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Abstract Gully erosion is one of the most complicated and destructive forms of water erosion. In order to prevent this erosion, the important factors controlling gully heads must be understood. This paper examines gully head advancement in the Hableh Rood Basin, Iran by (1) observing gully head advance between 1957 and 2005 using field studies, aerial photography and GIS analysis and: (2) applying and evaluating widely used experimental models including the, Thompson (Trans ASAE 7(1):54–55, 1964), SCS (I) and SCS (II) models, for estimating migrating headcuts over the study period. The results showed that the highest mean gully advancement (0.26 m year^{-1}) took place during the 1956–1967 period, with most gullies having lower and steady headcut retreat rates between 1967–2000 (0.21 m year^{-1}) and 2000–2005 (0.15 m year^{-1}). This suggests that the majority of gullies in the study area were still in the early stages of formation in the first study period and their formation may be linked to land use or climatic changes pre 1956. Analysis of the correlation between environmental characteristics of the study area and gully advancement indicated that the upslope area of head cuts and soluble mineral content of the soil

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were the two most important factors influencing the spatial and temporal variation of gully longitudinal development. Results of multiple regression revealed that the simple relation including upslope area and soluble minerals can explain 93% of total variance and relatively reflects the effects of runoff and waterfall process for headcut retreat. Application of statistical error analysis to evaluate the four gully advancement models showed that in comparison to other models, the second model of SCS has more reliable results for predicting longitudinal gully advancement in this study area and other similar regions. However, this study indicates that future modelling in the region should consider the role of soil soluble mineral content in predicting gully advancement.

Keywords Gully erosion · Empirical model · Evaluation · Headcut retreat · Environmental factors · Aerial photography

1 Introduction

Soils have inherent characteristics that interact to influence the soils stability and potential to erode. Soil erosion is important in Iran because about 70% of the country is dominated by an arid and semiarid climate where precipitation follow a temporal and spatial variation and increase susceptibility to land degradation. Under these conditions, a lack of sufficient vegetation cover and consequent increased runoff response have caused soil losses of up to 2.5 billion tons per year (Ahmadi 1999). It has also caused major damage through sediment deposition in reservoir dams, water canals, river beds and agricultural land in the country. For instance, estimation of soil erosion via empirical models indicated that soil loss has increased by four times between 1951 and 1999 in the country. This demonstrates the critical nature of this issue in Iran and the necessity for effective management (Ahmadi 1999). Preventing or controlling water erosion needs recognition of where in the landscape erosion is most significant and an understanding of the role of the different forms of water erosion in land degradation and sediment production.

The role of gully erosion in land degradation and sediment yield has been well documented in different parts of the world. For example the volume of the gullies on the Russian Plain is estimated to be about 4×10^9 m^3 (Sidorchuk 1999). In Western Europe the sediment contribution of gully erosion has been measured to be 30% to 80% (Poesen et al. 2003) while in Australia, the contribution of gully erosion to total erosion across the continent is estimated to be approximately 50% (Wasson et al. 1996), 80% in the continent's north west (Wasson et al. 2002) and in southeastern New South Wales is 95% (Krause et al. 2003). Assessments of gully erosion rates and volume in Iran are rare. Ghoddousi (2002) has reported that 25% of sediment in the Sefid Rood basin is related to gully erosion in upland areas and marl geological strata, while gullies also cause increases in the sheet and rill erosion in surrounding and uplands area.

Worldwide research has shown that of the different forms of erosion, gully and bank erosion are the major source of soil loss. Ghoddousi (2002), in his study titled "gully advancement and development in Sarcham area of Zanjan province, Iran" focused on large permanent gullies and found that gully advancement has a direct relation with the amount of soluble materials in the soil, concentration of surface runoff, properties of the soil horizons (such as silt and clay contents as well soluble salts), rainfall intensity and vegetation cover in an extensive area (78,000 ha). He concluded that in large scale, geological formations, soil type and land use are the main factors affecting gully advancement and extension (Ghoddousi 1994, 2002).

Betts and De Rosel (1999), using digital information and applying this on three series of aerial photos for two areas in New Zealand, showed the mean gully advancement within the study area was 0.01 to 0.73 m per year. They stressed that aerial photos have a good capacity for studying gully longitudinal advancement. Felfoar and Boussema (1999) used aerial photos over four time periods between 1952 and 1989 in a watershed covering 1400 (ha) area in Old Mires of Tunisia and related the area of each gully's drainage basin to its rate of advancement. This study found that there were differences in the longitudinal velocity of gully advancement in the studied time periods. Based on simple correlation analysis between gully advancement and environment characteristics, such as area of susceptible soils and annual average precipitation in different regions, they stated that annual average precipitation was the most important factor in gully advancement.

Vandekerckhove et al. (2003) using aerial photos and field control of satellite images calculated gully volume in the south east of Spain and identified aerial photos and satellite imagery as the primary information source for studying gullies in the long-term. Their results show that aerial photos as well as satellite images are advantageous to investigating gully change detection. Other research, conducted by Vandekerckhove et al. (2001) at 46 bank gullies in the southern arid region of Spain indicated an average volumetric retreat rate of 4.0 m^3 $year^{-1}$ and an average linear retreat rate of 0.1 m $year^{-1}$. This research revealed that the present drainage-basin area is the most important topographical parameter explaining annual headcut retreat rates, both in terms of eroded volume and linear retreat.

Although the significance of gully erosion and its role in land degradation is known, most soil erosion models have been developed based on rill and inter rill erosion processes. Therefore, there is a pressing need to develop and evaluate currents models that take into account gully erosion.

Knowledge about gully development has been incorporated into a small number of models that attempt to predict their future behaviour. Karimi (1997) studied the prevention of gully advancement in the Zahan area of the Khorasan province, Iran pointing out that among models presented for gully advancement, such as the SCSI and SCSII (USDA 1966) Beer and Johnson (1963) and Seginer (1966), the SCSII model is the best illustrating model for gully advancement estimation in arid areas. Ghaffari (1998) using remote sensing (RS) and geographic information systems (GIS) analysis techniques evaluated the ability of the EGEE[1] model for predicting gully longitudinal advancement in Charmahal and Bakhtiari with annual precipitation of 500 mm and found a good relationship between the predicted and measured gully head retreat.

