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Geodiversity of Italy

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ABSTRACT
In recent years, natural areas have been exposed to increasing anthropogenic pressure related to the growing need for natural resources. Comprehensive information on the geodiversity of a territory is essential for all stakeholders in order to define effective land management toolsusefull for preserving the natural heritage for future generations. We computed geodiversity map as the summary of lithological, morphological, paedological indicators and hydrological index using a workflow based on the grid analysis, performed in a Geographic Information System environment. The geodiversity map of Italy (main map) provides a synoptic view of the geographical distribution of the abiotic component of the landscape ranked into five classes varying from very high to very low geodiversity. This map is supplemented by histograms showing the percentages of geodiversity classes for each Italian region and a Regional Geodiversity Index map that assigns a geodiversity value to each Italian region.

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Geodiversity; grid analysis; sustainability; land management; geo-conservation

1. Introduction

Geodiversity is defined as the variety of rocks, minerals, fossils, landforms and soils forming the Earth's surface, and hydrological resource (Gray, 2004, 2008; Serrano & Ruiz-Flaño, 2007). Geodiversity gives information on the abiotic part of the natural world on which life develops and living organism interact, provides the essential nutrients for vegetation and regulates the quality and the quantity of water resources (Fox et al., 2020; Gordon et al., 2021). It can be considered as the variety of all the abiotic elements that together with biodiversity, which represents its biotic counterpart, constitutes and enhances natural diversity (Brilha, 2016).

In the last decade, geodiversity has received increasing interest from the scientific community involving not only the natural sciences but also social, cultural and economic ones. Recent studies search for a link between geodiversity and biodiversity considering them as closely related (Hjort et al., 2015; Ren et al., 2021). This aspect is discussed by Tukiainen et al. (2023), who points out a correlation between the high diversity of the abiotic environment and the presence of different ecological niches, that results in the increase of total biodiversity. Furthermore, ecosystems are becoming increasingly vulnerable to climate change and, in this context, the conservation of geodiversity is essential to make habitats and different ecological niches resilient. For this reasons, the International Union for Conservation of Nature (IUCN) published the 'Guidelines on Geoconservation in Protected Areas', which set out the goals of geodiversity studies and its role in the management of protected natural areas (Crofts et al., 2020).

Furthermore, Goal 11.4 *Strengthen efforts to protect and preserve the world's cultural and natural heritage*, one of the 169 goals listed by the 2030 Agenda for Sustainable Development, recognises the importance of protecting geoheritage, i.e. geodiversity sites characterised by high scientific value (Brilha, 2016). Alberico, Alessio, et al. (2023) pointed out the key role of geoheritage as a tool to educate on sustainability. These authors emphasised that a proper environmental education plays an important role in the preservation of natural heritage, which, in turn, is fundamental to maintain cultural identity and traditions. They showed as geoheritage can contribute fruitfully to Sustainable Development Goals by emphasising the importance of cultural and natural sites in improving the livability of a peri-urban areas (SDG 11 - Sustainable cities and communities), encouraging outdoor activities (SDG 3 - Good health and well-being), and protecting biodiversity (SDG 15 - Life on land), which, in terms of positive outcomes, complements actions against climate change (SDG 13 - Climate Action).

Geodiversity is also related to the geological resources which are part of the planet's 'natural capital', the stock of global natural assets. These assets offer

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Supplemental map for this article can be accessed online at https://doi.org/10.1080/17445647.2024.2340988.

many benefits, named ‘ecosystem services’, to society (Gray, 2019). This author recognises 25 major geosystem services, all of which are related to the planet’s geodiversity, grouped according to the MEA (Millenium Ecosystem Services, 2005) classification.

Several studies have pointed out the different roles of geodiversity maps as a tool in the identification of places of interest for geo-conservation (Dias et al., 2021), which are areas to be protected and improved to safeguard biodiversity (Crisp et al., 2023; Hjort et al., 2022; Ren et al., 2021) and to preserve available natural resources (Araujo & Pereira, 2018; da Silva et al., 2019). In this context, the Geodiversity map of Italy (Main Map) at 1:1.000.000 scale was drawn by using a semi-quantitative approach, based on the summary of lithological, morphological, paedological and hydrological indicators/indices (Alberico et al., 2023b). Furthermore, a Geodiversity index at regional scale, supplied with diagrams, was reported into the Main Map useful to easily communicate information to stakeholder. This work could also be a valuable aid in disseminating among people the importance of conserving natural assets to provide future generations with the same ecosystem services we enjoy today.

