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Multi-parametric GIS analysis to assess gully erosion susceptibility: a test in southern Sicily, Italy

Valerio Agnesi, Silvia Angileri, Chiara Cappadonia, Christian Conoscenti, Edoardo Rotigliano

Dipartimento di Scienze della Terra e del Mare (DiSTeM), Università degli Studi di Palermo, Italy,
e-mail: christian.conoscenti@unipa.it

Abstract: A GIS-analysis was carried out in a test basin of southern Sicily, the Magazzolo River basin, in order to assess susceptibility conditions to gully erosion phenomena. The linear density of ephemeral and permanent gullies computed within each class of nine environmental variables was used to generate a gully erosion susceptibility map for the area. A validation procedure carried out in order to test the reliability of the adopted method highlighted a clear correlation between the occurrence of gullies and the computed susceptibility levels.

Keywords: gully erosion, GIS, susceptibility, Sicily

Introduction

In the last decades several studies have been carried out aiming to develop and apply models of the assessment of soil-loss rates and the evaluation of erosion risk. Most of these methods quantify the eroded volumes of sediments by means of equations, empirically developed or physically based, linking soil loss rates to the values of a set of environmental variables and/or mechanical properties of terrains. The Universal Soil Loss Equation (USLE; Wischmeier & Smith 1965) and its revised versions (e.g. RUSLE, MUSLE), are the most adopted method among the empirical ones, while the WEPP model (Water Erosion Prediction Project; Nearing et al. 1989) is the physically-based model most frequently used. On the other side, there are also methods for the evaluation of susceptibility to erosion phenomena, by defining the geo-statistical relationships between the geographical variability of selected physical attributes and the spatial distribution of the evidence for the water erosion processes, *i.e.* erosional landforms. This approach allows to generate maps in which the investigated area is distinguished according to susceptibility levels, expressing the relative probability of erosion landforms to develop in the future. To the latter category can be ascribed the method based on the concept of the Erosion Response Units (ERU; Märker et al. 1999) and the approach proposed by Conoscenti et al. (2008a). The first methodology allows to discriminate areas characterized by different proneness to water erosion levels, on the basis of association of erosion features, characterized by similar intensity. The second one is applied to assess soil erosion susceptibility by using a multivariate geostatistical approach that exploits a probabilistic function, corresponding to the spatial density of erosion landforms, that is computed in homogeneous domains.

In the present research, the susceptibility conditions to gully erosion in a test area of southern Sicily, the Magazzolo River basin, are evaluated by adopting a modified version of the geostatistical approach proposed by Conoscenti et al. (2008a).

Setting of the study area

The Magazzolo River flows in the southern side of Sicily draining a basin that extends for 225 km^2, between sea level and 1,440 m a.s.l.; the main fluvial axis runs for about 36 km with a NE-SW direction from the southern slopes of the Sicani Mounts to the Sicilian Channel (Fig. 1). The climate of this sector

