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Geomorphodiversity index: Quantifying the diversity of landforms and physical landscape

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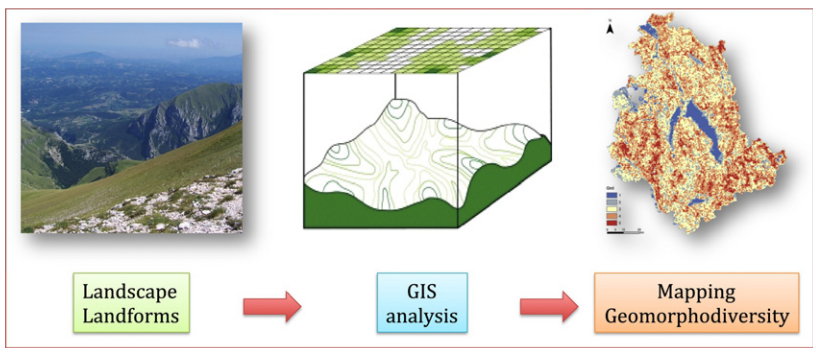
HIGHLIGHTS

- Geomorphodiversity assessment is fundamental for the promotion of the geoheritage.
- A geomorphodiversity index is computed stressing the topographic data.
- Spatial analyses in GIS and parameters from DEMs are the core of the method.
- High values of the index match areas with a great variety of landforms.
- The index is a key tool to assess the environmental complexity.

GRAPHICAL ABSTRACT



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ABSTRACT

The physical landscape is the mosaic resulting from a wide spectrum of environmental components. The landforms define the variety, or diversity, of the geomorphological component: the geomorphodiversity. Landforms are usually represented in thematic maps where the scale and the graphic solutions are widely heterogeneous. Since geomorphological maps are not always easy to obtain and standardize, topography might be used as a proxy to infer the morphological signature. To recognize, evaluate, and in some cases promote the geomorphodiversity of an area, a numerical assessment is preferable. Through the use of quantitative approaches, indexes can be defined which quantitatively characterize the physical landscape in a discretized space consisting of continuous and regular cells. In this approach each cell is labelled with an algebraic value, which increases with the diversity degree.

In this paper a quantitative index for geomorphodiversity is estimated stressing the topographic variables derived from Digital Elevation Models in a GIS environment. The resulting index is the sum of the variety of each terrain parameter taken into account. The areas characterized by the highest value of geomorphodiversity index show a good correspondence with well-known situations in the region where not always the geological heritage is properly acknowledged. The areas characterized by the lowest value of geodiversity correspond to the center of some intermountain basins of the region. Being the index strictly related to the topographic variety, this result is quite obvious but not easily predictable since in some flat areas the index is higher. Comparing the

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results with the geomorphological map of the area performs a validation procedure for the method. A positive correlation is found between the index calculated and the presence/absence of landforms.
The paper shows that the index is a useful and simple tool for the identification, analysis and promotion of the geological heritage.

1. Introduction

In the last decades many researchers have focused their attention on the definition of geodiversity and its relationships with biodiversity, natural environment conservation, ecosystem services, geotourism (Gray, 2004). Evaluating the diversity of an ecosystem involves the necessity to define indexes able to compare different geographical and morphological areas. The concept of the physiographic unit is one the main focal points defining the relationships between the different variables composing the landscape (Bailey, 2009; Fenneman, 1928; Hooson, 1968; Miliaresis and Argialas, 1999). Fennemans' (1928) method, still acceptable in the scientific literature, classifies the United States in physiographic provinces, and was the basis for many other studies developed for other countries. Since the beginning of the 20th century the concept of physiography was enlarged, including the more general idea of a geographic division of the landscape. The approach of a division of the terrestrial surface in homogenous districts characterized by particular processes and landforms is still a main topic for the earth scientists. To classify and divide areas with similar geomorphological arrangement is the basis for a correct planning of the territory for management and exploitation.

To this end spatial analysis and quantitative measurements of environmental variables are the basis for an innovative approach to investigate the mutual relationships between the different components of an ecosystem (Bétard, 2013; Hjort and Luoto, 2010; Hjort et al., 2012). Abiotic and biotic components are related to each other, but methods and techniques used for their assessment are not always comparable (Matthews, 2014). It is well recognized that the biotic richness and the diversity of an ecosystem, or biodiversity, strictly depends on the abiotic elements belonging to the same area. The geological substrate and the topographic setting, together with the morphological processes and the climatic conditions, create the basis for the weathering activity and the soil formation at the bottom of each biotic cycle (Musila et al., 2005). Accordingly, the definition and evaluation of the abiotic components is an essential step in order to compare and model the ecosystem evolution. Thus, since the last decade, the scientific community has started developing a specific field of research in the Earth Sciences aimed at the definition and measurement, in a quantitative perspective, of the diversity of the abiotic components, or geodiversity.

The geodiversity of an area is defined as its "natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, physical processes) and soil features" (Gray, 2004). The definition collects the three main abiotic components involved in landscape modelling: 1) the geological parameters, 2) the geomorphological processes and 3) the landforms and the resulting soil types, which are the starting conditions for the biotic cycles. In this qualitative characterization, no reference is given to how and how much these parameters need to be taken into account when studying an ecosystem.

Recent works focused on a semi-quantitative approach take into account the presence/absence of geosites (Reynard and Coratza, 2007) and their abundance and richness as indicators of high ranks of geodiversity. Ruban (2010) suggests a further clarification of the definition of geodiversity starting from the geosites, or the portions of the geosphere presenting a particular importance for the comprehension of Earth history, and considering their presence/absence in the study area as a measure for ranking the geodiversity. A semi-quantitative definition is also proposed, where geodiversity is the sum of "total quantity of geosite types occurring on a given territory" (Ruban, 2010). A complex geosite, described by different components has a rank equal to the maximum value observed among the counterparts' ranks. Thus, the geodiversity of an area is the sum of maximum rank scores of each type of geosites within a given territory.

In this work the geodiversity is not evaluated based on the presence of geosites. This choice is motivated by the fact that a landscape can be regarded as having a high value of geodiversity without hosting any geosite since the identification of a geosite requires some elements not directly linked to geodiversity as cultural and aesthetic values. For instance, in the Italian Geosites Inventory (www.isprambiente.gov.it) a large number of geosites are located in areas like the Padan Plain, where the morphological setting is quite monotonous and a low variety of landforms and processes are present. In these cases, the presence of geosites is not associated to a high geodiversity, but rather it is due to the meaning that the associated landforms have for that specific geographical area, like their social and historical context. In this context, it is important to reiterate that geodiversity is linked to the simultaneous presence in a region of a large number of processes and variables, while in order for an area to be a geosite only some peculiarities are required, not necessarily related to its scientific value. Following the decoupling of geodiversity from geosites, the second point is how the assessment of the abiotic components can be improved, moving towards a quantitative evaluation. This last approach has several advantages. First of all, a quantitative approach is an objective and repeatable procedure, thus allowing for the comparison of areas in different geographical contexts. Second, a geodiversity index (GI) value can be joined to a planimetric area, usually corresponding to a squared cell in a raster layer, so that large areas may be tiled in zones with similar GI values. Moreover, this approach would allow overlaying the GI to other spatial terrain information for different purposes. Geographical Information Systems (GIS) and remote sensing data are the best tools for a quantitative definition by exploiting digital terrain data (Yongxin, 2007). Geodiversity indexes have been mostly implemented for regional scale studies, improving the number and quality of historical cases in the recent years (Benito-Calvo et al., 2009; Hjort and Luoto, 2010; Melelli, 2014; Pereira et al., 2013; Serrano and Ruiz-Flaño, 2007; Silva et al., 2015; Vergari, 2009; Zwoliñski, 2010). In this context, the GI has been recently correlated with a new geovisualization technique in order to improve the digital cartography and the 3D virtual displaying (Martinez-Graña et al., 2014; Melelli et al., 2012). Useful implementations are also suggested for a wide range of purposes, such as geoparks and geoheritage characterization (Erikstad, 2013; Ferrero et al., 2012; Panizza and Piacente, 2009) or for hazard evaluation and prevention (Gordon et al., 2012).

The quantitative procedure for the GI assessment generally takes into account several terrain parameters, such as the geological, geomorphological, hydrographical and topographic datasets. Among these, the geomorphological data are the most difficult to include in an automatic procedure. Although geomorphological mapping production is aligned with new digital techniques (Gustavsson et al., 2006), currently the geomorphological characteristics are still the most difficult to obtain, in particular due to the lack of geomorphological maps for large areas. Moreover, the geomorphological information is extremely complex to be represented due to the huge amount of associated data, thus resulting in a map that is not easily converted to a digital format (Carton et al., 2005; Melelli et al., 2012). The large heterogeneity of symbols and legends used to represent landforms and their close dependence on the scale is one of the strongest barriers preventing the use of geomorphological datasets. Further, geomorphological mapping has a no continuous drawing. Symbols representing landforms are interposed with blank – empty space and in some cases the same area includes more than one landform.

Some geodiversity models already applied to Italian regional territories (e.g. Vergari, 2009) present some limits essentially due to i) the low number of components considered to assess geodiversity (i.e. those models in which the analysis is only limited to the lithology diversity) and ii) the a priori assignment of weights to the different geodiversity components.

