12 March 2024

Morphometric indices to describe Italian territory

Introduction

The Istat digital cartographic layers, continuously updated at municipality level, represent the reference point of the official territorial statistics spread by the Institute

These layers, thanks to the countless data linked to them, have a great deal of value related to statistical description of the Italian territory; and in addition to this, because of their capillarity, it can be used as an informative basis for land and use cover issues too.

To enrich the information assets of the geographic layers produced by Istat, it is proposed an experimentation based on the calculation of some statistical indices useful to describe the entire Italian territory according to its morphometric characterization. In fact, most of the physical and biological processes that occur on the environment are highly correlated to the topographic position of the zone on which they are occurring: top of the mountain, inside a valley, on an exposed ridge, on a lowland, and so on.

Some examples of these processes include erosion and deposition of soil, balance and hydrogeological response, exposure in windy areas. These biophysical characteristics represent some fundamental parameters to identify optimal habitat, composition, distribution and abundance of the animal and plant species.

The indices morphometric calculation task, described in this methodological note, is based on automatic procedures starting from raster[1] layer using GIS (Geographic Information System) tools[2]; the possibility of transferring all the calculation procedures in other software environments and of recalculating them whenever necessary (i.e. having up to date data), it allows to propose them as valid statistics that enrich the information base made available by the Institute.

These indices can also satisfy the need to publish statistics based on a regular grid, as Eurostat requires.

Reference data

As already mentioned above, in this activity, all the reference geographic layers are both raster and vector ones; among these, the most important is surely the DEM (Digital Elevation Model)[3]; therefore, an informed choice of this layer is a fundamental thing to extract the right values of the indices that represent the basis of the statistics about the morphometry of the Italian territory.

In our experimentation, during the preliminary phase in order to decide what the best data to

[1] A raster file is an image based on a rectangular grid of pixels.

[2] GIS: Geographic Information System is an instrument that allows you to analyze, represent, and interrogate features or events that happen on a specific geographic area.

[3] A **D**igital **E**levation **M**odel represents the bare earth surface, removing all natural and built features.

use was, it was decided to try two different DEM typologies: DSM (Digital Surface Model) and DTM (Digital Terrain Model).

The choice fell on the EU-DEM v1.1, a COPERNICUS[4] dell'*European Environment Agency*, which can be downloaded at the link:

https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1

as regards the DSM data.

As regards the DTM ones, we focused our attention on three products:

- DTM Tinitaly at 10 m of spatial resolution[5] (Tarquini et altri, 2023);
- DTM NASADEM_HGTv001[6]
- DTM Aster V3.

In fig.1a the screenshot of the internet page relating to EU-DEM v1.1; while in fig.1b the DTM Tinitaly one.

L'EU-DEM (European Digital elevation model) v1.1

The EU-DEM 1.1, although it is a DSM, and so not really suitable for a precise description of the morphometry, give us a lot of guarantees to produce a very high quality statistical data, because:

- it has a 25m pixel on the ground (spatial resolution); this allows us to describe the morphometry not only at a municipality level but sub-municipal too, for the entire Italian territory[7];

it was produced by a rigorous scientific methodology using a constellation of satellite techniques that permits a high reliability of the data;

- it is homogeneous for the entire Europe; this permits the comparison of the data at continental level.

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[4] Copernicus is the European Earth observation programme, looking at our planet and its environment to benefit all European citizens. The programme consists of a complex set of systems that collect data from multiple sources: Earth observation satellites and in-situ sensors such as ground stations, and airborne and sea-borne sensors. Users have full, free and open access to this data, which is also processed to provide a set of services based on reliable and near-real time information.
Copernicus services address six thematic areas: land, marine, atmosphere, climate change, emergency, and security. They support a wide range of applications, including environment protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection, and tourism.
For more information, visit the Copernicus website.

[5] For more info: http://tinitaly.pi.ingv.it/

[6] For all the information about: https://lpdaac.usgs.gov/products/nasadem_hgtv001/

[7] For the EU-DEM characteristics:

https://land.copernicus.eu/user-corner/technical-library/eu-dem-2013-report-on-the-results-of-the-statistical-validation

Look through the specifications of the EU-DEM, we can read: "*It is a hybrid product based on SRTM and ASTER GDEM data fused by a weighted averaging approach*". The fact that the starting points for its implementation were ASTER and GDEM, so NASA (National Aeronautics and Space Administrations) products, make it a reliable basis for our purposes.

The biggest problem derived from the fact that it is not yet validated, at least the 1.1 version. So, in this experimentation, the EU-DEM v1.1 is not be used.

IL DEM Tinitaly

The Tinitaly DEM, at 10m of ground resolution, is an elevation model realized by the Istituto Nazionale di Geofisica e Vulcanologia (sezione di Pisa); it is extremely reliable but it doesn't cover the entire Italian territory. In fact, it cuts off the Campione d'Italia municipality, located in the Province of Como (Lombardy), which is an Italian exclave in the middle of Swiss territory.

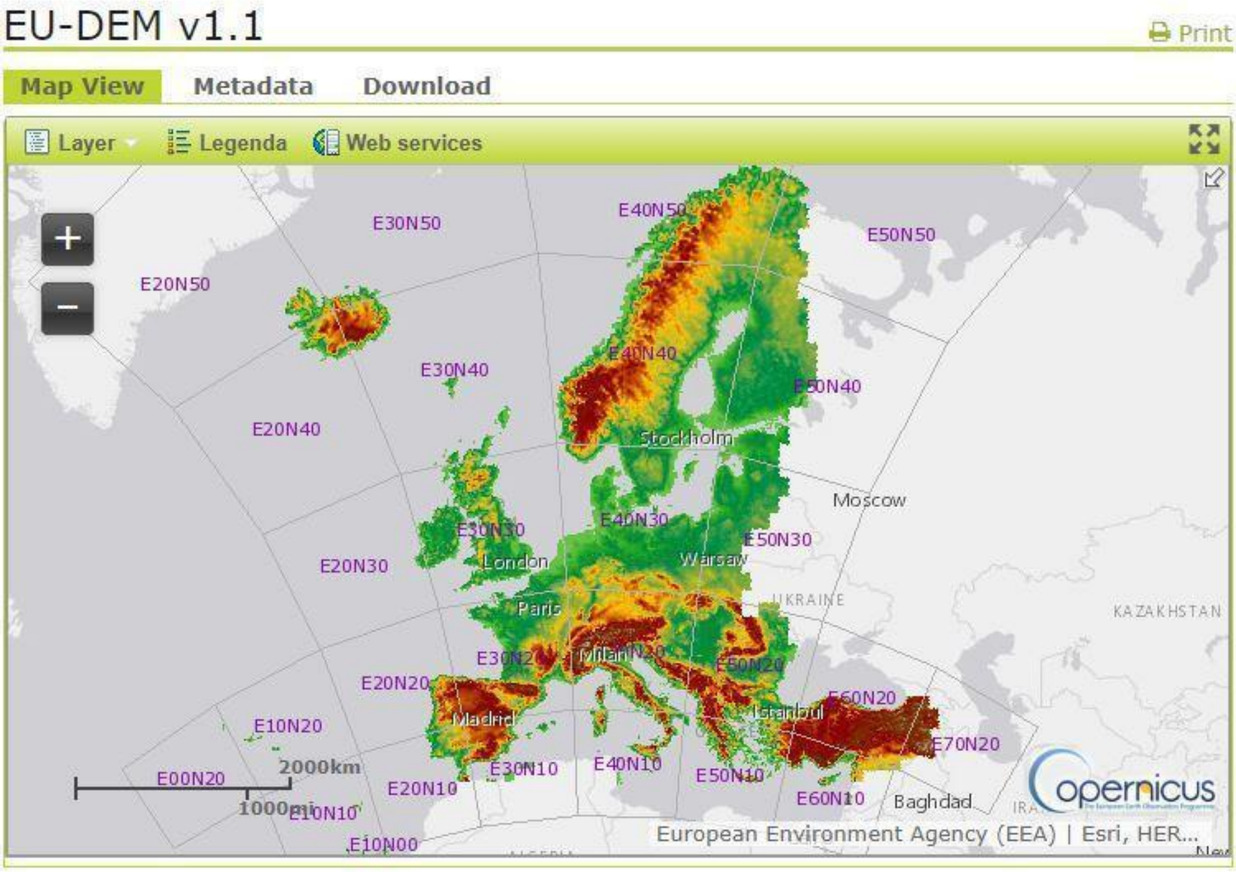
In short, it can be said that the starting data are heterogeneous: Regional Technical Cartography, Military Geographic Institute cartography, aerial laser-scanner data, GPS (Global Positioning System) data, etc.

So, on the base of these data, using interpolation methods, a 10m of resolution DEM is produced; it is therefore a DEM absolutely suitable to describe the Italian morphometry at municipality level.

In the accompanying note[8], however, is outlined: "*TINITALY supplies a 10 m-resolution DEM and a suite of DEM-derived products in grid format covering the whole Italian territory. The INGV and the TINITALY authors make every possible effort to supply the best available information, but no warranty, expressed or implied, is provided as to the accuracy and reliability of the data supplied in TINITALY. Users are cautioned to carefully consider the nature of the provided data before using it for decisions that concern personal or public safety or in relation with business involving substantial financial or operational consequences. Conclusions drawn from this Database, or actions undertaken on the basis of its contents, are the sole responsibility of the user*." In the light of the above, it is not compatible with the production of statistical indices, which, although experimental, must describe the territory with a very high accuracy.

