 1988).

Figure 12. The graph of relationship between topographic thresholds in 10 areas identified in Fig. 11.

Lines numbered 11 and 12 are results from this study at Fadagh and Alamarvdasht, respectively.

# Conclusion

This study determined that the power of the topographic threshold in the two study areas in Iran is negative, which indicates the dominant role of runoff in the formation of gullies. Topographic form properties exerted the strongest control on the topographic threshold for gullies in the study areas, followed by chemical and physical soil characteristics. In terms of the relationship between the threshold for gully expansion, dimensional factors, depth, and the ratio of width to depth exerted significant influence. Increased organic materials and improved gully depth lead to increases in the topographic threshold. Soil acidity has the least effect on the threshold, which can be considered unimportant. In areas where surface flow dominates the gully expansion process, a more convex upstream topography reduces the topographic threshold, causes more gully elongation, and increases the topographic threshold. Increased silt fractions usually decrease the topographic threshold, and increase the clay fractions usually increase the threshold. Our results show that increased absorption ratios of sodium increase the extent of barren ground, increase soil exposure, and thus decrease topographic thresholds. Losses of soil organic matter decrease the structural stability of soils, which tend to harden; consequently, runoff and gully erosion both increase. Subsurface flow also increases gullies. Many of the above threshold-reducing factors can be managed.

Mitigation of these factors may be achieved by establishing a thick vegetative cover with deep roots. Increasing organic components in soils and incorporating organic matter more deeply in soils may increase the topographic threshold as well. Restoration of vegetation by increasing surface roughness and organic fractions in soil can effectively control erosion and reduce the risk of gully formation. Modification of the salt content of soil using amendments can also reduce gully erosion. To prevent the expansion of gullies, vegetation must be increased to reduce runoff rates. In the short term, this would decrease the areal extent and volume of water generated in upslope drainages to help control their longitudinal expansion. Earthen dams may also be useful structures to control upslope runoff and help reduce runoff and diminish gully incision.

