DIGITAL MAPPING OF LANDSCAPE EVOLUTION IN A SAMPLE AREA IN THE NORTHERN APENNINES (ITALY)

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Abstract

The geomorphological analysis of a sample area in the Northern Apennines led to the following conclusions: 1) sediment yield (Tu) is related to long term landscape evolution; 2) shallow slides or flows and deeper movements feature critical slope angles (respectively about 14° and 17°); 3) different land use involves distinct geomorphologic behaviour; 4) fracturation, rather than bedrock composition, plays a fundamental role in slope instability.

1 Foreword

Three main factors favoured (and still do) the geomorphological evolution of the Romagna Apennines (Northern Italy): 1) a relatively humid climate, featuring precipitation rate amounting to about 750÷900 mm/year, highly concentrated in spring and autumn; 2) an intense agricultural exploitment leading to reduced soil cover; 3) bedrock lithology, mainly consisting of sandstones-marls or sandstones-clay sequences.
In order to analyze the complex relationships between five main geomorphological parameters, a sample area about 12 km^2 wide situated near Predappio (Forlì) has been investigated.

2 Introduction

The starting point of an analysis of the relationships governing landscape evolution is usually the production of thematic maps, carried out in raster or vector format.
Several authors were involved into the topics concerning environmental mapping and landslide hazard evaluation. We can divide the main currents into four approaches:

a) the geomorphological approach
The analysis of landslide hazard is carried out on the basis of field evidences, evaluated by an experienced researcher[31, 38]. Unfortunately, this approach relies on the subjective experience and skill of the operators, thus leading to potentially biased evaluations.

b) the univariate approach
A direct, linear relationship between the morphological parameters is expected. The research is directed towards the individuation of some threshold value [27,37,20,22] or critical ratio [36] betweeen a couple of variables in the area of interest. In these works the relationship most investigated was between the slope angle and the presence of landslides.

c) the "weighted index" approach
A number of thematic maps is produced to describe the main features of the region. Thus, each sub-area is characterized by an attribute attached to an index representing its «goodness». These indexes may be chosen on statistical basis [24, 10, 2, 28, 25, 5] or after subjective evaluation [3, 4, 21].
The maps resulting from the overlay of the input maps feature a large number of polygons, each one attached to new index values which account for the combined informations.

d) the multivariate approach

After the production and the overlay of the thematic maps, the spatial distribution of the variables over the area of interest is analyzed by means of the main multivariate techniques (factor analysis, discriminant analysis, cluster analysis, linear and logit regression) [32,1,14,13]. The smallest environmental unit can be chosen as a square cell of a regular grid or according to the natural hierarchical partition of the land following the watersheds. Nonetheless the former classification hardly reflects any natural boundary.
This appears to be the most scientific way of handling the data: in particular, very few assumptions are made by the operator, thus reducing the degree of subjectivity.
In these works, the statistical techniques adopted (mainly the discriminant analysis) resulted in some *black-box models*, suitable for the predictive purpose of the papers. Nonetheless, in a pilot study interested in detecting and explaining the modes of landscape dynamics from different point of view,, we resorted to a simpler approach [16], quite similar to the "Sieve mapping method" (see [39]).

3 Thematic maps

The cartography was organized into 5 independent layers, each one representing a "theme". Each of them included a number of graphic objects, which were classified into "classes", according to the data type. Any further attributes were managed by attaching custom fields to those records. The purpose of this hierarchical structure was to allow some "queries" upon part of informations, specified through some custom criteria.
The input to the computer facilities was obtained after digitalization through graphic tablet. The errors due to map distortion were eventually corrected, using the mathematical grid provided by the topographic maps.

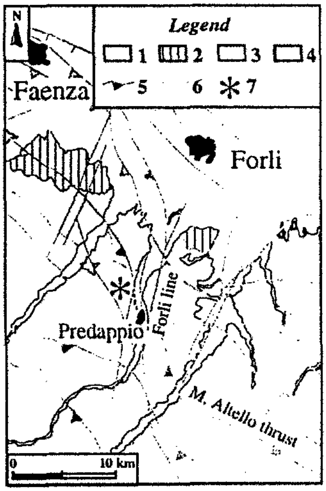


Fig. 1: Geologic scheme of the Romagna Apennines. Legend: 1- Alluvial deposits; 2- lower/middle Pleistocene ; 3- Pliocene; 4- Miocene 5- thrusts; 6- faults; 7- area of interest. (modified from [30]).