Since all models predicting gully development are based on environmental characteristics of the regions in which they were generated, it is necessary to assess their suitability for application on other study areas. Dehnamak is one of the sub catchments of the Hableh Rood basin in Iran (Fig. 1). Because of susceptible

[1] Ephemeral Gully Erosion Estimator.

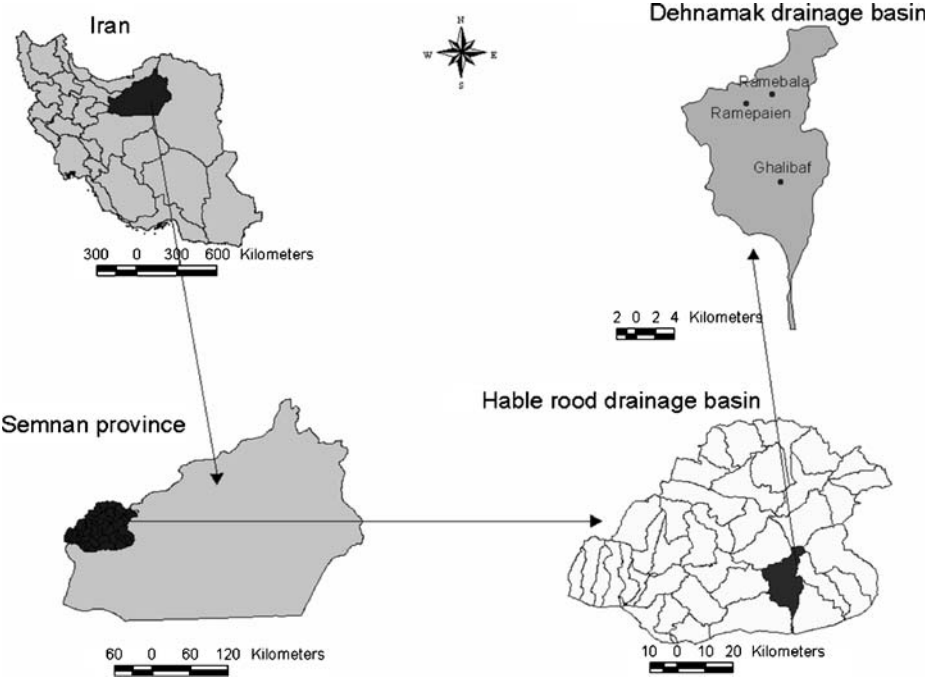


Fig. 1 Geographic position of Dehnamak basin

geological units (marl) and heavy rainfall intensities, accelerated water erosion in this catchment has led to the creation of different types of erosion including sheet and rill erosion while in the foot slopes of the area as well as croplands, gully erosion is distinguishable as the main soil degradation factor. Gullies in this study area have been generated along concentrated water flow paths on susceptible geological formations and their headcut depth vary from 1 m to up to 3.2 m (Fig. 2).

The main aims of this research are (1) examine gully growth rates in the Hableh Rood basin, Iran; to (2) identify the most important factors on gully advancement

Fig. 2 A large valley floor gully in marl formation of Dehnamak basin. The gully retreats to uplands area and causes degradation of arable lands

and (3) evaluate four wide spread experimental models for estimating migrating headcuts over the period between 1967 and 2005.

1.1 Gully Head Development Models

Most analyses of gully growth have empirical basis (Beer and Johnson 1963; Thompson 1964; Seginer 1966; USDA 1966). In the aforementioned models, the interaction between headcut retreat and environmental variables (e.g. precipitation, runoff, size of upstream watershed) is primarily based on statistical models. The second generation of gully erosion models such as EGEM (Woodward 1999) GULTEM (Sidorchuk 1999) and CHILD[2] (Tucker et al. 2001) are based on conceptual as well as physically based processes.

EGEM was especially developed to simulate ephemeral gully erosion, in particular in the USA. EGEM consists of hydrologic and erosion components. Erosion is driven by peak discharge and runoff volume, where peak discharge is assumed to occur as long as there is runoff. Gully depth is assumed to be constant along the length of the gully. It is assumed that the gully will erode vertically downwards until a less erodible layer is reached. The maximum allowed depth is 46 cm (18 in.) because deeper gullies are considered to be 'classical' gullies instead of ephemeral gullies. Nachtergaele et al. (2001) tested the model for Mediterranean conditions and stated that the EGEM is not capable to predicting ephemeral gully erosion for the stony soils in the Mediterranean study areas. They concluded that the theory underlying EGEM was also not based on Mediterranean conditions and might therefore not apply in this case. The climate condition of our study area is to some extent similar to dryland Mediterranean regions.

The CHILD model simulates the evolution of a topographic surface and its subjacent stratigraphy under a set of driving erosion and sedimentation processes and with a prescribed set of initial and boundary conditions. Nine process modules are incorporated in the CHILD model. Although the number of parameters in the model is potentially quite large it is not necessary that all of processes need to be, or even should be, considered in any particular application. The point of including a number of different processes is to allow one to investigate different types of geomorphic systems under different space and time scales, using a common modelling framework that handles the basic spatial and temporal simulation framework.

In this research the measured headcut recruitment were compared to the results of three models including: Thompson, SCSI and SCSII.

1. Thompson model

Thompson (1964) is based on statistical analysis of data collected in seven areas widely scattered in the central part of the United States. It is based on the most important factors affecting the gully erosion to be watershed area, rainfall of intensity higher than 12 mm per day, and clay content of the waterfall profile. His logarithmic model is as follows:

$$R = 0.15A^{0.49}S^{0.14}P^{0.74}E \tag{1}$$

[2]The Channel-Hillslope Integrated Landscape Development Model.