The first purpose of this work is to elaborate a procedure that exploits GIS and Digital Elevation Models (DEMs) to obtain an automatic and unbiased mathematical expression for the morphological component of GI, the geomorphodiversity index (GmI). The second fundamental aim is to propose an indicator of geomorphodiversity, attempting to replace the landforms by DEM-derived morphometric parameters. Although a geomorphological map is a thematic map, which cannot be replaced at all, because of its wealth of information, some topographic attributes can usefully outline to model the geomorphological setting of an area when the corresponding geomorphological map is not available. In this approach, topography is considered as a signature of the superimposition between exogenous and endogenous forces shaping the land surface. Moreover, using topographic attributes different geographical zones can be compared and large areas can be represented. Being the DEM the only input data, this approach allows acquiring topographic variables with different horizontal resolution and vertical accuracy, and testing more than one topographic data for the same area. This represents the main difference between the numerical model proposed in this work and the formulas already existing in the scientific literature. In this way, the proposed method uses the geomorphological data only to validate the result and not as input parameters, in order to avoid the above-mentioned limits of the geomorphological thematic mapping.

We apply our approach to the Umbria region (Central Italy) and the results are validated comparing the resulting GmI map with the available geomorphological maps of a selected part of the study area, considering the geomorphology of a territory as the result of the interactions among all the components contributing to define its geodiversity.

2. The study area

2.1. Topographic setting

Umbria (Central Italy) covers an area of 8456 km^2 (Fig. 1).

The Umbrian territory, despite its limited extent, is characterized by an outstanding diversity of geomorphological and geological contexts. The hilly setting is predominant (Fig. 1), and is characterized by both low (200–500 m a.s.l. 52% of the regional area) and high (500–800 m, 24% of the total) landscapes. The first is present in the entire regional area, with the exception of the northeastern sector, where the high hills are prevalent, and of the southeastern portion, occupied by mountains (14% of the total area, with an average altitude value higher than 800 m, and the highest peak being Cima del Redentore at 2448 m, in the Sibillini Mountains). The remaining 10% is below 200 m, confined to the Terni basin and the middle and lower Tiber valley. The region is longitudinally crossed by the Tiber River, starting from the northern boundary along the Upper Tiber Valley with an altitude of 320 m and flowing along 50 km of the regional territory. The Tiber River draws partially the Tiber Basin, the largest of the intermountain basins in the Umbria region (with an area of about 1800 km^2) with an overturned Y shape splitting near Perugia (Basilici, 1997 and references within). The morphological setting agrees with the topographic setting. In Fig. 2 slope values are grouped into four classes highlighting a spatial distribution very similar to the altitude values mapped in Fig. 1. The lowest range (class 1, slope values between 0° and 5°, 25% of the total area) is present in the main intermountain basins, along the alluvial plain and around Trasimeno Lake. A second slope class (5°–16°, 41% of total area) is widespread in the whole area, mostly in the western part while the highest slope values (30–76°) only cover about 6% of the region.

2.2. Geological setting

A well-defined relationship between the topographic arrangement and the geological setting is present on the entire area. For this reason the Umbria region is an excellent test area for evaluating the geomorphodiversity with the method proposed in this paper, being the superficial topographic an excellent mark of the past and present geological and geomorphological evolution. The most ancient endogenous event still recorded in the superficial morphology is a compressive tectonic phase (from Oligocene – Miocene to Pliocene) that has formed the northern Apennine, a succession of anticlines and synclines with a NW-SE direction, eastward dipping and bordering the Umbria region along the eastern limit. The Apennine is mostly formed by the carbonate complex (Upper Trias – Lower Miocene) cropping out continuously in the southeastern portion of the region, and, with a lesser extent, in correspondence with the reliefs in the central sector. Moving from the bottom to the top of the sedimentary multilayer, the lithological composition changes from limestone to marl limestone. This geological complex exhibits low values of drainage density. Fluvial erosion results in deep river valleys and rectangular drainage patterns.

In the higher part of the sedimentary sequence, the terrigenous synorogenic complex is present (Oligocene – Medium Miocene) and outcrops in the northern and central part of the study area. It consists in a sequence of limestone and arenaceous layers interbedded with marls and clays. Fluvial and gravitational processes mainly consisting of slides and flows are the predominant processes shaping the surface. Dendritic drainage patterns are characteristic of this complex; the drainage density increases with the percentage of clay. The fold system was involved in an extensional tectonic phase, which created sets of normal faults resulting in valleys and intermountain basins. Moreover an isostatic uplift started in the Medium – Upper Pleistocene and still active, involved the entire area creating an high energy relief. Superficial sediments infilled the tectonic depression, actually grouped in the post-orogenic Plio-Pleistocene deposits, that are marine and continental sediments with a great compositional heterogeneity constitute the post-orogenic complex (Pliocene – Holocene). Conglomerates, sands and clays are present.

In order to complete the geological description of the region, the volcanic complex (age of 600–130 ky) must be mentioned, although it only covers a limited portion in the southwestern part of the area and is mainly characterized by ignimbrite deposits and stratified tuffs. The extensional tectonic activity involving the complex affected the spatial organization of the drainage network.

3. Methods

The quantitative index, which we propose, is based on the concept of geomorphological diversity or geomorphodiversity (Thomas, 2012), thus restricting the input data only to those variables associated with the evolution of the physical landscape.

In order to parameterize the processes shaping the Earth surface, topographic attributes must be necessarily considered. It is natural, therefore, to rely upon methods and data that can be directly derived through the geomorphometric analysis of Digital Elevation Models (Evans, 2013; Pike, 2000). The primary and secondary parameters (sensu Hengl and Reuter, 2009) useful for landform representation such as slope, aspect, curvature and roughness are extensively described in the scientific literature (e.g. Bétard, 2013; Melelli and Taramelli, 2010; Taramelli and Melelli, 2009a, 2009b; Wu et al., 2008). The evaluation methods are fundamental for having reliable

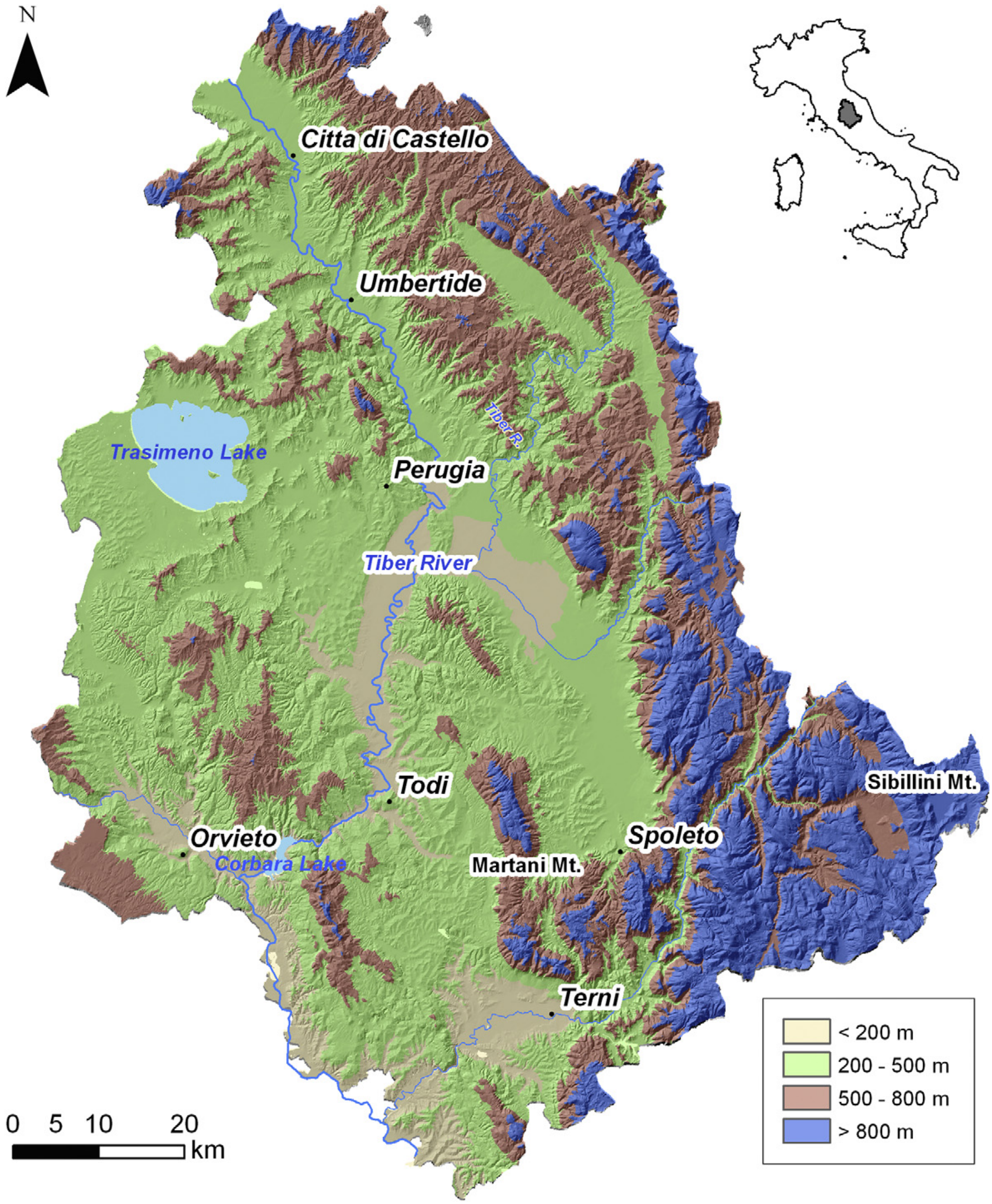

Fig. 1. Umbria region: location map and elevation ranges a.s.l. 1) <200 m, 2) 200–500 m a.s.l., 3) 500–800 m, 4) >800 m.

results. For this reason different approaches have been tested, which take into account the estimation accuracy and error (Honghu et al., 2011; Vaze et al., 2010; Warren et al., 2004). Some parameters have been investigated for better understanding their characteristics according to the topographic setting, in particular when they are derived from high-resolution digital terrain models (HRDTMs). Surface roughness is one of the most promising data. In order to capture the anisotropic and multiscaling properties of this attribute some attempts have been made (Trevisani and Cavalli, 2016).

