



# Topographic Threshold of Gully Erosion in Iran: A Case Study of Fars, Zanjan, Markazi and Golestan Provinces

# 25

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## Abstract

The relationship between the slope gradient ( $S$ ) and drainage area ( $A$ ) upslope the gully head or point of gully incision represents the topographic conditions for development and positions of gully erosion in different environments. In this study, 300 gullies from 4 provinces including Fars, Markazi, Zanjan and Golestan were selected, and their physical characteristics such as watershed, soil, ground surface and their dimensions were measured. A digital elevation model (DEM) was produced with ArcGIS 9.3, using topographical maps with 1:25,000 scale. The location of gullies was recorded using GPS in the field and transferred on the DEM; also, the boundary of the gullies was depicted using Av. SWAT. Upslope drainage area and slope of the soil surface of gullies were measured using DEM and field survey. The gullies were classified into homogeneous groups, using Cluster analysis method, and effective factors for categorizing were determined using factor analysis. Values, coefficient of determination and significance of the relationships were

determined using regression method in Minitab 16 and SPSS 23 software. The results of this research indicated a strong relationship between ground slope and drainage area in both cases of gully development and incision at 1% significance level. The relationship for gully development had an exponent ( $b$ ) equal to  $-0.365$  and  $R^2$  equal to  $0.564$ , indicating the dominant impact of overland flow on the gully development. Although using values of ground slopes measured on DEM did not decrease the significance level, values of exponent ( $b$ ), intercept ( $a$ ) and  $R^2$  decreased. Value of intercept ( $a$ ) indicates low resistance of landscape to gully erosion in the studied environments.

## Keywords

Gully erosion · Topographic threshold · Digital elevation model · Iran

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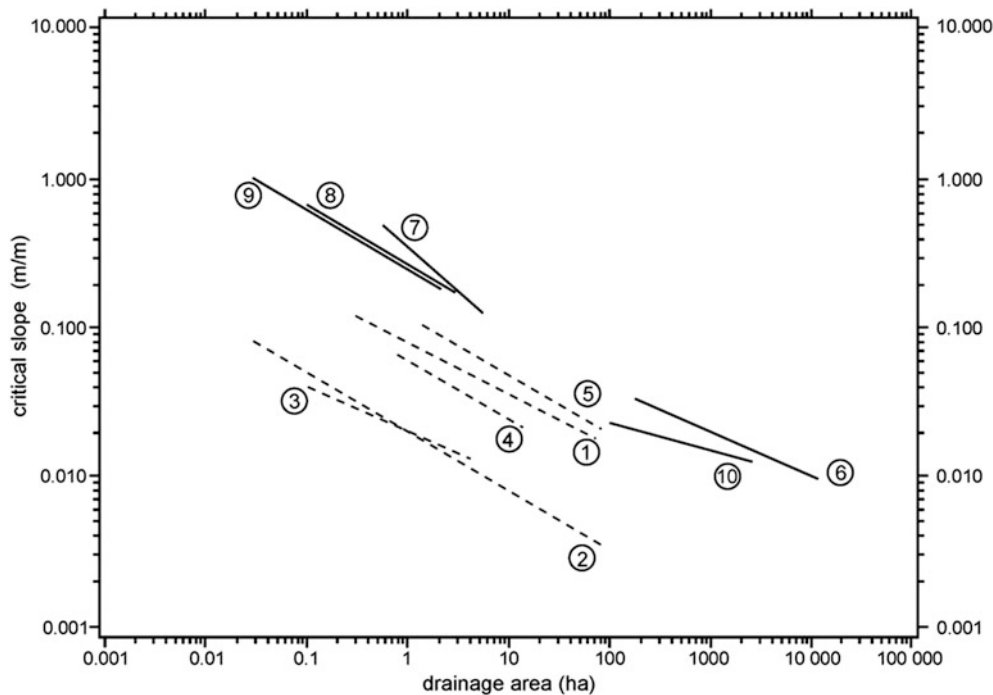
## 25.1 Introduction

Soil erosion is recognized as the key factor for soil degradation in the world (Oldeman et al. 1990; Valentin et al. 2005; Liniger and Critchley 2007; Gutierrez et al. 2009). Gully erosion as an important sediment source, conveyance of flow and sediment from upstream to downstream channel networks and contamination of water bodies by transported sediment and chemicals, needs to be better understood, managed and its effects mitigated (Poesen et al. 2003, 2011; Torri and Poesen 2014). Gully erosion as a geomorphic phenomenon has different thresholds including topographic, hydraulic, rainfall, soil and land use (Poesen et al. 2003; Phillips 2006). Different methods were used to define topographic conditions for gully erosion, such as stream power index (Kakembo et al. 2009), topographic wetness index (Gutierrez et al. 2015), and topographic threshold (Monsiers et al. 2015; Torri and Poesen 2014). Topographic threshold is expressed by the relationship between drainage area ( $A$ ) and slope of the soil surface ( $S$ ), controlling the development and position of

gully heads in various environments (Torri and Poesen 2014). This approach is applied to show the location of gully heads and threshold of the drainage area and slope gradient to initiate and/or retreat headcuts. The process of the retreat of gully heads at a global scale remains poorly understood (Vanmaercke et al. 2016). In spite of one century research on gully erosion, there is still some knowledge gap which needs to be addressed (Castillo and Gomez 2016).