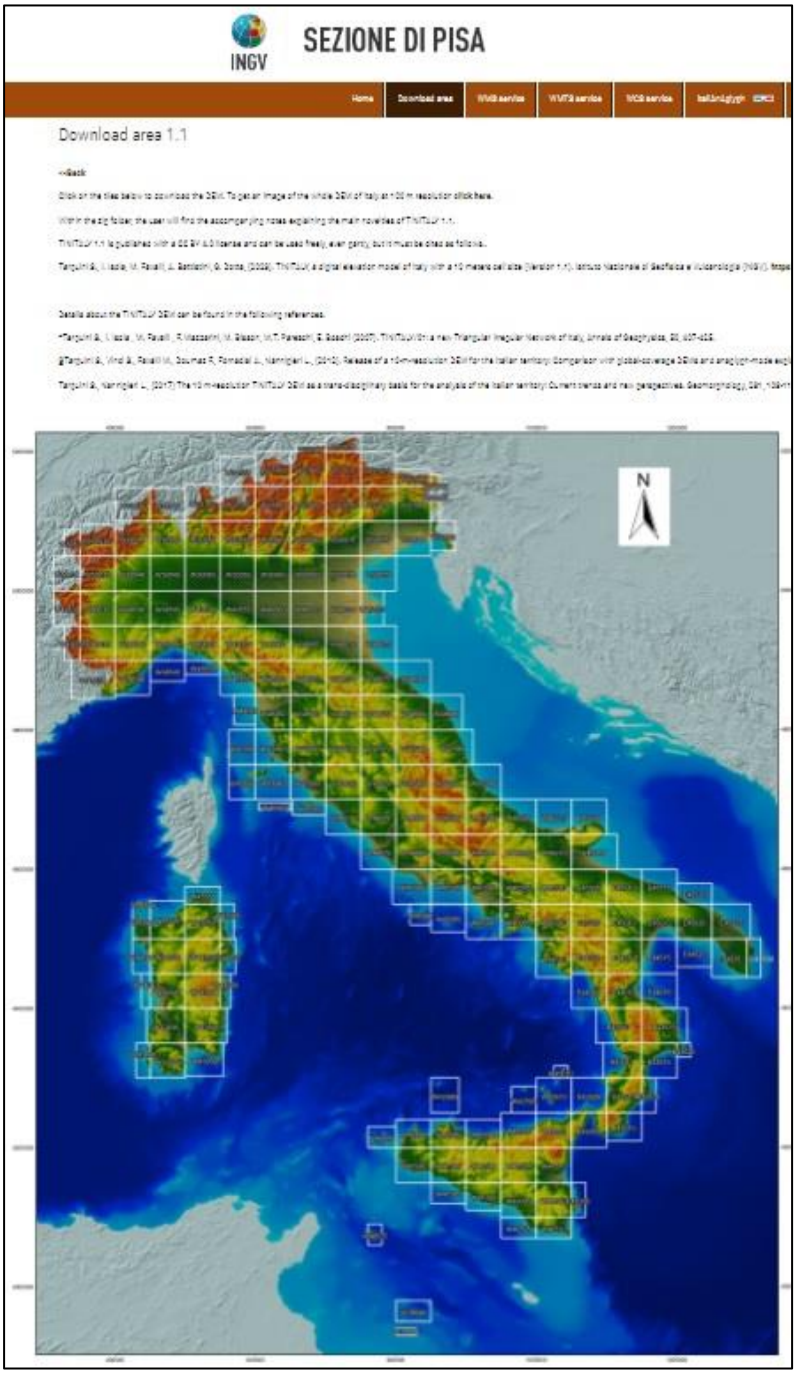
[8] https://tinitaly.pi.ingv.it/Tinitaly_1_1_AccompanyingNotes.pdf

Figure 1a – Excerpt of the EU-DEM v1.1 internet page



Source: https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1

Figure 1b - Screenshot of the DTM Tinitaly internet page



Source: https://tinitaly.pi.ingv.it/Download_Area1_1.html

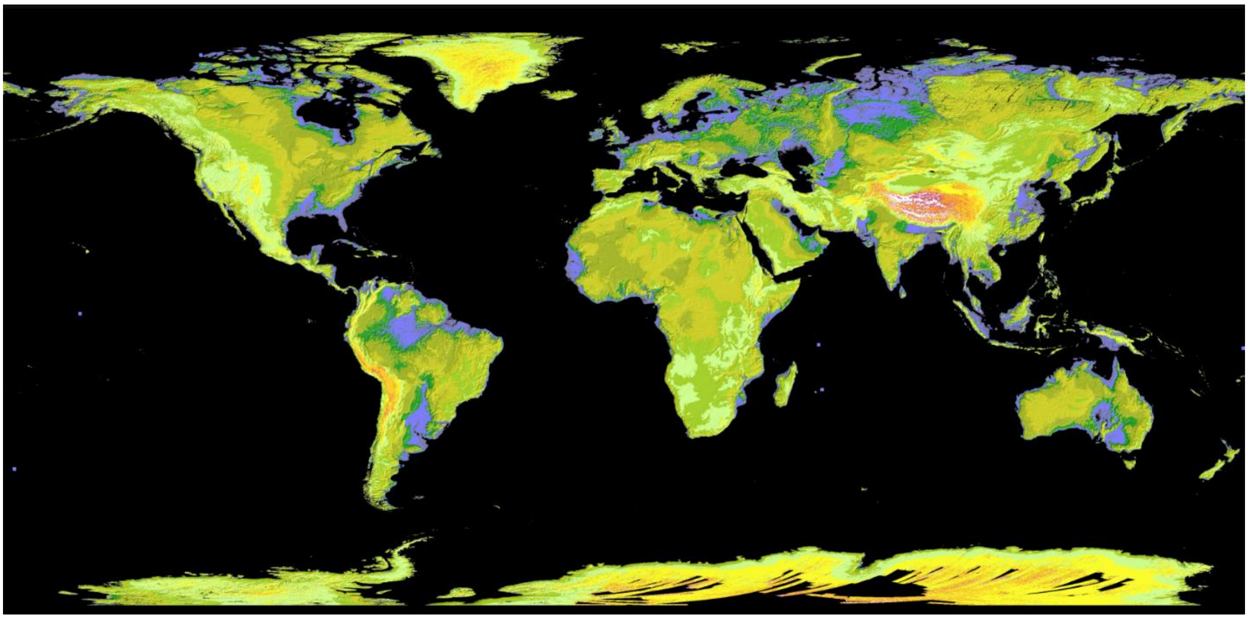
L'ASTER GDEM Version 3[9]

The Advanced Spaceborne Thermal Emission and Reflection Radiometer version 3 (ASTER V3), is a global DEM based on image processing methodology that involved about 2,3 millions of images acquired from ASTER archive. The spatial resolution is of an arcsecond for pixel.

This last concept, determines that the pixel is variable, when the ASTER V3 is re-projected at the coordinates system of the Istat cartography (WGS 84 32N – EPSG: 32632).

Despite this inconvenient, this DEM can be used for the morphometric indices production.

Below a theming of the ASTER GDEM.



Source: https://asterweb.jpl.nasa.gov/gdem.asp

IL NASADEM[10]

The NASADEM_HGTv001 is surely an extremely reliable product. This DEM it has been derived starting from telemetric data acquired in the ambit of the Shuttle Radar Topography Mission (SRTM) and it covers about of the 80% of the total surface of the Earth.

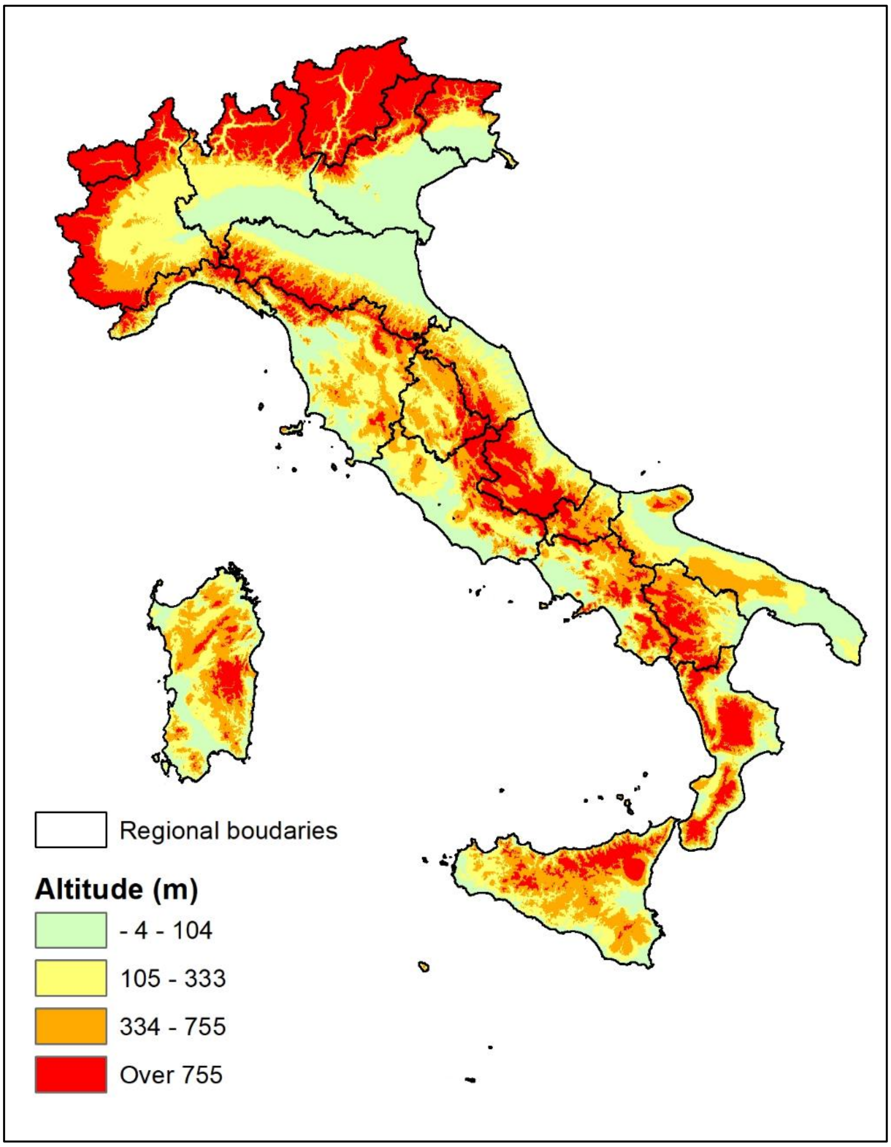
In addition to ASTER data, this product use also other satellite data to implement the accuracy of the measurements.