However, the information associated with these attributes in some cases is rather similar. As a result not all these attributes are included in the analysis to not overload the procedure with redundant data. Because of this, a pre-analysis was done crossing-comparing the most used topographic attributes for the study area and analysing their correlation. In particular, the curvatures (both the planar and the radial) are discarded from the input data because, as discussed in Section 4.3, they show behaviour similar to roughness. The remaining factors, selected in the pre-analysis, are all included in the formula for the index characterization.

All these variables are analysed and managed in the ArcGIS (© ESRI) environment, by using the spatial investigation in map algebra with local (Raster Calculator) and neighbourhood (Focal Statistics) functions tools.

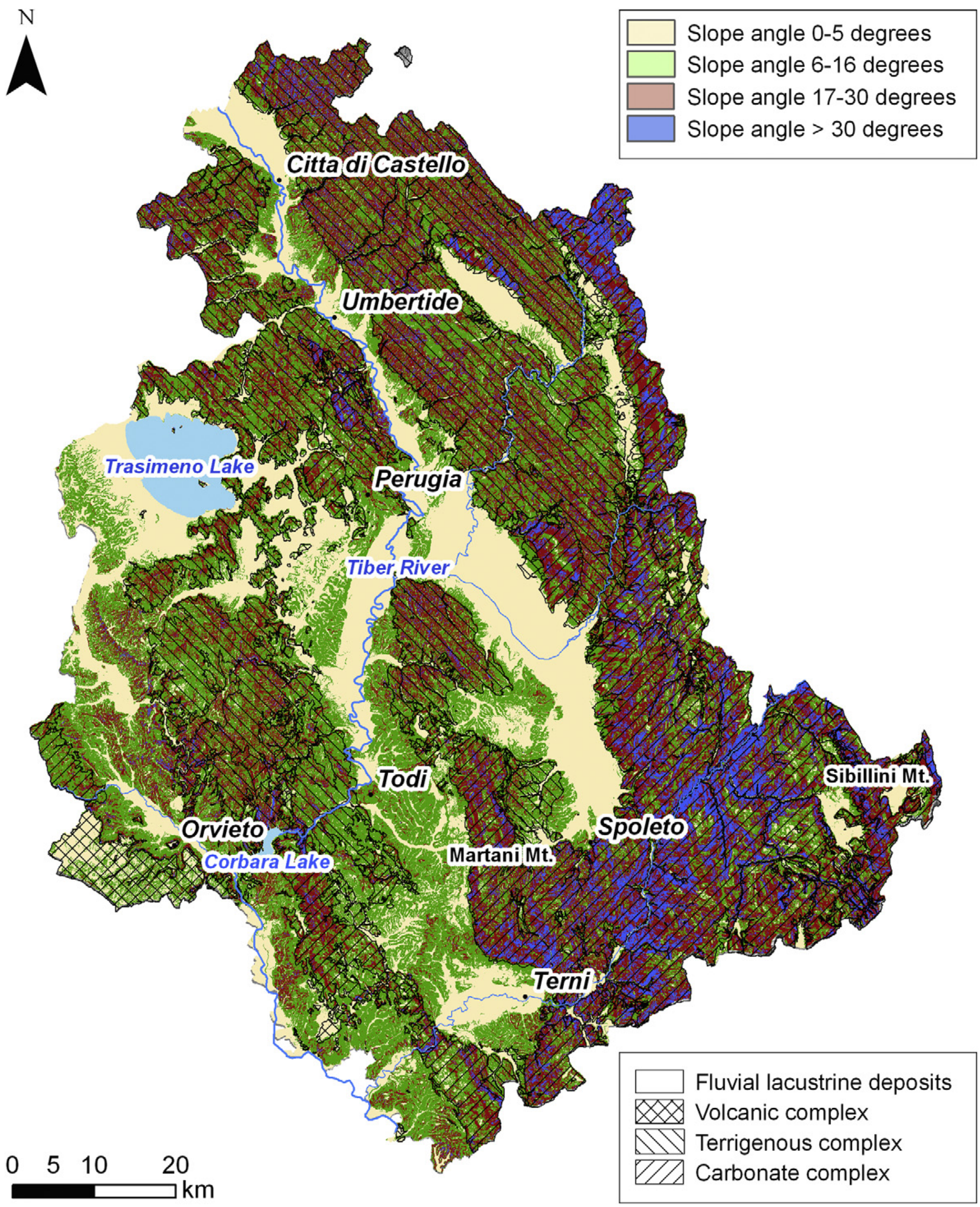

Fig. 2. Correspondence between slope angle values and lithological complexes. Slope angle classes: 1) 0°–5°, 2) 5°–16°, 3) 16°–30°, 4) >30°. Lithological complexes: 5) fluvial lacustrine deposits, 6) volcanic complex, 7) terrigenous complex, 8) carbonate complex.

The applied mathematical expression (1) is the sum of five factors; all of them are grids of different terrain parameters (Fig. 3).

$$GmI = Geo_v + Dd_v + Rg_v + Sp_v + Lc_v \quad (1)$$

where

- GmI is the geomorphodiversity index,
- Geo_v is the classified raster map of geological diversity factor,
- Dd_v is the classified raster map of the drainage density diversity factor,
- Rg_v is the classified raster map of the roughness diversity factor,
- Sp_v is the classified raster map of the slope position index diversity factor,
- Lc_v is the classified raster map of the landform category diversity factor.

Terrain data are derived from the DEM as a floating raster (Rg_v, Sp_v, Lc_v) or converted into a grid raster from a starting vector layer (Geo_v, Dd_v). Two functions are used: the focal function, and the local one (ArcGIS 10.x © ESRI).

In order to evaluate the diversity of each parameter, a focal function (neighbourhood statistic function) is applied resulting in the variety

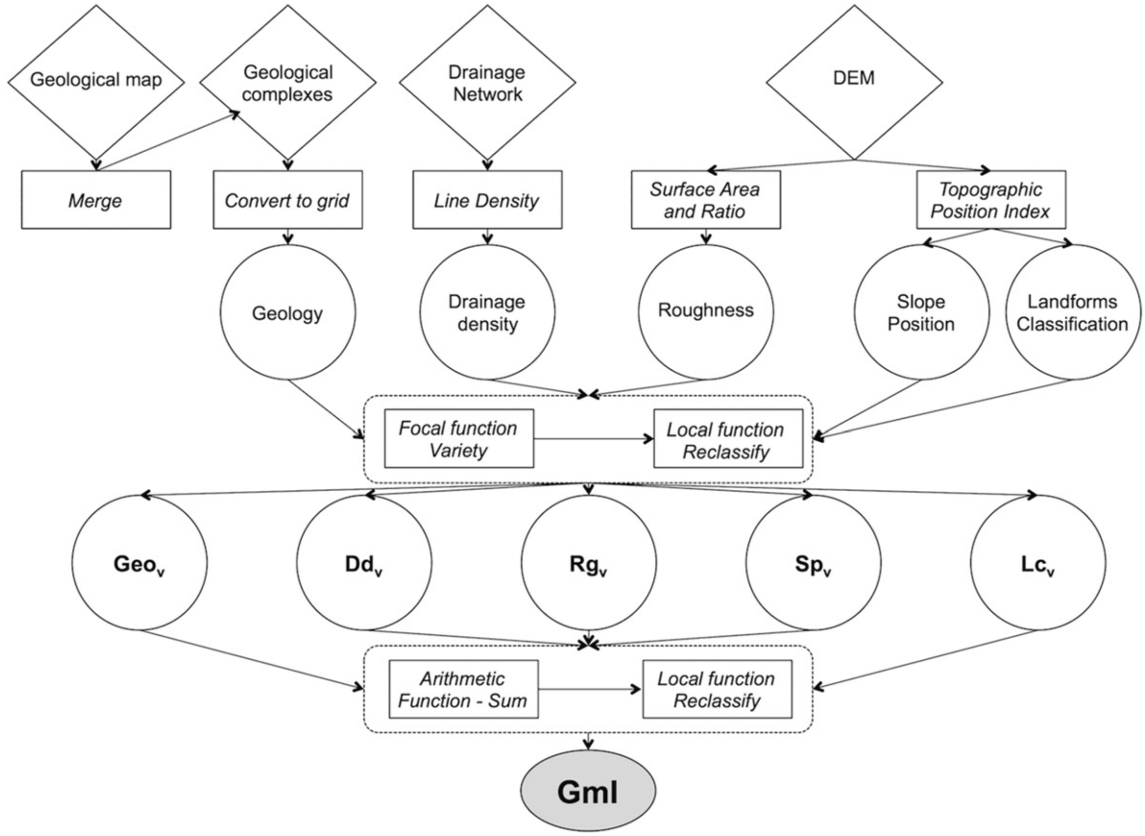

Fig. 3. Flow chart showing the steps of the analysis.

value. In the map algebra syntax for variety the input defines the argument list to evaluate the majority value for each cell location. A number can be input as an argument, but it will be converted to a raster at the current window and cell size set in the analysis environment, with each location containing the input number.

