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PREDICTION OF GULLY EROSION SUSCEPTIBILITIES USING DETAILED TERRAIN ANALYSIS AND MAXIMUM ENTROPY MODELING: A CASE STUDY IN THE MAZAYEJAN PLAIN, SOUTHWEST IRAN

ABSTRACT: ZAKERINEJAD R. & MÄRKER M., *Prediction of gully erosion susceptibilities using detailed terrain analysis and maximum entropy modeling: a case study in the Mazayejan plain, southwest Iran*. (IT ISSN 0391-9838, 2014).

Gully erosion is one of the most severe environmental problems in large areas of Iran. Land degradation and accelerated desertification are the consequence in susceptible areas. Gully erosion normally takes place when surface runoff is concentrated and thus, detach and transfer soil particles down the slopes into the drainage network. In traditional soil erosion studies these processes often have been neglected. In this study we investigate the spatial distribution of gully erosion processes with a quantitative method since in many national assessment approaches just qualitative models were applied. For this study we utilized a detailed terrain analysis and a stochastic modeling approach using mechanical statistics. Moreover we predict the potential spatial distribution of gullies in the Mazayejan plain of Fars province in southwestern Iran where gully erosion is the main environmental threat. Our methodological approach consists in the following steps: i) mapping of gully erosion phenomena in a test area based on Google Earth images; ii) development of a digital elevation model (DEM) with 10 meter resolution, iii) detailed terrain analysis deriving more than 20 terrain indices, iv) application of the Maxent model for the test area using the gully erosion forms as dependent variable and topographic indices as predictor variable and finally v) prediction of the spatial distribution of gully erosion potential for the entire study area. Model performance was evaluated by the Receiver Operating Characteristic (ROC). The results obtained show that the Maxent model perform very well and thus, it is suitable for the prediction of the gully erosion potential in the area. Among the terrain indices utilized in the prediction the most important ones are: convergence index, plan curvature, and slope. The proposed methodology allows conducting a proper gully erosion assessment in order to identify the priority areas for soil conservation and land use management.

KEY WORDS: Gully Erosion, Maxent Model, Terrain Analysis, Iran, Fars, Mazayejan Plain.

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MAXENT: پیشگویی فرسایش خندقی با استفاده آنالیز منطقه ی ومدل
منطقه مورد مطالعه : دشت مزایجان, جنوب غرب ایران

چکیده

فرسایش خندقی یکی از عوامل شدید تخریب محیطی در سطح وسیعی از اراضی ایران می باشد. تخریب اراضی و بیابان زایی از عوامل شدید تهدید کننده در این نواحی حساس محسوب می گردند. فرسایش خندقی زمانی که رواناب به صورت متمرکز موجب کنده شدن ذرات خاک و انتقال آنها به رودخانه می شود. در مطالعات صورت گرفته این نوع فرسایش کمتر مورد مطالعه قرار می گرفت. در این تحقیق به ارزیابی توزیع مکانی فرسایش خندقی با استفاده از مدل های کمی می پردازیم زیرا که در بسیاری از تحقیقات صورت گرفته تنها از مدل های کیفی بهر جسته شده است. در این مطالعه با استفاده از آنالیز منطقه ای و مدل های آماری به پیشگویی پتانسیل فرسایش خندقی در منطقه مزایجان شهرستان زرین دشت در استان فارس می پردازیم. اهداف این تحقیق شامل: 1- ترسیم نقشه ی مناطق فرسایش خندقی با استفاده از تصاویر گوگل ارث 2- تهیه نقشه رستری ارتفاع با دقت 2 متر 3-آنالیز منطقه ای با 20 شاخص توپوگرافی مستخرج از نقشه ی رستری ارتفاع 4-استفاده از مدل مکسنت که نقاط فرسایش خندقی به عنوان پارامتر مستقل و شاخص های توپوگرافی به عنوان عوامل پارامترهای وابسته جهت پیشگویی مناطق دارای پتانسیل خندقی استفاده گردید. ارزیابی مدل با استفاده از اندکس منحنی مشخصه عملکرد سیستم (ROC) صورت گرفت. نتایج این پژوهش نشان داد که مدل مکسنت به خوبی مناطق دارای پتانسیل خندقی را پیشگویی می نماید. از میان پارامترهای توپوگرافی به عنوان پارامترهای مستقل شاخص های اندکس همگرایی، شاخص انحنا و شیب می باشند. با استفاده از نتایج این تحقیق می توان اقدامات مدیریتی مناسب جهت جلوگیری از فرسایش خاک را در مناطق دارای حساسیت بالا انجام داد.

کلمات کلیدی:فرسایش خندقی، مدل مکسنت، آنالیز منطقه ای،دشت مزایجان.