Where:

R, is gully head advancement (ft), A is drainage area above the gully head (Acres), S is slope of approach channel above the gully head (%), P is the summation of rainfall for 24 h that is equal or grater than 0.5 in., in inches; and E: percentage of clay content of soil profile through which the gully head is advancing.

Thompson stated that these variables can explain the 77% of headcut retreat variance.

2. First model of the USDA (SCS I)

Experience of Soil Conservation Service of USDA during 1960s indicated that the prediction of the future rate of gully advancement, based on the historical rate alone, can lead to serious errors of prediction and evaluation unless proper consideration is given to those factors which may have a major influence on the rate of advancement. Condition factors such as the characteristics of the geologic materials, topography, land use, and volume of runoff control the rate of gully advance. A change in conditions above an advancing gully head changes the rate of advancement (USDA 1966). Based on the result of SCS field measurements on 210 gullies in six widely scattered land resource areas east of the Rocky Mountains in the United States the first model of SCS representing headcut retreat was developed:

$$R = 1.5\ A^{0.46} P^{0.2} \tag{2}$$

Where:

R, is rate of headward advancement (ft/year), A is drainage area above headcut (Acres) and P: the summation of 24-h rainfalls of 0.5 in. or greater occurring during the life of the gully, converted to an average annual basis, in inches.

3. Second model of the USDA (SCS II)

Four other factors were added to the SCSI model: (1) changes in erodibility of soil material through which the gully advances, (2) the slope of the approach channel above the headcut, (3) changes in runoff due to changes in land use and practices in watershed and (4) the influence of ground water. Judgment must be used in adjusting for the effect of these factors on the future rate of gully head advance as determined from the procedure given below. With the foregoing knowledge and using the principle of proportions, it is possible to establish an equation for predicting the future rate of headward erosion, if the past rate is known and the future changes in conditions can properly be anticipated (USDA 1966). Therefore the second model to predict headcut retreat was developed by replacing coefficient 1.5 with Rp factor as follows:

$$R = Rp\ (A1/A2)^{0.46}\ (P2/P1)^{0.2} \tag{3}$$

Where:

R, is gully longitudinal growth in the future years (ft/year) Rp: past average annual rate of gully head advance (ft/year), (A1/A2) ratio of the drainage area of a given upstream reach to the drainage area of the reach through which the gully has moved (P2/P1) ratio of the expected long term average annual inches of rain from 24-h

Table 1 Soil characteristics of studied gullies

Soil type	Horizon, cm	Sand%	Clay%	Caco3%	OM%	pH	N%	Ec, ds m^{-1}
Lithic	0–65	48	4	30.4	1.2	7.48	0.069	16.3
xerothents	65–100	42	4	31.9	1	7.45	0.063	13.5
Lithic	0–65	46	3	18.6	1.1	7.68	0.073	16.3
torriothents	65–100	72	2	21.1	0.9	7.59	0.054	14

rainfalls of 0.5 in. or greater (P) to the average annual inches of rain from 24-h rainfalls of 0.5 in. or greater for the period.

It is important to mention that with regards to R_1, this model was used in this study only for periods of 1967 to 2000 and 2000 to 2005 in the study area.

2 Study Area

Dehnamak is one of the sub basins of the Hableh Rood basin, Semnan Province (Fig. 1) located to the north of Dehnamak village situated 52 42′ 36″ to 52 48′ 0″ East longitudinal and 35 15′ 13″ to 35 32′ 33″ north latitude and covers 243.25 km^2 area. Rainfall is low in the region, with precipitation primarily arising from the Mediterranean circulation that influences the area from the west in autumn to spring. However, the watershed occurs in a rain shadow formed by the central Alborz, which dominates the upper limit of the watershed while the southern part of the watershed is adjacent to the Dasht-Kavir desert. Based on analysis of the nearest rain gauging station's data, the mean annual rainfall in this area for a 15 years period is about 273 mm.

Eocene rocks have extended and formed the oldest alluvial deposits in this area. To the east, west and north, old rocks are seen as out crops, but due to the development of Tertiary rocks in the majority of the study area no older sediments can be seen. All gullies in this area occurred in sedimentary and susceptible rocks related to Oligocene–Miocene including marl strata. Four soil types are found in the study area. Lithic Xerothents (USDA and NRCS 1998) dominate the study area (55%) and Lithic Torriorthents (43%) are the second most represented soil type. Based on field sampling and soil analyses all the studied gullies located in Lithic Xerothents soil and the general characteristics of soil horizons in gully area are shown in Table 1. These data clearly indicate very slight variation in soil attributes of studied gully site. The geomorphology of the area includes vegetation-covered pediment with flat areas and mountain-surrounded plains and gullies (with their upland watershed area) cover 48% of the area, indicating the role of gully erosion in land degradation. The main land use consists of cool season rangeland and grass and forbs species form the major vegetation cover.

Table 2 Data related to photograph scales and georefrencing

Date	Photograph scale	Scanning resolution μm	Pixel size after georefrencing	RMSE (pixel)
1956	1:50,000	28	1.4 × 1.4	0.6
1967	1:20,000	56	1.12 × 1.12	0.4
2000	1:40,000	28	1.12 × 1.12	0.5

3 Methods

3.1 Preparation of the Primary Data

The basic data consists of information including meteorological data, maps and existing reports on the study area including:

Topographic maps with a scale of 1:50,000 (National Cartographic Center).
Geologic maps with a scale of 1:100,000 (Geology Survey Organization)
Aerial photos with scale of 1:55,000 (1956), 1:20,000 (1967) and 1:40,000 (2000) from NCC.