Its pixel is variable, as ASTER GDEM v3 is, so a control and correction activity is necessary to better approximate the results for each territorial division. But, this fact, doesn't affect the validity of the results; so, the NASADEM is the best starting data, among all those experienced, to extract the morphometric indices at municipality level.

[9] For more information: https://lpdaac.usgs.gov/news/nasa-and-meti-release-aster-global-dem-version-3/

[10] For more details: https://lpdaac.usgs.gov/products/nasadem_hgtv001/

In picture below, the NASADEM thematised on the base of the quartiles of the altitude expressed in meters.



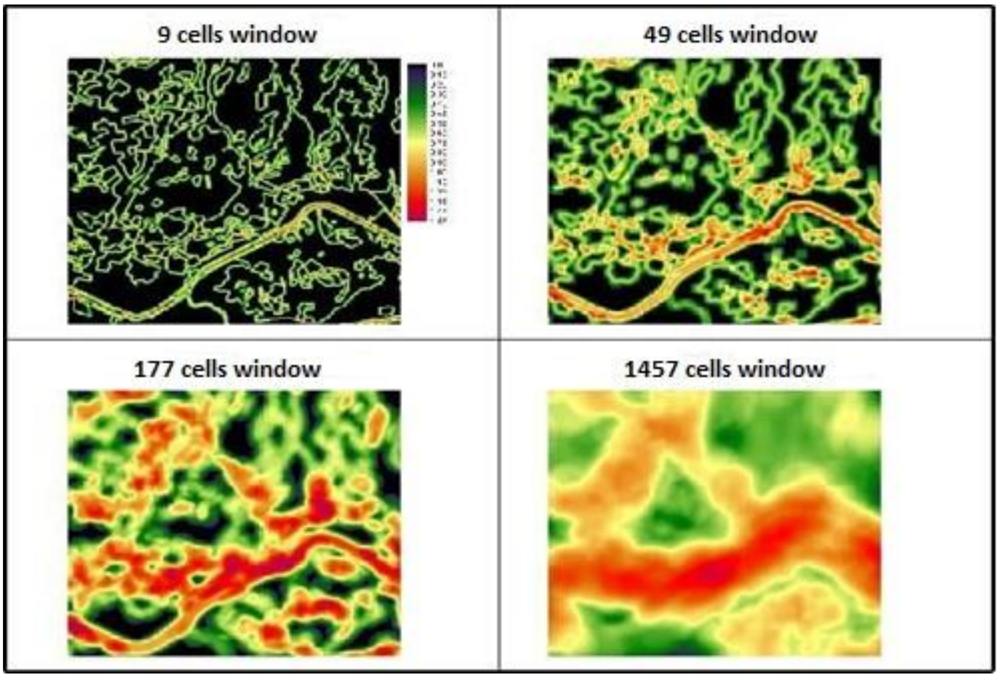
Source: Istat elaboration on NASADEM data

Geomorphometry

Introduction

Quantitative geomorphology (also called geomorphometry) allows us to obtain a measurement of the shape of the landscape. The geomorphological analysis indices analyze the landscape on the basis of a prevalent quantitative parameter, i.e. the elevation. Among the basic geomorphological indices that depend on the resolution of the reference DEM image, different sizes of the reference window can be obtained which is inversely proportional to the resolution (Fig. 2).

Figure 2 – Some examples of processing geo-morphological indices dependent on the size of the reference window.



Fonte: https://e-l.unifi.it/pluginfile.php/880797/mod_resource/content/1/disp_3_operatori_focali.pdf

The choice of window size therefore depends on:

a. the type of analysis you want to carry out: if you want to emphasize transition phenomena between classes, small windows must be used, but if they are important phenomena deriving from the territorial mosaic, large windows are preferable;
b. by the resolution of the DEM: the size of the window will be inversely proportional to the resolution of the DEM.

Geomorphological indices can be divided into:

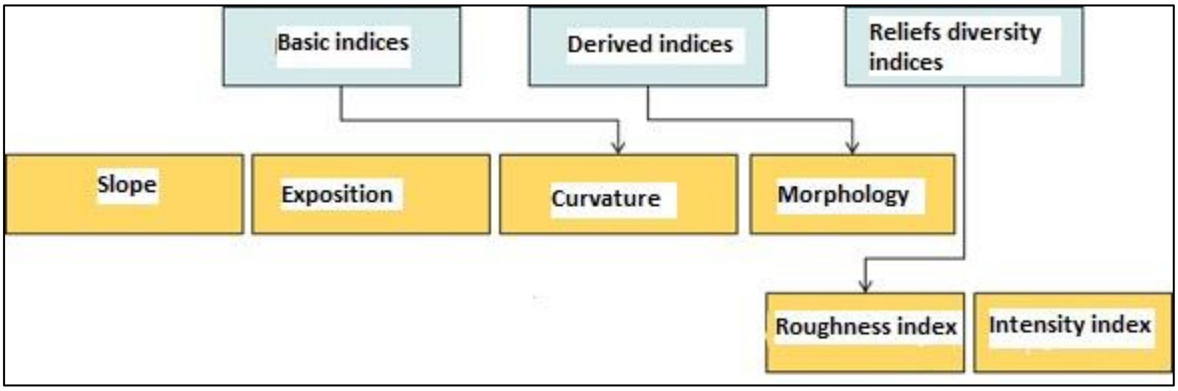
1. basic Indices;
2. derived indices;
3. survey diversity indices.

The basic indices refer to the slope, exposure and curvature of the territory. The derived indices refer to the morphology of the territory, while the diversity indices are represented by the roughness and intensity of the phenomena[11] (Fig. 3).

[11] For a better knowledge of topics:

https://e-l.unifi.it/pluginfile.php/883732/mod_resource/content/1/lezione_4_10_2019.pdf

Figure 3 – Summary diagram of the subdivision of the geomorphological indices.



Source: https://e-l.unifi.it/pluginfile.php/883732/mod_resource/content/1/lezione_4_10_2019.pdf

Geomorphological indices, at a theoretical level, make extensive use of the concept of the derivative of mathematical functions representative of the landforms obtained by interpolation.

The difficulty and complexity of this procedure have led to the increasingly widespread use of approximate formulas based on raster models, such as the Dozier and Strahler formula[12]

Even if they are not used in this experimental project, they provide some fundamental concepts for the basic understanding of the topic.

One of the parameters that characterize the geomorphological indices is the shape of the slopes which can be described through the combination of values relating to:

- profile curvature;
- planar curvature.

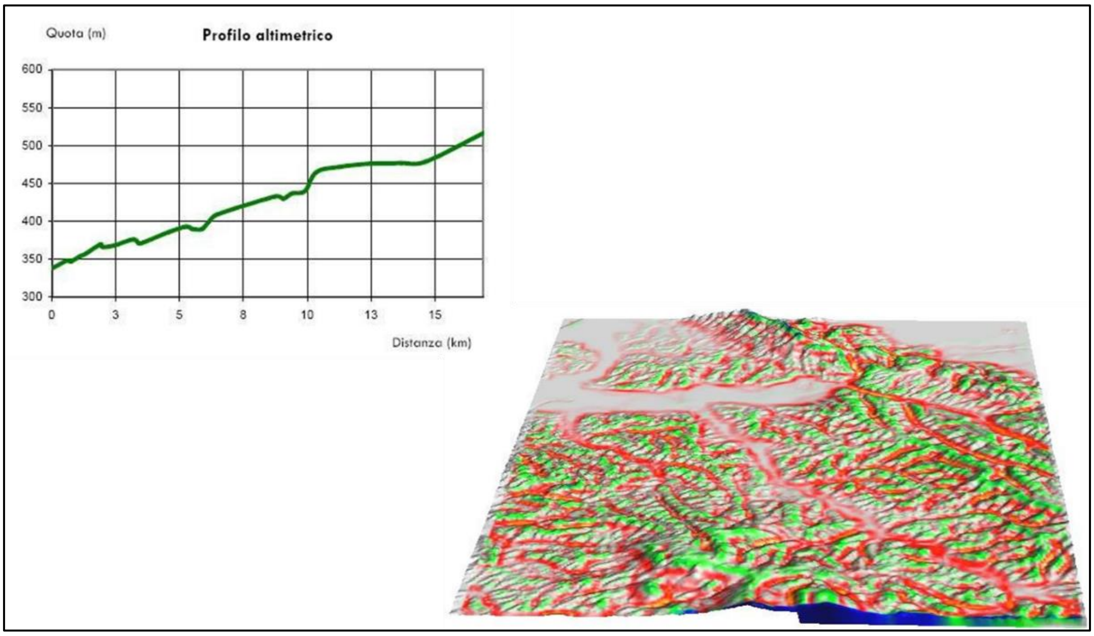
The profile curvature identifies concave or convex areas along the maximum slope line of the slope; through the vertical curvature it is therefore possible to distinguish ridges, slopes inclined in a concave or convex way, or flat areas depressions and watersheds.

The planar curvature, on the other hand, refers to a section orthogonal to the maximum slope, and is related to the convergence or divergence of a flow along the slope, in other words, along the level curves (Fig.4 and Fig.5).