INTRODUCTION

Gully erosion has been defined as a steep-side channel caused by erosion due to the intermittent flow of water and often recurs in narrow channels and removes the soil from this narrow area to considerable depths (Poesen, 1996; Poesen & *alii*, 2003). It is a serious problem in many parts of the world because of specific climatic, lithologic, soil, land use and land cover conditions that favor gully erosion processes (Torkashvand, 2008). Gully erosion take place when excessive surface run off flows with high velocity and thus, detach and transfer soil particles down slope

(Ehiorobo & Audu, 2012). Hence, gullying is an important type of water driven erosion processes that cause land degradation and instabilities in natural and agricultural landscapes (Nekooeimehr & Emami, 2007). Moreover, gully erosion has also a great impact on the drainage dynamics of soils and, hence, influence soil moisture conditions and ground water dynamics, especially in arid and semi arid regions (Avni, 2005; Nyssen & *alii*, 2004). Several studies on gully erosion in Southern Iran show that this phenomenon and the related processes are leading to accelerated desertification in the susceptible areas (Isaie & Soufi, 2007; Soufi, 2008; Sadeghi & Noormohamadi, 2011; Shahrivar & *alii*, 2012).

This study was carried out in the Fars province in Southwestern Iran (fig. 1). Gully erosion is very frequent and is threatening large areas and seriously damage agricultural land. However due to onsite damages such as soil loss, decreasing soil fertility and water holding capacity and off site damages like siltation of reservoirs, gully erosion has attracted more and more attention in the recent years in Iran (Soliemanpour & *alii*, 2010).

Gully erosion is generally considered as an indicator for desertification (Shruthi & *alii*, 2011), therefore this phenomena is often used by different qualitative desertification assessment methodologies as indicator for water erosion (FAO-UNEP,1984; Nikegbal & Farajzadeh, 2007; Sepehr & *alii*, 2007; Khosravi, 2005; Fozoni, 2007). Approaches like the Iranian Model of Desertification Potential Assessment (IMDPA) (Ahmadi, 2004) have been applied in many studies in the Southern parts of Iran. IMDPA considers nine criteria to assess desertification, namely: climate, geology, geomorphology, soil, vegetation cover, agriculture, water, erosion (including wind and water erosion), socio-economics, and technology of urban development. Proxies for these criteria are normally used to identify areas with a higher degree of degradation susceptibility or hazard and thus of a certain desertification status that is described relatively e.g. in four classes: slight, moderate, severe, and very severe. However, these qualitative models often rely on expert knowledge and subjective decisions in the scoring procedure. Moreover the qualitative assessment methods are only rarely based on detailed spatially distributed information.

This is the reason why gully erosion phenomena often have been neglected because of the spatial and temporal heterogeneity of the related processes and the difficulties to measure and monitor the processes quantitatively, especially in remote areas (Gomez & *alii*, 2003; Sidorchuk & *alii*, 2003; Poesen & *alii*, 1996; Märker, 2001; Vázquez Selem & Zinck 1994). Consequently, the prediction of gully development using numerical models is difficult, time consuming and expensive since the different input parameters involved in the prediction are not so easy to determine (Ehiorobo & Audu, 2012). However, soil erosion assessment in Iran is mainly based on empirical prediction models and hence, more research is required to understand the role and spatio-temporal distribution of gully erosion in Iran (Nazari Samani & *alii*, 2010; Bayramün & *alii*, 2003).

Even though recently several studies have already been carried out on the morpho-genesis of gully erosion (Shahrivar & *alii*, 2012; Soliemanpour & *alii*, 2010**;** Soufi, 2004; Nazari Samani & *alii*, 2009) few studies exist that assess the spatial distribution of gully erosion on larger areas considering the relevant environmental driving factors. Albeit, digital elevation models and terrain analysis were already applied in Erosion Risk Assessments (see Pallaris, 2009, Suriyaprasit, 2008) there are only very few studies combining stochastic models and terrain analysis (e.g. Kheir & *alii*, 2007; Angileri, 2012; Hughes & Prosser, 2012, Conforti & *alii*, 2010, Gutiérrez & *alii*, 2009a, 2009b).

Therefore, this study in the Mazayejan plain of Southern Iran aims at investigating the distribution of gully erosion with a quantitative method based on terrain analysis and mechanical statistics. Moreover, we want to identify the most important environmental indices triggering gully erosion in the study area and finally derive a map of the spatial distribution of gully erosion susceptibility.