Patton and Schumm (1975) and Begin and Schumm (1979) began modelling of gully erosion as a threshold process when flow shear stress ( $\tau_f$ ) overcomes the shear strength of the channels ( $\tau_{\text{soil}}$ ). This is developed by Montgomery and Dietrich (1994). The topographic threshold conditions for gully erosion are reported as a logarithmic plots of the upslope drainage area ( $A$ ) and slope gradient of the soil surface as  $S = aA^b$ , where  $A$  (ha) is the area of the catchment draining towards the gully head and  $S$  (tangent, m/m) is the slope of soil surface at the gully head. The threshold coefficient ( $a$ ) reflects the resistance of the site to gully development. The lowest values were observed for cropland followed by values for rangeland, pasture and forest (Torri and Poesen 2014). Negative exponent ( $-b$ ) showed the reverse

relationship between the slope gradient and drainage area which means surface runoff while positive exponent ( $b$ ) reveals that subsurface runoff is a dominant hydrologic process acting on gully development. Montgomery and Dietrich (1994) suggested exponent  $b$  between 0.5 and 0.875 corresponding to supercritical laminar flow and turbulent flow, respectively. Although most of the exponent  $b$  represented laminar flow, they are rare for concentrated flow in the fields (Torri and borselli 2003). The results of recent studies about threshold conditions for a variety of land uses in some parts of the world revealed that cultivated croplands need less topographic threshold than noncultivated lands for gully development (Poesen et al. 2003; Fig. 25.1). Land use change reduces the topographic threshold due to reduction of soil resistance and biomass. Therefore, the range of drainage area and slope of the soil surface were between 0.2–10,000 ha and 0.01–1 m/m in noncultivated lands and between 0.02–100 ha and 0.003–0.8 m/m in the cultivated croplands (Table 25.1). The results of previous research indicated that the field survey of the drainage area and the slope of soil surface (Fig. 25.1, line 1) produce larger values than analysis of the aerial photos and topographic maps



**Fig. 25.1** The relationship between drainage area and critical slope of the soil surface for incipient gully development in some parts of the world (Poesen et al. 2003). Dotted lines indicate the threshold conditions for ephemeral gully development in cultivated cropland (1–5), and solid lines indicate the threshold conditions for gully head development in noncultivated land (6–10), (1) central Belgium, field survey (Poesen 1993); (2) central Belgium, measurement on aerial photos and topographic maps (Vandaele et al. 1996); (3) Portugal, analysis of aerial photos and topographic maps (Vandaele et al. 1996); (4) France, analysis of aerial photos and topographic maps (Vandaele et al. 1996);

(5) Southern Britain, field survey (Boardman 1992); (6) USA (Colorado), sage brush and scattered trees, analysis of photos and topographic maps (Patton and Schumm 1975); (7) USA (Nevada), field survey, open oak woodland and grassland (Montgomery and Dietrich 1988); (8) USA (California), coastal prairie, field survey (Montgomery and Dietrich 1988); (9) USA (Oregon), field survey, logged forest (Montgomery and Dietrich 1988); (10) Australia (New South Wales), swampy, reed covered valley floors, field survey (Nanson and Erskine 1988)

**Table 25.1** The values of drainage area and slope of soil surface for threshold conditions in different land uses and methods of survey

Slope of soil surface (m/m)	Drainage area (ha)	Land use	Method	References
0.02–0.12	0.2–70	Cultivated land	Field survey	Poesen (1993)
0.003–0.8	0.02–100	Cultivated land	Analysis of aerial photos and topographic maps	Vandaele et al. (1996)
0.015–0.04	0.1–2	Cultivated land	Analysis of aerial photos and topographic maps	Vandaele et al. (1996)
0.025–0.07	0.5–10	Cultivated land	Analysis of aerial photos and topographic maps	Vandaele et al. (1996)
0.015–0.1	1–80	Cultivated land	Field survey	Boardman (1992)
0.01–0.04	200–10,000	Sage brush and scattered trees	Analysis of aerial photos and topographic maps	Patton and Schumm (1975)
0.02–0.5	0.2–4	Oak wood land and grassland	Field survey	Montgomery and Dietrich (1988)
0.3–0.7	0.2–2	Coastal prairie	Field survey	Montgomery and Dietrich (1988)
0.02–1	0.2–1	Logged forest	Field survey	Montgomery and Dietrich (1988)
0.015–0.025	100–2000	Swampy reed cover	Field survey	Nanson and Erskine (1988)

(Fig. 25.1, line 2). This means different methods of measurement in the same or similar locations yield different results.

The results of the research conducted in China (Sun et al. 2014) and in Australia (Monos-Robles et al. 2010) indicated the importance of slope gradient and drainage area on the rate of gully erosion. Vanmaercke et al. (2016) believed that the volumetric rates of gully head retreat (GHR) were significantly correlated to the runoff contributing area of the gully and rainy day normal. Topographic threshold could be changed based on the morphometric characteristics of the gullies such as gully depth in loess plateau of Belgium (Nachtergaele et al. 2002). Deeper gullies had a larger intercept ( $a$ ) and exponent ( $b$ ). Monsiers et al. (2015) presented the lowest intercept ( $a$ ) values (0.078–0.090) for catchments treated with sloping drainage ditches and the highest ones (0.198–0.205) for stone bund catchments on the contour in Northern Ethiopia. The majority of studies indicated that exponent ( $b$ ) varied between  $-0.2$  and  $-0.7$  (Vandaele et al. 1996; Desmet et al. 1999; Vandekerckhove et al. 2000; Nachtergaele et al. 2002; Hessel and Asch 2003; Vanwallegem et al. 2005). Dietrich et al. (1993) believed a vast range of slope gradient was required to determine the relationship between the drainage area and slope of soil surface because of the effect of various natural and human factors on this relationship. Different methods of measurement of drainage area and slope gradient have been used by recent studies. Some of them (e.g. Morgan and Mngomezulu 2003) used the average slope gradient of catchment upslope the gully head; others used slope gradient of the valley bottom (e.g. Boardman 1992); some others used basin area per flow width (e.g. Prosser and Abernethy 1996); and also others used division of the difference of elevation to gully head area (e.g. Hancock and Evans 2006). Due to the vast

area of gully erosion in Iran about 14,000 km<sup>2</sup> (Soufi et al. 2017; Soufi and Bayat 2015, 2016) and huge damages to croplands and rangelands, roads, bridges and village and increased migration, it is necessary to study the topographic threshold of the gullies to manage and mitigate them. Therefore, four provinces from southwest (Fars), central (Markazi), northwest (Zanjan) and northeast (Golestan) were selected for the study of topographic conditions of gully erosion in Iran.