1.1. Study area

The Italian territory and the surrounding areas have undergone a complex long-term geological and palaeogeographical evolution described in detail in Alberico, Casaburi, et al., 2023, and references therein, that has resulted in distinct regional geotectonic structures, such as thrust belt, orogenic system, foreland basin system, horts and graben structures, back-arc basin and oceanic basin, and volcanic provinces. The landscape is unique and highly diversified, characterized by large mountain ranges, fluvial and glacial valleys, alluvial and coastal plains (Figure 1). The morphological and geological variety of the Italian territory, the great diversity of natural environments and landscapes, and the richness of natural resources and soil types are reflected in a significant diversification of geo-natural systems. This is also evidenced by the presence of several UNESCO Global Geoparks, which include geoheritage of international importance.

The wide variety of geological environments present in Italy is due to its long-standing position on passive to active plate margins. The physical configuration of Italy is due to the collision between the African and Eurasian plates that took place in the Coenozoic after the break-up of Pangea. This important geological event led to the closure of the Tethys Sea and the formation of the Alps and the Apennines Mountain ranges. These processes have produced a great variety of tectonic structures and rocks, including pre-orogenic bedrock of crystalline-metamorphic and igneous nature and marine to continental sedimentary sequences.

During Trias - Cretaceous period, the European and African (Adria and Apulia) passive margins were characterised by large carbonate platforms and pelagic basin. During Coenozoic, the geological history was dominated by the progressive convergence of Eurasian and African tectonic plates, that caused oceanic basin closure and Alpine and Apennine orogenic processes during Middle Cretaceous to Pliocene. Quaternary evolution has been controlled by glacial climatic events, sea level variations and geodynamic activity, as evidenced by the presence of volcanoes (Latium-Tuscany volcanic provinces, Somma-Vesuvius, Campi Flegrei, Aeolian islands Etna) and frequent strong earthquakes.

The Alps are a thrust belt consisting of two distinct mountain ranges of double vergence separated by a series of major faults (e.g. the Insubric Line). The ‘Alpine’ chain is formed by crustal nappes of continental margin and metamorphic ophiolites with European vergence. The ‘Southern Alps’ is a younger tectonic system, composed of Mesozoic sedimentary rocks as the Apennines, which since the Miocene has developed a southern vergence, i.e. towards the Po plain. This large plain is an alluvial area formed by an earlier marine sedimentation and a more recent fluvial sedimentation fed by the Po River and its tributaries, where the fronts of the northern Apennine and Southern Alps thrust belts face each other.

The Apennine thrust belt, interposed between the back-arc Tyrrhenian basin to the West and the undeformed Apulian-Adriatic foreland to the East, is the result of the subduction of the Ligure-Piemontese oceanic lithosphere and the following collision during Miocene – Pliocene of the western African continental margin with the Sardinia – Corsica block.

The Calabrian-Peloritan Arc extends through the Messina Strait to the northeast of Sicily. It is a segment of the Alpine chain that was located close to Sardinia before the opening of the Tyrrhenian basin. The arc consists mainly of east-verging nappes including Palaeozoic granites and metamorphic basement. The island of Sicily is the easternmost segment of the Maghrebian chain, belonging to the northern African continental margin. It consists of several south-verging nappes and a foreland area in the southeast corner (Iblei Mts.). The island of Sardinia, together with the Corsica Island (France), is a fragment of the European continent that separated about 30 Ma ago from the Iberian peninsula subplate and reached about 18 Ma ago its present position. A large part of the island is formed by Palaeozoic granites and methamorphic rocks formed during the Hercynian orogenesis.