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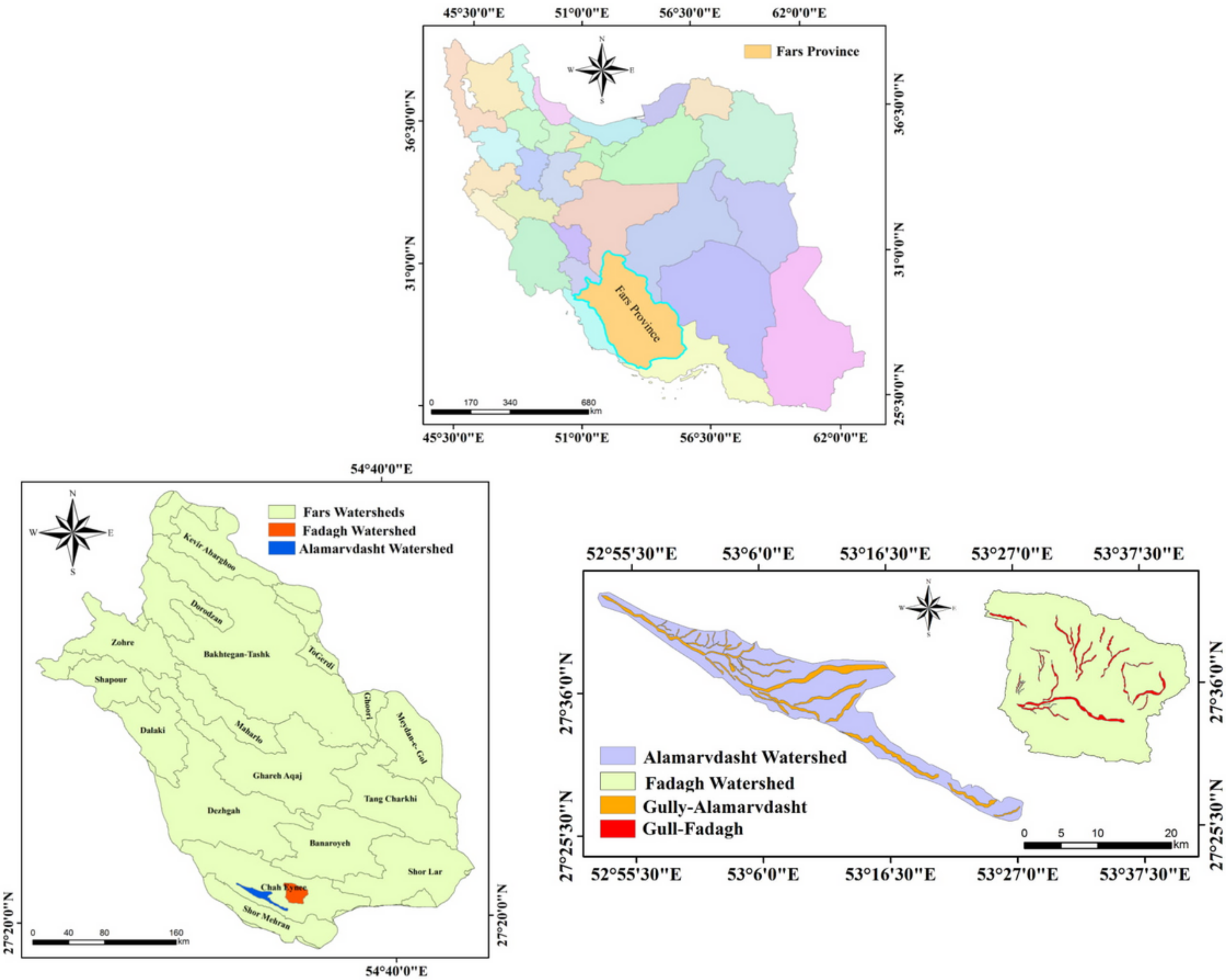