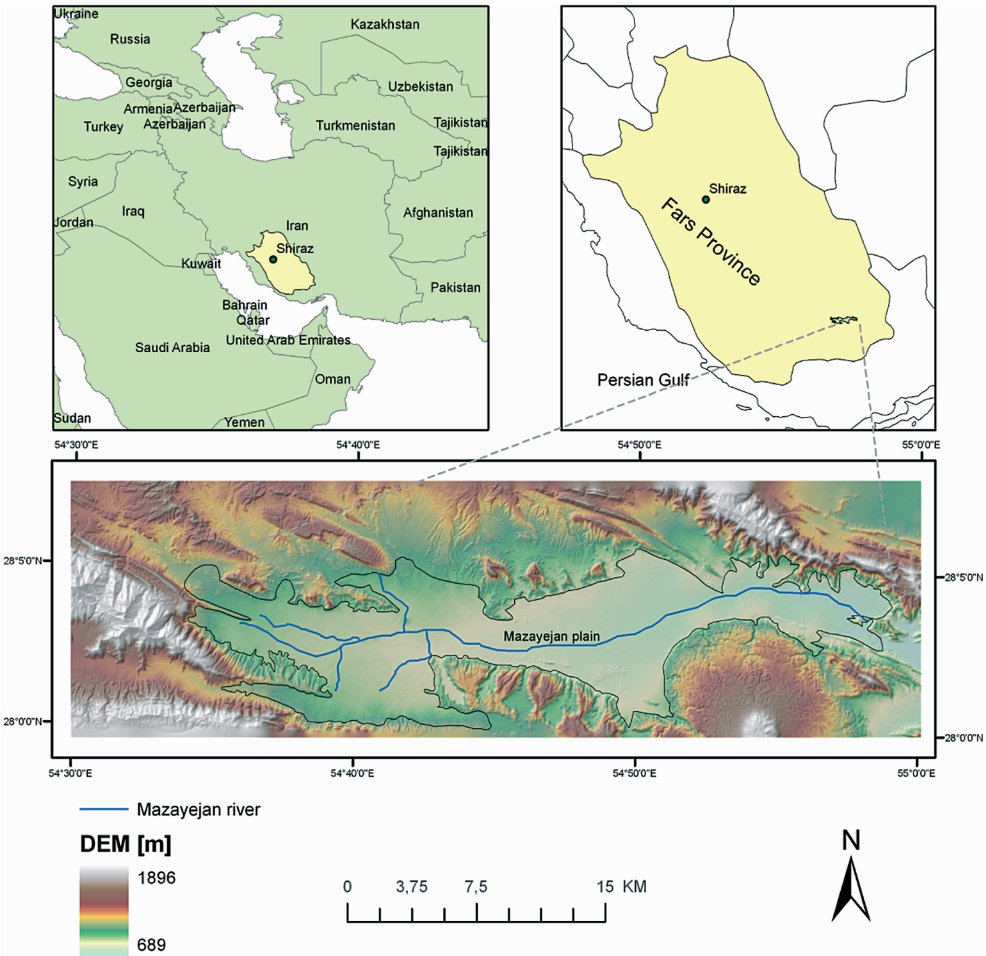
STUDY AREA

The study area is located in the Fars province, southwest of Iran, (54° 34' to 54° 44' E and 27° 59' to 28° 5' N) (fig. 1). The area covers ca. 20.000 ha and is drained by the Mazayejan river. According to the national topography map (1:25.000; Iranian Cartographic Center,1994) the elevation is ranging from 693 m a.s.l. to a maximum altitude of 1.371 m a.s.l.. The annual average rainfall is around 243 mm with a high inter-annual variability characterized by very dry summer months (June to September) followed by short period of heavy rainfall from December till March which often provokes severe erosion and flooding events (Iranian Natural Resources Centre, 2006). The 30-min precipitation intensity for a 2 year return period amounts to 23.5 mm h^{-1}. The 25 years return period is about 56.1 mm h^{-1}. Particularly gully erosion processes and forms are very common in the area. In this arid environment, the hottest month is August and the coldest is February, with mean monthly maximum and minimum temperatures of 31 °C and 18 °C, respectively. The above cited climate data was calculated using the following meteorological stations (tab. 1). The precipitation data was spatialized using an elevation based co-kriging (Rossiter, 2012)

TABLE 1 - Calculated R factor values of selected meteorological stations

Station	Longitude	Latitude	Elevation	Meanannual rainfall (mm)
Darb ghale	54 23	28 55	1430	344
Ghozan	54 27	28 49	1300	347.6
Hajiabad	54 25	28 22	1060	248.3
Brak	53 09	28 39	870	354
Farag	55 12	28 22	890	213.5
Khasoe	54 23	28 33	1070	241.5
Layzgan	54 58	28 41	2000	492.9

FIG. 1 - Study area: Mazayejan Plain in Fars province Southwestern Iran.



The Mazayejan plain has a variety of different landscapes due to its diversity in morphology, soils, geology and vegetation characteristics. The substrates and sediments are of quaternary origin and underwent climatic changes. The area is dominated by pediments and field observations showed gullies that are especially located in areas with fluvio-aeolian Quaternary deposits. Approximately 5% of the study area has slopes exceeding 20% and 60% of the area has slopes with less that 2% inclination. The average elevation of the area is 733 m a.s.l..