The accessible aerial photographs related to 1965, 1967 and 2000 were used to determine head cut retreat. The scale of photographs ranges between 1:20,000 and 1:50,000 (Table 2). According to photo scale and scanning resolution the pixel size of photos ranges between 1.12 × 1.12 m and 1.4 × 1.4 m. Georeferencing of aerial photos was carried out on the basis of collecting Ground Control Points (GCP) from topographic maps and camera calibration. The accuracy of georeferencing was assessed through field checking of the extracted gully location maps. The overall accuracy (Residual Mean Square Error) of georeferenced photos varied from 0.4 (0.4 m) up to 0.6 (0.84 m) pixel size (Table 2). The minimum calculated RMSE is related to 1967 photograph with value of less than 0.4 pixel (1.12 × 1.12 m) while the maximum is equal to 0.6 pixel (1.4 × 1.4 m) of 1956. While the temporal distribution of rainfall is not available for this site, the annual average precipitation was calculated based on the nearest rain gauge (Bonekoh and Rameh) located 35 Km far from the study area.

3.2 Gully Mapping

Sixteen gullies in the area, with densities over 5 km/km^2, were selected for analyses based on interpretation of aerial photos and field surveys (Fig. 3). In order to determine the extent of formations and the spatial location of gullies on the aerial photos, all drainage channels of the selected gullies were delineated by field surveying using a hand held Garmin GPS with spatial accuracy of 4 m and European 1950 datum. Determination of the corresponding location of selected gullies on the aerial photos was conducted using both the georeferenced aerial photos and field data.

The location of headcuts in 1957, 1967 and 2000 was based on visual interpretation of the appropriate aerial photos, while the current position (2005) of headcuts was determined based on field surveying. Finally the gully advancement rates of each headcut, along the flow path, over the study periods were calculated by GIS analysis in ArcView 3.2 (Fig. 3).

Since the accuracy of photograph georeferencing varies from 0.44 to 0.82 m in the studied span of time intervals, the effects of error of estimated headcut retreat over the studied span times can not be significant. For instance: the average of total headcut retreat from 1965–196 (11 years) was estimated at 26.1 m, while the total RMSE of photograph data for the period was about 1.288 m (4.9%).

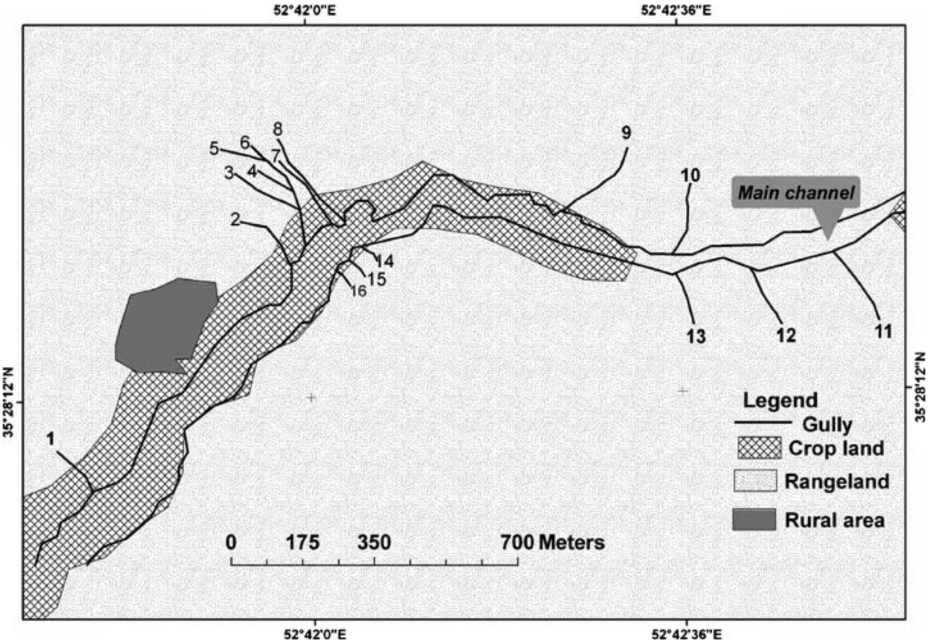


Fig. 3 Map of spatial position of gullies headcut and landuse

3.3 Model Application and Evaluation

As described above, the models applied in this study required data relating to the upslope contributing area, precipitation characteristics and soil textural properties (% clay in the Thompson model only) of a gully head. Upslope contributing area was calculated using the D8 flow direction algorithm in ArcView 3.2 and a 20 m DEM constructed by digitizing 10 m contour lines from the 1:25,000 topographic maps and interpolating using the grid module of Arc/Info 3.5.1. The precipitation values required were obtained from analysis of rainfall data collected at the gauging station nearest the study area and percent clay was acquired by analysis of samples taken from field study.

The gully development models were evaluated by comparing the predicted growth estimates with those measured from the aerial photography, using absolute and relative error:

– Absolute error percentage: Absolute error is the amount of error between model estimation and measured data as a ground truth calculated via dividing estimated rates to measured values,
– Relative Error: Relative error gives an indication of how good a measurement is relative to the size of the thing being measured.

$$\text{Relative error percentage} = \frac{\mathrm{O} - \mathrm{E}}{\mathrm{O}} \times 100 \tag{4}$$

Where:

O measured rate of gully advancement
E estimated rates of gully advancement via models

4 Results and Discussion

4.1 Gully Advancement (Spatial and Temporal Pattern)

The results of the gully longitudinal growth measurements are shown in Table 3 and Fig. 4. Results indicate that during the study period the mean gully head advancement rate was 0.20 m year^{-1}and ranged from 0.10–0.39 m year^{-1} (Fig. 5). In comparison to other results reported in the literature these values indicate a relatively slow gully advancement rate. Ionita (2006) has calculated 0.92 m year^{-1} as a mean advancement of gully heads in the Moldavian Plateau of Romania, while Nachtergaele et al. (2002) reported an average gully retreat rate of 1.8 m year^{-1} for loess-derived soil in Belgium. However, in a similarly arid region Vandekerckhove et al. (2001) reported an annual gully advancement 0.1 m year^{-1} for a short (two year) study. The slower rates reported by others may be due to be linked to their short study period, with our longer term study able to incorporate lower frequency, higher erosive rainfall events responsible for gully erosion during longer terms (Poesen et al. 2003; Vente et al. 2007). However, both studies indicate that arid zone gully advancement rates are slower than those occurring in more humid regions. Hortonian overland flow is the major factor responsible for gully migration in arid regions (Montgomery and Dietrich 1994), thus low precipitation capable of low generating runoff and consequently causes lower gully advancement rates.