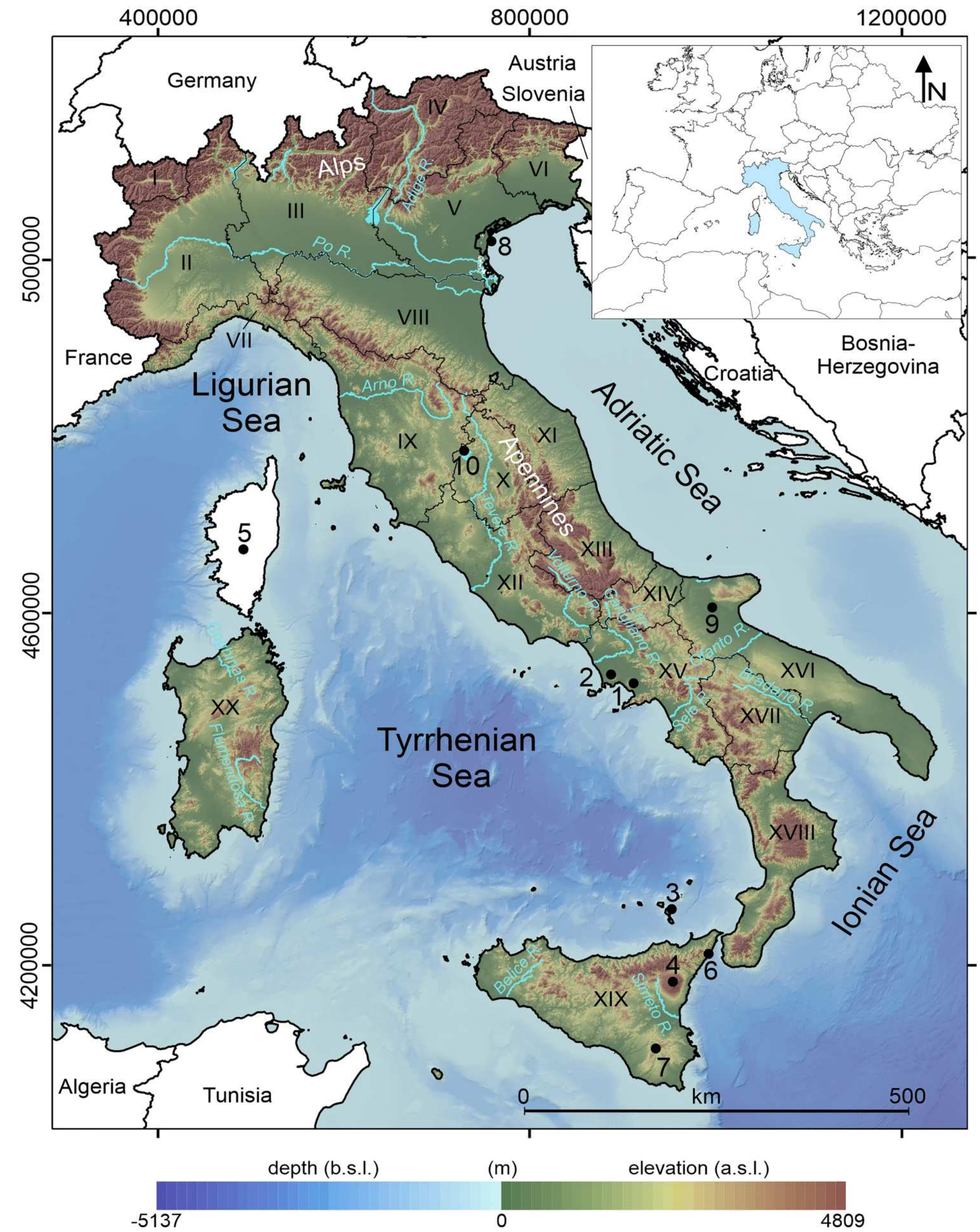

Figure 1. The physical map of Italian territory shows the main mountain ranges (Alps and Apennine), rivers and plains. The location of the study area is reported in the upper right of image. **Place names:** 1. Somma-Vesuvius, 2. Campi Flegrei, 3. Aeolian islands, 4. Etna, 5. Corsica, 6. Messina, 7. Iblei Mts., 8. Venice lagoon, 9. Tavoliere delle Puglie, 10. Trasimeno Lake. **Italian Regions**; I. Valle d'Aosta, II. Piemonte, III. Lombardia, IV. Trentino-Alto Adige, V. Veneto, VI. Friuli-Venezia Giulia, VII. Liguria, VIII. Emilia-Romagna, IX. Toscana (Tuscany), X. Umbria, XI. Marche, XII. Lazio (Latium), XIII. Abruzzo (Abruzzi), XIV. Molise, XV. Campania, XVI. Puglia (Apulia), XVII. Basilicata, XVIII. Calabria, XIX. Sicilia (Sicily), XX. Sardegna (Sardinia).