The Mazayejan alluvial plain is characterized by Aghajari marls, Bakhtiyari conglomerates, Mishan carbonates, siliciclastic facies deposited in a carbonatic rimmed shelf and Gachsaran Anhydrite, Marl, and Salt formations (Lasemi & *alii*, 2001; Hasbekarji, 2006). The chemical properties in these deposits are very sensitive to water erosion and are also affecting the quality of ground water. Generally, the groundwater is of bad quality with high chloride and sodium contents. The area is drained by the Mazayejan River which is an ephemeral drainage system flowing towards the East. According to Soil Taxonomy the soils of the study area are mainly Aridisols and Entisols. Soils are generally poorly developed. Due to water shortage and arid climate the main land use is pasture, rain fed cultivations and irrigated agriculture. Main crops produced are winter wheat, cotton and barley. Animal husbandry often leads to overgrazing and consequently, to the destruction of the vegetation cover favoring rill-interrill and gully erosion phenomena. Large part of the population is working in the agricultural sector.

MATERIAL AND METHODS

Gully erosion involves a complex set of factors, causing a variety of damages to the environment and destroys the soil cover. It is closely related to many environmental factors but especially to topographic characteristics and features especially when substrates and climate are very homogeneous. We extracted these topographic characteristics from a digital elevation model (DEM) with 10 m resolution. This DEM is based on an interpolation of contour lines of a 1:25000 topographic map (Iranian Cartographic Center, 1994) using a thin plate spline algorithm proposed by Hutchinson (1991). The DEM was preprocessed with low pass filtering to extract artefacts and errors like local noise and terraces (Märker & Hedary Guran 2009; Vorpahl & *alii*, 2012) using ARCGIS 9.3 (ESRI, 2010). Subsequently, the DEM was hydrologically corrected eliminating sinks using the algorithm proposed by Planchon and Darboux (2001).

Digital terrain analysis is a process to quantitatively describe the terrain using a DEM. We can differentiate between morphometric parameter describing i) the morphology of the surface, ii) hydrological parameters to describe runoff generation and potential flow pattern, iii) transport and deposition of sediments and iv) climatic parameters (Hengl & *alii*, 2003). A DEM consists of a spatially registered set of elevation points that collectively describe a topographic surface (Montgomery & Dietrich, 1994). This in turn has an important role for the runoff and the concentration of water on the soil surface. We performed a detailed Terrain Analysis on the DEM using SAGA2.0.3 (System for Automated Geo-scientific Analyses, Conrad, 2006). For the further stochastic analysis we selected especially those topographic indices that describe the erosive power of runoff, flow velocity and transport capacity and thus, have an important effect on erosion and especially on gully erosion.

STOCHASTIC MODELING OF GULLY EROSION

In this study we applied the Maximum entropy distribution or Maxent Model (Phillips & *alii*, 2006). Maxent is a type of machine based learning algorithm based on mechanical statistics. Here we use version 3.3.3k (http://www.cs.princeton.edu/~schapire/maxent/) to assess the environmental relations responsible for the spatial distribution of gully erosion features. The model requires presence only data and a set of environmental variables that are spatially continuously distributed. In this case the probability distribution of gullies is estimated using the presence of gully features and environmental predictor variables (continuous or categorical) that are delineated form the DEM (Kumar & Stohlgren, 2009). The advantage of the use of presence-only information lays in the fact that the absence of a feature or species at a certain location is difficult to proof or may not be evident (Phillips & *alii*, 2004; Elith & *alii*, 2006; Phillips & *alii*, 2006; Howard, 2012). In this study we used mapped gullies to train the model and to decipher susceptible areas for gully erosion. The model assigns an a priori probability in absence of problem specific information (Phillips & *alii*, 2006). Maxent calculates the spatial distribution of probabilities for a specific process, in this case gullies. Probabilities are ranging between 0 which means no susceptibility or probability for gullying and 1 standing for a very high susceptibility or probability for the occurrence of a gully. The model was trained and tested using a sample of 65.536 points showing gully erosion phenomena. Here we use 90% (N_{train} = 58982) of the data to train the model and 10% of the data to test the model (N_{test} = 6554).

MAPPING SPATIAL DISTRIBUTION OF GULLY FEATURES

In order to train the Maxent model we mapped the gully systems in our study area. In the past gullies have been mapped through conventional field surveying, which is expensive for large areas and time consuming (Johansen & *alii*, 2012). For this study we utilized a satellite image from Google Earth (GE). GE provides free access to very high resolution satellite images (Potere, 2008; Angileri, 2012). In this case the GE images available for the Mazayejan plain are based on Spot images with a 2.5 meter resolution. The availability of very high resolution satellite imagery is providing new solutions for a quick appraisal of gully networks over large areas (McInnes & *alii*, 2011). Shruthi & *alii* (2011) showed that object-oriented image analysis based gully mapping is quicker and more objective than traditional methods. Thus, satellite image with high resolution are required to cover vast areas for the assessment of gully erosion. Due to the fact that the study area is characterized by an arid climate with poor vegetation cover it is unproblematic to distinguish and map gully features and forms based on GE satellite images with high accuracy. In contrast, McInnes & *alii* (2011) describe the limits of the methodology especially in forested catchments in combination with small gully systems.