In Eq. (1) the statistical value used is the variety. This parameter defines the diversity of the values (the number of unique values) on a cell-by-cell basis within the analysis mask. The output is always an integer grid. The analysis mask can be defined as a rectangle of any dimension, a circle or annulus of any radius or an oriented wedge in any direction. The dimensions of each geometric figure are in cells or map units. The selected mask is a circle. The radius value is identified in map units in order to obtain a circle area equivalent to 1 km^2. The radius is selected considering a meaningful area comparable to the DEM resolution and suitable for the aim of the analysis. Even if a rectangle mask produces the best resolution enhancement, this shape also creates a blocky-looking output that results from the fact that peaks or sinks are included (Guzzetti and Reichenbach, 1994). In order to avoid this disadvantage, the circle optimizes an omnidirectional resolution.

Therefore, for each terrain parameter the grid of variety is computed. Since each parameter produces a variety grid with a range of values, which differs from the ranges obtained for the other parameters, all the input data are reclassified in five classes. This procedure scales all the input grids to the same number of classes and standardizes the values of cells from 1 to 5, whit 1 representing the minimum variety and 5 representing the maximum variety.

The choice to use five classes is the final result of several attempts where the qualitative geomorphological information is compared with the resulting areas of the reclassification. With five classes the cells are properly grouped, representing homogenous areas with the same characteristics in terms of geomorphodiversity. A lower number of classes limit the diversity inside some areas where, on the contrary, a large variety is well known. A higher number of classes change the aim of the procedure, which is to group the cells to highlight areas with homogeneous characteristics in terms of geomorphodiversity.

This procedure ensures that the range of classes is equal for all the parameters. The statistical method used to classify each dataset is the Jenks' natural breaks algorithm, which clusters the data values based on their distribution (Jenks, 1967). The algorithm reduces the variance within groups and maximizes the variance between them.

The final sum of the input raster data is then performed. The sum provides the GI value of an area. To obtain this value it is not necessary to use a weighted overlay, since the reclassification, according to Jenks algorithm, has already assigned the proper rank to each class of each input parameter. The sum assigned the same rank to each input parameter according to Jenks algorithm. In the final sum, the cell size is lowered to the minimum value of all the terrain parameters, i.e. 500 m. The choice of lowering the cell size is made by taking into account the resolution of the data entries, in order to increase the reliability of the output data. With this approach in mind, it is preferable to reduce the initial data with high spatial resolution rather than increasing the lowest ones.

4. Input data

4.1. Geological vector (Geo$_v$)

In order to obtain a geomorphodiversity index, which is capable to express the effects of modelling processes on the relief, it is necessary to consider a factor expressing the spatial variation of the main bedrock characteristics. For this reason a geological factor has been added to the input data.

The geological layer has been extracted from the official vector geological map of the Umbria region (http://www.regione.umbria.it/paesaggio-urbanistica/cartografia-geologica-informatizzata-vettoriale) stored in a GeoDataBase (ESRI © model). The shapefile, completed in 2012, derives from field surveys at scale 1:10,000. The original vector data has a total of 46,982 features, being the subdivision of the outcropping lithotypes and sediments hierarchically organized.

The litostratigraphic units are split in formations and members. The sediments are grouped into chronostratigraphic units defined by unconformity-bounded regional bodies: supersynthems, synthems and subsynthems. The characteristics related to the response in terms of geomorphodiversity assessment are the geological properties that are relevant to morphogenetic processes. Consequently, the outcrops have been grouped according to the type of rock or sediments and properties in term of topographic response (cohesion, permeability, tectonic style) to erosion processes. This grouping does not take into account the chronostratigraphic data and merge the levels considering only the properties relevant for the index assessment.

In this way seven classes have been obtained:

- Alluvial deposits constrained to river tracks on flat areas,
- Debris and fluvial deposits (mainly gravels),
- Fluvial and lacustrine deposits (mainly sands),
- Fluvial and lacustrine deposits (mainly clays),
- Terrigenous complex,
- Carbonate complex,
- Volcanic complex.

The final shape file is converted to a grid with a cell size of 25 m. Then, the diversity of the values is computed, obtaining an integer grid that is a raster format where a terrain value is assigned to each pixel, or cell. It was then reclassified in five classes and the break values were identified according to the Jenks algorithm.

4.2. Drainage density (Dd_v)

While topographic attributes and the derived indexes are adequate to highlight the geomorphological diversity in mountains and hilly areas, they fail in the flat ones. In plain territories, the low or null difference in altitude decreases the efficiency of slope parameters thus affecting their capability to describe morphometric characteristics.

The flat regions of the study area correspond to alluvial plain crossed by several rivers and streams. In active alluvial plains the morphogenetic processes can be fast, especially near the stream channels, developing a large number of erosional and depositional landforms. Hence, the drainage network may be a valid input parameter, useful for geomorphodiversity assessment.

In order to find an efficient numerical attribute to link the presence/absence of the river network to the geomorphology, the drainage density (Dd) is considered (Tucker et al., 2001). The drainage density parameter (Horton, 1945) is a function of erodibility and permeability and, therefore, it can be also connected to the degree of fracturing. Many studies on the spatial variation of the Dd values highlighted their usefulness in identifying zones with different geological and geomorphological characteristics (Del Monte, 1996; Lupia Palmieri et al., 2001; Strahler, 1958). The Dd, defined as the total length of the entire river network in a drainage catchment divided by the area of the basin, also depends on climatic conditions, slope angle, land use and landcover. Thus, it is an excellent parameter to identify and highlight the relationships between the hydrographical component and the geomorphological characteristics of an area.

Rather than to extract the rivers from the DEM with GIS-based synthetic network extraction we preferred to digitize the drainage network from the topographic maps with an equivalent scale (1:25,000). Even if the digitalization is strictly dependent on the spatial scale, it produces more reliable results on flat areas. The GIS-based procedures, instead, typically fail where the flow direction and accumulation are not well emphasized by clear differences in altitude, such as on flat areas. Furthermore, the algorithm may not consider neither the artificial channels, which sometimes do not follow the maximum slope direction, nor the meandering rivers with a radius of curvature lower than the cell size of the DEM. Considering that the alluvial plains are just the portions of the study area where Dd should improve the GI index, we preferred to rely upon input data with a higher level of accuracy.

In this way, a polyline vector layer was obtained. The topological relationships between the segments of the networks are added by converting the shape into a 3D vector layer. To compute the Dd value, the Line density Tool in ArcGIS was used. The magnitude per area unit is derived from the polyline features (rivers) falling within a given radius around each output raster cell, thus obtaining, as output, a grid data. Density is calculated in units of length per unit area, similar to the Dd parameter. Several values were tested for the radius in order to find the optimal resolution in an output grid with a cell size of 500 m. This spatial resolution has been chosen since it is the lowest one among those of the data entries. Once again it is important to highlight that drainage density is added in the GmI evaluation mostly to better define the diversity of the geomorphological aspect on flat areas. Where the topographic model is quite monotonous and the climatic conditions allow it, the fluvial process is the most important factor favouring and increasing geodiversity.

4.3. Roughness (Rg_v)

The topographic attributes derive from a DEM with a cell size of 25 × 25m. The terrain model is obtained from the digitalization and interpolation of contour lines and spots heights drawn on topographic maps with similar resolution. The altitude values are interpolated in order to obtain a grid DEM. The input data were the digital contour lines obtained from IGMI topographic maps, consisting of 131 digital topographic sheets at a scale of 1:25,000. The DEM was processed in three steps. In the first step the elevation values and the geometry of the contour lines were checked. In the second steps all the 131 topographical sheets were assembled in 21 partially overlapping maps (Taramelli et al., 2008). In the final step a Triangulated Irregular Network (TIN) was derived from contour lines and then converted in a raster grid. In order to reduce the errors, in particular in flat areas, detailed topographic maps at a 1:10,000 scale were introduced in the model. In the final DEM, sinks and peaks were erased (Taramelli et al., 2008).