## 25.2 Materials and Methods

### 25.2.1 Study Area

This survey was carried out on 13 regions with massive gully erosion in four provinces including Fars, Golestan, Markazi and Zanjan in Iran (Fig. 25.2 and Table 25.2). Five regions including Lamerd, Alamarvdasht, Mishan, Baba Arab and Ghazian were studied in Fars province (Table 25.2). Gully erosion covers more than 300 km<sup>2</sup> in Lamerd and Alamarvdasht; the land type is alluvial which has originated from Miocene geologic formation. These regions are located 50 km far from Persian gulf with 150 and 200 m above the sea level; the average annual temperature and precipitation were 27 °C, 240 mm and 250 mm, respectively (Lamerd and Alamarvdasht stations, 20 years). Land use is rain-fed farms, poor rangeland and palm gardens. Most part of the area is poor rangeland. Mishan is located in the southwest of Fars province with semi-arid climate, 620 m above the sea level with hilly area; the average annual temperature and precipitation were 24 °C and 645 mm (Abdegah station, 18 years) and land use was rain-fed wheat and barley. Baba Arab is



**Fig. 25.2** The studied provinces for topographic threshold of gully erosion in Iran, Gully erosion in Bidgineh, Zanjan (above left), Zahirabad, Markazi (below left), Hajighoshan, Golestan (above right) and Lamerd, Fars (below right)

located in the east of Fars with hilly land type and mild arid desertic climate, and 1093 m above the sea level; the average temperature and precipitation were 23 °C and 245 mm (Baba Arab station, 31 years), respectively, with 90 mm maximum daily rainfall and rain-fed farms. Also, Ghazian is located in the north of Fars province with hilly land type and cold semi-arid climate; the average annual temperature and precipitation there were 12.5 °C and 239 mm, respectively, with 61 mm maximum daily rainfall (Dehbid station, 30 years), and land type was irrigated farms.

Three regions including Robatturk, Zahirabad and Peik were studied in Markazi province (Table 25.2). Robatturk is located in the alluvial river terrace near Delijan city with arid climate. It is located 1959 m above the sea level. Average annual temperature and precipitation were 13 °C and 235.7 mm, respectively (Moteh station, 20 years). Land type is irrigated farms and gardens on deep soil. Zahirabad (Gavar station, 25 years) is located 2237 m above the sea level near Shazand, with semi-humid climate and average annual temperature and precipitation equal 11.6 °C and 457 mm, respectively. Gullies are located in old alluvial terrace with irrigated and rain-fed farms on semi-deep soil. Peik region is located near Zarandieh city on a plateau land type and is 1146 m above the sea level with mild arid climate. The average annual temperature and precipitation were 13.4 °C and 235 mm, respectively (Peik station, 18 years). The gully area is located around the Shoor river on deep soil with irrigated farms and poor rangeland with gravel fragments on the soil surface.

Three regions including Alagol, Tamargharaghozi and Hajighoshan were studied in Golestan province (Table 25.2). Alagol is located on the hilly area 20 m above the sea level and mild desertic arid climate. Average annual temperature and

precipitation were 17.2 °C and 200 mm, respectively (Chaat station, 13 years). Land type is hilly with salt loess, and the land use is poor rangeland with loam soil texture. Tamargharaghozi region is located on a hilly old loess plateau 140 m above the sea level with mild semi-arid climate. The average annual temperature and precipitation were 17.4 °C and 521.6 mm, respectively (Kalaleh station, 11 years). Dominant land use is poor rangeland with rain-fed farms in some locations on the soils with salt and heavy texture. Hajighoshan region is located in the east of Ghonbad-kavoos city. It is located on loess hills 180 above the sea level with mild semi-arid climate. Average annual temperature and precipitation were 17.6 °C and 417 mm, respectively (Gonbad kavooos station, 29 years). Land use is dominantly very poor rangeland with rain-fed farms in some parts of the region. Its soil is similar to that of Alagol region with high silt and SAR and exchangeable sodium.

Two regions including Bidgineh and Chapchap were studied in Zanjan province (Table 25.2). Bidgineh region is located in the east of Zanjan province with cold semi-arid climate in 1802 m above the sea level. Average annual temperature and precipitation were 16 °C and 358.5 mm, respectively (Galtoog station, 30 years). Land type is hilly marl and sandstones. Soil texture varies between loam and loam clay. Land use is rain-fed farms and gardens resulting from rangeland change. Chapchap region is located on hilly land which is 1235 m above the sea level with extra cold semi-arid climate in the west of Zanjan province. The average annual temperature and precipitation were 20 °C and 250.7 mm, respectively (Filehkas station, 8 years). Soil texture varies between loam and loam sand. Land use is dominantly poor range land with rain-fed farms in some parts of the region.