Based on our knowledge of the study area and using the images provided by GE we identified and mapped gullies as polygons which are later on transformed into points. Although it is sometimes difficult to distinguish gullies from streams due to the common ephemeral character of the drainage system we followed the general definition of gullies that are related to streams or drainage lines of third or greater order (McInnes, 2011; Peasley & Taylor, 2009). With regard to this definition of gullies we utilized a stream network layer of the basin to facilitate the identification and mapping of gullies and to distinguish between gullies and streams. We mapped several areas distributed randomly over the whole basin to cover the entire heterogeneity of environmental situations present within the basin. In the next step we converted this layer from GE-KML format to a shape file format (see fig. 2).

ENVIRONMENT LAYERS

For this study we derived a set of 12 topographic indices (tab. 2) that included: elevation, slope, aspect, analytical hill

TABLE 2 - Topographic Indices used as environmental predictors in the Maxent model

Topographic indices	Method
Watershed sub bins	Olaya & Conrad, 2008
Wetness index	Olaya & Conrad, 2008
Stream power	Olaya &Conrad, 2008
Slope	Zevenbergen & Thorn,1987
LS-factor	Olaya & Conrad, 2008
Profile curvature	Olaya & Conrad, 2008
Plan curvature	Zevenbergen & Thorn,1987
Catchment area	Olaya & Conrad, 2008
Curvature classification	Dikau,1988
Curvature	Zevenbergen & Thorn,1987
Convergence index	Köthe & Lehmeir, 1993
Channel network base level	Olaya & Conrad, 2008
Channel network	Olaya & Conrad, 2008
Aspect	Zevenbergen & Thorn,1987
Altitude above channel network	Olaya & Conrad, 2008
Elevation	Preprocessed in ArcGIS9.2

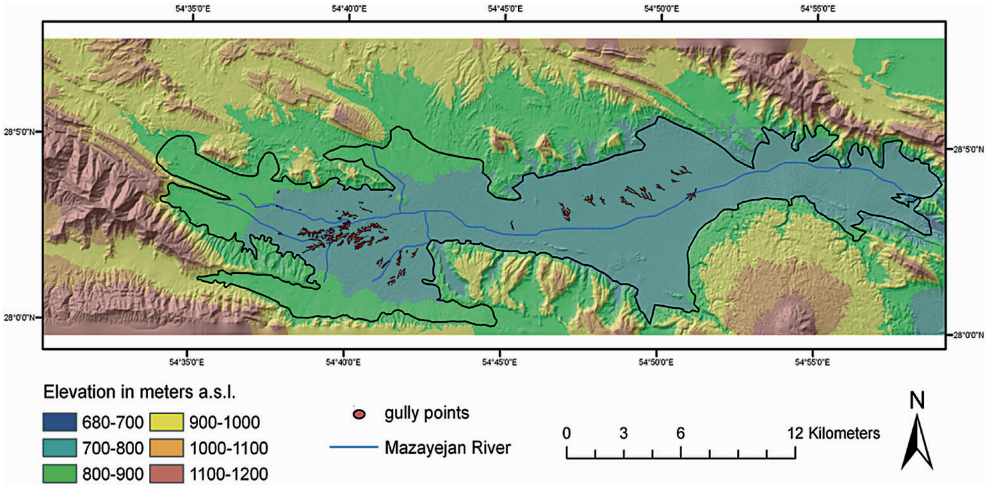


FIG. 2 - Mapped gully locations of Mazayejan plain using Google Earth images.

shading, plan- and profile curvature, curvature classification, convergence index, altitude above channel network, catchment area, stream power index, length-slope factor (LS-factor), topographic wetness index. These indices were used to predict gully erosion by means of the Maxent method. Tab. 2 shows these indices and the respective method applied for their delineation from the DEM. We used SAGA 2.0.3 software to derive the topographic indices at a 10 m resolution. The layers were post-processed and transformed into ascii raster data with the same spatial reference (WGS84, Zone 40) and resolution (10 m). Tab. 3 reports the statistics of the single environmental layers.

MODEL VALIDATION

To evaluate the performance of the model and its predictions we divided the data randomly into a training- and a test subset, thus creating quasi-independent data for model testing (Fielding & Bell, 1997). In this study the Maxent model was applied to a 10% random test dataset (N_{test} = 6554) selected from the entire data set of gully points (N_{tot} = 65.536). Model results were evaluated using the receiver operating characteristic (ROC) curve for training and test data. In an ROC curve the true positive rate (sensitivity) is plotted over the false positive rate (1-specificity) for all possible cut-off points (Sweets, 1988). Each point on the ROC plot represents a sensitivity/ specificity pair corresponding to a particular decision threshold. A perfect discrimination between positives and negatives has an ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity), so that the area under curve, AUC, is 1 (cf. Märker & *alii*, 2012). Therefore, the closer the ROC plot to the upper left corner, the higher the overall accuracy of the test. According to Hosmer and Lemeshow (2000), AUC values exceeding 0.7/0.8/0.9 indicate acceptable/excellent/outstanding predictions.