The landscape roughness is the measure of how a topographic surface is irregular (Hani et al., 2011). In a geomorphometric approach, roughness can be based on different topographic attributes, such as the standard deviation of slope or elevation (Cavalli and Marchi, 2008; Frankel and Dolan, 2007). In this context, and with the purpose of avoiding redundant data in the calculation of the GmI index, the roughness was compared with other topographic attributes in a pre-analysis phase, through the use of a multivariate analysis. The topographic attributes taken into account were the slope angle, the planar and the radial curvature. In detail the curvature was computed as the second derivative of the input surface on a cell-by-cell basis. For each cell, a fourth-order polynomial of the form: $Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$ is fit to a surface defined by of a 3 × 3 window. The coefficients from A to I are calculated from this surface.

This analysis was performed using the ArcGIS Statistics tool (Band Collection Statistics) in order to highlight the correlation between parameters and avoid redundancy. The tool provides statistics for the multivariate analysis of a set of raster bands. As an output a correlation matrix was provided showing the values of correlation coefficients that represent the relationship between the crossed datasets. The correlation index is the ratio of the covariance between couples of layers divided by the product of their standard deviations. The range of the index is between +1 and −1. A positive correlation suggests a direct relationship between two layers. Results obtained from this procedure highlighted a good correlation between roughness and slope (correlation value equal to 0.84). The planar curvature has a correlation value with the radial one equal to 0.94, suggesting that the two variables are redundant. The correlation value of the curvature with the roughness is not particularly high (about 0.6). However, the curvatures (both planar and radial) are removed from the input data also considering that the drainage density is a suitable parameter for modelling the watershed lines of water accumulation (positive planar curvature), and the ridges lines (negative planar curvature). Based on these results, both the slope and the curvature were discarded for the computation of the GmI. Roughness is strongly affected by the scale, since the concept of roughness may be applied on a multi-scale level (Hollaus et al., 2011). In this study roughness was computed in a grid format as the ratio between the real surface area and the planimetric one of the same square cell (Jenness, 2004). High values of roughness identify zones where valleys and ridges are frequently alternated and are associated with heterogeneous geological substrate or with an intense geomorphological activity (Melelli, 2014). Therefore, the higher the value of roughness, the higher the probability to detect landforms. The surface area for a cell is calculated considering the elevation of that cell plus the elevations of the 8 adjacent cells (Jenness, 2004). A 3-dimensional space is built starting from the centerpoints of each cell, achieving nine columns with height proportional to the elevation value of each cell. Then the Euclidian distance between the focal cell's centerpoints and the centerpoints of each of the eight surrounding cells is calculated. It is important to highlight that this distance is not the planimetric one, being in a 3D space. A triangulation is performed using the centerpoints as vertices and the distances as sides. By limiting the area values only to the portion of the triangles lying within the cell boundaries, the surface area for that cell is estimated (Jenness, 2004).

4.4. Slope position index (Sp_v) and landform category (Lc_v)

The last two addends in the GmI formulation derive from a common morphometric value defined as a Topographic Position Index (TPI; De Reu et al., 2013; Weiss, 2001). The TPI is defined as the difference between a cell elevation value and the average elevation on a neighbouring area around the cell. Positive TPI values are associated with cell elevations higher than the surrounding, inside the mask analysis; negative TPI are associated with the lowest and near zero elevations in flat areas. TPI is scale-dependent; thus, attempts must be made to find the best resolution for the analysis. The final classification, based on Sp and Lc, depends on the scale used to analyse the landscape.

The TPI is computed considering a 100 m radius circle neighbourhood. The TPI is a scale-dependent parameter. The same location may be either a flat plain at a fine scale or the bottom of a deep canyon at a coarser scale of several kilometers. In order to select the best radius several attempts were made. The choice of a threshold of 100 m was considered appropriate for the morphostructures and morphosculptures present in the study area. Thresholding the TPI values at a given scale and pointing out the slope values near zero, slope position classes (Sp_v) can be extracted. In our analysis the threshold of 100 m is the same of the TPI grid and the slope position classes are six, distinguished in: valley, lower slope, flat slope, middle slop, upper slope and ridge. The TPI values below the threshold are classified as valley or lower slope, while those above the threshold are classified as upper slope and ridge. Flat slope and middle slope are the classes for TPI values near zero. Comparing the TPIs obtained at two different scales derives a further index. A set of rules is used for determining how landform values may be classified. The resulting grid is a landform category (Lc_v). In our analysis the scale range is between 500 m and 1000 m cell size maps. The detected landforms are grouped into ten classes (Table 1).

In the first class canyons and deeply incised streams are present; in the second one, midslope drainages and shallow valleys are considered. Upland drainage and headwaters, U-shaped valleys, plains, open slope, upper slopes and mesas, local ridges and hills in valleys, midslope ridges and small hills in plains, mountain top and high ridges are the other eight classes. For both Sp and Lc the focal function of variety is applied and the resulting grids are classified into 5 classes.

Table 1
Landform classes in landform category parameter.

Number	Morphological units
1	Canyons, deeply incised streams
2	Midslope drainages, shallow valleys
3	Upland drainages, headwaters
4	U-shaped valleys
5	Plains
6	Open slopes
7	Upper slopes, mesas
8	Local ridges, hills in valleys
9	Midslope ridges, small hills in plains
10	Mountain tops, high ridges

5. Results: the GmI map

The GmI is the sum of the variety of each terrain parameter taken into account. Each variety grid is classified into five classes in order to attribute the same weight to each parameter in the final sum (Figs. 4 and 5).

The percentage of the variety classes is: variety (v) v_1 (lowest), 12% of the total area; v_2, 38%; v_3, 36%; v_4, 12%; v_5 (highest), 2%. The lowest values (v_1 and v_2) are distributed along the larger valleys and where the terrigenous complex is more extended (northern part of Umbria), the highest values (v_3 and v_4) are uniformly distributed in the rest of the study area with some spots of v_5 along isolated zones on the south-western portion of the Umbria region.

The drainage density variety (Dd_v) classifies the original data into five classes, where the v_1 represents the 43% of the total area, v_2 14%, v_3 32%, v_4 9% and v_5 2%.

The highest values (v_4 and v_5) mainly occur in the western part of the region and, although they are also present, to a smaller extent, in the north eastern part, where fluvial lacustrine and terrigenous rocks prevail. The roughness final reclassified grid (Rg_v) shows a v_1 equal to 34% of the total area, v_2 38%, v_3 20%, v_4 6% and v_5 2%. The five classes of roughness show a good correspondence with the geological substrate, with the highest values belonging to the carbonate complex and to some portions of the terrigenous one. On the contrary the lowest values are distributed on the alluvial and fluvial-lacustrine deposits. The low values on the flat or gentle hillslope areas, although quite common, are a consequence of the DEM resolution and accuracy. The quality of the elevation model is not high enough to well represent the roughness of these areas. It is noteworthy, however, that high resolution DEMs are not always easily available for large areas. In particular for the Umbria region the high resolution DEMs as Lidar (Light Detection And Ranging) are available only for restricted areas along the Tiber river valley. Therefore, the choice of using a DEM with a coarser resolution to derive roughness appears to be a good compromise complementing the aim of the analysis and the data available for a regional evaluation.

The percentage of Sp_v they are as follows: v_1, 4% of the total area; v_2, 1%; v_3, 3%; v_4, 47%; v_5, 45%. The Lc_v shows the lowest variety; both v_1 and v_2 only cover 5%; v_3 covers 18%, v_4 31% and v_5 the remaining 40%. It is worth noting that Sp and Lc show the highest percentages in the upper classes of variety relative to the other parameters in the GmI equation (Eq. (1)). The different trend of the variables depends on the neighbouring area used for their estimation. For each variable the radius of the moving window is a consequence of the observed spatial distribution of the variables.

The final GmI map (Fig. 5a) is the result of the application of Eq. (1). The dataset is in a grid format with a cell size of 500 m. The coarser resolution, in comparison to the data entry cell size equal to 25×25m, is due to the drainage density map, obtained at a 500 m resolution. The values of the output grid (GmI) range from a minimum of 5 to a maximum of 25. Cells with value equal to 5 correspond to the minimum