2. Material and methods

In the present work, geology, geomorphology, pedology and hydrology are the data used to draw the Geodiversity Map of Italy at the scale 1:1.000.000 (Main Map).

2.1. Material

A brief description of data implemented into a GIS framework is reported in the following sentences, for more details see Alberico, Casaburi, et al. (2023). The source of lithological data is the Geo-lithological Map of Italy derived from Bucci et al. (2022) by the union of 277 geological maps at a scale of 1:100.000 of Geological Survey of Italy (ISPRA, Servizio Geologico d'Italia, http://sgi.isprambiente.it/geologia100k/). The lithological classes are described in Appendix 1, Table 1. Morphological data were acquired from the slope values of the Digital Terrain Model of Italy (http://www.pcn.minambiente.it/viewer/index.php?services = dtm_20 m) reclassified, according to Granell-Perez (2001), into six morphological classes proposed by Steinke et al. (2016) (Appendix 1, Table 2). The soil data were taken from the soil map of Italy (Costantini, 2012), which is supported by a detailed legend explaining the characteristics of the soils

Table 1. Data source considered for the geodiversity assessment. Scales and references are listed. The asterisk marks the data source for hydrological index assessment.

Data source	Scale	Reference	Source data	Scale	Reference
Lithological map of Italy	1:100.000	Bucci et al. (2022)	Hydrographic network *	1:250.000	ISPRA
Digital Elevation Model of Italy (morphological map)	Pixel size: 20 m side	Ministry of the Environment	Lakes and inland waters *	1:25.000	Ministry of the Environment
Soil map of Italy	1:1.000.000	Costantini, (2012)	Wetlands *	1:25.000	ISPRA, RAMSAR
Coastline *	–	ISTAT, 2022	Glaciers *	satellite resolution 10 m	Paul et al. (2019), Italian Glaciers Database

(Appendix 1, Table 3). Hydrological data (rivers, lakes, glaciers, wetlands, aquifer, seas) were taken from various sources (Table 1).

2.2. Method

Grid analysis, implemented in a Geographic Information System environment (da Silva et al., 2019; Pereira et al., 2013), was applied for the geodiversity assessment (Figure 2). It is based on the use of a grid, a structure that discretise the study area into cells, that records the contribution (indicator/index) of single data source (Figure 2). An indicator is a measure useful to simply illustrate and communicate complex phenomena, including trends and progress over time (EEA, 2020) while an index is an aggregation of indicators (OECD, 1993).

According to the geodiversity definition (Gray, 2004; 2008; Serrano & Ruiz-Flaño, 2007), the variety algorithm was applied to the lithological, morphological and paedological data source for the indicators assessment (Figure 2). For each data, this function