Table 3 Measuring of gully head retreat in the three studied periods with using aerial photos (where bolded values are gullies classed as having a more juvenile advancement regime)

Gully number	Gully length (m)	Gully head retreat over period of time (m year^{-1})			
		1956–1967	1967–2000	2000–2005	Mean longitudinal growth
1	41.7	0.23	0.10	0.09	0.14
2	55.3	0.53	0.32	0.30	0.39
3	56.2	0.65	0.26	0.13	0.34
4	31.2	0.13	0.17	0.01	0.11
5	25.0	0.27	0.48	0.25	0.33
6	16.5	0.15	0.34	0.19	0.23
7	62.7	0.29	0.13	0.13	0.19
8	80.9	0.34	0.09	0.02	0.14
9	70.5	0.18	0.13	0.13	0.15
10	57.2	0.39	0.07	0.02	0.16
11	62.7	0.08	0.07	0.03	0.06
12	73.0	0.06	0.07	0.04	0.05
13	40.8	0.37	0.24	0.24	0.28
14	17.7	0.14	0.37	0.37	0.29
15	18.0	0.13	0.37	0.43	0.31
16	16.6	0.19	0.14	0.05	0.13

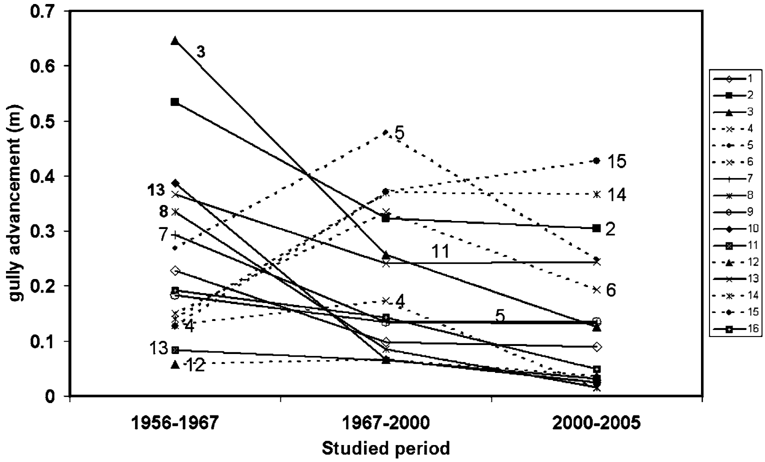
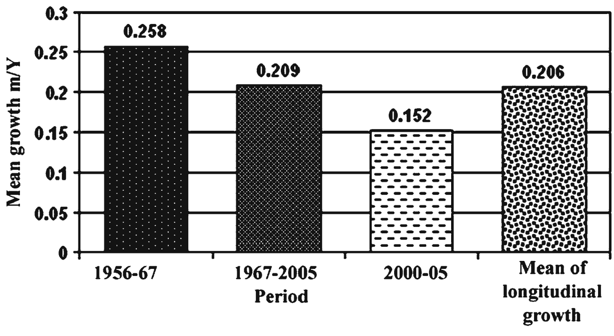


Fig. 4 Gully advancement behavior over the studied periods, *dashed lines* show the six different 'juvenile' gullies in contrast to other gullies. *Solid lines* show the trend of older gullies

The values indicate a fast erosion rate in the first period (1956–1967) and a gradual decreasing in the two other periods (1967–2005). In other words, of the total annual mean gully advancement, 42% resulted between 1957 and 1967. However the results of Fig. 4 indicate that gullies 4, 5, 6, 12, 14 and 15 exhibit a different behaviour over the studied periods, with upward headcut advancement from 1956 to 2000, followed by either a subsequent decrease, steady or slight increase to 2005. It seems that after a rapid start, channel extension by head cut retreat declines over the next period. Some researchers have reported such similar behaviour (e.g., Nachtergaele et al. 2002; Sidorchuck 1999; Schumm et al. 1987, cited in Nachtergaele et al. 2002). The possible major factors responsible for this unequal distribution are decline of contribution catchment area and it will be discussed later in details. Although these gullies are located in the same area, there is no difference between the landuse and geology, as well as soil attributes, of the two groups of gullies. Unfortunately, due to a lack of rainfall gauging station in the catchment it was not possible to completely analyze the precipitation variation over these periods. Also, according to land use maps and field questionnaires with stockholders settled in the watershed there has

Fig. 5 Variation of annual gully advancement in three studied periods



not been a significant change in landuse over the past 20 years. Moreover, to examine climate change, data of the nearest climatologic station (Bonekoh) were analyzed for recognizing trend in annual rainfall records. Figure 1 shows the moving average of annual rainfall, also Kendal's rank- correlation (Patra 2001) test of rainfall data indicated no trend from 1967 to 1992, however, compared to the long-term annual rainfall between 1993 and 1999 annual rainfall declined and again increased between 2000 and 2005 (Fig. 6).

Furthermore, the observed temporal variation of gully advancement is not correlated with annual precipitation. In another word, the annual precipitation for 1967–2000 was 141 mm while at the period 2000–2005 it was 163 mm. It means that in spite of increasing trend of precipitation, the gully development has showed a decreasing trend. Also the studied gullies are in similar climatic condition which suggests that temporal variation in longitudinal advancement of gullies is affected by the stage of development as well as other environmental factors.

