Geomorpho: a methodology for the classification of terrain units

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Abstract—**In order to perform a thorough quantitative analysis of the morphology of an area, a methodology has been developed, able to deal with a Digital Elevation Model (*DEM*), that classifies the *DEM* pixels starting from the eight topographical gradients, computed as differences between each pixel and the eight surrounding ones, and provides for each class a complete set of statistics of terrain attributes, including elevation, slope, and aspect. In addition, a thematic colour map may be built, with hue and saturation attributed according to both mean aspect and slope of each class, respectively. As an example, Mount Soratte in Italy has been analysed in two different ways.**

I. Introduction

The study of the terrain morphology is based on the identification of the morphometric parameters of each terrain unit within the study area. In particular, altitude, aspect, and slope, are within the most used topographic attributes to take into account [1][2][3]. In this respect, the analysis of Digital Elevation Models (*DEM*) significantly helps this investigation, since through their processing it is possible to obtain a quantitative description of the relief. Several studies have been carried out so far, in order to automatically extract most information from *DEM*s [4][5][6][7][8][9].

The classification of terrain units, considering morphological attributes, was performed since long in literature [1][2][3][4][5][6][7][10][11][12]. Our approach, based on Parchiaridis *et al.* [13], distinguishes from the others since it avoids to use slope, aspect, and other terrain attributes, calculated through procedures that may lead to different results, depending on the analysis procedures and the different weighing of the characters in the classification process. Instead, in agreement with [13], we propose to create an 8-layers stack of the topographic gradients, measured along the 8 azimuth orientations of each *DEM* pixel neighbourhood. This is obtained by computing, for each pixel, its differences in elevation values with respect to the eight closest neighbours. Such a simple approach, allows to quickly estimate the spatial distribution of different types of slope steepness, so that the studied area may be partitioned into classes with similar local terrain attributes [14][15][16][17]. Hence, changes in shape, orientation, and steepness are highlighted.

The partition may be performed in several ways, providing a set of classes, whose relevant statistics may be studied in order to both understand and describe the different terrain units that may be found in the study area. In addition, if appropriate colours may be attributed to each class, the thematic map, obtained by colouring this way the pixels, may provide an immediate overview of the area structure and maybe even approach a 3-dimensional vision Error: Reference source not found.

Here, we present a methodology, fully implemented in a Fortran 95 program (not yet available for distribution), that starts from the *DEM* of a study area, performs a classification of the pixels based on the eight gradients, and provides both a complete set of statistics of the main land surface parameters, and a basis file for a thematic map, in which the pixels are coloured according to the mean aspect and slope of the class of belonging.

II. Theoretical aspects

The aim of the methodology is to partition the set of pixels that compose the area under study in homogeneous geomorphometric classes. Considering that they usually form a nearly continuous pattern, the partition may not be *natural*, in the sense that usually discontinuities do not appear in the pattern itself that suggest the existence of isolated natural classes. Thus, we consider that the adopted *Tandem* technique may be a good explor-

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atory method to partition the set of pixels in a nearly optimal way for the purpose.

The methodology starts with a submitted *DEM* file, in which the non-interesting part has been filled with zeros. This allows to limit attention and computation only to the selected part of the *DEM*. Then, for each pixel eight gradients are computed, as its elevation differences with the eight contiguous ones, along *NW, N, NE, E, SE, S, SW*, and *W* directions. A positive difference means that the central pixel is higher than the neighbour. At the same time, both slope and aspect values are computed [10][11][12][15][16][17].

Then the program runs a classification of the pixels according to the *Tandem Analysis* (*TA*, [19]), that consists in a *Principal Component Analysis* (*PCA*, [20][21]) followed by a classification performed on the coordinates issued by *PCA*. *TA* is largely used in exploratory studies, in which a partition is sought to better understand and describe a data structure, in particular when no natural structure in classes exists. The *PCA* used before a classification allows to better control the variables at hand, since the principal components are uncorrelated. This reveals useful to equilibrate the data variability, usually larger along the direction of highly correlated original variables and reduced along the non-correlated ones.

PCA is performed on the eight gradients, since the use of slope and aspect as input variables is not convenient, *i)* because their computation in different ways would give different results [10][11][12]; *ii)* because the aspect is circular: this means that there is no way to take into account the identity between the extreme values 0º and 360º, not even the use of sine and cosine of aspect may be appropriate here. A large number of preliminary applications of *PCA* to topographic gradients showed that usually the first two principal components summarize, in a relative weighed way, most of the data variability (always over 90%) and their spanned plane corresponds, up to reflections and a rotation, to the rose diagram. In addition, the third one, that summarizes most of the remaining variability, usually opposes peaks to pits. Thus, it is up to the researcher to decide to limit the following classification to the first two or three principal components: the use of standardized coordinates for the classification reduces on one side the differences in variability among the first two principal components, so that the obtained classes would be distinguished according only to slope and aspect; on the other side, the use of three factors would dramatically enhance the variability along the third one, so that local elevation maxima and minima may be better put in evidence.