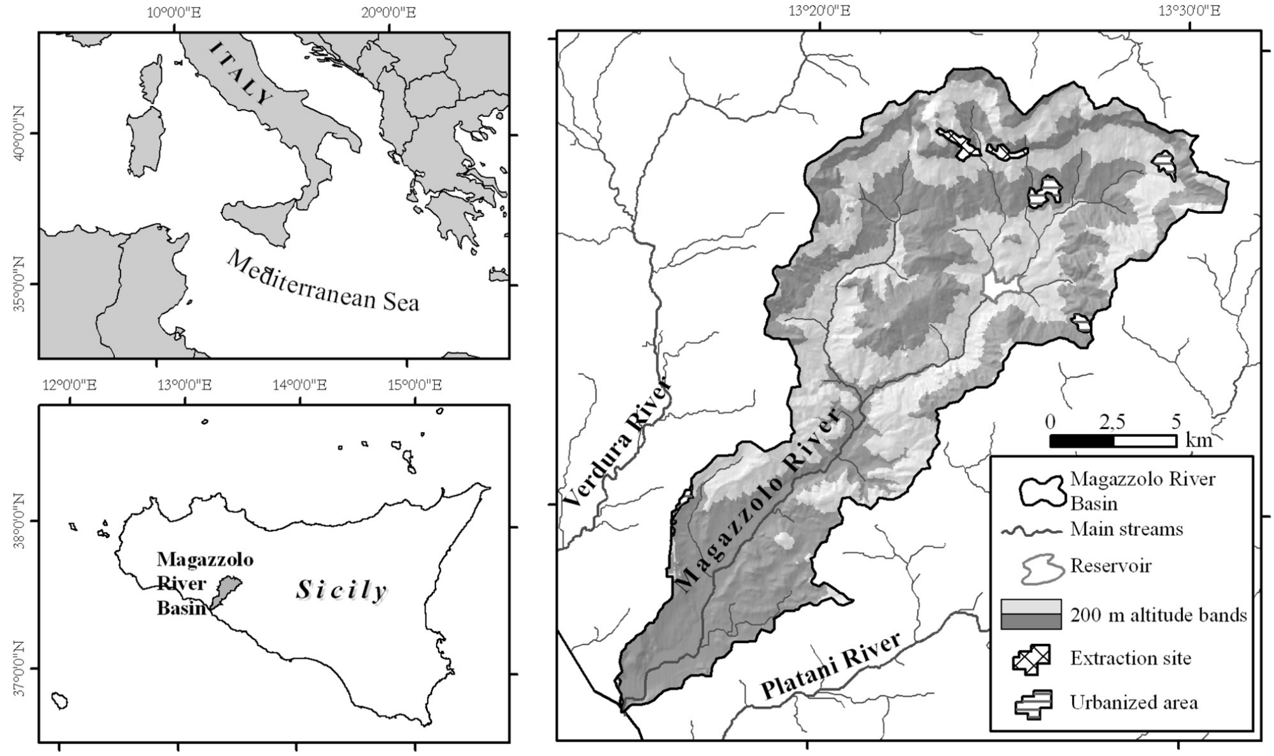

Fig. 1. Magazzolo River basin location and hillshaded DEM

of Sicily represents an example of a Mediterranean type, being characterized by wet and mild winter periods and hot and dry summer times; rainfalls, which mean annual value calculated in the period 1956–2000 is some less than 700 mm, are concentrated mainly in few of the winter semester days, while, on the other hand, summer times are characterized by an almost continuous drought conditions.

In the studied area, which is located in the mildly folded foredeep – foreland sector of the Sicilian collisional complex (Catalano et al. 1993), the outcropping rocks are: limestones (Lower Liassic-Upper Trias), dolomitic limestones (Lower-Middle Jurassic), pelagic marly limestones and marls (Upper Cretaceous-Eocene) pertaining to the Sicanian basinal succession; marls and limestones (Oligocene) of the Trapanese Platform; conglomerates, clayey sandstones and marls (Upper Tortonian-Lower Messinian) of the Terravecchia Formation; carbonates, gypsum rocks and marls of the Messinian Evaporitic succession (Upper Messinian); pelagic marly calcilutites (Lower Pliocene) of the Trubi Formation; actual beach, fluvial and slope deposits.

The Magazzolo River watershed (Fig. 1) develops from NE to SW with an elongated shape, that narrows down to the middle and the coastal sector. The analysis of the geomorphological setting of the area allows to delineate three different zones: a mountain area, a hilly area and a coastal area. The mountain sector occupies a narrow band in the head zone of the basin; this area is characterized by the outcropping of carbonate rocks, which give rise to steep slopes and scarps affected by debris and rock falls. A hilly area can be recognized from the foot of the northern carbonatic slopes to the narrowest section of the basin in the middle zone; this area, which is formed by gentle slopes given by clays and sediments of the evaporitic succession, is affected by landslides and severe water erosion phenomena. The coastal zone is characterized by wide alluvial plain and almost flat areas, set up on marls, calcarenites and clays.

Materials

The water erosion susceptibility expresses the spatial probability that a specific erosion landform could develop in the future. Differently from the hazard assessment, the probability component is provided in relative spatial terms rather than in absolute time and magnitude units; therefore, the more susceptible areas are those most prone to be eroded when compared with the others forming the whole investigated area (Conoscenti et al. 2008a).