RESULTS

Spatial distribution of mapped gullies

According to the digitized gully distribution mapped using GE and own field observations the gullies normally form in rangeland and agriculture areas, with U shaped cross sections and a digitate form. The average gully depth at 50% of its length is 1,5 m and the top width is 9,6 m. The medium heights of the head cuts are around 0.80 m (Soufi, 2004). Moreover the clay content in top soil (up to 20 cm) is higher than in the sub-subsoil layer in the gullied area indicating high surface run off potential and thus intense erosion processes (Soufi; 2004).

As illustrated in fig. 2 the gully density is generally higher in the southwest of the study area because of the very low vegetation cover and silty loam to loamy soil surface texture.

The EC and SAR of this area is very high indicating high Sodium contents that amplifies gully erosion and the degradation of rangeland (Shahrivar & *alii*, 2012; Masoudi & Zakerinejad 2010, Faulkner & *alii*, 2003). Moreover, there are several problems related to socioeconomic impacts such as i) overgrazing, ii) land use changes from rangeland to dry land, and iii) overexploitation of ground water for irrigation that promote and favor gully formation.

MODEL PERFORMANCE

The Maxent model was trained using 90% of the mapped point type gully data (N_{train} = 58982) as target or dependent variable and the raster type environmental layers derived from the DEM as independent variable. The resulting model is then validated using the randomly selected 10% of mapped gully data (N_{test} = 6554). Figure 3 shows the ROC graph and integral (area under curve, AUC) for training data with AUC values of 0.95. The validation test data yield AUC values of 0.941. According to Hosmer & Lemeshow (2000) these values indicate an out-

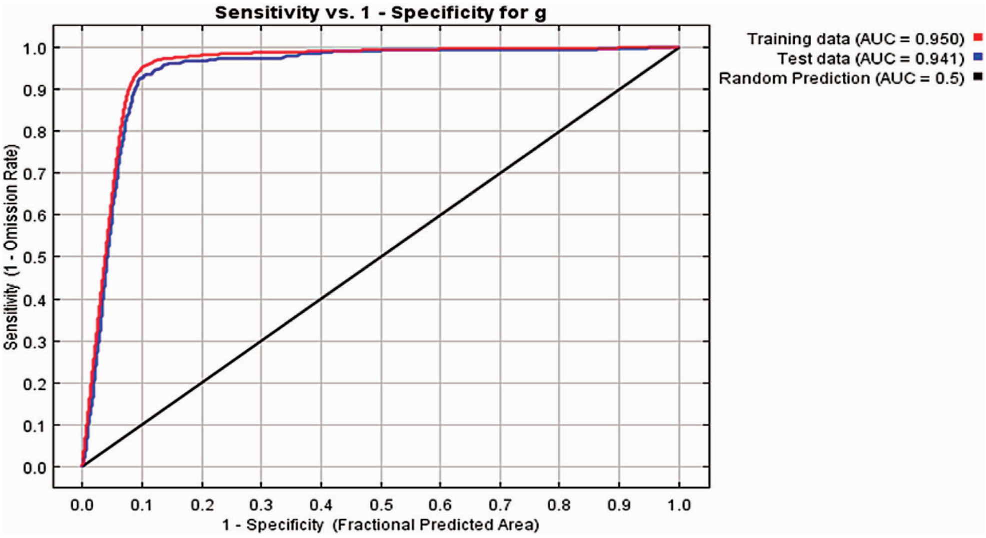


FIG. 3 - The Receiver-Operating Characteristic (ROC) Curve and related AUC values (red = training data set; blue = test data set).

standing performance for both train and test dataset. Hence, the models can be considered as highly robust in terms of sensitivity and specificity.

VARIABLE IMPORTANCE

According to the model performance we can point out the relevance of the topography for the modeled gully susceptibility. Stochastic approaches like statistical mechanics provide a powerful tool to study the relations between gully location and environmental characteristics that in this case consist exclusively of topographic indices.

As shown by various authors (see Vandekerckhove *et a,* 2001; Nazari Samani & *alii*, 2010; Kheir & *alii*, 2007; Flügel & *alii*, 2003; Märker & *alii*, 2012) in areas with comparatively homogeneous substrates, soils and land use, the spatial distribution of gully areas is mainly depending on topographic constraints expressed here as topographic indices. Among these topographic indices especially curvatures, slope and catchment area show a high variable importance. The entire distribution of variable importance is reported in fig. 4.