After *PCA*, a classification, based on the Euclidean distances among pixels in the two- or three-dimensional space spanned by the principal components, is performed in four steps: *i)* a first *K-means* algorithm ([22][23]) is run, to create 100 homogeneous classes; *ii)* a *Hierarchical Ascendant Classification* (*HAC*, [23][24]) is performed on the 100 classes, through the *minimum variance clustering* method [25]; *iii)* a partition in *k* classes is chosen, according to the suggestions of two different methods; *iv)* a second *K-means* procedure is run on this chosen classification. All methods' objective functions aim at minimizing the within-classes variability and maximize the between-classes one. The first step of the clustering algorithm is used to get the procedure faster, the second to get information concerning the most suitable number of classes, and the third to optimize the chosen partition by minimizing the within-classes variability. To select the best partition, the Calinski and Harabász method [26] is adopted, considered the best by Milligan and Cooper [27] for this purpose, together with the identification of the partitions followed by a larger increase of within-classes variability. This second method was introduced since the first one, albeit more reliable, may not always suggest a partition in the range 10-25 classes that we consider the most appropriate to describe terrain attributes.

Once defined the partition, for each class means and standard deviations are calculated for both the eight gradients and the three geomorphometric characters height, slope, and aspect. It must be pointed out that for the aspect, measured by an angle, special circular statistics based on trigonometric functions [28] were considered, in order to avoid misleading values for some class [28][29]. The problem is particularly important for a class whose mean value is close to 0º = 360º, since the deviation from the mean would appear highest, only due to the (wrong) difference between 1º and 359º that, without this care, would appear of 358º and not only 2º.

The statistics are useful to characterize the classes: this is achieved by arranging them in a table in which each class is described according to the given statistics. Eventually, colours are set for each class, according to the Hue-Saturation-Lightness (*HSL*) colour modelling [30], by transforming the respective mean aspect and slope into hue and saturation values, whereas lightness is kept fixed (average) for all classes. All these results are reported by the program both in text and *ENVI* format, the latter to be used in Geographical Information System environments for a fast building of graphics.

III. An Application: Mount Soratte

As case study, an application to Mount Soratte is shown. Soratte is a *NW-SE* stretching, isolated, medium relief carbonate massif within the Italian Latium region [16]. The used *DEM* has 551×623 pixels, each one measuring 10×10 meters, in which all pixels not belonging to the relief were masked. Two geomorphometric classifications were performed, based on the coordinates of two and three factors issued by *PCA*, in 10 and 15 classes, respectively.

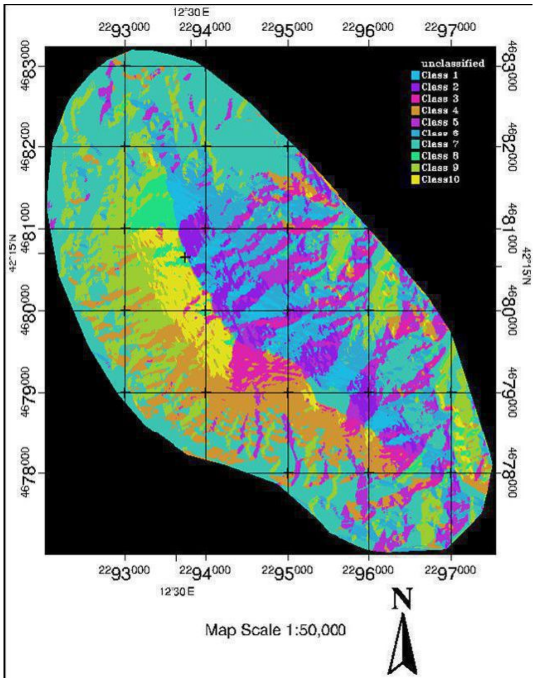

Fig. 1 - Thematic map of Mount Soratte coloured according to the 10 classes partition based on the first two *PCA* factors.