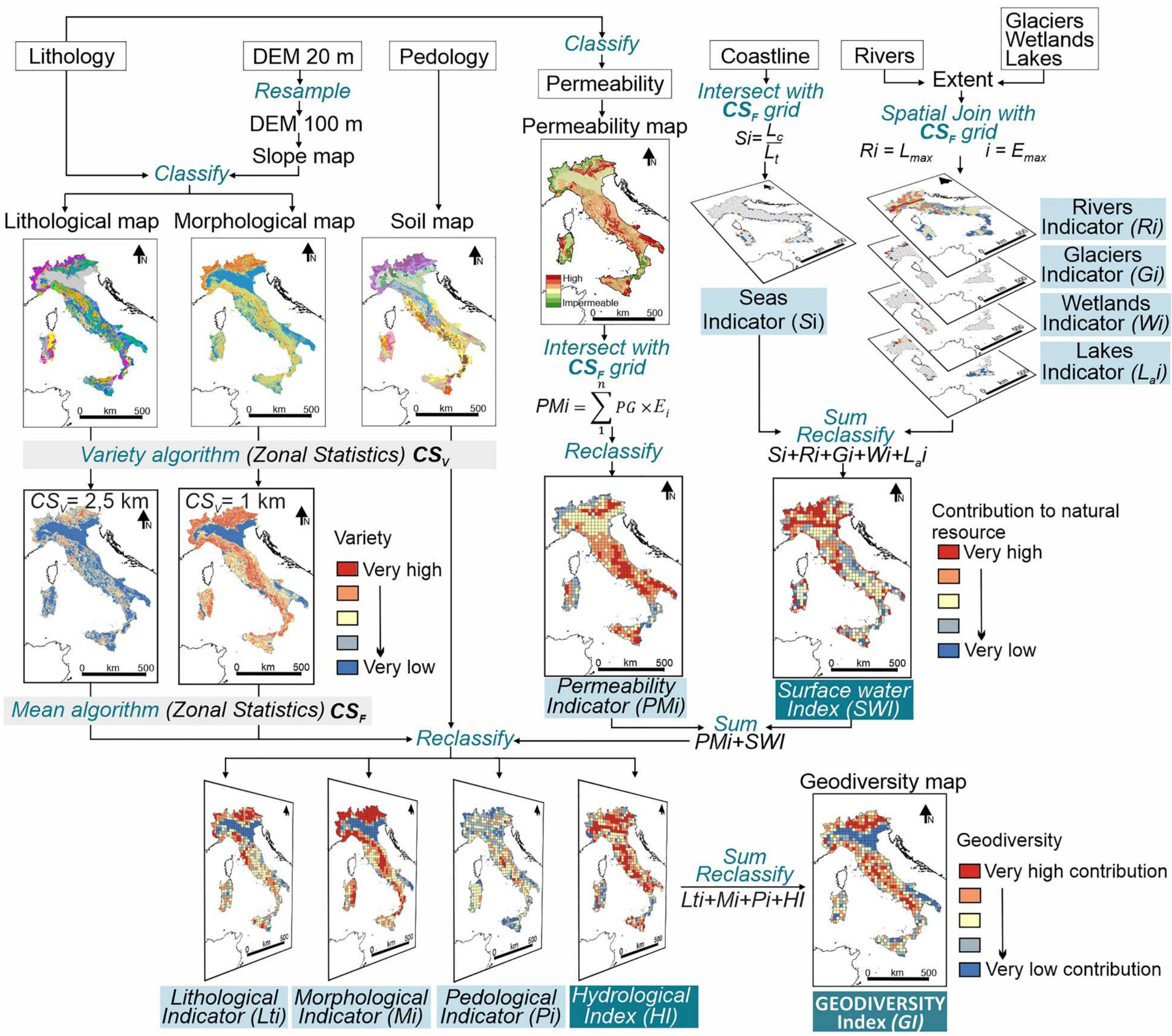

Figure 2. The flowchart illustrates the methodology adopted for the geodiversity assessment. The indicators and indices are highlighted with blue and cyan colours, respectively. The applied algorithms are shown with cyan text.

counts the number of different elements (e.g. for the lithological data source: the number of different lithologies) present in each cell. Furthermore, the use of the cell avoids the procedure of normalising data source, which is necessary for all spatial analyses based on administrative or morphological units characterised by different extents (Totaro et al., 2020). The novelty of the method here proposed is mainly based on the use of a double-step procedure to preserve the relevant abiotic information of the territory in the Geodiversity Map without losing the detail of data source.

Grids with different cell sizes (hereafter 'CS_V') were generated to preserve the shapes of the geographical data (Figure 2). The suitable grid size (p) was estimated by using the relation $p = \frac{\sqrt{SN^2 * MLD}}{2}$ where MLD (considered equal to 0.25 cm^2 by Vink, 1975) is the Minimum Legible Delineation and SN is the Scale Number of map. The 'p' value was then used to define the cell size of the grids adopted for the calculation of data variety. For this purpose, the rule of thumb that considers 'p' to be 10% of the variety grid cell size was used (Alberico, Casaburi, et al., 2023).