Relative values are scaled to the most important one. These variables have specific value ranges illustrated in tab. 3. The most important index is the convergence index calculated following Köthe & Lehmeir (1993) with 38.7%. The convergence index is a proxy for the accumulation or distribution of water, thus, for concentrated and turbulent runoff and hence for erosion and sediment transport (Vigiak & *alii*, 2009). The second important index is plan curvature with 36.4% contribution. It was calculated using the algorithm of Zevenbergen & Thorn (1987). Especially in plain type landforms with low slope gradients the plan curvature, like the convergence index, indicates the accumulation or distribution of surface runoff (e.g. Angileri, 2012; Capra & Scicolone, 2002). Finally, slope and aspect with 7% and 4.6% respectively were the most important indices after convergence and plan curvature index. Generally slope determines the velocity of runoff and thus is directly linked to soil erosion. The aspect gives important information on microclimate and on evaporation and soil

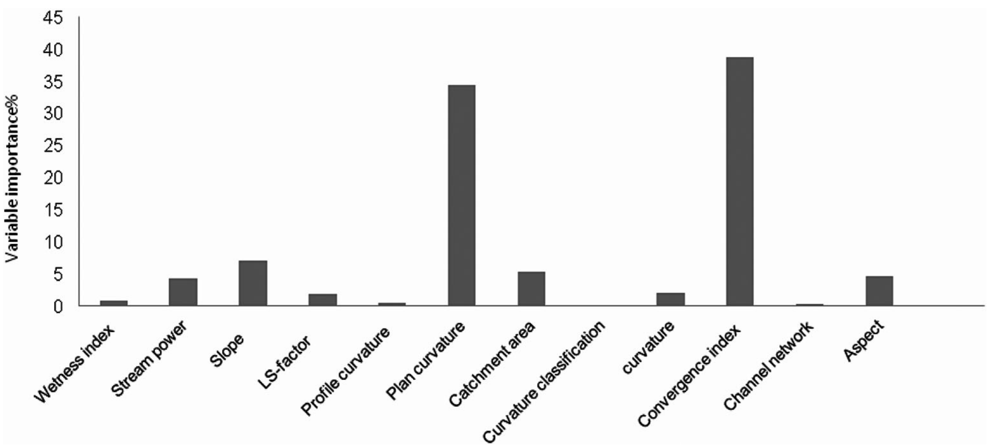


FIG. 4 - Variable importance for the environment layers.

TABLE 3 - value range and standard deviation for topographic indices in the study area

Topographic indices	Interval	Std. dev.
Watershed sub bins	1/8039	2269.40
Wetness index	5.44/14.68	2.57
Stream power	0.1/132255.12	64965.53
Slope	0/31.42	4.2
LS-factor	0/79.84	29.16
Profile curvature	-0.0068/0.0063	0
Plan curvature	-0.00621/0.00681	0.001
Catchment area	100/19699814	9691480
Curvature classification	0/8	
Curvature	-0.0105/0.0105	0.01
Convergence index	-27.29/27.277	13.44
Channel network base level	689.98/118.94	144.65
Channel network	-1/694	322.19
Aspect	0/360	102.38
Altitude above channel network	0/91.65	31.21

moisture (Wilson & Gallant, 2000). Also very important is the catchment area (5.4%) characterizing the discharge volumes (Hengl & Reuter, 2009).

SPATIAL PREDICTION

Figure 5 illustrates the spatial distribution of gully susceptibility. During a field stage in March 2012 the map was validated in the field showing very high correspondence between observed and modeled gully areas (fig. 6). The model was subsequently applied to the whole data set in order to predict the gully locations for the entire study area. We classified the resulting map of gully erosion probabilities in four susceptibility classes: i) no gully erosion (0-10% probability; 99.79% of area); ii) slight gully erosion (10-15% probability; 0.96% of area), iii) moderate gully erosion (15-30% probability; 0.21% of area) and iv) high gully erosion probability (30-100%; 0.033% of area). If we relate the susceptibilities only to the gullied areas we have 79.95% with slight gully susceptibility, 17.74% with moderate gully susceptibility, and 2.8% of the gullied area is belonging to the high gully susceptibility class. As the map of predicted gully erosion susceptibilities shows (fig. 5) the south and south west of the Mazayejan plain is generally more sensitive to gully erosion. This area is characterized by less vegetation cover and thus more or higher run off than in the other areas.