**Table 25.2** Characteristics of the studied regions in the selected provinces in Iran

Location	Climate	Annual precipitation (mm)	Land use	Land type	Coordinates
Fars (Iamerd)	Arid	250	Cultivated cropland (dry farm)	Alluvial plain	27°15'; 2720'N 52°30'; 53°, 45'E
Fars (Alamardasht)	Arid	240	Cultivated dry farm and poor rangeland	Alluvial plain	27°28'; 2754'N 52°36'; 53°, 18'E
Fars (Mishan)	Mild semi-arid	620	Cultivated dry farm	Hill	30°00'; 30°02'N 50°53'; 53°, 57'E
Fars (Babaarab)	Mild arid	90	Cultivated cropland	Hill	28°30'; 30°38'N 53°40'; 53°59'E
Fars (Ghazian)	Cold semi-arid	239	Cultivated cropland	Hill	30°25'; 30°30'N 53°04'; 53°12'E
Zanjan (Bidgineh)	Cold semi-arid	358.5	Cultivated cropland and gardens	Hill	36°29'; 36°32'N 48°10'; 48°18'E
Zanjan (Chapchap)	Extra cold semi-arid	250.7	Rangeland and rain-fed farms	Hill	36°57'; 36°59'N 47°57'; 47°59'E
Golestan (Alagol)	Cold semi-arid	355.1	Rangeland + cultivated cropland	Hill	37°20'; 37°25'N 54°32'; 54°3'E
Golestan (Tamargharaghozi)	Mild semi-arid	521.6	Rain-fed wheat and barelt farms	Hill	37°29'; 37°31'N 55°30'; 54°32'E
Golestan (Hajighoshan)	Mild semi-arid	417	Poor rangeland and rain-fed farms	Hill	37°26'; 37°28'N 55°22'; 55°24'E
Markazi (Zahirabad-Shazand)	Cold semi-arid	457	Irrigated and rain-fed farm	Plateau (old alluvial and colluvial)	33°53'; 33°55'N 49°14'; 49°17'E
Markazi (Robatturk-Delijan)	Cold arid	235.7	Irrigated farm and garden	Hill	33°42'; 33°46'N 50°49'; 50°52'E
Markazi (Peik-Zarrandieh)	Mild arid	235	Poor rangeland + irrigated <i>Pistacia</i>	Plateau	35°17'; 35°20'N 50°39'; 50°50'E

## 25.2.2 Methodology

### 25.2.2.1 Measurement of Drainage Area and Slope of Soil Surface Upslope of Gully Heads or Point of Gully Incision

Measurement of ground slope with different methods yielded different threshold lines (Vandaele et al. 1996); therefore, to produce standard values for interpretation, it is necessary to use field survey and compare other methods in different landscapes (Poesen et al. 2003; Torri and Poesen 2014). Drainage area and slope of soil surface were measured upslope of the gully heads (for development) and the point of gully incision (for incision). Slope of soil surface was measured using digital elevation model (DEM) and field survey. Slope was measured few metres far in the upstream of headcuts (for gully development) and upstream of points that gullies formed using Sento clinometers in the field survey. Also, slope was measured on DEM at the so-called points. DEM was produced using topographic maps with a scale of 1:25,000 in the environment of Arc/view.

## 25.2.2.2 Statistical Methods

### 25.2.2.2.1 Cluster Analysis

The relationship of drainage area and slope of soil surface was established in three cases. In the first case, the relationship was estimated for the total 300 gullies. In the second case, the gullies were divided into homogeneous groups using cluster analysis by Minitab software, version 16. Homogeneous groups were determined using Ward and Average methods in the 60% similarity level. The result of Ward method was used for estimation of the relationship between the drainage area and slope because of the least variance and more groups. In the third case, the gullies were divided into different groups based on their class area.

### 25.2.2.2.2 Factor Analysis

Analysis of principle components was used to determine the degree of determination or dependence of different variables in order to omit independent variables. Recognition of data suitability was done using coefficient of KMO, using SASS software. Data are suitable for factor analysis if KMO is more

than 0.5. Factor analysis used diagrams of loading plot and score plot. The method of Varimax rotation was used to produce smaller groups of variables with strong determination for simplicity of interpretation and also factors could be defined based on fewer variables.

### 25.2.2.3 Geometric Characteristics of Drainage Basin

Position of each gully including headcut and point of gully incision was recorded using GPS and transferred to DEM. The border of each gully basin was determined using Av. Swat software. In this method, the boundary of drainage basin for gully heads and points of gully incision was depicted. Geometric parameters of drainage basin including area, perimeter, and length were measured for each gully basin for development and incision stages in Arc/View environment, and then different indices were estimated for drainage basin of each gully.

### 25.2.2.4 Indices of Drainage Basin (Alizadeh 1998)

- Compactness coefficient of Gravelius: division of basin perimeter to perimeter of a circle with an area equal to basin area. Relationship of Gravelius is  $C = 0.28P/\sqrt{A}$  in which,  $P$  is perimeter and  $A$  is area of drainage basin. This coefficient is near 1 for circle basins and more than 1 for elongated basins.
- Form factor: dividing average width by the length of the drainage basin or the length of the longest stream. Length and width of the drainage basin were obtained using topographic map of the basin and dividing the area by the basin length, respectively. Therefore, form factor could be shown as  $FF = A/L^2$ , in which,  $L$  is the length and  $A$  is the area of drainage basin. Form factor equal to 1 represents the circle basin and smaller than 1 indicates the elongated one.
- Elongation ratio: dividing the area by the width of drainage basin. Its relationship is shown as  $Re = 2/L(A/\pi)^{0.5}$ . Smaller ratio from 1 represent the elongated drainage basin.
- Circle ratio: dividing the drainage area by a circle area that has equal perimeter of drainage basin. Its relationship is  $R_c = A/A_c \frac{A}{A_c}$  in which  $A$  is the drainage area and  $A_c$  circle area with equal perimeter to the drainage area. Ratio equal to 1 indicates the circle basin and elongated one has smaller ratio than 1.