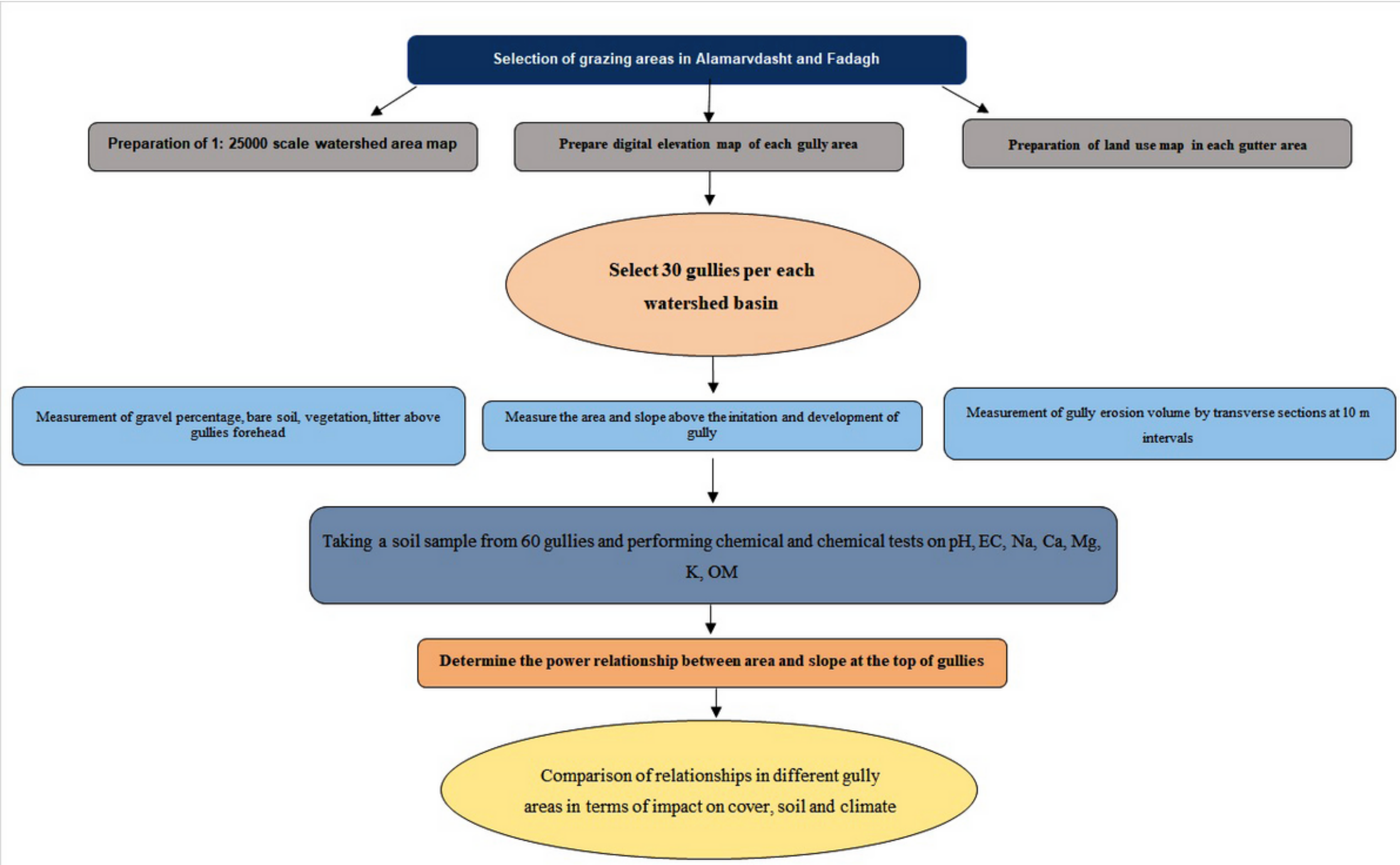
# Figures