The experimental research results of Kosov et al. (cited by Sidorchuk 1999) and Nachtergaele et al. (2002) on gully formation clearly show that there are different stages in gully development. The first stage takes about 5% of gully lifetime which is relatively short, but more that 90, 60 and 35% of a gully's length, area and volume are formed respectively during this period (Sidorchuk 1999). While at the second stage of gully development the gully is near to be stable (Sidorchuk 1999). It seems that as the gully head migrates because of different processes of headcut erosion, the upstream area of the gully head decreases and consequently less runoff will be available at the gully head. This could result in stabilization of the gully head; however side wall erosion processes will continue to contribute sediment yield at the outlet of the gully (Burkard and Kostaschuk 1997).

Based on these studies, the two groups of gullies identified appear to indicate gullies that were in stage 1 between 1956 and 1967 and a second set of gullies that were in stage 1 between 1967–2000 or 2005. It has important implications for soil conservation, with priority given to focusing remedial activities on gullies that are identified as being in stage 1 of their development (gullies:4, 5, 6, 12, 14 and 15).

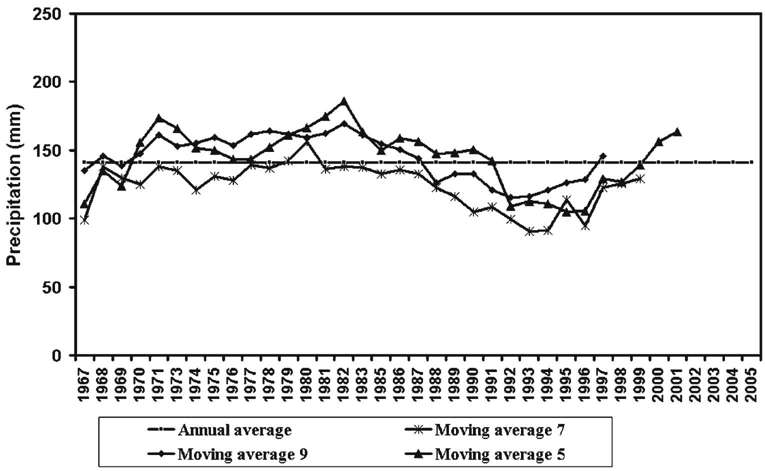


Fig. 6 Moving average of annual precipitation of Bonekoh rain gauge station

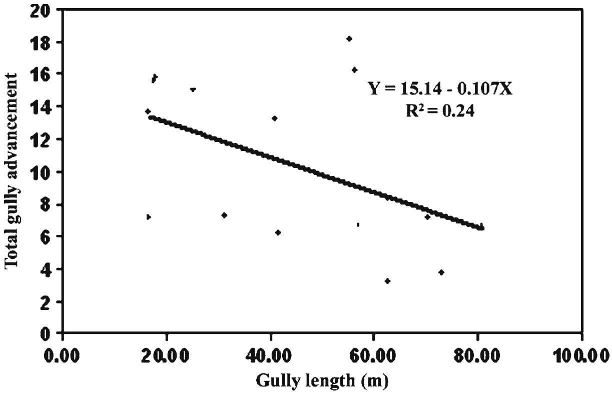


Fig. 7 Relationship between gully growth and length of gully

However, analysis of the relationship between gully length and gully advancement (Fig. 7) indicates that a weak relationship exists ($R^2 = 0.24$, $P < 0.05$) and that gully maturity is more likely to be linked to other environmental factors.

4.2 Influence of Environmental Characteristics on Gully Development

Previous research on gully erosion and their associated environmental characteristics indicate that gullying is a threshold phenomena controlled by a wide range of factors including geology, climate, landuse, soil type, hydrology and topography (Poesen et al. 2003; Valentin et al. 2005). Geology, climate and land use, based on field observations and interviews with local farmers, are constant across the gullies studied here and, as such, we have investigated the relationship of gully growth to soil properties (percentage clay/silt/sand and mineral soluble contents), topography (gully bed slope) and hydrology (up slope contribution area) (Table 4).

The results show no significant correlation between gully longitudinal development and gully bed slope and silt and sand content of the gully head soils (confidence level of 0.95) and only low correlation with clay content ($R^2 = 0.67$, $P < 0.05$). Vandekerckhove et al. (2003) attempted to relate headcut retreat rates in Southeast Spain with environmental characteristics such as soil attributes. Interesting to note

Table 4 Correlation of mean annual gully growth and environmental characteristics

Environmental factors (independent variable)	Type of relationship	Equation[a]	R^2	Significant level
Gully channel slope (%)	Linear	$Y = 4.85Xs - 30.64$	0.8	0.12[ns]
Clay content (%)	Linear	$Y = 4.95X_C - 0.58$	0.67	0.033[a]
Silt content (%)	Linear	$Y = 0.095X_{Si} + 31.17$	0.04	0.38[ns]
Sand content (%)	Linear	$Y = 69.7XSa - 0.62$	0.34	0.41[ns]
Soluble mineral contents (%)	Linear	$Y = 332.65Xmi + 5.97$	0.92	<0.001[b]
Decreasing of upslope contribution area (ha)	Linear	$Y = 0.152Xa + 0.898$	0.98	<0.001[b]

[ns] non significant
[a] In all equation Y is mean annual mean of gully head retreat (m/year)
[b] Significant level 5%
[c] Significant level 1%

is that they found a positive correlation between volumetric retreat rate and clay as well as soil rock fragment content and provided no direct explanations for these correlations by them. It seems that linear retreat rate was not correlated with any soil parameter. Finally they concluded that the 'pure' effect of soil parameters is difficult to detect due to a large number of interactions with other site parameters. This finding is similar to our finding about soil characteristics and head cut retreat. However, the low correlation between the soil physical properties and gully development is in contrast with findings by other researchers, such as Thompson (1964), Oostwoud Wijdenes et al. (2000), Ghoddousi (2002) and Poesen et al. (2003), but is likely to be related to the small variation in lithology, and consequently soil type, across the study area. As it has already mentioned all studied gullies located in the similar soil type derived from marls, and consequently was a small variation in clay content. It should be mentioned that a wider range of soil types and more accurate field work would be necessary in order to find effects of soil properties by other researchers. On the other hand among all physical soil attributes the clay content showed significant correlation with gully head advancement, but in contrast to other factors namely: upslope contribution area and soluble minerals the explained variance (R^2) is lower.