In the water erosion susceptibility model here adopted, the gullies spatial density value is considered as the function expressing the proneness to this erosion phenomenon; differently from the model adopted in Conoscenti et al. (2008a), the length of the gullies, instead of the area of gullies, was used. The linear density values for ephemeral and permanent gullies, computed for each class of nine selected conditioning factors, were used to obtain susceptibility levels of homogenous domains, defined by combining together all layers of the factors; these homogenous units express unique conditions of the parameters and correspond to the concept of the Unique Conditions Unit, widely adopted in landslide hazard studies (Carrara & Guzzetti 1995; Clerici et al. 2002; Conoscenti et al. 2008b).

Gully erosion landforms

Remote and field surveys allowed to recognize several gully erosion landforms (Fig. 2) affecting the Magazzolo River basin. In particular, by means of stereographic analysis of 2,000 aerial photograms, 1:10,000 on scale, a map representing the spatial distribution of ephemeral and permanent gullies on the investigated area was gained; then, field surveys conducted in 2006 were used as a tool to test the reliability of the remote analysis and to improve the gully map in critical zones. This procedure provided a more accurate geographic distribution of gullies in the basin and allowed to generate the erosion landform map needed for the susceptibility analysis. To this aim, the gullies map was turned into a GIS vector layer by using ArcView GIS 3.2 (ESRI 1998).

Gully erosion controlling parameters

As erosion susceptibility is controlled by both the erodibility of outcropping materials and the erosivity of runoff waters on slopes (Conoscenti et al. 2008a), nine physical attributes were selected, in order to express the geographic variability of these properties. In particular, bedrock lithology (LTL), soil texture (TXT) and landuse (USE) where exploited as erodibility parameters; slope angle (SLO) and aspect (ASP), plan curvature (PLC), stream power index (SPI), topographic wetness index (TWI) and length-slope USLE factor (LSF), were selected as erosivity parameters. A 40 m grid layer was produced for all the physical variables (Fig. 3a–i), by integrating data derived from thematic maps and field surveys, for the erodibility parameters, and by processing a digital elevation model (40 m cell), for the erosivity variables.

By exploiting a GIS spatial analysis tool (Jenness 2006), the nine GIS-layers of the erodibility and erosivity variables were combined in a Unique Conditions Unit layer (UCU).

Results

Gully erosion susceptibility assessment

In the framework of this research, gully erosion susceptibility was defined adopting the probability theory (Davis 1973; Carrara & Guzzetti 1995) according to which, the density of a specific landform, computed on homogenous domains, corresponds to its susceptibility level.

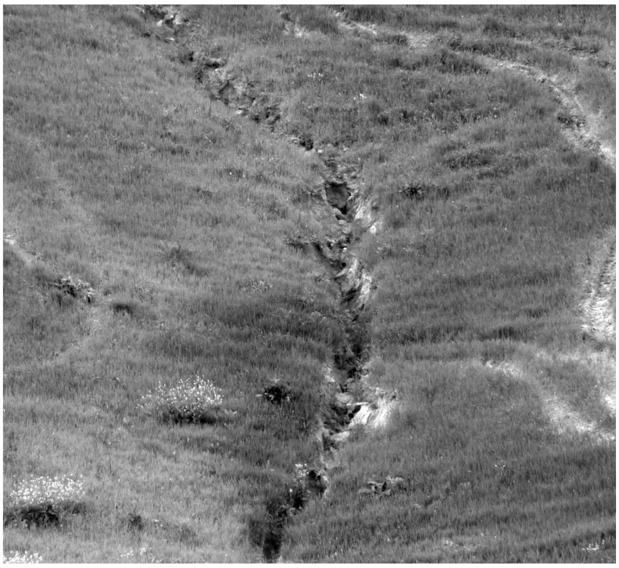

Fig. 2. Example of gully-erosion observed in the studied area

The linear density values of ephemeral and permanent gullies, evaluated for each of the classes of the selected physical parameters, by intersecting the gully layer with those of the controlling parameters, were used to estimate the susceptibility levels of each combination of the UCU layer; following a multi-parametric approach, the mean value computed from the density values of the combined parameter classes was used to define the susceptibility level of each of the specific combinations (UCU values) and, finally, to generate the gully erosion susceptibility map of the Magazzolo River basin (Fig. 4). The latter depicts, according to an equal area ranked scale, how the proneness to gully erosion phenomenon spatially changes on the investigated area.