## Figure 1

General view and location of the Fadagh and Alamarvdsht study areas in Fars Province, southern Iran




## Figure 2

Flowchart of the research methodology.

**Figure 3**

Photographs of gully sites in the Fadagh study area.

Figure 4

Examples of active gullies in the Alamarvdasht case study area.

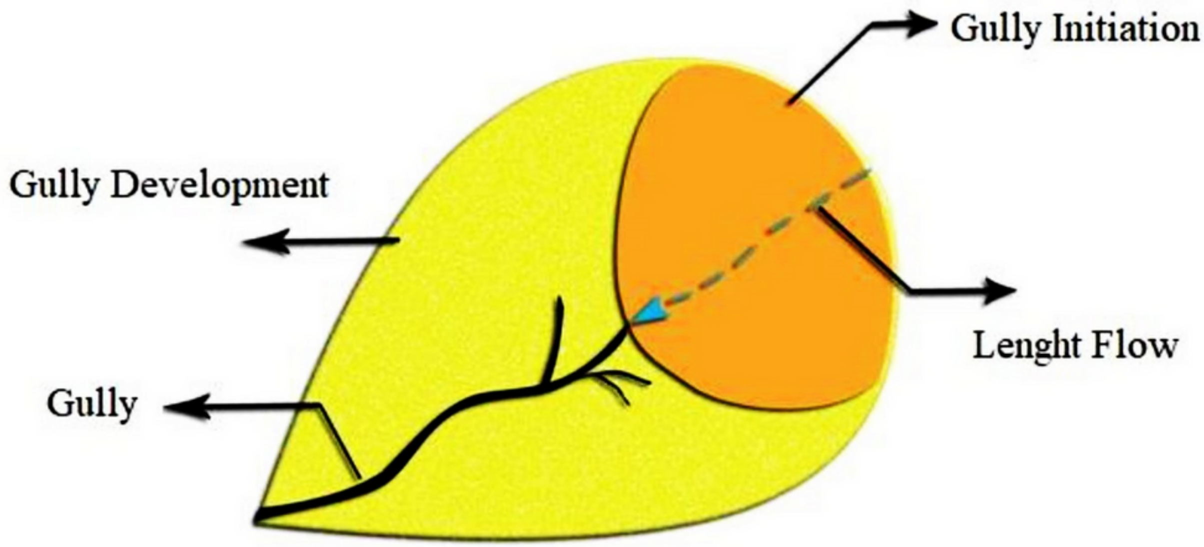
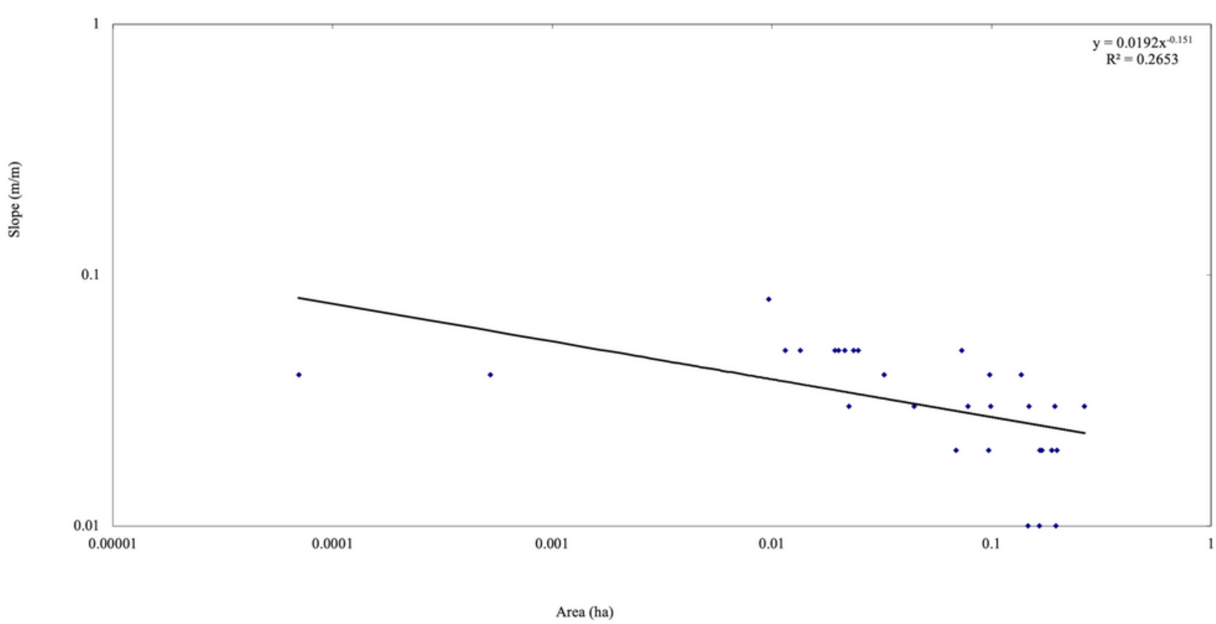