### 25.2.2.5 Gully Dimensions

Dimensions of the first-order gullies including length, top width, bed width and depth were measured using a tape meter in the field. Depth and width of the gullies were measured in a distance from the gully head with a uniform cross-section shape.

### 25.2.2.6 Physical and Chemical Characteristics of Soil

Soil characteristics were measured from the collected soil samples from the gully heads and gully banks from the surface layer in which the dominant plant roots existed. Particle size and bulk density were determined using hydrometer and steel cores, respectively. The cores were dried up in an oven for 24 h with 105 °C temperature. Bulk density was calculated by dividing the dry weight by volume of cores. Organic carbon was measured using Walkley–Black method. Ec and pH were measured by Ec and pH meter device using saturated soil extract. Potassium and sodium were measured using flame photometer. Calcium and magnesium were measured using titration with EDTA (Handbook no. 467, Soil and Water Research Institute 2008).

### 25.2.2.7 Land Use and Characteristics of Soil Surface

Characteristics of the soil surface including vegetation cover, litter, surface gravel fragments and bare soil were measured in quadrates with 1 m per 1 m dimensions on the ground surface around the gullies. At least 10 quadrates were used for each gully head and also gully bank. Land use and its condition were determined by field survey.

### 25.2.2.8 Relationship Between Drainage Area and the Slope of Soil Surface

The relationship between the drainage area (independent variable) and slope of soil surface (dependent variable) was determined for three cases including total gullies (300), homogeneous groups by cluster analysis, and the area class of the drainage basin with specific interval for two stages of development and incision. The relationship between the drainage area and slope was determined using Regression method in SPSS version 21. The type of relationship was power. The unit of the drainage area and slope was hectare and meter/meter, respectively. Data were plotted on the logarithmic scale. Negative exponent shows the surface runoff and positive one indicates the dominant role of subsurface runoff as the most important hydrologic process accounting for gully development or/and incision.

## 25.3 Results and Discussion

### 25.3.1 Values of the Measured Parameters for Development Stage

Values of 26 parameters were compared for gullies in 4 provinces, as shown in Table 25.3. Maximum, minimum and average values were compared. Seventy three percent of the studied gullies had a drainage area lower than 1 ha and

**Table 25.3** Comparison of statistical values of 26 parameters measured for upslope of the gully head of 300 gullies in Fars, Markazi, Golestan and Zanjan provinces

Variable	Average	Minimum	Maximum
Drainage area (ha)	115.79	0.01	5138.34
Ground slope (%)	6.45	0.01	38
Basin Perimeter (m)	2374.95	26.1	41,179.0
Basin length (m)	894.99	11.04	15,508.0
Form factor	0.30	0.01	0.86
Compactness coefficient	1.54	0.20	15.48
Elongation ratio	0.50	0	1.11
Circle ratio	0.78	0.06	9.8
Clay (%)	27	0	66
Sand (%)	32	5	75
Silt (%)	39.5	11	72.2
EC (ds/m)	5.36	0.10	68
pH	7.92	5.6	17.2
Na (meq/l)	22.99	0.27	310.46
Ca + Mg (meq/l)	24.98	1.16	344.4
Bulk density (g/cm <sup>3</sup> )	1.31	1.04	1.55
Organic carbon (%)	0.53	0	3.9
Land use	Poor rangeland	Rain-fed farm	Irrigated farm and garden
Top width (m)	4.10	0.3	29.8
Bed width(m)	1.58	0.2	50
Depth (m)	1.80	0.07	15
Top width/depth	3.87	0.27	42.31
Vegetation cover (%)	19.5	0	80
Litter (%)	4.3	0	20
Gravel fragment (%)	17.4	0	81
Bare soil (%)	58.9	2.1	100

16% of them had a drainage area between 1 and 10 ha. Results indicated that 99.3% of the studied gullies had a slope of soil surface lower than 15°.

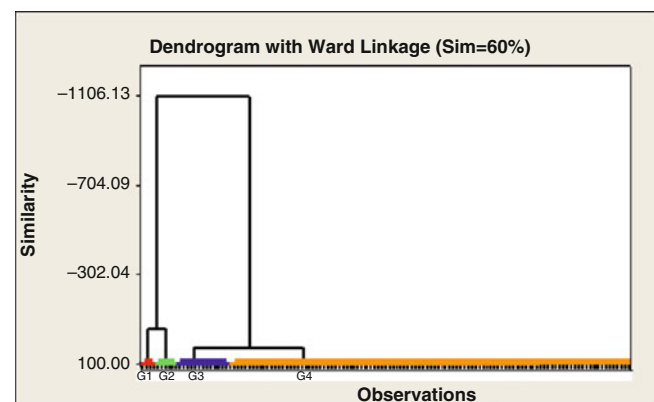
The average data for 300 gullies indicates that gully erosion occurred in basins with overgrazed poor rangelands with 20% vegetation cover versus 58.9% bare soil and 17% gravel fragments on the semi-salt soil with loam texture, and rain-fed farms with low organic carbon (0.5%). Medium size gullies were formed in semi-elongated basins with an average depth of 1.8 m and width/depth ratio of 3.87 (Table 25.3).