[12] For more info:

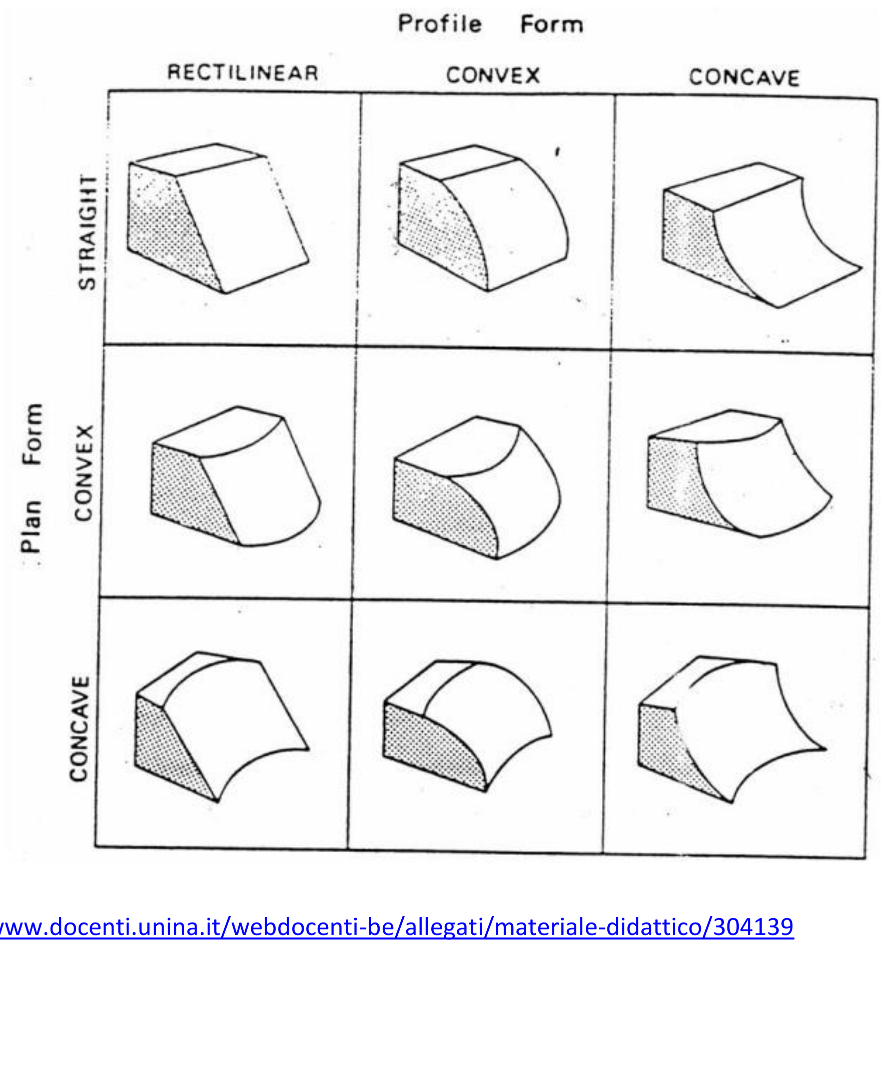
https://e-l.unifi.it/pluginfile.php/880797/mod_resource/content/1/disp_3_operatori_focali.pdf

Figure 4 – Schematic representation of the concept of vertical curvature



Fonte: https://e-l.unifi.it/pluginfile.php/883732/mod_resource/content/1/lezione_4_10_2019.pdf

Figure 5 – Geometric classification of the morphological analysis of the slopes

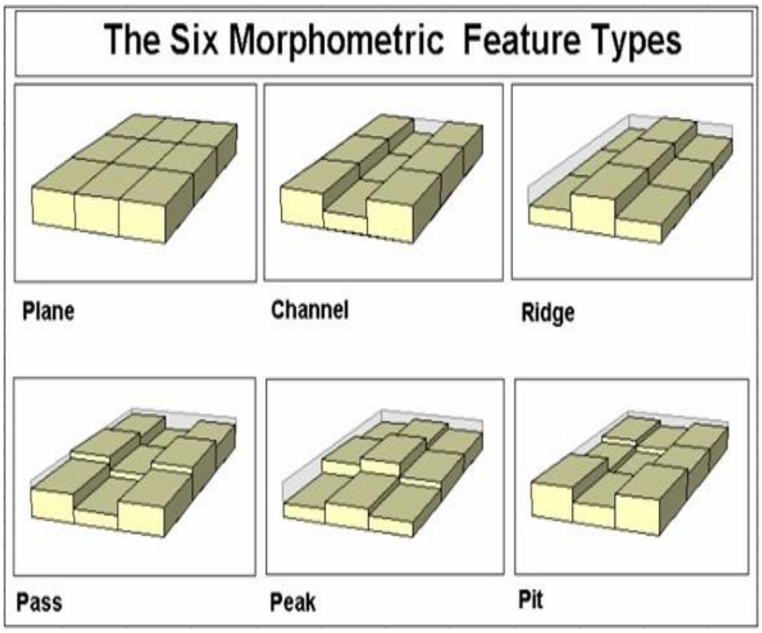


Fonte: https://www.docenti.unina.it/webdocenti-be/allegati/materiale-didattico/304139

The combination of planar and profile curvature allows you to understand and accurately define the flow along a slope and, consequently, analyze in detail the areas most subject to erosion or accumulation of material.

Geomorphological indices represent the shape of the land and can be represented dy different morphometric '*feature*' classes, schematically reported in figure 6.

Figure 6 – The 6 classes of 'morphometric features' (Wood, J.D., 1996)



Source: https://e-l.unifi.it/pluginfile.php/880797/mod_resource/content/1/disp_3_operatori_focali.pdf

In summary, the relevant diversity indices are represented by:

- Roughness indices: variability of a topographic surface at a given scale of analysis, where the scale of analysis is chosen according to the form of landscape being studied;
- Relief intensity indices: they are based on the measurement of the maximum difference in altitude in the moving.

The first roughness index (Topographic ruggedness index) was proposed by Riley et al.[13] to highlight the difference in elevation in a landscape. The proposed index is based on the calculation of the square root of the sum of the height differences between the central cell of a moving window and the neighboring cells, each squared.

The relief intensity index is based on the measure of the maximum values difference inside the sliding window.

Below we present in detail the indices proposed for this study developed for the Italian municipal and provincial divisions with the aim of classifying them also according to geomorphometric aspects.

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[13] Riley S.J., DeGloria, S.D. and Elliot, R. (1999). A terrain ruggedness index that quantifies topographic heterogeneity, Intermountain Journal of Sciences, 5:1-4

The geomorphology of a territory is, in fact, a very important element for the ecology of a landscape and together with the bio-climatic factors, harmonized with the social and economic components, leads to the definition of different landscape territorial units fundamental for developing use projects of the territory that preserve its natural integrity as much as possible.

In this experimentation however, we focus on the concept of morphometry[14].

INDICI MORFOMETRICI

Steepness indices

Slope

'*In mathematics, the slope or gradient of a line is a number that describes both the direction and the steepness of the line*'[15]

The function angle between the horizontal plane and that tangent at a determined point on the ground surface (Florinsky, 2017) (*slope)* represents the percentage change for each cell of a DEM. It is the first derivative of a DEM.

In a GIS, 'the slope is computed as the rate of change of the surface in the horizontal and vertical directions from the center cell to each adjacent cell. The basic algorithm used to calculate the slope is as follows[16]' (*Planar method*):

$$\textit{Slope} = \arctan(\sqrt{d^2 + e^2})$$

where the parameters *d* and *e* derived from equation

$$Z = aX^2 + bY^2 + cXY + dX + eY + f$$

where Z is the height of the DTM surface and X and Y are the horizontal coordinates. The coefficients can be solved within a window using simple combinations of neighboring cells, the basis for terrain analysis in most commercial GIS, whether they use grid-based methods or a mathematical representation of the DTMS[17]

Slope can be expressed in degrees or as percentage increase:

- DEGREE: the range of the valus is from 0 to 90;
- PERCENTAGE INCREASE: The slope is expressed as percentage values. In practice, the values range is from 0 to 100. A flat surface is 0%, and a surface at a 45-degree angle is 100%. The more vertical the surface becomes, the higher the percentage increase.

By default, the output of the Slope function appears as a grayscale float image.

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[14] 'Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface and of the shape and dimension of its landforms' (Atrayee B., et al., 2014)