Figure 5

Drainage area from gully initiation point and gully development.

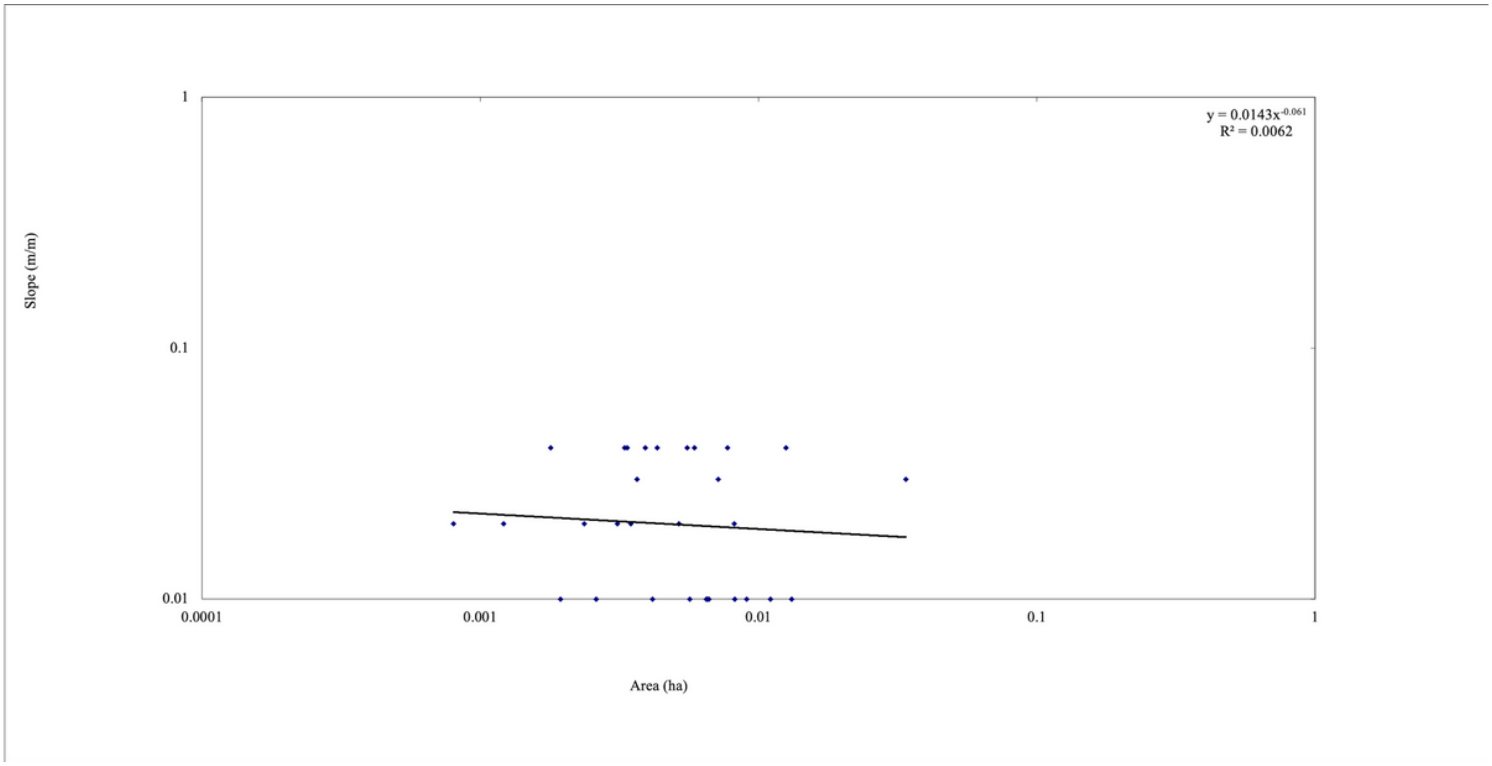
## Figure 6

Measuring land cover and percentages of gravel and bare soil using sampling quadrats.