In a second step, the data were synthesised with the mean algorithm (Zonal Statistics Tool) in a grid with a fixed cell size of 25 km side (hereafter 'CS_F') calculated according to the output scale of the Italian Geodiversity Map (Figure 2). In the geodiversity map processing, the effect of the grid size on the accuracy of spatial modelling have been discussed by several authors (e.g. Hengl, 2006 and reference therein) and very recently by Lopes et al. (2023) which uses several descriptive statistical parameters, calculated for several dimensions of the cell size, to select the most adequate dimension for geological and geomorphological data. The method here proposed is simple, easy to use and reliable since the calculated cell sizes are very close to those derivable from the regression between cell sizes and the extent of the studied areas from various scientific works (Alberico, Casaburi, et al., 2023). The source of data, the CS_V and CS_F sizes and indicators/indices are reported in Table 2.

The lithological (Lt) and paedological (P) indicators show the spatial variety, classified into five classes, of data provided in the respective input maps (Figure 2). The morphological indicator (M) points out the morphological variety of the Italian landscape through a reclassification of slope map proposed by Steinke et al. (2016) (Appendix 1).

In agreement with Serrano and Ruiz-Flaño and reference therein (2007), we considered surface waters (springs, marshes, lakes, rivers) and seas to be significant abiotic elements in the study of geodiversity. They represent important natural resources to which we have added glaciers and aquifers, as freshwater reserves. Concerning the hydrological index (HI), it is the sum of: (ì) permeability indicator, it is a qualitative measure of aquifer storage capacity; (ìì) the accessibility to the sea (coastline), it indicates the possibility of access to abiotic resources of transitional zones; (ììì) availability of freshwater (rivers, lakes, glaciers) and (ìììì) natural wetlands, important habitat for many different kinds of wildlife and plants (Figure 2).

The permeability indicator (PMi) was defined by the intersection of permeability map, derived from the geolithological map of Italy (Appendix 1, Table 4), with the CS_F grid. The permeability of single cell (PMi) was calculated as:

$$PM_i = \sum_{1}^{2} PG \times E_i \tag{1}$$

where E_i is the extent of single polygon in a cell and PG is the permeability grade value (Figure 2). The PM_i values were then reclassified from 1 (very low permeability) to 5 (very high permeability).

The Seas Indicator (S) (Figure 2) was derived by the intersection of coastline (ISTAT, 2022) with CS_F grid and calculated as:

$$S_i = L_c / L_t \tag{2}$$

where (L_c) is the length of coastline falling in the single cell and L_t is the Italian coastline length.

The Rivers Indicator (R) represents the contribution of rivers to the freshwater resource (Figure 2).

Table 2. For each data source, variable (CS_V) cell size, fixed (CS_F) cell size and indicator names are listed. The elements considered for hydrologic data are marked with an asterisk.

Data source	Note	Indicator
Lithological map of Italy	Some lithological units were grouped. A total of 16 classes were preserved. $CS_V = 2.5$ km side.	*Lt*
Digital Elevation Model of Italy	Resampled to 100 m to facilitate computational operations. Slopes were ranked into six geomorphological classes which summarise the main erosional processes and landforms (Steinke et al., 2016). $CS_V = 1$ km side.	*M*
Soil map of Italy	$CS_V = CS_F = 25$ km side.	*P*
Lithological map of Italy	Lithologies are classified according to their permeability grade (PG)	*PM*
Coastline *	$CS_F = 25$ km side	*S*
Hydrographic network *	$CS_F = 25$ km side	*R*
Lakes and inland waters*	$CS_F = 25$ km side	*L*
Wetlands *	$CS_F = 25$ km side	*W*
Glaciers *	$CS_F = 25$ km side	*G*

In order to preserve the branches of the hydrographic network structuring the Italian territory (i.e. Po, Tevere, Arno), from the others, *R* was estimated as

$$R_i = L_{max} \tag{3}$$

where L_{max} is the maximum length among all rivers contained in each CS_F.