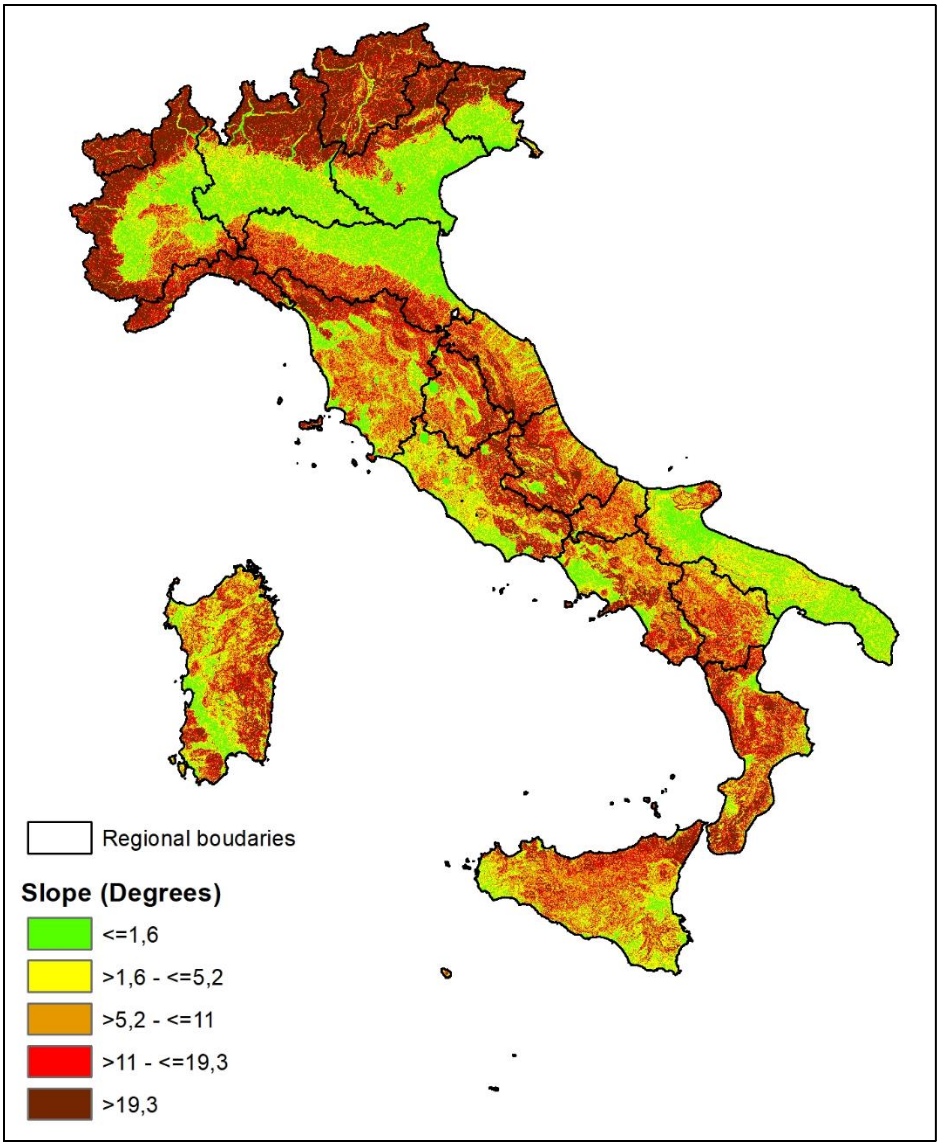
[15] https://en.wikipedia.org/wiki/Slope

[16] For more info: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-slope-works.htm

[17] For further information: M.J.F. Wilson et al., 'Multiscale Terrain Analysis of Multibeam Bathymetry Data for Habitat Mapping on the Continental Slope'; Marine Geodesy, 30: 3–35, 2007 Copyright © Taylor & Francis Group, LLC ISSN: 0149-0419 print / 1521-060X online DOI: 10.1080/01490410701295962.

In figure 7, In Figure 7, the result for the entire Italian territory is shown using a colormap (green color indicates flat areas, while brown color represents areas with steeper slopes; the data is expressed in degrees - Quintiles).

Figure 7 – Slope function (Quintiles in degree)



Source: Istat elaboration on NASADEM data

Roughness indices

All surfaces of real objects are typically subject to geometric irregularities known as '*roughness*'. These irregularities can be either random or exhibit preferential patterns. '*Surface roughness*' is measured by imagining the surface being sectioned along a plane called the "relief plane," which is orthogonal to the surface itself. The "real profile" is the resulting line from the intersection of the actual surface with the relief plane. Surface irregularities or roughness can also be measured through mathematical operations based on Digital Elevation Models (DEMs) using GIS tools and algorithms.

Below, we describe the most commonly used ones in territorial statistical analysis:

Roughness index (standard deviation dello Slope)[18]

The standard deviation of slope remains the most effective measure of surface roughness, due to its simplicity of calculation, fine-scale detection at the local level, and reliable performance across a wide range of scales (Grohmann et al., 2011).

The calculation of this index requires a reference area, which in our case could be the vector layer of Italian municipalities[19] or the 1 km2 grid released by Eurostat[20].

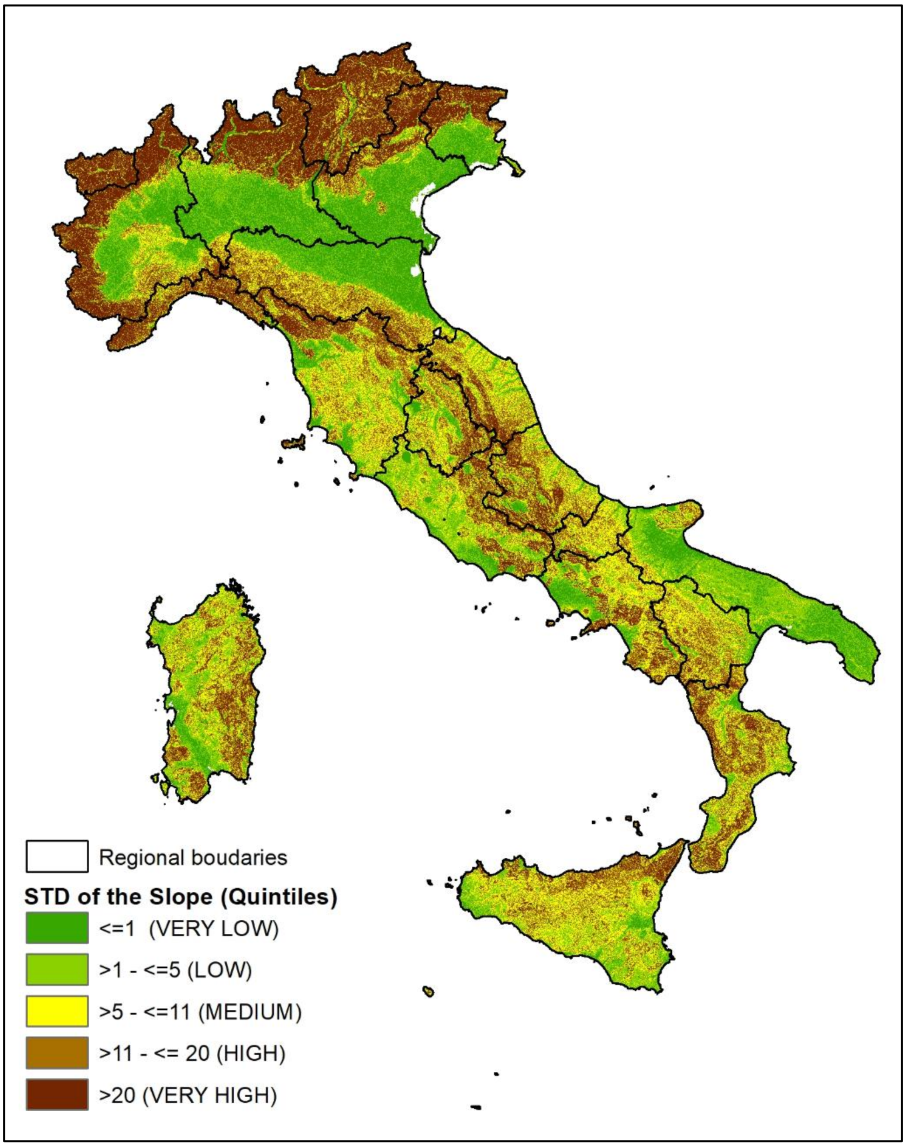
In Figure 8, the roughness index for the entire Italian territory is classified according to the standard deviation of the slope.

[18] It's important to keep in mind that this parameter, calculated on a Digital Surface Model (DSM), may exhibit "intrinsic artifacts" in areas with varying degrees of forest cover or urban settlements, significantly altering the final result.

[19] Italian municipality vector layer for statistical aims, can be freely downloaded at the link: https://www.Istat.it/it/archivio/104317#accordions under the heading ‘Confini amministrativi.

[20] La griglia a 1km^2 Eurostat è liberamente scaricabile al link: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat.

Figure 8 – The Italian territory classified according to the standard deviation of the slope (Quintiles)[21]



Source: Istat elaboration on NASADEM data

Topographic Ruggedness Index

The *Topographic Ruggedness Index* (TRI) is a measure developed by Riley et al. in 1999[22] to express the elevation difference between adjacent cells of a Digital Elevation Model (DEM).

The process quantifies the difference in elevations between the central cell and its eight adjacent cells. This is done by squaring the elevations of each individual cell adjacent to the central one to ensure that all values are positive; the average of these squared values is then calculated. The TRI is the square root of this average and corresponds to the average elevation gap between the central cell and its 8 adjacent cells

[21] In addition to the numerical value, a qualitative indication of the index is provided for a better understanding of the phenomenon.

[22] Riley S.J., De Gloria S.D., Eliot R., 'A Terrain Ruggedness Index that quantifies Topographic Heterogeneity'; Intermountain Journal of Sciences, Vol.5 n.1-4:23-27, December 1999.

From an algebraic perspective, let's consider x as the central cell of the 3*3 cell square; x_i, i = 1,…,8 are the values of the surrounding cells; r represents the TRI.

The formula of the index tells us that r^2 is equal to the sum of $(x\_i-x)^2$.

Two values can be easily calculated:

(1) the sum of the values of the adjacent cells $s = \sum\{ x\_i \} + x$;

and (2) the sum of the squares of the values $t = \sum\{ x\_i^2 \} + x^2$.

Expanding the square:

$\mathbf{r^2} = \sum\{(x\_i - x)^2\}$

$= \sum\{x\_i^2 + x^2 - 2*x*x\_i\}$

$= \sum\{x\_i^2\} + 8*x^2 - 2*x*\sum\{x\_i\}$

$= [\sum\{ x\_i^2 \} + x^2] + 7*x^2 - 2*x*[\sum\{ x\_i \} + x - x]$

$= t + 7*x^2 - 2*x*[\sum\{ x\_i \} + x] + 2*x^2$

$= \mathbf{t + 9*x^2 - 2*x*s}$.

Considering, therefore, the 3*3 square of contiguous cells

1	**2**	**3**
4	**5**	**6**
7	**8**	**9**

We have, x = 5, s = 1+2+...+9 = 45, t = 1+4+9+...+81 = 285.