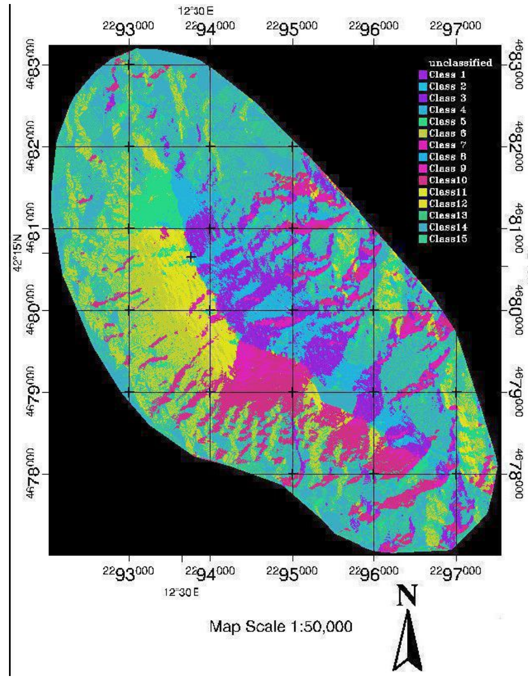

Fig. 2 - Thematic map of Mount Soratte coloured according to the 15 classes partition based on the first three *PCA* factors.

The corresponding maps are displayed in Figs. 1 and 2 and may be compared with the shaded relief of the same area, displayed in Fig. 3. The results of the two classifications are in part similar, and show the differences of the Soratte's main landforms according to both slope and aspect values of terrain units. In addition, the classification based on three factors yielded three pair of classes very similar according to these mean values, but highly different according to the local topographic gradients settings, that result concave in one case and convex in the other. Moreover, other three classes, of mostly flat areas, represent respectively local pits, peaks and real plains. This separation does not appear in the two factors classification, in which these peculiar classes are merged in one class only. In this respect, the classification based on three factors provides some extra characterization to the landforms. To get a better comparison among the two partitions, in Fig. 4 a rose diagram is shown in which all classes' mean and standard deviation of both slope and aspect are displayed. This way, it is easy to see the agreement of the classes of the two partitions.

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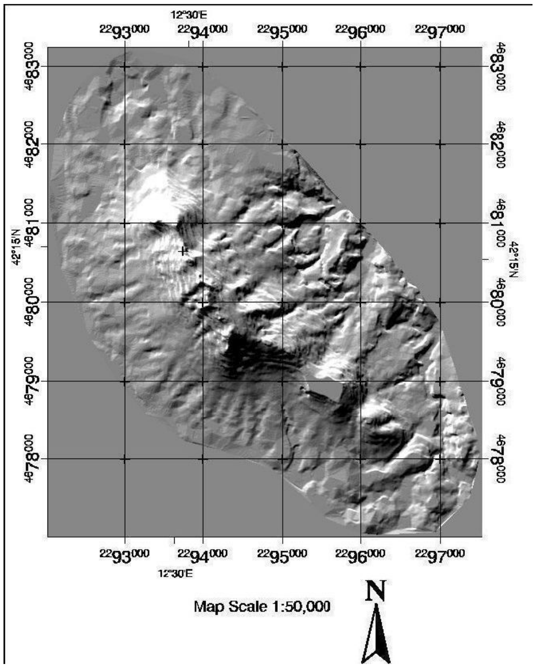

Fig. 3 – The shaded relief of Mount Soratte.

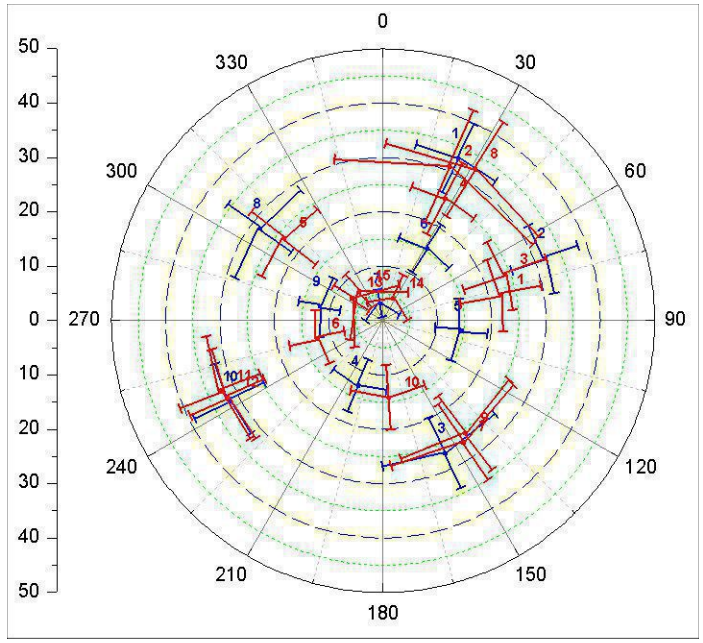

Fig. 4 – Rose diagram showing the mean and standard deviations of both mean and aspect of each class of the two partitions of Mount Soratte. Blue: partition in 10 classes based on two *PCA* factors; red: partition in 15 classes based on three *PCA* factors.

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