DISCUSSION & CONCLUSIONS

Gully erosion is an important sediment source (Poesen & *alii*, 1996) and is causing serious land degradation (Valentin & *alii*, 2005). Thus, gully erosion is a major hazard especially for agricultural areas in the South of Farce province. Consequently, the knowledge of the spatial distribution of gully susceptibilities is a valuable and useful prerequisite to identify hazardous areas and to develop effective measures to cope with and eventually prevent soil loss due to gully erosion processes. In this study we show that terrain analysis and stochastic modelling are powerful tools for the spatial prediction of gully erosion susceptibilities. The topographic indices derived from high resolution DEM allow to characterize the topographic constraints for the development of gully erosion. Different authors showed

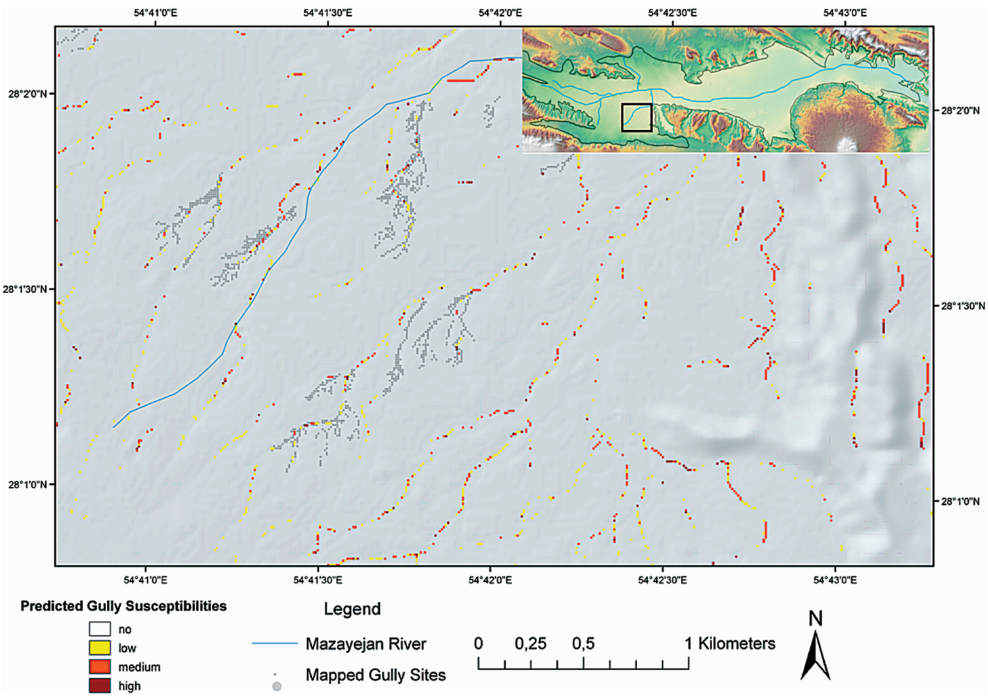


FIG. 5 - Predicted gully erosion susceptibilities in Mazayejan plain.

FIG. 6 - Photo of Gully head cut sections in Southwest of Mazayejan plain.

that the location of gullies is strongly associated with topography, and especially with the upslope contributing area and slope degree: e.g. Koco (2006) analysed old permanent gullies in the Bardejov basin in Slovenia, or Poesen & *alii* (2003) studied gullies in the Belgian Loess Belt.

In Iran Nazari Samani & *alii* (2010) illustrates the importance of topographic indices such as contribution area, slope or curvatures for gully erosion in Hableh Rood Basin. However, most studies conducted on gully erosion in Iran analyze single gullies in terms of morphology and stages of gully development (Nazari Samani & *alii*, 2009; Ahmadi & *alii*, 2007; Sadeghi & Noormohamadi, 2011; Shahrivar & *alii*, 2012) but there are no studies that stochastically predict the spatial distribution of gully susceptibilities. Beside the prediction of the areas susceptible to gully erosion, the model provides also information on the most important environmental layers triggering gully erosion processes in the Mazayejan plain. As expected, the most important topographic indices like curvatures, slope and catchment area depict concave morphologies and medium sized contributing areas. The latter ones produce enough runoff that concentrates (concave curvatures) and at a certain point become turbulent and start eroding the substrates. In our study area we found a threshold in the contributing (or upslope catchment area) of about 10 ha for the location of the gull head cut points. Thus higher susceptibilities in the upper parts of the drainage network generally indicate the point where the runoff becomes turbulent under the given climatic conditions and hence often head cuts are formed. This was also revealed by the field work and mapping campaign conducted in the Mazayejan plain. Moreover, the very good model performance with AUC values of 0.95 for training and 0,94 for the test data set suggests that gully erosion in the Mazayejan plain seem to be only dependent on the topography. This means that land use and vegetation as well as substrates are very homogeneous. This is confirmed by fieldwork showing a very homogeneous distribution of surface texture. Moreover, the land use is also not varying very much. The Mazayejan plain is mainly characterized by range land and rain fed agriculture.

According to the proposed methodology we were able to analyse the spatial distribution of gully susceptibilities especially in areas with lacking ground data. Following our methodology we identified and spatially predict gully susceptibilities using GE images and DEM derived information as well as a mechanical statistics approach. With the obtained results a proper management of susceptible area is feasible since we know the triggering mechanisms and the spatial distribution of susceptible areas.

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