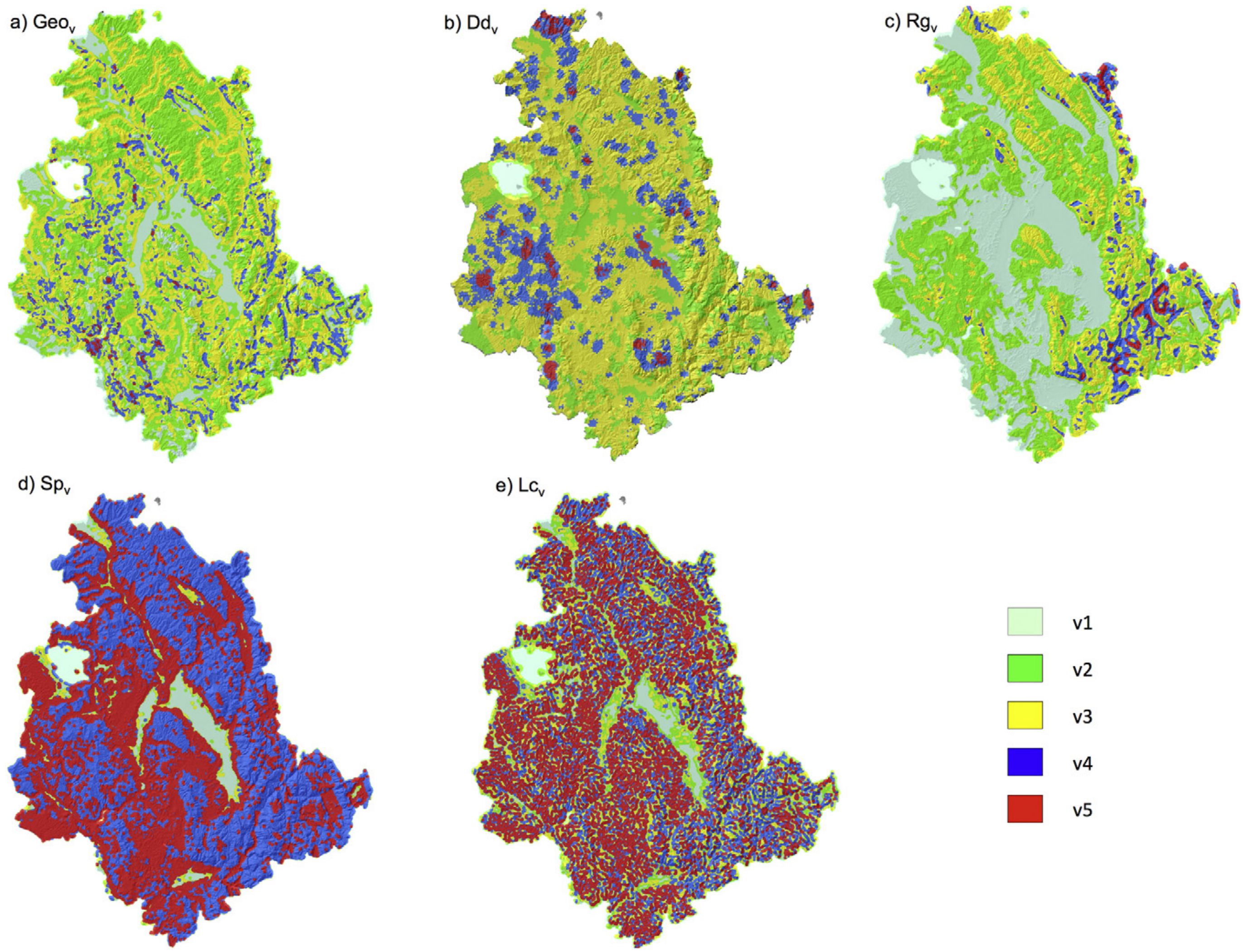

Fig. 4. Variety maps in grid format. a) Geological factor, b) drainage density, c) roughness, 5) slope position, 6) landform category. Colours indicate the variety, which increases from class v1 (lowest) to class v5 (highest).

variety for all the input parameters; values equal to 25 indicate that all the terrain data show the maximum variety. In the range 5–25 all the possible combinations are present.

The GmI grid was classified into 5 classes according to Jenks' algorithm, similarly to all the previous reclassification done on the data entries. As shown in Fig. 6, the index distribution is strictly linked to the topographic arrangement: where the amplitude of relief is high the GmI shows the highest values; on the contrary, the lowest value uniformly characterizes the main flat areas of the region.

However, this trend is not observed everywhere and some further considerations must be made. In order to better highlight the areas where the GmI reaches the lowest and the highest values (class 1 and class 5 respectively) the two classes were extracted from the GmI total grid, thus obtaining two grids representing class 1 and class 5. Each of the two grids was converted to a point vector layer allowing the usage of a density point tool to generate a density map. The density was calculated for the points falling in a neighbourhood. If no points fall into the moving window, a NoData value is assigned to the output cell. The density value is directly proportional to the number of points falling into the mask. Lowest GmI values (Fig. 7a, class 1, 5% of the total area) cover a large areal extent and correspond to the central part of the main intermontane basins, i.e. the northern part of the Upper Tiber Valley (number 1 in Fig. 7a), the Umbrian Valley (number 2 in Fig. 7a) and along the opposite segment of the Tiber Basin Valley (number 3 in Fig. 7a) as well as in the Terni basin (number 4 in Fig. 7a).

However, it is worth noting that the portion coincident with the class 1 of GmI is always limited to the center of the basins, whereas the index value increases towards the edges. It is important to note also that the lowest value is not so widespread in the Gubbio basin and on the flat uplands of the eastern regional limits; here the class 2 (12% of the total area) is present. In both cases the plain areas are less wide than in the Tiber basin segments. Consequently, the increase of the GmI value can be interpreted as the result of the close proximity of the mountain ridges bordering the basins. The abrupt change in energy relief along the transition between mountains and plains, usually occurring along a normal fault system, is responsible for the diversity of the geological component and, above all, of the topographic setting. The spatial irregularity of these components is again the main cause of the abiotic diversity. The GmI classes 3 and 4 (respectively 37% and 38%) are equally distributed on the hilly areas and on some portions of the mountainous areas.

The most meaningful result is the spatial distribution of the density map of class 5 (Fig. 7b), which shows a very good agreement with the locations of the sites having the greatest natural importance in the study area. Five main areas of interest, characterized by the highest values of density, are detected. In the northern part of the Umbria region

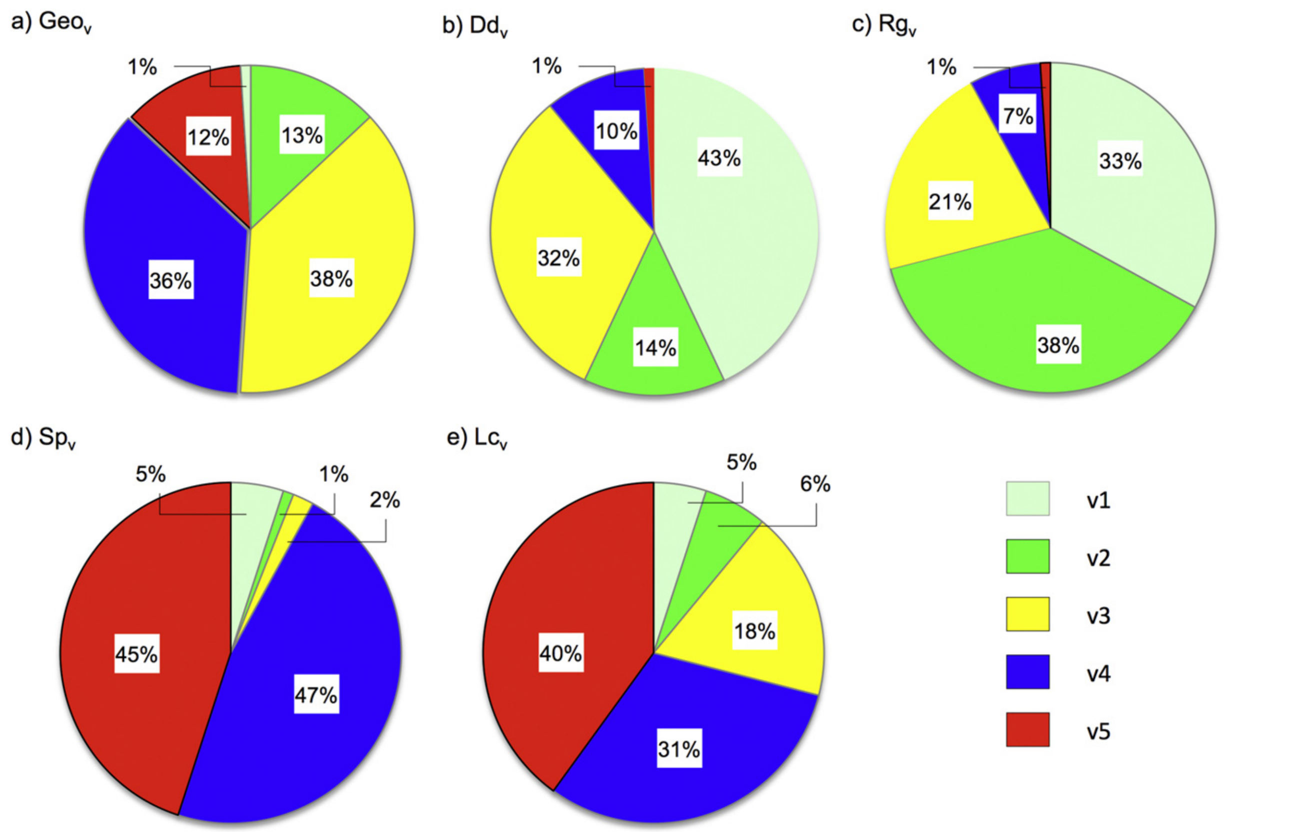

Fig. 5. Pie charts showing the percentages of each variety class for the maps shown in Fig. 4. a) Geological factor, b) drainage density, c) roughness, 5) slope position, 6) landform category. The colours indicate the variety which increases from class v1 (lowest) to class v5 (highest).