### 25.3.2 Relationship Between Drainage Area and Ground Slope with Field Measurement

#### 25.3.2.1 Clustering Gullies into Homogeneous Groups

Clustering was done using 26 parameters for the development stage and 22 parameters for the incision stage, as shown in Table 25.3. Parameters related to gully dimensions were not used for clustering in the incision stage. Four

homogeneous groups of gullies were created in the ward method (Fig. 25.3 and Table 25.4). Groups 1 and 2 included gullies of Fars province. Group 1 (Table 25.4) included 7 gullies with drainage areas between 5138 ha (gully no. 1) and 1907 ha (gully no 20). Group 2 (Table 25.4) included



**Fig. 25.3** Dendrogram of Ward method for categorizing of gullies into four groups in the development stage (G1 = group 1, red line with 96.3% similarity, G2 = group 2, green line with 93% similarity, G3 = group 3, blue line with 91% similarity and, G4 = group 4, yellow line with 90% similarity)

**Table 25.4** Homogeneous groups of gullies using Ward method in the development stage

Gully group	Method	Case	Gully numbers	No. of gully
G1	Field survey	Development	20-11-9-6-4-2-1	7
G2	Field survey	Development	-42-30-29-25-22-21 -15-10-7-5-3	11
G3	Field survey	Development	8-13-14-16-18-19-23- 24-26-27-28-40-45- 61-536-G28	16
G4	Field survey	Development	Fars (117 gullies), Zanjan (total), Markazi (total-G28) and Golestan (total-536)	266

11 gullies with drainage areas between 1318 ha (gully no. 25) and 245 ha (gully no. 5) from Fars province. Group 3 included 16 gullies, 15 gullies from Fars with drainage area between 339 ha (gully no.16) and 59 ha (gully no. 23) and 1 gully from Golestan province. The remainder included 117 gullies of Fars province, total gullies in Zanjan, Golestan (minus 1) and Markazi (minus 1) provinces which had less than 10 ha drainage area.

### 25.3.2.2 Effective Factors for Categorizing Gullies

Adequacy of data was determined for factor analysis using the average value of KMO. For 300 gullies, it was equal 0.6762; therefore, effective factors for categorizing gullies were classified into seven categories based on the values obtained (Table 25.5). Effective factors for the stage of gully incision and for the method of DEM were the same. Data shown in Table 25.5 indicated that the most important group of effective variables belonged to the drainage basin of gully heads (factor 1) including the area, length and perimeter, and particle size was the least effective variable (factors 6 and 7) for categorizing the gullies into homogeneous groups (Table 25.5). Other factors such as soil characteristics and gully dimensions had an intermediate importance (Table 25.5). The same results are shown in Fig. 25.4; as shown, more important variables such as drainage area, length and perimeter of the basin had larger values than other variables (Fig. 25.4, above left); concentrations of

gullies are shown in groups (Fig. 25.4, above right), and the importance of each variable is shown by Eigen (specific) values (Fig. 25.4, below left).

## 25.3.3 Relationship Between Drainage Area and Slope of the Soil Surface for the Gully Head

### 25.3.3.1 Relationship for Total 300 Gullies Without Categorizing

The results indicated that power relationship between the drainage area and slope of the soil surface existed for 300 selected gullies from four provinces of Iran (Table 25.6). Table 25.6 shows that the relationship between the drainage area and slope was significant at 1% level and had negative exponents ( $b$ ) for both development and incision stages for both methods of field surveying and digital elevation model (DEM). Data in Table 25.6 indicate that the field measurement of slope yielded values for exponent ( $b$ ), intercept ( $a$ ) and coefficient of determination bigger than DEM measurement in the development stage. In other words, in development stage, the values of  $b$  and  $a$  for field measurement of the slope, were 0.365 and 0.025 versus 0.326 and 0.017 for DEM (Table 25.6, rows 1 and 2). Negative exponent indicates the reverse relationship between the drainage area and slope of the soil surface and implies that surface runoff is the dominant hydrologic process for gully head development in the four provinces studied. The coefficient of determination ( $R^2$ ) in the gully development with field surveying is equal to 0.564 (Table 25.6, row 1). This means that 75.5% of variation in the slope of the soil surface upslope in the gully heads could be interpreted by the variations in the drainage area. For gully incision, coefficients of the Eq. (25.3) (0.012 in row 3 in Table 25.6) were smaller than those (0.025 and 0.017) for gully development (Eqs. 25.1 and 25.2 in Table 25.6).