Therefore, $(1\text{-}5)^2 + (2\text{-}5)^2 + ... + (9\text{-}5)^2 = 16 + 9 + 4 + 1 + 1 + 4 + 9 + 16 = 60 = r^2$;

therefore, an algebraic check is explicitly performed: 60 = r^2 = 285 + 9*5^2 -2*5*45 = 285 + 225 - 450 = 60.

Transferring the entire reasoning to a Digital Elevation Model (DEM) yields:

- Calculation of s = ‘Focal sum’ of the contiguous cells of a square window 3*3 of [DEM];
- Calculation of DEM^2 = [DEM]*[DEM];
- Calculation of t = ‘Focal sum’ of the same contiguous cells square window 3*3 as s of $[DEM]^2$;
- Calculation of $r^2 = [t] + 9*[DEM^2] – 2*[DEM]*[s]$.

In the end, we have: $r = \sqrt{r^2}$

The calculation of the TRI consists of 9 steps to be performed either with the *'Raster calculator'* tool of commonly used GIS software, both proprietary and open source, or with scripts or batches in Python exportable to all programming environments.

The TRI is not an average change in elevation since the change itself can be both positive and negative; the TRI is a mean square value of the elevation change; it is not equivalent to the *Topographic Position Index*, which will be described later.

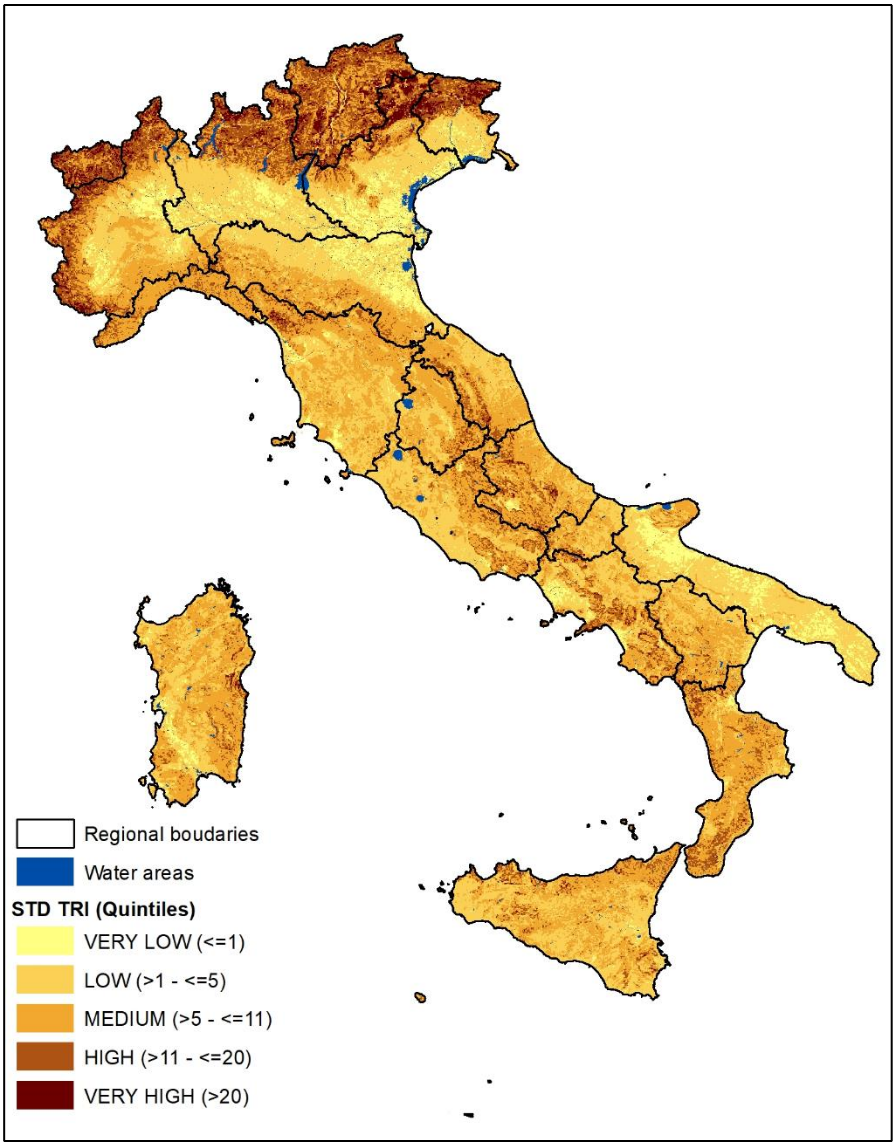
In figure 9 the Eurostat Grid of 1 Km^2 thematized according to the standard deviation of the TRI

(Quintiles).

The scale used for classification according to the TRI is descriptive in nature, and the legend entries are derived from the quantile division of the obtained results

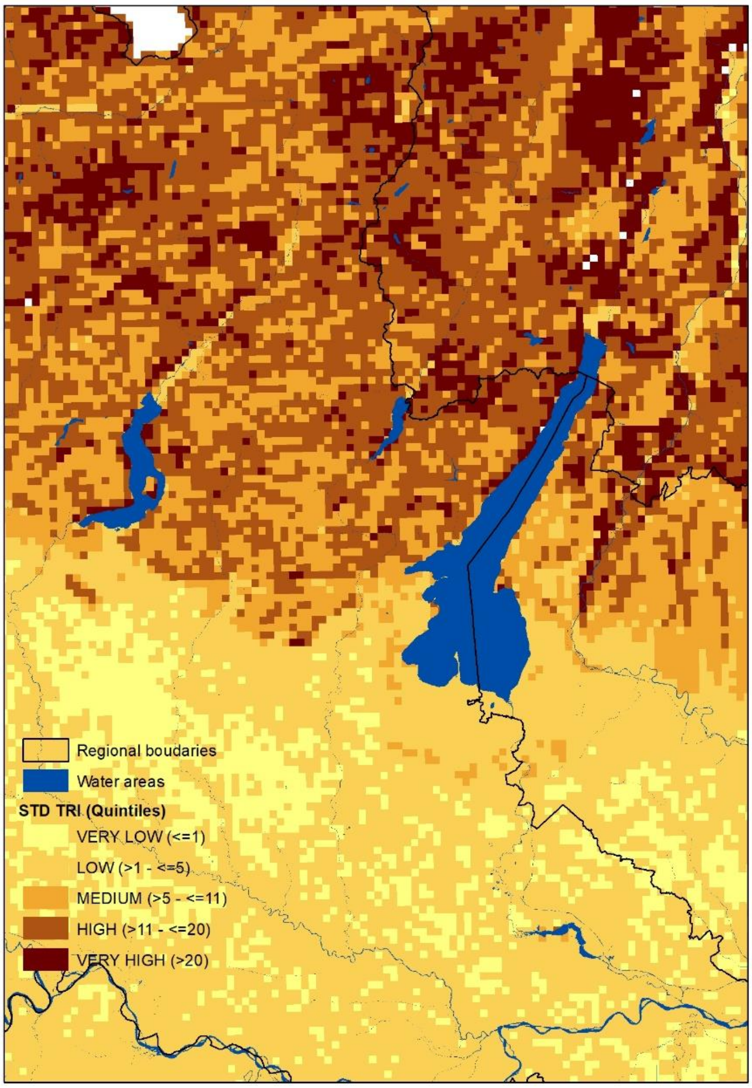
In figure 9a, a focus on the Lake Garda area is shown, where it is possible to identify the thematization of each individual cell of the EUROSTAT Grid. The thematization is based on quintiles. In the cartogram of figure 9, major bodies of water and watercourses are also included to provide additional territorial references

Figure 9 – Eurostat Grid of 1 Km^2 thematized according to the standard deviation of the TRI (Quintiles).



Source: Istat elaboration on NASADEM and Eurostat data

Figure 9a – Detail of Figure 9 for the area surrounding Lake Garda.



Fonte: Istat elaboration on NASADEM and Eurostat data

***Topographic Position Index (TPI)*[23]**

The *Topographic Position Index* (TPI) compares the elevation of each cell in the DEM to the average elevation of adjacent cells within a specific contiguity window. Various contiguity window configurations can be used, such as ring, square, etc.

Since only the DEM is required as an input, TPI can be easily calculated at any scale. Positive TPI values represent areas above the average elevation of their contiguous areas (ridges), while negative values represent areas below the average elevation of their contiguous areas (valleys). TPI values close to zero indicate flat areas (where the slope value is also close to zero) or areas with constant slope (where the slope value of the considered cell is significantly greater than zero).

TPI is inherently dependent on the scale of the phenomenon considered. For example, in a canyon, at a distance of 10 meters from the point under consideration, the TPI value could be related to a completely flat area. This observation scale might be useful for investigating phenomena related, for instance, to the water balance of a specific area. At a scale of several kilometers, the TPI value for the same point in a canyon with a depth of 1500 meters could be significant, especially for investigating hydrogeology, mesoclimate, wind-related phenomena, or cold air currents.

Ecological characteristics of a site and the distribution of plant species, for example, show a significant correlation with TPI at distances of 300, 1000, and 2000 meters. In this case, TPI can even be the second most important parameter to consider after altitude (Guisan et al., 1999)[24].

The TPI involves few parameters and is calculated, for a well-defined scale factor, as follows:

TPI $_{\text{<scale factor>}}$= int[(DEM – focal mean(DEM, neighborhood, neighborhood settings, statistics type)] + *k*)

Dove:

- *int*: function for converting a continuous file (float) to an integer one, easily thematizable;
- *neighborhood*: specifies the shape of the contiguity area around the cell object of the calculation;
- *neighborhood* settings: setting parameters of neighborhood;
- *statistics type*: statistic to be calculated;
- *k*: value used to highlight the analyzed phenomenon.

A TPI is calculated as follow,

TPI_{250} = int((DEM – focalmean(DEM, annulus, 5, 10)) + 0.5)

And it's a way to highlight the main and secondary ridges and drainage lines of an area.