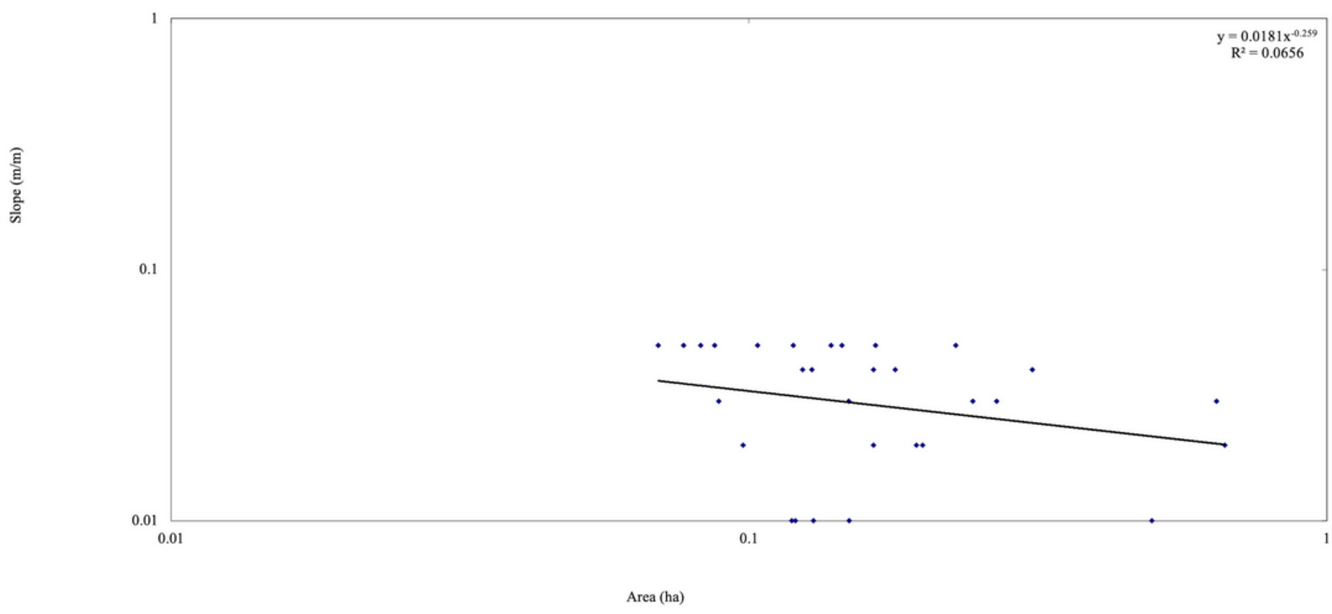

## Figure 7

The topographic thresholds for gully erosion in the Fadagh and Alamarvdasht study areas (Figs. 7 to 10) were lower than those reported by Vandekerckhov and Poesen (1998) in study areas in Spain and Portugal. This divergence most likely reflects differences in vegetation cover in drainages upstream of the gullies. However, these results are generally in line with those of Vandekerckhov and Poesen (1998) and Poesen et al. (2003).



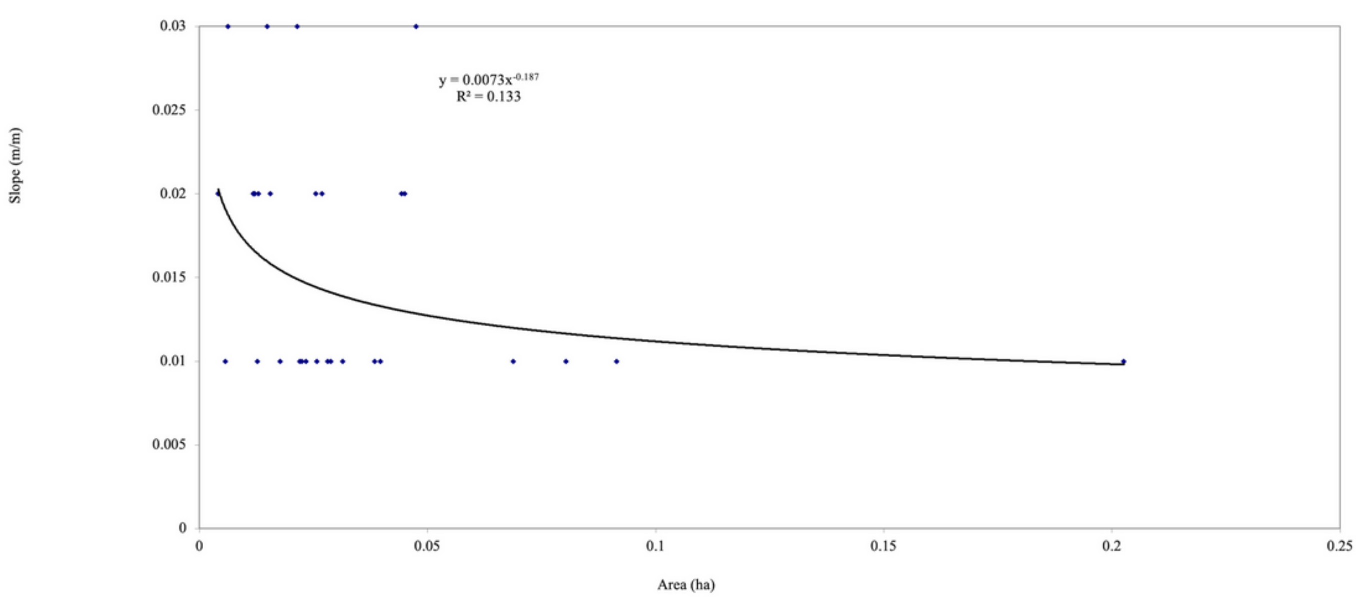

## Figure 8

The topographic thresholds for gully erosion in the Fadagh and Alamarvdasht study areas (Figs. 7 to 10) were lower than those reported by Vandekerckhov and Poesen (1998) in study areas in Spain and Portugal. This divergence most likely reflects differences in vegetation cover in drainages upstream of the gullies. However, these results are generally in line with those of Vandekerckhov and Poesen (1998) and Poesen et al. (2003).



