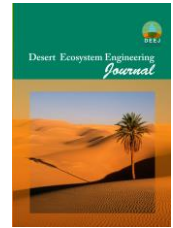




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Identifying the Factors Influencing the Probability of Occurrence of Different Gully Erosion Types Using the Maximum Entropy (MaxEnt) Model

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Extended Abstract

Introduction

Soil is a fundamental natural resource that plays a critical role in food security, ecosystem functioning, and sustainable land management. Historical evidence suggests that soil erosion has contributed to the decline of major civilizations. In Iran, millions of tons of fertile soil are lost annually due to inadequate vegetation cover and intensified erosional processes. Among the various forms of soil erosion, gully erosion is one of the most destructive, resulting from the complex interactions between environmental conditions and human activities. Gullies represent an advanced stage of linear erosion and have been reported to account for 10–94% of sediment yield in many watersheds. From a hydrological perspective, gullies facilitate the transport of sediment and associated pollutants, resulting in economic losses, reduced soil fertility, and damage to infrastructure. The initiation and development of gullies are complex and site-specific processes influenced by surface runoff, subsurface flow, piping, and mass movements. Previous studies have investigated gully erosion modeling using various approaches, including fuzzy operators, Shannon entropy, and certainty factor methods. However, most existing studies have focused on the presence or absence of gullies, with comparatively less attention given to gully head morphology and planform shape. Furthermore, significant gaps remain in the application of nonlinear, presence-only modeling approaches to gully erosion assessment. In Bushehr Province, approximately 29,500 hectares of agricultural land have reportedly been lost due to gully erosion, highlighting the importance of assessing its spatial distribution and contributing factors. Accordingly, this study aimed to: (1) predict areas susceptible to gully erosion using the Maximum Entropy (MaxEnt) model; (2) evaluate the relative importance of environmental predictor variables using percent contribution, permutation importance, and Jackknife analysis; and (3) examine the relationship between gully planform types and cross-sectional morphology as a complementary morphological analysis.

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Materials and Methods

The Darreh Kareh watershed is located approximately 40 km north of Bushehr, Iran, and covers an area of 29,750 ha (51°15'7"–51°25'25" E, 28°59'–29°10.5' N). A total of 145 gullies were identified through aerial photograph interpretation and field surveys. For each gully, the location of the headcut, cross-sectional shape (V-shaped or U-shaped), planform morphology (linear, lateral, or dendritic), soil properties (texture, organic matter content, salinity, and pH), and morphological characteristics (height, length, width, depth, and upstream slope) were recorded. Environmental variables, including catchment area, aspect, distance to streams, the Topographic Wetness Index (TWI), and the Normalized Difference Vegetation Index (NDVI), were derived using a digital elevation model (DEM) and ArcGIS. The TWI was calculated using the following equation:

where (A) represents the specific catchment area and (β) denotes the local slope angle. Soil property maps for clay, silt, and sand content were generated using kriging interpolation. The Maximum Entropy (MaxEnt) model was used to assess gully erosion susceptibility based on a set of environmental predictor variables, including slope, aspect, TWI, distance to streams, soil texture, organic matter content, land use, lithology, NDVI, flow accumulation, and the LS factor. The Shannon entropy index was integrated with logistic regression as part of the modeling approach. Model performance was evaluated using the area under the receiver operating characteristic curve (ROC-AUC). Jackknife tests and permutation importance were used to assess the relative contributions of the environmental predictor variables. In addition, the relationships between gully planform types and cross-sectional shapes were examined using cross-tabulation and chi-square tests.