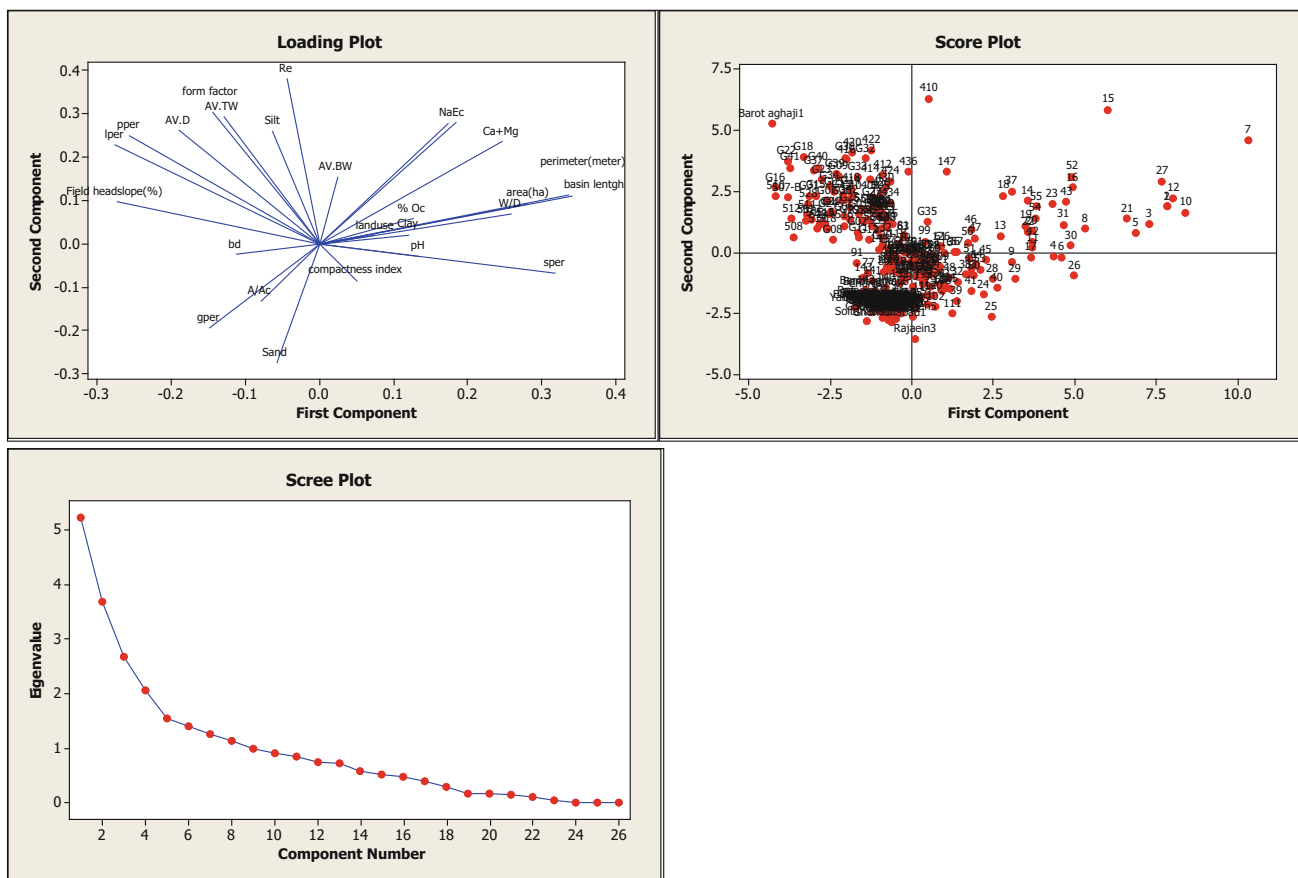
### 25.3.3.2 Relationship Between the Drainage Area and Slope for the Gully Groups Using Cluster and Factor Analysis

For development stage, cluster analysis divided the gullies into four groups (Table 25.4). Relationships for groups 1 and

**Table 25.5** The factors affecting the categorizing of gullies in the development stage

Factor	1	2	3	4	5	6	7
Variable	X1 = basin area X3 = basin perimeter X5 = basin length	X14 = Na X12 = Hydraulic conductivity X15 = Ca + Mg	X19 = Ave. width X21 = Ave. depth	X6 = form factor X7 = Re	X23 = vegetation cover (%) X26 = Bare soil (%)	X11 = silt X10 = sand	X9 = clay
Value	X1 = +0.956 X3 = +0.950 X5 = +0.936	X14 = -0.920 X12 = -0.915 X15 = -0.832	X19 = +0.920 X21 = +0.902	X6 = -0.899 X7 = -0.874	X23 = +0.901 X26 = -0.670	X11 = +0.828 X10 = -0.822	X9 = +0.939





**Fig. 25.4** The loading (above, left) score (above, right) and scree (below, left) plots of effective variables for categorizing gullies in development stage and field survey

**Table 25.6** Comparison of the relationships between the drainage area and slope of the soil surface upslope gully head and point of gully incision in Iran

Eq.	Method	Case	Equations	R <sup>2</sup>	P
25.1	Field survey	Development	Slope(%) = 0.025(Area) <sup>-0.365</sup>	0.564	≤0.000
25.2	DEM	Development	Slope(%) = 0.017(Area) <sup>-0.326</sup>	0.435	≤0.000
25.3	Field survey	Incision	Slope(%) = 0.012(Area) <sup>-0.309</sup>	0.189	≤0.000

2 were not significant, but they were significant for groups 3 and 4 with a significance level of 5% and 1%, respectively (Table 25.7). Group 3 with 16 gullies from Fars (14), Markazi (1) and Golestan (1) had a determination coefficient equal to 0.266. The relationship with  $a = 0.037$  and  $b = -0.502$  implies the dominant impact of surface runoff on the gully development (row 1, Table 25.7). Group 4 with 266 gullies (Table 25.4) had a higher level of significance (1%), but smaller intercept ( $a$ ), exponent ( $b$ ) and determination coefficient ( $r_2$ ) than group 3 (rows 1 and 2 on Table 25.7).

For the incision stage, groups 3 [with 50 gullies from Fars (45), and Golestan (5)] and 4 [with 223 gullies from Fars (81), Zanjan (total), Markazi (total) and Golestan (total-5) provinces] were significant at the level of 5% (rows 3 and

4, Table 25.7). These groups had a smaller intercept ( $a$ ) and exponent ( $b$ ) (rows 3 and 4 in Table 25.7) than group 3 and 4 for gully development (rows 1 and 2 in Table 25.7).

Comparison of slope values between the two methods of measurement (field and DEM) using paired samples  $t$ -test indicated that there was a significant difference between them at 5% level; therefore, the relationship between the drainage area and slope of soil surface was estimated for DEM groups. Cluster analysis divided the gullies into four groups in the case of DEM. Relationships for groups 1, 2 and 3 were not significant, but there was a significant association only for group 4 with a significance level of 1%. Determination coefficient and intercept ( $a$ ) were smaller (row 5 in Table 25.7) than group 4 with field survey (row 2 in

**Table 25.7** Comparison of the relationships between the drainage area and slope of soil surface upslope gully head and point of gully incision for different homogenous groups of gullies in Iran

Group no. and no. of gullies	Method	Case	Equations	$R^2$	$P$
3(16)	Field survey	Development	$S = 0.037(A)^{-0.502}$	0.266	$\leq 0.041$
4(266)	Field survey	Development	$S = 0.031(A)^{-0.263}$	0.243	$\leq 0.000$
3(50)	Field survey	Incision	$S = 0.018(A)^{-0.428}$	0.089	$\leq 0.035$
4(223)	Field survey	Incision	$S = 0.014(A)^{-0.194}$	0.025	$\leq 0.017$
4(266)	Digital elevation model (DEM)	Development	$S = 0.019(A)^{-0.285}$	0.196	$\leq 0.000$

Table 25.7), but its exponent ( $b$ ) was a little bigger than that for field survey (row 5 and 2 in Table 25.7).