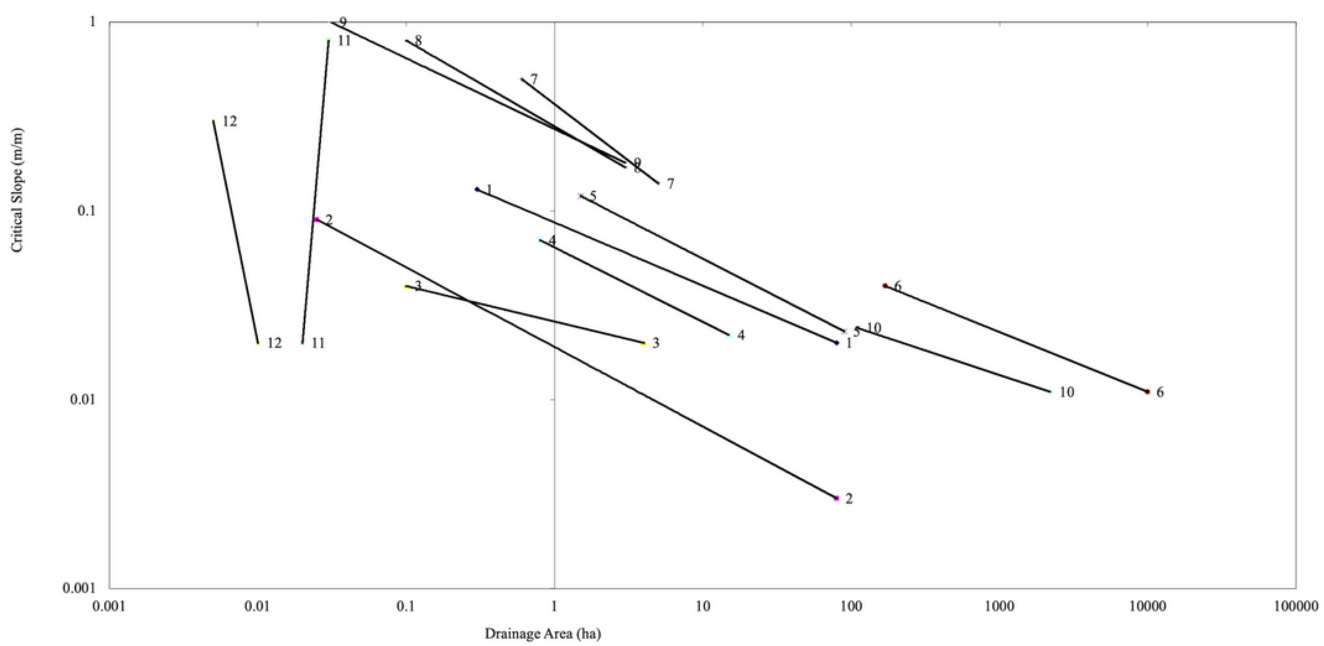

## Figure 9

The topographic thresholds for gully erosion in the Fadagh and Alamarvdasht study areas (Figs. 7 to 10) were lower than those reported by Vandekerckhov and Poesen (1998) in study areas in Spain and Portugal. This divergence most likely reflects differences in vegetation cover in drainages upstream of the gullies. However, these results are generally in line with those of Vandekerckhov and Poesen (1998) and Poesen et al. (2003).




## Figure 10

The topographic thresholds for gully erosion in the Fadagh and Alamarvdasht study areas (Figs. 7 to 10) were lower than those reported by Vandekerckhov and Poesen (1998) in study areas in Spain and Portugal. This divergence most likely reflects differences in vegetation cover in drainages upstream of the gullies. However, these results are generally in line with those of Vandekerckhov and Poesen (1998) and Poesen et al. (2003).




## Figure 11

The relationship between slope and land use of the gully drainage areas. Note: Dashed lines show the use of agricultural land and bold lines show the forest, prairie, and woodland settings. The numbers refer to (1) central Belgium (Poesen, unpublished data); (2) central Belgium (Vandaele et al., 1996); (3) Portugal (Vandaele et al., 1996); (4) France (Vandaele et al., 1996); (5) South Downs, United Kingdom (Boardman, 1992). (6) Colorado, USA (Patton and Schumm, 1975); (7) Sierra Nevada, California, USA (Montgomery and Dietrich, 1988); (8) California, USA (Montgomery and Dietrich, 1988); (9) Oregon, USA: (Montgomery and Dietrich, 1988); and (10) New South Wales, Australia (Nanson and Erskine, 1988).