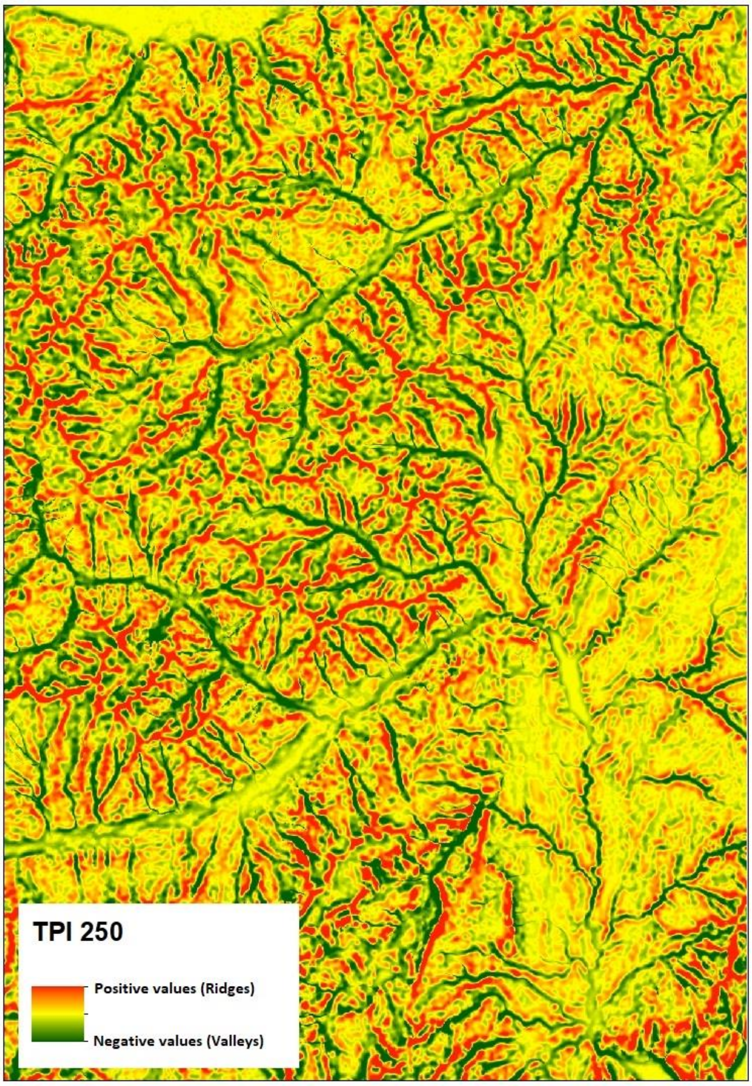
In figure 10a the result of the TPI calculated at 250m[25].

[23] For details: http://www.jennessent.com/downloads/tpi-poster-tnc_18x22.pdf

[24] Guisan, A., S. B. Weiss, A. D. Weiss 1999. GLM versus CCA spatial modeling of plant species distribution. Plant Ecology 143: 107-122

[25] Per la dimensione della finestra di riferimento si è tenuto conto di:

Figure 10a – TPI calculated at 250 meters



Source: Istat elaboration on NASADEM data

https://geodati.gov.it/resource/id/r_emiro:2011-10-21T161736

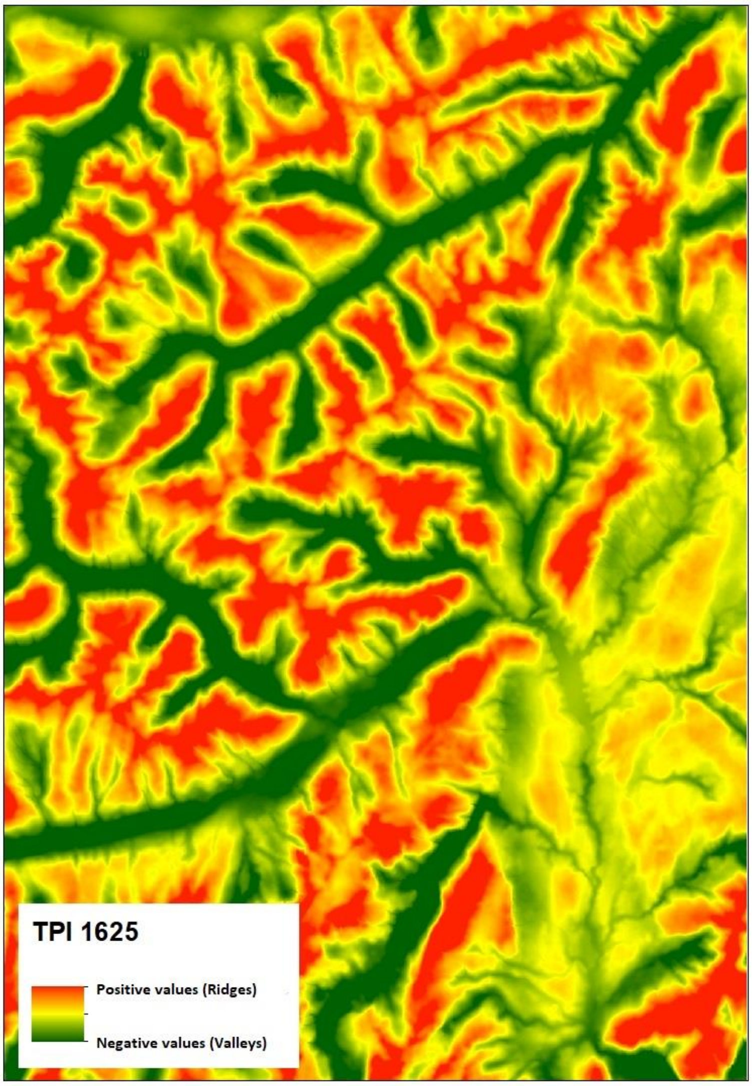
A less detailed scale TPI (e.g. TPI_{1625}), calculated according to the formula:

TPI_{1625} = int[(DEM – focalmean(DEM, annulus, 60, 65)] + 0.5)

Highlights major ridges and drainage lines while minor features fade away.

In figure 10b a TPI calculated at 1625 meters.[26]. The same area as figure 10a

Figure 10b – TPI calculated at 1625 meters; same area as figure 10a



Source: Istat elaboration on NASADEM data

The thematic representation of the TPI

As we mentioned, the result of the processing is always a continuous raster file (float). By applying a threshold to certain values, classified files with discrete classes can be obtained, which can be useful for describing the phenomenon in a simple and immediate manner.

[26] http://www.jennessent.com/downloads/tpi-poster-tnc_18x22.pdf

For TPI (Topographic Position Index), the best thematic representation to highlight the morphological features of an area at any scale is undoubtedly the use of standard deviation units. An easily repeatable method is to create 6 classes that highlight the various morphological characteristics of the study are.

1. Ridge > + 1 STDV
2. Upper slope > 0.5 STDV =< 1 STDV
3. Middle slope> -0.5 STDV, < 0.5 STDV, slope > 5 deg
4. Flats slope >= -0.5 STDV, =< 0.5 STDV, slope <= 5 deg
5. Lower slopes >= -1.0 STDV, < 0.5 STDV
6. Valleys < -1.0 STDV

In Figure 10c and Figure 10d, the classification of Figures 10a and 10b is presented according to six classes linked to the standard deviation.

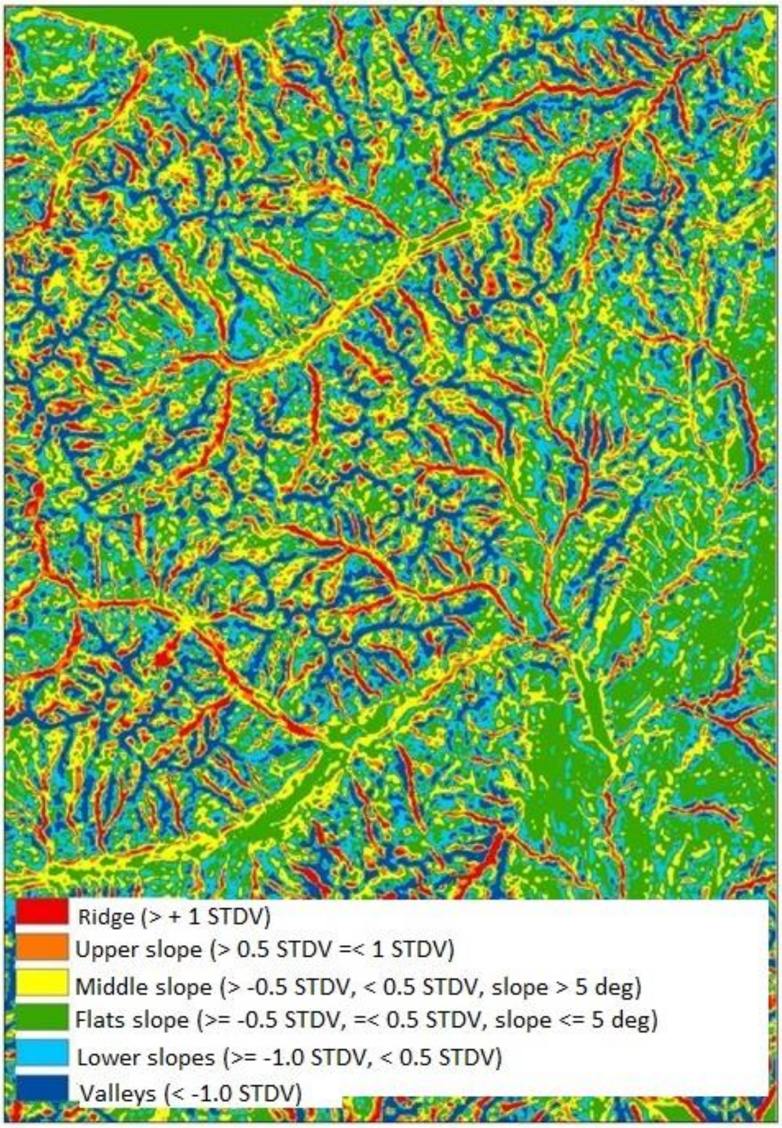
The exact threshold values between the classes can also be chosen manually to optimize the classification for a specific area and issues related to territorial morphology.