Validation

In order to test the reliability of the adopted model and that of the relative gully erosion susceptibility map, a validation procedure was exploited; this procedure is based on a *random time partition* (Chung & Fabbri 2003) of the erosion landforms in two numerically balanced subset: a *training* and a *test* subset. The latter, which simulates the *unknown target pattern* (*i.e.* the future gullies) is used to test the predictive performance of the model, that, for the validation strategy, is instructed only on the training subset.

The goodness of the susceptibility model is assessed by analyzing its *prediction-* and *success-rate curve* (Chung & Fabbri 2003; Conoscenti et al. 2008a; Conoscenti et al. 2008b). These curves are drawn in a XY scatter diagram by interpolating points whose coordinates are given by the cumulative portion of the study area (X-axis) and by the cumulative fraction of the total length of test gullies, for the prediction-rate curve, and of the training gullies, for the success-rate curve (Y-axis); the susceptibility levels, which are derived from the spatial distribution of the training gullies and are classified according to an equal-area criterion, are arranged in decreasing order along the X-axis. The prediction- and success rate curves so derived are plotted in Fig. 5, together with a diagonal trend that represents the validation results of an hypothetical predictive

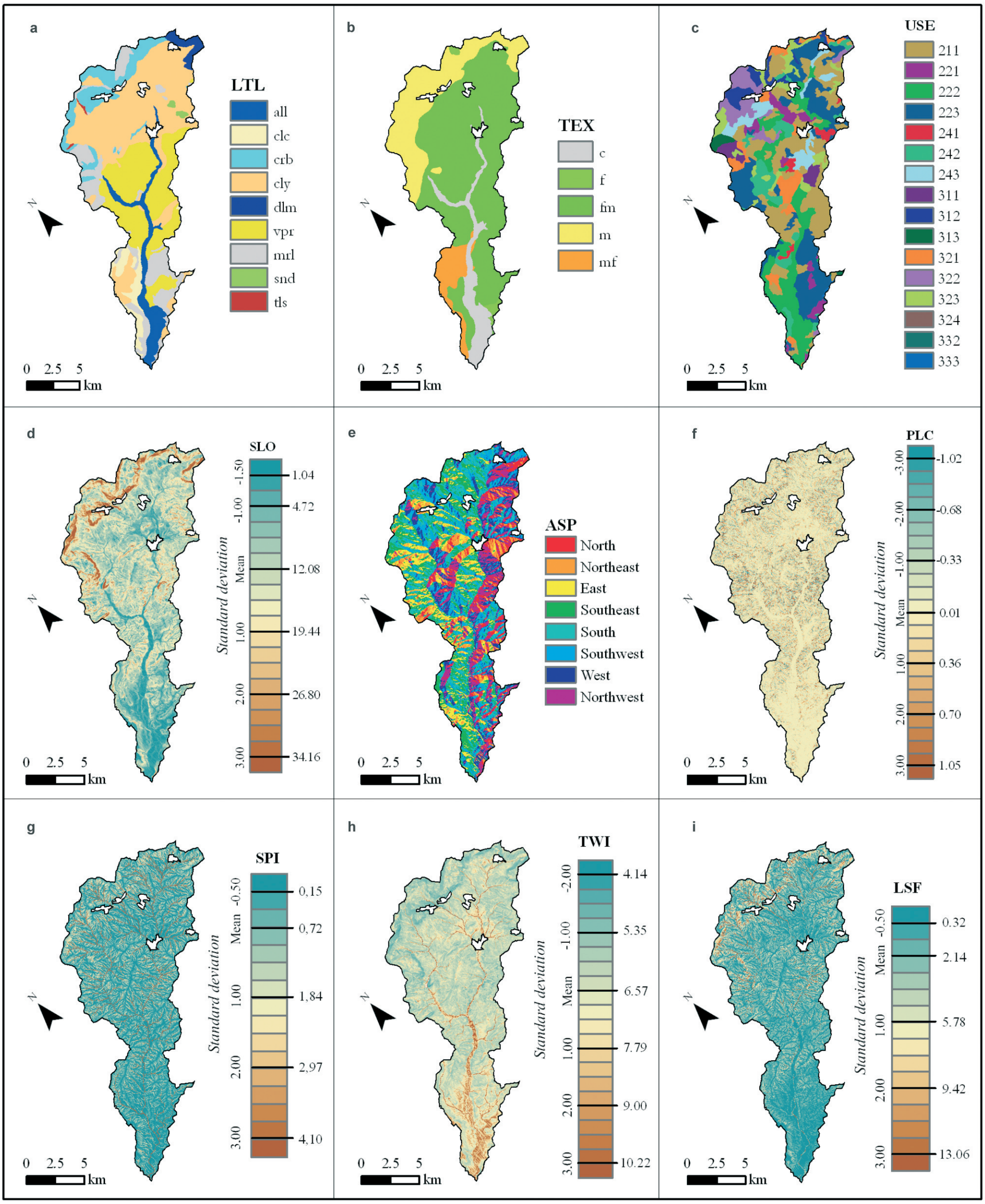

Fig. 3. Spatial variability of the erodibility and erosivity parameters: LIT (a), TEX (b), USE (c), SLO (d), ASP (e), PLC (f), SPI (g), TWI (h) and LSF (i)