the first relevant area is identified in the Mt. Cucco Regional Park area (number 1 in Fig. 7b). This protected area is known as the 'womb of the Apennines' with a complex hypogean system and karst phenomena (Gregori et al., 2005). Moreover, here some very particular geosites are present due to the complex interaction between slope evolution and geomorphic processes. In the central and southern portions of the Umbria region, moving from west to east the other main relevant areas are present. In the western sector the zone between Allerona, Fabro and Ficulle (number 2 in Fig. 7b) is famous for the badlands covering large areas, creating an amazing landscape, not so common in the Umbria region. Then, moving eastward a belt elongated north south is present around the Corbara Lake (number 3 in Fig. 7b). The Tiber River crosses the area along the Forello Gorge. As said above, this zone is meaningful for the geomorphological evolution of the entire regional territory: a fault system created the valley deflecting the Tiber River path in the lower Pleistocene. According to this tectonic evolution, the entire area is very far from an equilibrium condition, for both the river drainage network and the slope assessment. Therefore, the geomorphological evolution is active and well evident. The remaining two areas characterized by high-density values of the highest GmI class are located in the carbonate complex, corresponding to the mountainous part of the Umbria region. One of these zones (number 4 in Fig. 7b) is part of the Valnerina, a valley well known for being one of the best tourist destinations due to its natural values. The maximum density partially coincides with the extent of the "Valnerina geologic park and Geologic Study Centre". Geosites and geomorphosites are present in this park, as well as georoutes. The last area (number 5 in Fig. 7b) is surrounded by the National Park of the Sibillini Mountains. The zone (700 km^2) is the only national park present in the Umbria region (Fig. 8).

It contains some geological uniqueness including polje, karstic features and fluvial landforms (alluvial fans). Moreover, the area is enriched with spectacular glacial (glacial cirque) and periglacial (stratified talus slope deposits e.g. grèze litée) landforms dated to the Middle Pleistocene and now involved in mass wasting phenomena.

6. Validation

In order to validate the results a comparison with a geomorphological digital map was performed.

In the geomorphological digital dataset each landform is represented as a vector (point, polyline or polygon) with an attribute table where the type of feature and the process responsible for each landform are always mentioned. The vector geomorphological map was converted to a raster dataset, with a cell size of 50 m, in order to compute the landform multiplicity (focal statistics tool in the software ArcGIS) and compare it with the geodiversity index map. The landform classification was computed considering i) the number of landforms and ii) the number of landform types, in a 1 km^2 circle neighbourhood.

The relation between the number of landforms of the geomorphological map and the values of the GmI was evaluated using the Zonal Statistics tool in GIS, in order to quantify the capability of the GmI to detect the geomorphological diversity of the area.

The validation was tested in a portion of the Upper Tiber Valley (Sansepolcro sub-basin, Fig. 1) where the GmI shows the lowest value of diversity. The area is an intermontane basin with a width of up to 4500 m, completely covered by the Tiber River alluvial deposits and infilled with tens of meters of Holocene alluvial deposits. The eastern boundary is characterized by a "bajada" of large alluvial fans; along

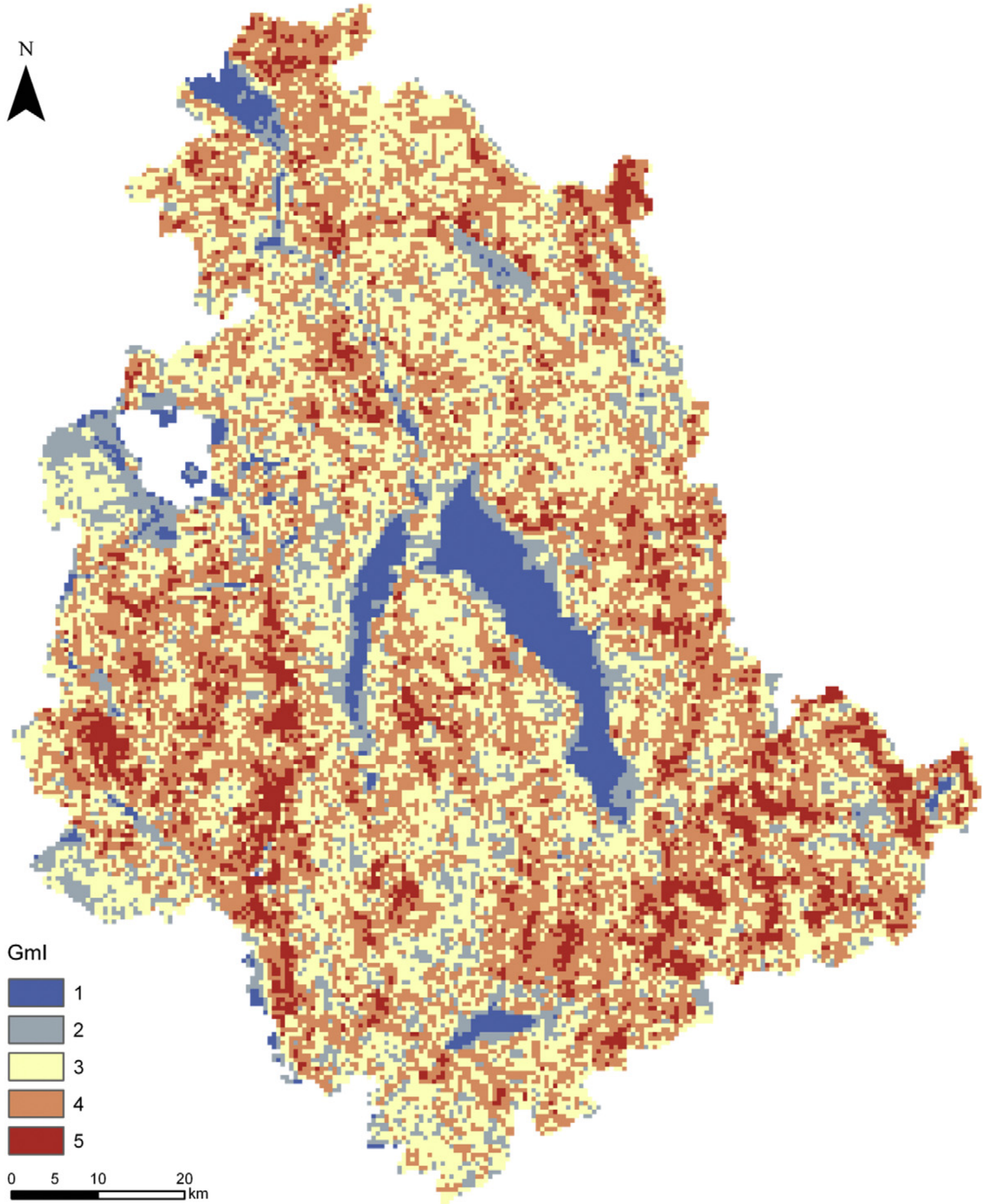

Fig. 6. Geomorphodiversity index (GmI) map. The value of GmI increases from 1 (lowest) to 5 (highest).

the western boundary alluvial terraces are present. The normal faults activity bordering the basin generated an intensive subsidence (Melelli et al., 2014). The morphological arrangement is a large flat area whose monotony is interrupted only near the bordering limits. This area was chosen as a test area in order to observe if, despite the presence in the geomorphological map of a certain number of fluvial and tectonic landforms, the correlation between presence/absence of features and GmI is verified.

As shown in Fig. 9a, the range of the number of different types of landform per each GmI value is higher as GmI increases. Moreover, the index value is very well correlated to the average number of landforms (Fig. 9b).

To conclude, the outcomes of the validation analysis indicate that the GmI index is capable of representing very well and with a high degree of accuracy the diversity of landforms occurring in the study area.

7. Discussion

The algorithm proposed in this work is inspired to the expression proposed by Serrano and Ruiz-Flaño (2007), where the geodiversity index is computed as the multiplication between N and R, divided by lnS. In this formula N is the arithmetic sum of the physical elements, R is the roughness and S is the real surface. The Naperian logarithm is introduced to normalize the result with the area of the unit. In the