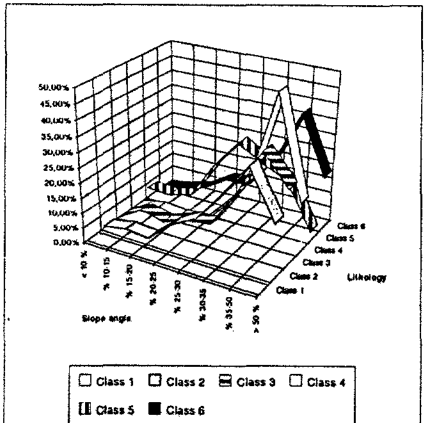


Fig. 2: Slope angle vs. lithology

From the tectonic point of view, the area is characterized by a ductile deformation, associated with a widespread brittle deformation.

This structural setting is controlled by the M.Altello-Faenza line - a regional apenninic thrust - cut by the Forli line, a main regional antiapenninic transversal fault [12, 8] (Fig. 1). The deformations range from upper Miocene to upper Pleistocene.

Hence we determined the categories of the lithological/structural map keeping in mind both the lithological criterion and qualitative informations about fracturation and bedding orientation (Table 2).

3.2 *Slope map*

This map was graphically produced using the "clinometric scale" [11] directly from the the main contour lines (every 25 m). This method was preferred to others, such as Delaunay Constrained Triangulations [35] or DTM methods [15, 26], because of its higher precision (especially in the headscarp zones), required by the scale and the purpose of the study.

Bearing in mind both the agronomic aspects and the critical ranges which emerged from the geotechnical experience available in the surrounding areas, eight slope classes well representing the steepest intervals too were divided (Table 3).

%	°	%	°
0 - 10 %	0° - 6°	25 - 30 %	14° - 16°40'
10 - 15 %	6° - 8°30'	30 - 35 %	16°40' - 19°20'
15 - 20 %	9°30' - 11°20'	35 - 50 %	19°20' - 26°30'
20 - 25 %	11°20' - 14°	> 50 %	> 26°30'

Table 3: Categories of slope map, in percent slope (%) and degrees (°)

3.3 *Land use map*

Most of the area is devoted to agricultural land use and pastured, apart from small urban areas. Table 4 displays the nine categories recognized in the land use map .

Urban areas	Shrubbery	Orchard
Forested areas	Uncultivated land	Vineyard
Evergreens	Meadows and pastured	Sowable areas

Table 4: Categories of land use

3.4 *Landslides map*

The landslides were recognized by direct field survey and classified following Varnes' classification [38]: slumps, earth-slides, earth-flows, debris-flows, and complex movements were mapped; for each one the headscarp, transition and deposition areas were distinguished.

3.5 *Sediment yield*

In order to evaluate the erosion in the hydrographic cells, the sediment yield Tu (expressed in ton/km^2 per year) has been evaluated, adopting the well tested equation [7, 17]:

$$\log Tu = \log D + 0.13985\, \Delta a + 1.05954$$

where D = drainage density (km/km^2)
Δa = hierarchical anomaly index [17].

The range of variability has been divided into 11 discrete categories (Table 5).

The maximum values, amounting to over 3000 ton/km^2/year, correspond to badland-type landscapes, as pointed out by previous works [18, 19], whilst minimum erosion values (less than 1000 ton/km^2/year) are associated to fractured bedrock . The weighted mean amounts to about 1737 ton/km^2/year, slightly superior to the average values for this sector of the Apennines.

< 210	1070 - 1500
210 - 350	1500 - 1700
350 - 500	1700 - 2000
500 - 750	2000 - 3300
750 - 900	>3300
900 - 1070	----------------

Table 5: Categories of sediment yield (Tu), expressed in t/km^2/y

4 Data analysis

The adopted procedure consists of a search of the common areas from each pairs of polygons belonging to different thematic maps. Two kinds of output were produced: a graphic one - in the form of maps -, and a numeric one, allowing data handling by means of spreadsheet and diagrams tools.

4.1 Slope angle vs. lithology (Fig. 2)

It is possible to point out some threshold values for slope angles, referring to the lithologic classes used here. Worth noting is the fact that marly terrains (class 4) display higher values of this threshold (about 11°20') than sandstone interested by intense fracturation (classes 2 and 3 - 8°30'). This observation means that - in the sample area - slope angle is more likely to be related to some structural factor than to lithological nature of the bedrock.