Strong relationships were found between gully growth and soluble minerals content (%) ($P < 0.01$) and the upslope contributing area (ha) of the gully heads (Fig. 8). High soluble mineral contents in the soil profile often causes an increase in the susceptibility to piping and seepage processes by affecting the swelling/shrinking properties and cohesion of soil materials (Gallart et al. 2002). In fact soluble minerals affect on aggregates of the soil material and represent themselves as a erodibility index.

Upslope drainage area, which is directly related to discharge (Leopold et al. 1964), is also well recognized as an important factor in predicting the initiation and location, as well as trajectory of gullies (Cited by Vandaele et al. 1996; Desmet et al. 1999; Vandekerckhove et al. 2000).

Moreover a multiple statistical analysis, enter and stepwise regressions, were performed to select the factors showing the highest relationship with gully advancement. The stepwise regression procedure fit the best relation between dependent and independent variables through avoiding a problem of multicollinearity by means of the variance inflation factors (VIF) of the variables. The parameters for both

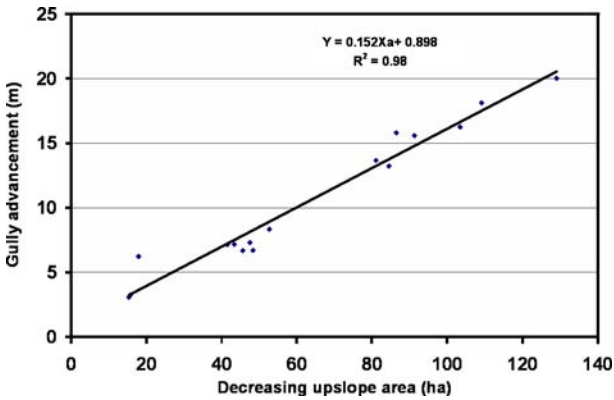


Fig. 8 Relationship between upslope contribution area and gully growth

Table 5 Results of the multiple regression analysis based on enter and stepwise procedure

	B	*P* value	Partial	VIF
Enter method				
($R^2 = 0.95$)				
(Constant)	−179.26	0.267	–	–
soluble minerals	37.10	0.006	0.57	7.61
Upslope area	0.38	0.004	0.79	8.25
Clay	1.74	0.275	0.36	15.61
slop%	0.65	0.105	0.51	1.44
sand%	1.78	0.269	0.36	145.00
Silt%	1.79	0.259	0.37	130.29
Stepwise procedure				
($R^2 = 0.93$)				
(Constant)	5.63	0.051	–	–
Upslope area	0.32	0.000	0.83	2.81
soluble minerals	117.87	0.015	0.61	2.81

R^2 coefficient of determination of the multiple regression, *B* coefficient of regression, *VIF* variance inflation factor

methods are given in Table 5, together with the model R^2, the partial R^2 of the selected prameters, and the *P*-value of the parameter estimates. If all parameters are used as input (enter method), they provide a good reflection of the controlling factors with explained variance, $R^2 = 0.95$, whereas stepwise method is limiting the input to predictive parameters with $R^2 = 0.93$ ($P < 0.05$) and. provides a more simple and useful tool to estimate the future advancement. In addition the VIF indicates that all physical attributes of soil have a high multicollinearity and this is the main reason that none of these parameters input in stepwise model. Hair et al. (1998) stated that the threshold value for high multicollinearity is 10 and as it is shown the VIF for clay, silt and sand content are more than threshold value (Table 5). The slope parameter appeared non significant relation both in simple and multiple regressions. Results indicate that upslope drainage area is represented in all equations, and explains the main proportion (74%) of the total variation while the contribution of the soluble minerals is about 26%. Results of simple as well as multiple regressions remarkably indicate that upslope area is the most significant factors to use for estimating future retreat of gully head as it has been emphasized be previous studies (e.g. Thompson 1964; Seginer 1966; Vandekerckhove et al. 2000) and it relatively reflects the effects of runoff and waterfall process for headcut retreat. Vandekerckhove et al. (2000) have also concluded that the total amount of water reached to the gully during its lifespan, through either surface or sub-surface sources, determines its total eroded volume from gully head expansion.

4.3 Model Application and Evaluation

The results of the model application are summarized and shown in Table 6 and Fig. 9. The Thompson model consistently predicts mean gully advancement values larger than those predicted by the SCS I and SCS II models and the observed mean longitudinal growth. Table 6 shows the absolute error, relative error and the coefficient of variation when the model results are compared with the observed mean longitudinal growth. Of the model tested, SCS II model best fit the gully development in this area (Table 7).

Table 6 Estimation of gully head retreat with using Thompson, SCS I and SCS II models

Gully number	Thompson (m year^{-1})			SCS I (m year^{-1})			SCS II (m year^{-1})	
	1956–1967	1967–2000	2000–2005	1956–1967	1967–2000	2000–2005	1967–2000	2000–2005
1	0.26	0.32	0.23	0.23	0.25	0.13	0.2	0.08
2	0.87	1.05	0.77	0.53	0.25	0.43	0.48	0.29
3	0.40	0.48	0.34	0.31	0.12	0.16	0.27	0.1
4	0.12	0.14	0.10	0.26	0.22	0.02	0.24	0.01
5	0.41	0.49	0.35	0.05	0.12	0.3	0.11	0.2
6	0.34	0.41	0.29	0.57	0.12	0.25	0.51	0.17
7	0.41	0.49	0.36	0.29	0.25	0.18	0.26	0.12
8	0.12	0.14	0.11	0.06	0.122	0.02	0.05	0.01
9	0.41	0.49	0.36	0.18	0.24	0.18	0.16	0.12
10	0.24	0.29	0.21	0.13	0.24	0.03	0.12	0.02
11	0.24	0.28	0.21	0.17	0.23	0.04	0.15	0.03
12	0.24	0.28	0.21	0.14	0.24	0.05	0.13	0.03
13	0.69	0.83	0.61	0.36	0.24	0.32	0.32	0.21
14	0.88	1.07	0.78	0.14	0.25	0.49	0.12	0.33
15	0.75	0.91	0.66	0.13	0.26	0.51	0.12	0.34
16	0.42	0.51	0.37	0.07	0.25	0.06	0.06	0.04
Add up	6.78	8.21	6.00	3.61	3.44	3.19	3.34	2.14
Mean growth	0.42	0.51	0.38	0.23	0.215	0.199	0.208	0.134