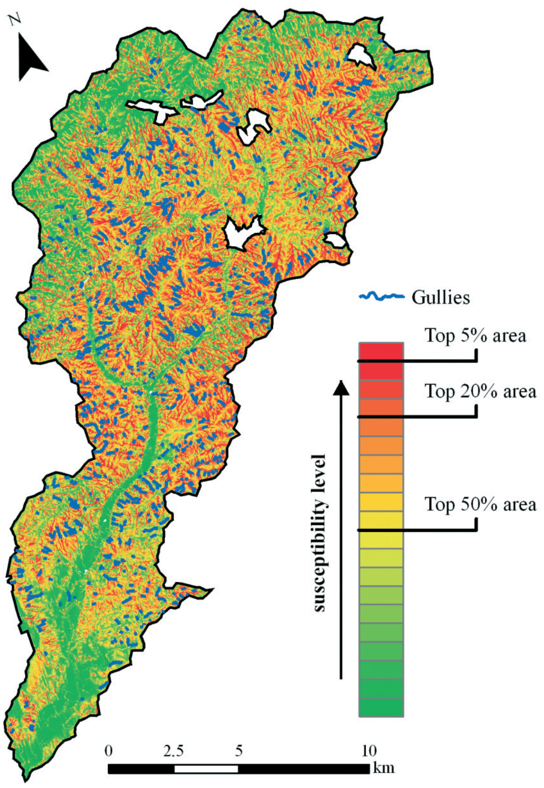

Fig. 4. Map of the susceptibility to gully erosion phenomenon for the Magazzolo River basin

model, totally uncorrelated with the spatial distribution of the gullies. The further from the diagonal trend the validation curves are, the higher is the predictive performance of the model; moreover, a good assessment is demonstrated when the prediction-rate curve tend to overlap the success-rate curve, both having a monotonically decreasing steepness that starts from very high values (Chung & Fabbri 2003, Remondo et al. 2003).

Discussion and concluding remarks

Gully erosion phenomenon on the Magazzolo River basin was investigated by exploiting the actual spatial distribution of landforms and its relationships with the geographical variability of nine selected controlling parameters; these relationships were mathematically defined computing the linear density of ephemeral and permanent gullies for each class of the nine controlling variables. The density values obtained, which were assumed as an index of the proneness to gully erosion of homogenous territorial units, generally agree with what was expected for linear water erosion phenomena: evidence of ephemeral and permanent gullies are in fact more associated with erodible bedrock lithologies (clays and evaporitic rocks), fine and fine-medium soil textures, concave (negative values of PLC) portions of slopes and sectors characterized by highly erosive water flow (high values of SPI).