4.2 Land use vs. slope angle(Fig. 3)

From the collected data the following points can be extracted: 1) shrubby, forested and uncultivated terrains seem to have a similar distribution vs. slope angle, displaying a maximum in the class 35-50%. Uncultivated areas are less common in slope steeper than 50%, mainly due to slope instability, whilst the presence of shrubbery or forested areas grants a certain stability (as far as shallow movements are concerned); 2) meadows and sowable areas reach a maximum for steepness between 30 and 35%; for higher slope values meadows are most common, because of the smaller influence of ploughing that induces autumn and spring surface instability.

4.3 Land use vs. lithology (Fig. 4)

The diffusion of forested areas is closely related to the presence of sandstone bedrock. Where the marly fraction prevails (class 4), uncultivated areas and shrubbery take place, probably due to the development of badland-type cells. Meadows and sowable areas are concentrated in class 5.

4.4 Land use vs. landslides (Fig. 5)

Earth-slides mostly occurs into cultivated land (especially meadows and sowable areas). This is largely due to the fact that all these areas insist upon slopes not very steep, thus producing mostly slow, shallow landslides. For the same reason, either shrubby vegetation or uncultivated areas are commonly interested by debris-flow or flows in bedrock.

4.5 Landslides vs. lithology (Fig. 6)

Rotational slides tend to concentrate on highly fractured (with subvertical planes) sandstones. The depth of the slip surfaces varies from 6 to about 15 m.
Clayey or sandy-clayey (ratio near 1:1) terrains are mostly interested by flow processes.