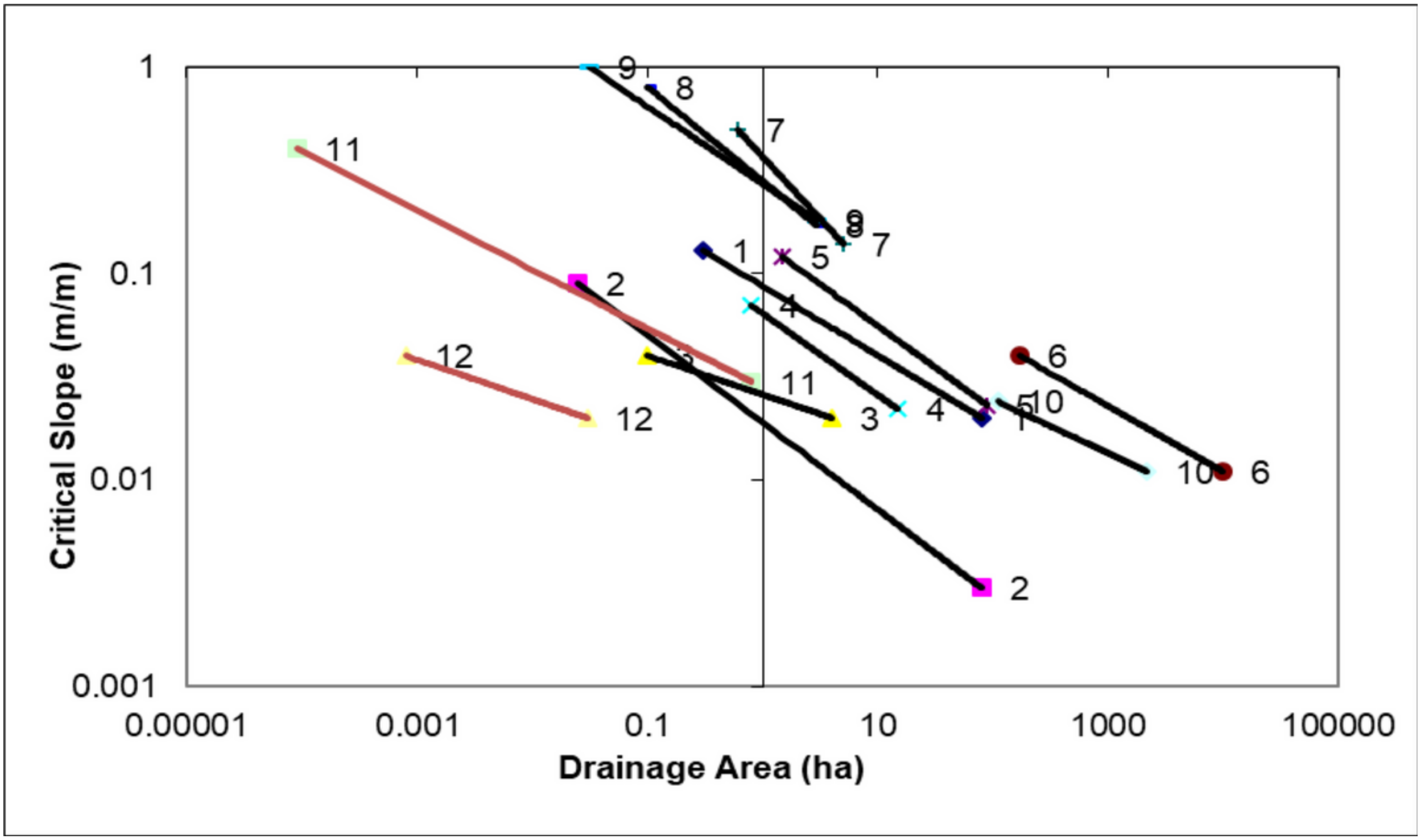



**Figure 12**

The graph of relationship between topographic thresholds in 10 areas identified in Fig. 11. Lines numbered 11 and 12 are results from this study at Fadagh and Alamarvdasht, respectively.

## Supplementary Files

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