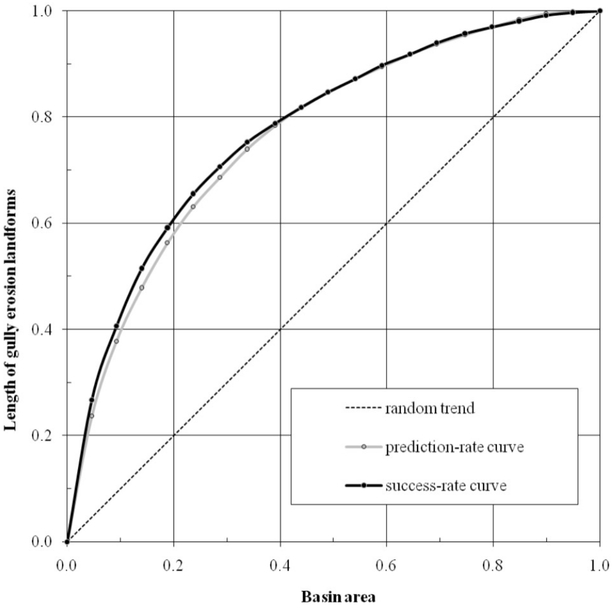

Fig. 5. Prediction- and success-rate curves for the susceptibility model of gully erosion

The density values, derived for the classes of physical variables, were averaged for each specific combination of the UCU layer in order to calculate, on a multi-parametric basis, their susceptibility levels and, finally, to generate the gully-erosion susceptibility map. The latter shows two large susceptible zones in the northern and in the central part of the basin. In particular, the central susceptible zone, where the two main tributaries converge and give rise to the Magazzolo River, is characterized by almost undifferentiated high susceptibility conditions. On the other hand, very low susceptibility values are associated with the bottoms of the main valleys, the alluvial plain and the sector near the northern part of the water divide.

As the superimposition of the gully layer above the susceptibility map shows (Fig. 4), the adopted multi-parametric approach allowed to assign high susceptibility conditions also to portions of slopes, that, even if lacking of linear erosion landforms, are associated to high susceptible classes of some of the combined parameters. Moreover, differently from a multivariate approach, the applied multi-parametric model, which is derived by computing the average of the nine gully densities falling inside each UCU value, avoid to have large areas with null density value; this condition is frequent when density of linear (therefore of limited areal extension) landforms is computed by using a multivariate approach on a layer which combines many parameters. A large number of cells with null density values leads to some problem in defining the susceptibility levels in accordance with an equal area criterion and, in general, decreases the predictive performance of the model.

The validation procedure, based on a random time partition strategy of the mapped gullies, is here applied to the aim of testing the predictive performance of the methodology used to derive the gully erosion susceptibility map. The prediction- and success-rate curves, obtained by intersecting the prediction image with the test and training subset of gullies respectively, show a clear correlation between the spatial distribution of ephemeral and permanent gullies and the geographical variability of the susceptibility levels. The shapes of the validation curves reflect in fact the characteristics that a good predictive performance should have: the steepness of the curve is high in the first part and monotonically decreases from the most to the less susceptible levels; the prediction tends to overlap the success-rate curve and they are both far from the diagonal trend. Moreover, a spatial correlation between the model and the objects of prediction is quantitatively demonstrated considering that 40% and 80% of the total length of the predicted gullies (those of the test subset) fall inside the 10% and the 40% of the most susceptible portion of the basin, respectively.

Finally, the research pointed out that starting from a set of GIS layers, describing at basin scale the spatial distribution of gully erosion landforms and the geographical variability of erosivity and erodibility parameters, a reliable susceptibility map of water linear erosion phenomena could be produced. Besides, such a method requires data usually available for large areas at regional- or basin-scale resolution, or achievable without high cost- and time-consuming procedures, so it could be easily exported to other watersheds and reproduced with the aim of analyzing how linear water erosion phenomena temporally evolve.

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