Fig. 3: Slope angle vs. land use

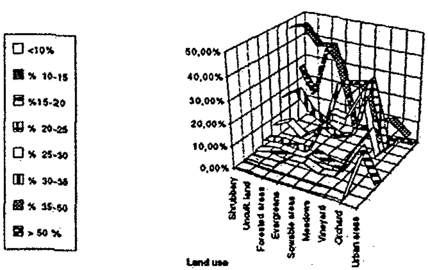


Fig. 4: Land use vs. lithology

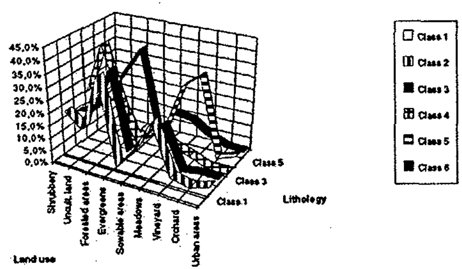


Fig. 5: Landslide areas vs. land use

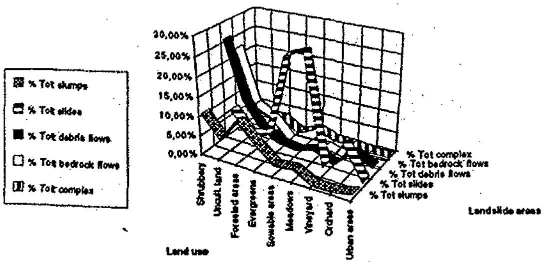


Fig. 6: Landslide areas vs. lithology

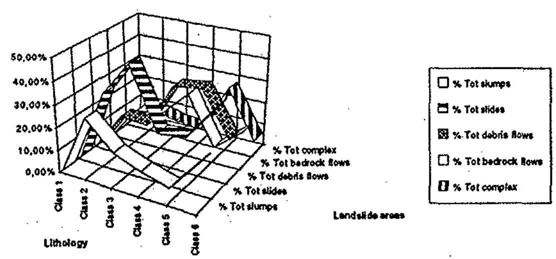


Fig. 7: Landslide areas vs. slope angle

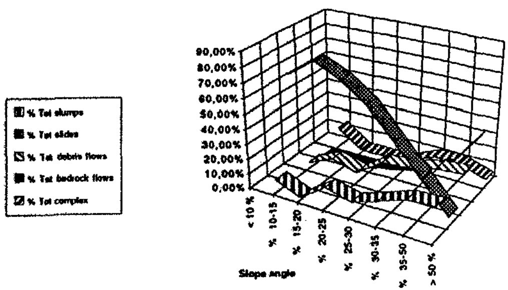


Fig. 8: Landslide areas vs. sediment yield

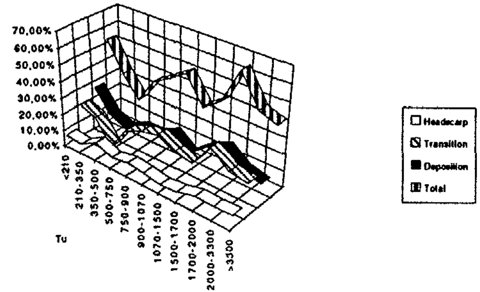


Fig. 9: Slope angle vs. sediment yield

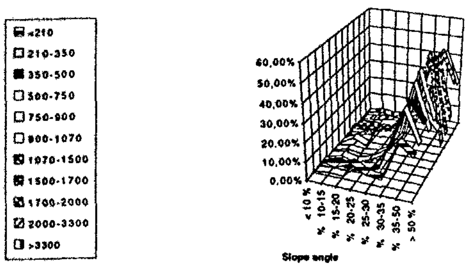
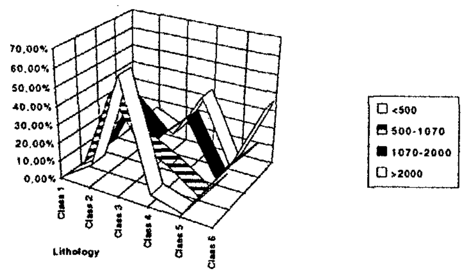


Fig. 10: Sediment yield vs. lithology



Shallow slides and bedrock flows developed in sandstones dipping steeper than slope . From direct observation of these phenomena, it can be claimed that shallow slides take place ad the head of hydrographic cells, whilst flows are closely related to the drainage net.

4.6 *Landslides vs. slope angle (Fig. 7)*

Some threshold angles can be extracted: 1) for slope angles lower than 14° only shallow slides and flows occur; 2) deep movements occur starting from slopes 14° steep; 3) where the slope exceeds 26°, shallow slides and flows disappear, whereas instability is given by deeper phenomena.
This trend correctly represents the overall tendency for each landslide area (headscarp, transitional, deposition area): as far as deposition areas are concerned, it can be stated that they are concentrated upon surfaces featuring slope angle lower than 20°.

4.7 *Landslides vs. sediment yield (Fig. 8)*

In the class <210 ton/km^2/year there is a concentration of remnant/dormant landslides. Mass wasting decreases (especially in the deposition area) as the erosion increases until 500 ton/km^2/year. Those landslides are essentially rotational (deep rooted) or shallow soil - slides.
For Tu values exceeding 500 ton/km^2/year, the growing of erosion involves an increase of active movements.
This positive trend goes on until the mean erosion value (1737 ton/km^2/year) is reached. For higher Tu values, a decrease in landslide area is observed, which could be claimed as the "erasing effect" of new erosional phenomena.

4.8 *Sediment yield vs. slope angle (Fig. 9)*

The main trend, followed by almost every class of erosion, features a peak into the slope angle class 35-50 %. The overall tendency can be summarized in the following points: 1) for lower Tu values (less than 500 ton/km^2/year), erosion increases together with slope steepness; 2) as Tu exceeds 2000 ton/km^2/year slope instability is triggered, and a feedback process continues, with formation of steepest areas; 3) in the intermediate range of Tu (500 - 2000 ton/km^2/year) the instability produced is just enough for reaching an equilibrium profile, with reduction of the areas with slope angle exceeding 50 %.

4.9 *Sediment yield vs. lithology (Fig. 10)*

For a clearer interpretation of this relationship, the intervals of Tu were regrouped in four major classes, chosen in respect of the significant ranges claimed by Ciccacci et al.[18, 19]: >500, 500-1070, 1070-2000, >2000 ton/km^2/year.
Classes 4 and 6 display a positive correlation erosion-lithology, whilst classes 2 and 3 show a negative one.
A Tu threshold may be established for these classes, being Tu <1000 ton/km^2/year for fractured sandstone (classes 2 and 3) and Tu>1000 ton/km^2/year for classes 4 and 5 (marls and clays).

5 Conclusions

The interpretation of the resulting maps and diagrams led to the following conclusions:
1) the values of sediment yield reflect the general long-term evolution trend, starting from the post-glacial period, mainly controlled by the geological-structural framework (lithology, fracturation). Antropic modifications look locally significant;
2) soil erosion by shallow slides and flows is most common, becoming significant for slope angle higher than 14° (25%). Deeper movements are much less frequent, and are related to slopes steeper than 17° (30%);
3) the distribution of both landslides and slope angle suggests two distinct kind of soil behaviour: firstly, soil-covered cultivated land is affected by shallow slides or debris-flows; on the other hand areas covered by forest trees and shrubbery;

4) the pattern of landslides and slope angles compared to lithologic distribution confirms the field observations that landslide occurrence is much more sensitive to discontinuity (fractures, faults and bedding planes) density than to lithological composition of bedrock.

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