### 25.3.3.3 Categorizing Gullies Based on Drainage Area

Torri and Poesen (2014) did not recommend using of gullies with big drainage area because of the occurrence of rainfall in a small portion of basin. Therefore, using larger drainage areas might yield wrong results due to smaller exponent ( $b$ ) than reality for topographic threshold. Based on this theory, the selected gullies were divided into five classes (0.006–0.1, 0.11–0.99, 1–9.99, 10–1000 and > 1000 ha). Results in Table 25.8 indicated that the relationship between the drainage area and slope of soil surface was significant at the significance levels of 1% and 5%, respectively, for gullies at 6 out of 12 class areas. With increasing drainage area, the exponent ( $b$ ) decreased in development and incision stages with field surveying method (Table 25.8, rows 1–4). The results revealed that result reported by Torri and Poesen (2014) was proved for the method of field surveying in gully development and incision stages. It means that with increasing the class area from 1–9.99 ha to 10–1000 ha in the development stage and from 0.1–0.99 ha to >1000 ha in the incision stage, exponent ( $b$ ) decreased from 0.688 to 0.288 and from 1.37 to 0.766, respectively. However, for the method of DEM, the exponent ( $b$ ) did not decrease with increasing drainage area. For example, exponent ( $b$ ) increased from 0.359 to 1.070 with increase of the class area from 0.1–0.99 to 1–9.99 class area (rows 5 and 6 in Table 25.8).

Also, intercept ( $a$ ), determination coefficient and significance level in the development case for both methods of filed survey and DEM decreased in the line of increasing drainage area (Table 25.8, rows 1–2, 5–6), but in the case of incision, the intercept ( $a$ ) increased with increasing drainage area

(Table 25.8, rows 3–4). The first class area (0.1–0.99 ha) had a positive exponent; this means that the subsurface flow acted as the dominant process for gully incision in basins smaller than 1 ha. Results of this research indicated that exponent ( $b$ ) of the significant relationships for the total gullies were between  $-0.309$  and  $-0.365$  (Table 25.6); it was between  $-0.194$  and  $-0.502$  for four gully groups by cluster analysis (Table 25.7) and between  $-0.288$  and  $1.37$  for gullies grouped by the class area. These values are comparable with those presented by Nazari Samani et al. (2005) for southwest of Iran, Hessel and Asch (2003), Cheng et al. (2007) for loess plateau of China, Vandekerckhove et al. (2000) for Portugal and Spain and Vandaele et al. (1996) for loess belt of Belgium and Gutierrez et al. (2009) for SW Spain.

Montgomery and Dietrich (1988) presented  $b = 0.5$  for laminar overland flow and  $0.8$  for turbulent flow, so the values of exponent for the relationships between the drainage area and slope of the soil surface for group 3 in the development and incision stages with field survey were  $0.502$  and  $0.428$  that implies the existence of laminar flow. Some exponents (rows 1, 4 and 5 in Table 25.8) were between  $-0.688$  (row 1, Table 25.8) and  $-1.070$  (row 5, Table 25.8), revealing the turbulent flow. Comparison of intercept ( $a$ ) in Tables 25.6, 25.7 and 25.8 indicated low resistance of the sites to erosion because most cases had an intercept near  $0.03$  that is similar to that for cultivated land in recent studies, such as that of Vandaele et al. (1996).

## 25.4 Conclusion

The results of this research indicated that power relationship existed between the drainage area and slope of the soil surface for 300 selected gullies from four provinces of Iran.

**Table 25.8** Categorization of the gullies based on drainage area for the development case using field measurement of slope

Class area (ha)	Method	Case	Equations	$R^2$	$P$
1–9.99	Field survey	Development	$S = 0.033(A)^{-0.688}$	0.169	$\leq 0.006$
10–1000	Field survey	Development	$S = 0.015(A)^{-0.288}$	0.16	$\leq 0.017$
0.1–0.99	Field survey	Incision	$S = 0.004(A)^{1.37}$	0.209	$\leq 0.000$
>1000	Field survey	Incision	$S = 0.292(A)^{-0.766}$	0.441	$\leq 0.004$
1–9.99	Digital elevation model (DEM)	Development	$S = 0.025(A)^{-1.070}$	0.343	$\leq 0.000$
0.1–0.99	Digital elevation model (DEM)	Development	$S = 0.032(A)^{-0.359}$	0.050	$\leq 0.022$

This sort of relationship existed for different stages of development and incision and different methods of slope measurement. The sign of power in most cases was negative that implies the dominant impact of overland flow for gully erosion. The value of  $b$ ,  $a$  and coefficient of determination decreased with changing the method of slope measurement from field to DEM and from development to incision stage.

The relationship between the drainage area and slope of the soil surface was significant for the basins area 1–9.99 ha and 10–1000 ha in the development stage and 0.1–0.99 ha in the incision stage. Exponent  $b$  was negative for both categories of area in the development stage (1–9.9 ha and 10–1000 ha), but it was positive for basin area 0.1–0.99 ha that shows the impact of the subsurface flow in the incision stage. The results are in the same line with those of the research conducted by Vandaele et al. (1996), Cheng et al. (2007), Hessel and Asch (2003) and Vandekerckhove et al. (2000).

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