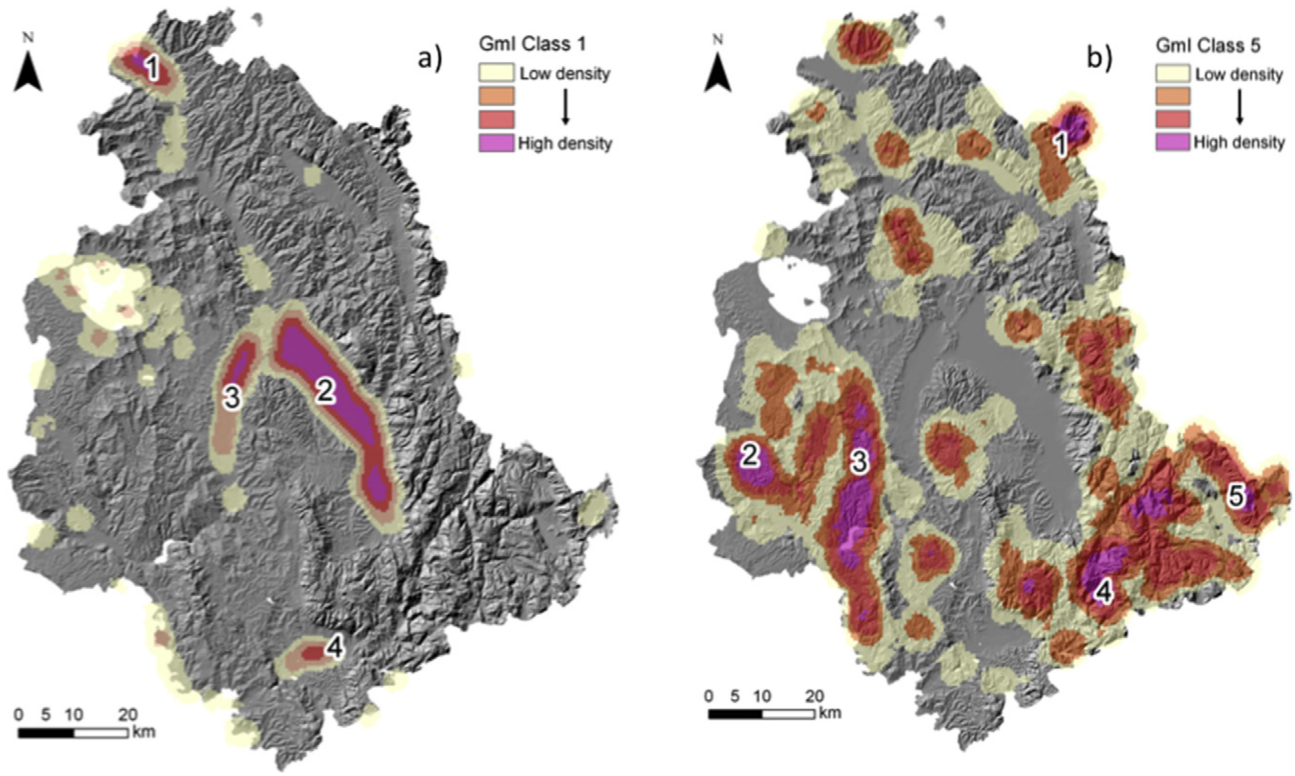

Fig. 7. Maps of the spatial density of the GmI values belonging to: a) class 1 (lowest values of GmI); b) class 5 (highest values of GmI).

equation proposed here (Eq. (1)) only the arithmetic sum of the physical elements is taken into account. The reason is that in this work only the geomorphodiversity is evaluated; therefore, the morphometric parameters are considered as the most important factors for the analysis. The only parameter, which is not strictly morphometric, is the geological factor. The choice of considering this parameter is based on the consideration that the lithotypes affect the response of the relief to the geomorphic agents, and, consequently, of the resulting landforms. All the input parameters are strictly related to the morphology of the surface. To compute the geomorphodiversity, we assumed that all of

Fig. 8. Pian Grande with Mt. Vettore in the background (left). In the foreground the Mergani River (photo by G. Mulazzano).

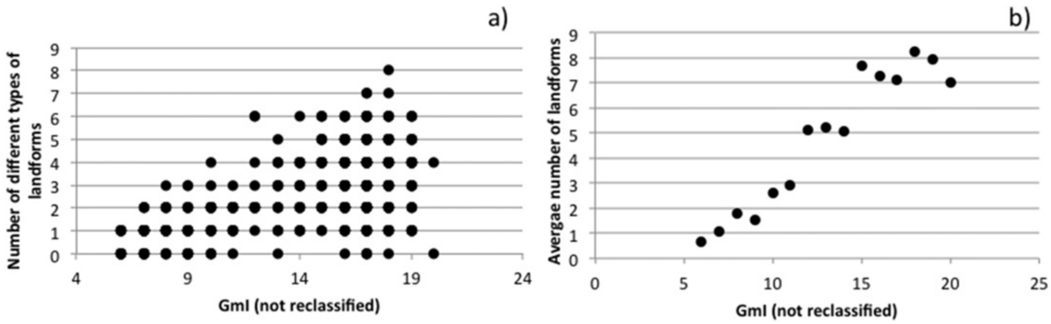

Fig. 9. Results of the validation. Relationships between: (left) GmI and average number of landforms; (right) GmI and number of different types of landforms.

them have the same weight since the grids of their variety are added to each other, once reclassified in the same number of classes. For that reason the roughness is simply added, and not multiplied, to the other factors. We neglected the natural logarithm of the cell size because the analysis is confined to the invariable medium-scale of horizontal resolution of the DEMs used.

The main advantage of this formula is that the diversity of each input data is already a measure of the diversity of the abiotic components. This is a very important point because we do not simply sum a quantity as is commonly done in most of the previous scientific approaches. The focal function allows measuring the variety in well-defined surrounding areas, thus converting the initial terrain information to an intermediate step, which leads to treat the data in terms of 'diversity'. Moreover, the source of the input data (except for the geological layer) is the grid DEM. The great availability of DEMs derived from remote sensing allows analysing large areas, while terrain data (as geomorphological or geological dataset) are not always available and not always uniform. However, the quality of DEMs analysis depends on the spatial resolution. In particular some of the input parameters in Eq. (1) depend on the scale of analysis; these include the roughness, the slope classification and the landform classification. A good compromise to minimize this problem is to restrict the analyses to the scale range typical of meso-scale features, i.e. from few tens of meters to some hundreds of meters. According to this limit the DEMs cell size is selected with a medium resolution, capable to guarantee the required precision needed for the application of the method.

We validated the method using traditional geomorphological maps, although these thematic maps are excluded as input data. The aim is to compare the qualitative classification of the landscape based on landforms and shaping processes with the quantitative method proposed. The good spatial correlation reported between the geomorphodiversity index values, the number of landforms and with the number of different types of landforms seems to confirm the quality and robustness of the proposed quantitative approach.

The GmI index is inspired to the previous ones proposed in the scientific literature (Benito-Calvo et al., 2009; Hjort and Luoto, 2010; Pereira et al., 2013; Serrano and Ruiz-Flaño, 2007; Zwoliñski, 2010). Some similarities may be underlined, that is the spatial analysis in a GIS system and the raster format preferred for the data input. However this index has two main differences compared to the other numerical methods. The first is that in the final sum of the formula the single addends do not derive from a sum of a quantity of elements (i.e. the number of geological lithotypes outcropping in a pixel) as in many other formulations (Hjort and Luoto, 2010; Pereira et al., 2013; Zwoliñski, 2010). In this formula the addends are grids with values from 1 to 5 measuring the variety of the input parameter. This way a specific focal function is used with the aim of evaluating the diversity in each pixel (or cell). The second main difference is that the proposed method, with the exception of the geological layer, takes advantage of Digital Elevation Models for deriving all the input parameters. Digital Elevation Models are widely accessible for large areas and often available for free downloading. Starting from the topographic signature allows releasing the index from thematic maps that are not always available to reproduce the method in different geographic regions.

Moreover, comparing the geomorphodiversity with the method for delimiting the physiographic units could highlight some important points of convergence between the two concepts as much as substantial differences. The quantitative procedure proposed in this work and the results in terms of spatial diversity may be, in our opinion, a valuable parameter to be considered in the definition of the physiographic units.

8. Conclusions

The natural heritage is one of the most important wealth in many areas of the Earth surface. The diversity of natural ecosystems manifests itself as biodiversity and geodiversity, which are mutually dependant. The topographic surface, where the geomorphic agents are acting, is the layer where the abiotic and the biotic elements interact; at the same time, it is the constraint for the geomorphological evidence.

Geomorphodiversity is the aspect of geodiversity associated with the geomorphological diversity or the quantity and number of types of landforms.

A quantitative evaluation in GIS requires digital data as input parameters. Landforms are generally represented in geomorphological maps as objects in a vector format deriving from a semantic approach. According to this method, a landform is the result of a classification that simplifies the "real world", depending on the scientists' background and the research context.

However, the need to classify the landscape in well-defined shapes can lead to some limitation if the traditional mapping techniques are used. The geomorphological maps show a high heterogeneity in terms of graphical techniques used for the cartographic output. The map scale involves subjective choices for landform representation and localization. These limits strongly affect the extent and the shape of each single landform represented on a map. Therefore the landform representation depends on the scale and may be depicted with a point, a polyline or a polygon, thus varying the spatial extent of the input data and their consequent weight in the spatial analysis.

Based on these considerations, the use of a GIS-based approach like the one proposed in this work should be preferred for regional analyses. In this approach, extracting the topographic primary and secondary attributes from the terrain data performs the analysis of the morphological input factors. The range, the ranking and the spatial distribution of these topographic attributes allow classifying the morphology using an unbiased method.

The high correspondence between the physical landscape and the factors at the base of the geomorphodiversity in the Umbria region confirms that the concept of geomorphodiversity is another way to explore the physiography of a territory (Bailey, 2009; Fenneman, 1916). If on one hand the geomorphodiversity excludes the biotic components and the human pressure, on the other it includes all the fundamental variables that characterize the geomorphological arrangement of an area.

Since the geomorphological landforms and processes are strictly linked to the geological evolution of an area, the proposed index may highlight, better than other methods, the areas where the abiotic components are more active and are modifying the landscape. This approach is particular meaningful in areas such as the Umbria region where the endogenous and exogenous forces are still working to built a unique landscape in which – quoting the French geographer H. Desplanques (1911–1983) – "the contrasts overlap almost for fun".

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