Similarly to the slope classification, some additional values, such as, for example, the variance of elevation, *slope* or *aspect*[27] within the contiguity grid, can be useful for delineating morphology more accurately and allowing for a more precise extraction of various morphological features.

In the appendix to this methodological note, the TPI (Topographic Position Index) is not provided as it is meaningful for much localized areas.

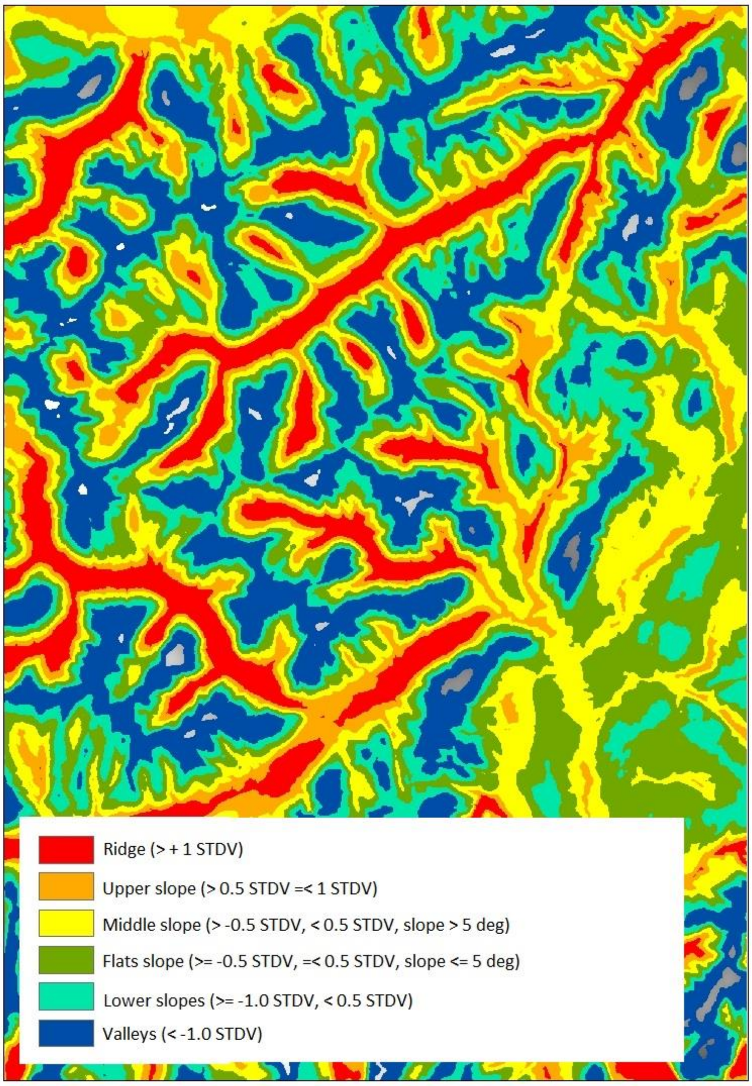
[27] *Aspect* identifies the direction of the maximum slope in relation to the four cardinal points for the central cell of the 3*3 window with respect to its contiguous cells.

Figure 10c: The TPI at a scale factor of 250, classified into 6 standard deviation classes.



Source: Istat elaboration on NASADEM data

Figure 10d: The TPI at a scale factor of 1625, classified into 6 standard deviation classes



Source: Istat elaboration on NASADEM data

Concluding remarks

As can be deduced from what has been stated above, the calculation of morphometric indices is highly versatile and can be easily adapted to any new scenario, both in terms of the territorial partition layer for which they are to be calculated and the reference DEM.

Morphometric indices are essential for making assessments regarding the slopes of terrains, and it is useful to relate them to other territorial information.

Indeed, integrating the results derived from morphometric indices with data and analyses related to other territorial themes (lithology, vegetation, geology, etc.) can enhance the assessment of geological risks.

For instance, competent lithologies, characterized by a high resistance to erosion, are less likely to trigger instability even in steep areas compared to less competent lithologies, which can contribute to the high susceptibility to landslides in the territory. Hence, the integration of morphometric data with thematic maps (lithological, geological, vegetation, etc.) is crucial for improving the assessment of geological risks such as landslides, floods, seismic events, etc.

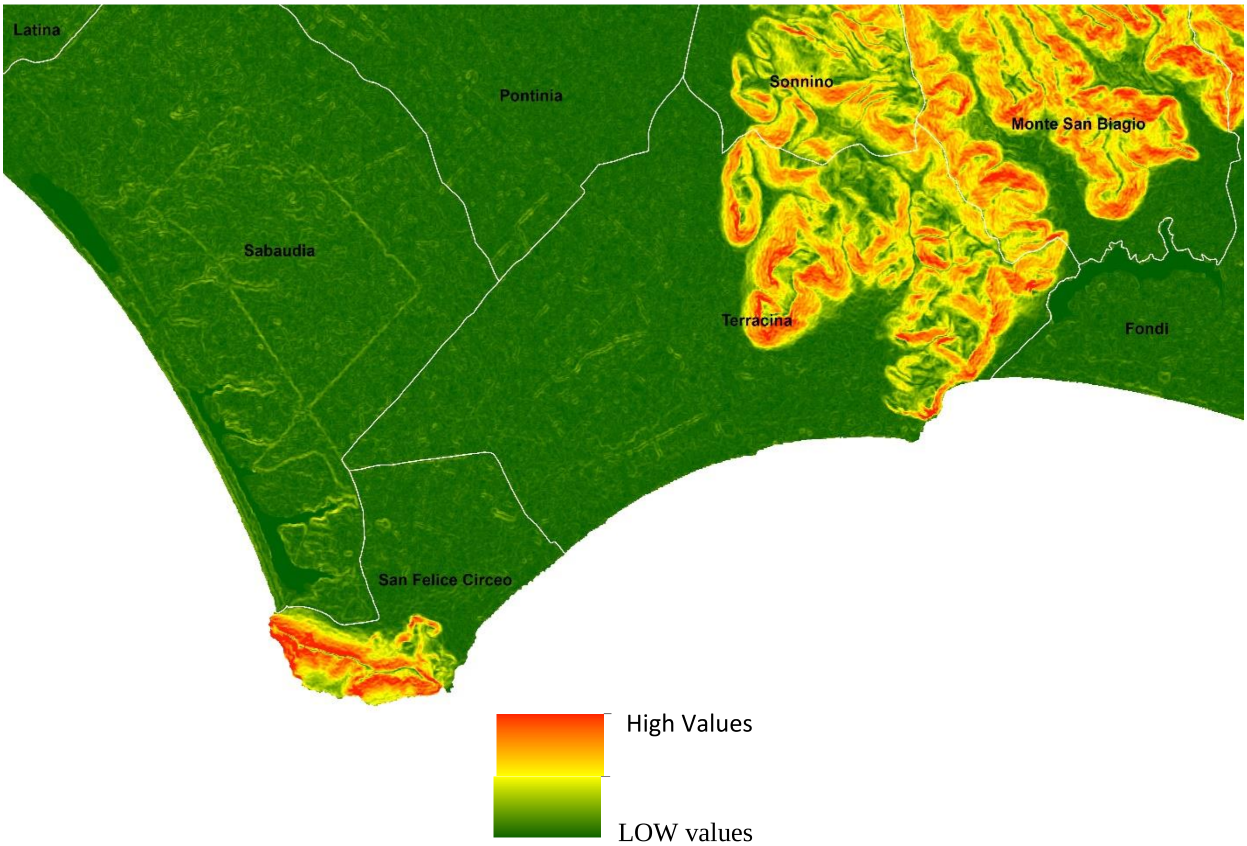
The calculation of indices can be performed using tools that are now an integral part of both proprietary and open-source GIS. Moreover, various stages of the calculation algorithms can be incorporated into scripts or batch files, fully compatible with common development environments (e.g., Python). Therefore, these are useful, usable, and versatile indicators.

In addition to this, the values extracted for each index can be compared with other values obtained using a different methodology or with the same methodology but starting from a different DEM, both in terms of spatial resolution and temporal resolution (i.e., more recently acquired and therefore more representative of the current topography). This statistical operation can be useful whenever there is a territorial change or to assess differences in outputs based on different territorial layers.

The significance of values translated into territorial partitions primarily depends on the surface area of the partition in relation to the resolution of the reference DEM (DSM or DTM). The larger the DEM cell, the lower the significance of the index for territorial partitions with a smaller surface area. It is useful to specify this effect, especially in a territory like Italy where municipalities vary greatly in terms of their surface area. With the DTM used in this experiment, there is no issue for provincial or larger partitions (NUTS2 and NUTS1), while for smaller municipalities, lower significance may be observed.

It is also important to consider that the derived values represent a sum of local specific situations within each territorial partition. For illustrative purposes, Figure 11 depicts the situation of the municipalities of Terracina and San Felice Circeo in the province of Latina. From the figure, it is evident that the two municipalities are characterized by two morphologically distinct areas: one entirely flat (shown in green in the figure) and one with greater relief energy, identified in the figure with shades from yellow to red. In these cases, the morphometric indices represent a sum of the municipal territory weighted by the relative surface areas of each class.

Figure 11 - Detail of the slope index for the municipalities of San Felice Circeo and Terracina (LT).



Source: Istat elaboration on NASADEM data

The index that most expresses the morphometric characteristics of Italian municipalities is undoubtedly the standard deviation (STD) of the slope, which is also the simplest and most straightforward to read and interpret.

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