Results and Discussion

The Shannon entropy analysis indicated that soil-related factors exerted a greater influence on gully erosion susceptibility than physiographic factors. Consistent with this finding, the MaxEnt percent contribution analysis identified caso0_50 (calcium carbonate content at a depth of 0–50 cm) as the most influential predictor, accounting for approximately 43% of the total contribution, followed by clay50_end (clay content in the deeper soil layer), with a contribution of approximately 40%. These results highlight the prominent role of soil properties in model development and suggest that soil characteristics are important predictors of gully erosion susceptibility in the study area. The permutation importance analysis identified clay50_end, silt0_50, and ec0_50 (electrical conductivity at a depth of 0–50 cm) as relatively important predictors, despite their lower percent contributions. Differences between percent contribution and permutation importance suggest that the apparent influence of individual predictors depends on the evaluation method and may reflect relationships among environmental variables. The Jackknife analysis further indicated that caso0_50 yielded the highest AUC when used individually, whereas its exclusion resulted in the greatest reduction in model performance. Taken together, these findings emphasize the importance of soil properties in explaining the modeled spatial distribution of gully erosion susceptibility, while topographic and hydrological variables appear to play supplementary roles. These results are consistent with previous studies by Arabameri et al. (2019) and Shahrivar and Christopher (2012).

The MaxEnt model achieved AUC values of 0.91 for the training data and 0.92 for the test data, with a reported standard deviation of 0.019. These values indicate strong discrimination between presence locations and background or absence locations, depending on the evaluation design. The similar training and test AUC values suggest that the model performed consistently across the two datasets and provide no clear indication of substantial overfitting. However, further assessment using spatially independent validation would be necessary to establish the model's transferability to other areas. The chi-square test revealed a statistically significant association between gully planform type and cross-sectional morphology ($\chi^2 = 29.954$, (df = 12), (p = 0.003)). U-shaped gullies were the most frequent cross-sectional form and were associated primarily with dendritic and linear planform patterns. These associations may reflect differences in the relative development of lateral erosion and channel widening. In contrast, V-shaped gullies occurred predominantly in association with linear planforms, potentially indicating a greater contribution of vertical incision. Trapezoidal gullies were less frequent and were associated with dendritic planforms, possibly reflecting more advanced stages of morphological development. One UV-shaped gully was also identified, representing a transitional cross-sectional form. These morphological patterns are broadly consistent with the findings reported by Wen et al. (2024) and Modak et al. (2023).

Conclusion

This study demonstrated that gully erosion is a complex geomorphological process influenced by the combined effects of soil physicochemical properties, geomorphological conditions, and human activities, rather than by slope alone. Among the environmental predictors examined, soil properties, particularly calcium carbonate and clay content, emerged as important factors associated with gully erosion susceptibility. These relationships may be related to their effects on soil permeability, runoff generation, and soil structural stability, although the underlying mechanisms depend on local soil and environmental conditions. Transitional geomorphological units, such as piedmonts and old alluvial surfaces, exhibited the greatest overlap with areas identified as susceptible to gully erosion. The morphological analysis revealed a statistically significant association between gully cross-sectional shape and planform morphology, highlighting the potential value of these characteristics for interpreting spatial variations in gully development. The observed morphological patterns may reflect differences in flow concentration, headcut retreat, and lateral expansion. Accordingly, gully morphology can provide complementary information for understanding erosion dynamics and potential stages of morphological development. The MaxEnt model demonstrated strong discriminatory performance in identifying areas susceptible to gully erosion, while the assessment of predictor importance helped identify the environmental variables most strongly associated with the modeled distribution. These findings indicate that combining presence-only modeling with environmental data and geomorphological analysis can provide valuable insights into the spatial patterns of gully erosion. Human-related factors, particularly land-use changes and proximity to roads, may further contribute to erosion processes and represent potential targets for management interventions, provided their effects are supported by the corresponding model results. The resulting susceptibility map can serve as a practical tool for prioritizing conservation measures, guiding soil and water management interventions, and supporting the mitigation of gully erosion hazards. Integrating soil properties, geomorphological characteristics, human-related factors, and quantitative modeling approaches provides a useful framework for assessing gully erosion susceptibility and informing land management decisions. Future research should extend the spatial coverage of investigations, examine temporal changes in gully development, and incorporate long-term hydrological observations to improve understanding of erosion processes and support more sustainable management strategies in arid and semiarid regions.

Keywords: Sustainable watershed management, Shannon entropy, Topographic indices, Headcut morphology