In contrast to SCS I the higher accuracy of SCS II model is likely to be attributed to its use of R_p factor instead of coefficient 1.5. In fact with having knowledge about past rate the future rate can properly be estimated. These results are similar to those of Karimi (1997), Ghoddousi (2002) and Mortazaii (2005) who investigated five models of gully erosion advancement in the Zanjanrood basin, northern Iran with similar conditions to our study area. They stated that as dryland regions are dominated by high intensity storms and soils with low infiltration rates and crusted

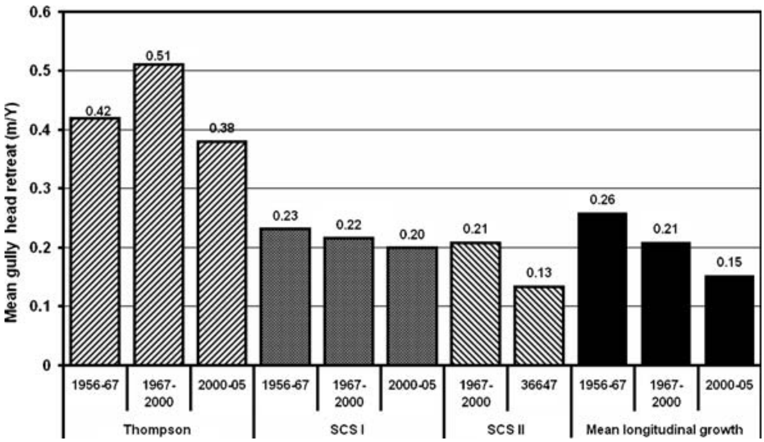


Fig. 9 Results of mean annual advancement of gully head through three different models and measured advancement though aerial photographs over the studied periods

Table 7 Mean amount of relative error percentage and absolute error of studied models

Model	Mean of relative error (%)	Mean of absolute error (%)
Thompson	46.63	213.95
SCS I	5.06	64.09
SCS II	4.61	37.32

surfaces, Hortonian overland flow is the dominant process for runoff generation and that gullying is therefore commonly associated with the concentration of this flow Consequently, catchment area is a suitable index for predicting gully erosion advancement (Ghoddousi 2002; Mortazaii 2005). This is also supported by our analyses of environmental correlates with gully advancement that found decreasing contributing area to be highly correlated with gully advancement rates.

The poor performance of the Thompson model is associated with its inclusion of soil physical properties [clay content of the soil (E)], as well upslope drainage area (A) and the slope of the approached above channel (S). Analysis of environmental correlation (Table 4) indicated the clay content has only a minor relationship with gully advancement in our study area. This, and the relative importance of the E factor with an exponent of 1 (in comparison to A and S with exponent of 0.49 and 0.14 respectively), causes the larger predictions of gully advancement by the Thompson model. Also, Thompson (1964) used a function of different variables in his analysis based on short term observations. Therefore, the coefficient and power of variables in Eq. 1 is subjected to serious uncertainty for long term predictions.

Our analysis of the influence of environmental characteristics on gully development indicated that soluble mineral content is highly correlated with gully advance and as such should be incorporated in future modelling in the region (particularly marl formation).

So far, many studies have attempted to model gully advancement in different environment conditions (i.e: Thompson 1964; Seginer 1966; Radoane et al. 1995; Burkard and Kostaschuk 1997; Vandekerckhove et al. 2001, 2003), however none of them have considered chemical characteristics of soil such as mineral soluble content and dominant process, e.g. hydraulic erosion, landsliding, seepage and piping, responsible for gully advancement at the same time. As previously discussed, it is therefore clear that future modelling in this region needs to consider these important factors and dominant process of gully erosion (or process based modelling) to better predict the rate of gully growth.

5 Conclusion

Gully heads advancement are a real danger for construction and transport facilities, and may result in the loss of agricultural and residential lands. Therfore, understanding the expansion rate of gullies is a useful tool to explain and estimate future gully behaviour for land resource managers. In this research the rate of gully head advancement from 1956 to 2005 was studied in the Hableh Rood basin, Northern Iran, through field measurement, aerial photographs and GIS analysis. Our results indicate that gully advancement rates in the study area are slightly higher than other arid zone studies (0.26 m year^{-1}). Based on gully heads expansion rate they were separated to two groups.The majority of gullies had high rates of expansion between 1956 and 1967, but lower rates between 1967 and 2005, while the second group had higher extension rates between 1967 and 2005 relative to 1956 and 1967. This likely to be linked to the development age of the gully, with high rates of gully advancement often linked to the early stages in gully development and has important implications for the future land management above these gullies. Upslope contribution area and soluble minerals are the key variables to explain the spatial variations in gully advancement rates.

Based on multiple correlation analysis the mentioned two variables can explain 93% of longitudinal advancement of gully head variance while soil texture had no impact on this relationship. Although a simple relation was obtained from regression analysis but it is a useful tool for predicting future gully head advancement.

Modelling of gully advancement in the region using the Thompson, SCS I and SCS II indicated that the second model of SCS is the most suitable model for predicting longitudinal gully advancement in this study area and other similar regions in the north of Iran. However, this study indicates that future modelling in the region should also consider the soluble mineral content of the soil.

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