Similarly, Lakes (*Li*), Glaciers (*Gi*) and Wetlands (*Wi*) indicators were calculated as:

$$i = E_{max} \tag{4}$$

where for the single indicator, *E* is the maximum extent among all elements contained in each CS_F. The value was assigned to the grid with a *Spatial Join* algorithm. This procedure preserves the lateral continuity of the geographical elements that shape the landscape.

The *Si, Ri, Li, Gi* and *Wi* values were reclassified into five classes, with the Natural break method (Jenks & Caspall, 1971), ranging from 1(very low contribution to natural resource) to 5 (very high contribution to natural resource) and summed in the Surface waters Index (*SWI*), which was added to *PM* to calculate the Hydrological Index (*HI*) (Figure 2).

Finally, the sum of lithological (*Lti*), Morphological (*Mi*), Paedological Indicators (*Pi*) and the Hydrological Index (*HI*) produced the Geodiversity Index (GI) map (Figure 2).

$$GI = Lti + Mi + Pi + \ HI \tag{5}$$

Before this sum each parameter has been reclassified into five classes ranging from '1' that indicates very low variety (i.e. cells with few lithological classes) and values '5' that indicates very high variety (i.e. cells with many lithological classes). This step is essential to make all data, characterised by a different range of values, comparable and synthesizable (Lirer et al., 2010) into summary map. For the hydrological data, the value '1' indicates a contribution to natural resources very low and '5' very high.

Finally, in order to improve the visual appearance of the geodiversity map (Araujo & Pereira, 2018; da Silva, 2019), an Inverse Distance Weighting (IDW) interpolation of the GI values, associated with the centroids of the CS_F grid, was performed.

2.3. Regional geodiversity index map

The geodiversity of Italian Regions was investigated since the Region represents the main local administrative authority of the Italian State with relevant administrative and territorial management autonomy.

The Regional Geodiversity Index (*RGI*) was calculated from the Geodiversity Map of Italy (Main Map) into two steps. Firstly, the ratio (E_i) between the extent of each geodiversity class falling into a Region (*Ei*) and the Regional extent (E_R) was calculated as:

$$E_i = Ei/E_R \tag{6}$$

Secondly, the classes of the Geodiversity Map of Italy varying from 1 (very low geodiversity) to 5 (very high geodiversity) were used as weights (GI_i) as:

$$RGI = \frac{\sum_1^n E_i \times GI_i}{\sum_1^n GI_i} \tag{7}$$

The values of RGI associated to the single Region were grouped into five classes, varying from very high to very low geodiversity (Sketch map in the Main Map).

3. Results

The Geodiversity Map of Italy provides an overview of geographical distribution of five geodiversity classes, varying from very low to very high geodiversity, at 1:1.000.000 scale (Main Map). The high and very high geodiversity classes (37% of Italian territory) encompass the Alpine and the Apennine Mountain chains, which are systems characterised by intense regimes of natural disturbance (tectonic movements, intense erosion and denudation, landslides …) that make them intrinsically geo-diverse (Chakraborty; 2021). The medium class (28% of Italian territory) coincides with the transitional zones between mountain zones, alluvial and coastal plains which in turn are characterised by very low and low geodiversity classes (35% of Italian territory).

The RGI map and histograms (Main Map) were used as geodiversity descriptive tools. The former defines the geodiversity of each region with a single value and the latter shows the percentage of the five geodiversity classes for each Region. In addition, maps of the four indicators/indices (Figures 3–6), that contributed to the geodiversity assessment, were also shown to highlight differences in geodiversity.

The Emilia-Romagna, Veneto, Puglia and Sicilia regions are characterised by very low and low *RGI*. The Emilia-Romagna region has the 60% of territory characterised by very low and low geodiversity classes (histogram in main map) largely corresponding to the Po Plain (Main Map), which, as any alluvial plain, has low lithological variety due to the prevalence of alluvial deposits (Figure 3(a)) and small elevation changes (Figure 3(b)).

The medium and high classes typify the Apennine sector (Main Map) where lithological and morphological indicators have high variety (Figures 3(a,b)). The soils show a low variety (Figure 3(c)) in both the lowland, characterised by low difference in elevation and thus little climate variability, and hilly areas. The hydrological index is high in the coastal zone, due to the accessibility to marine resources,

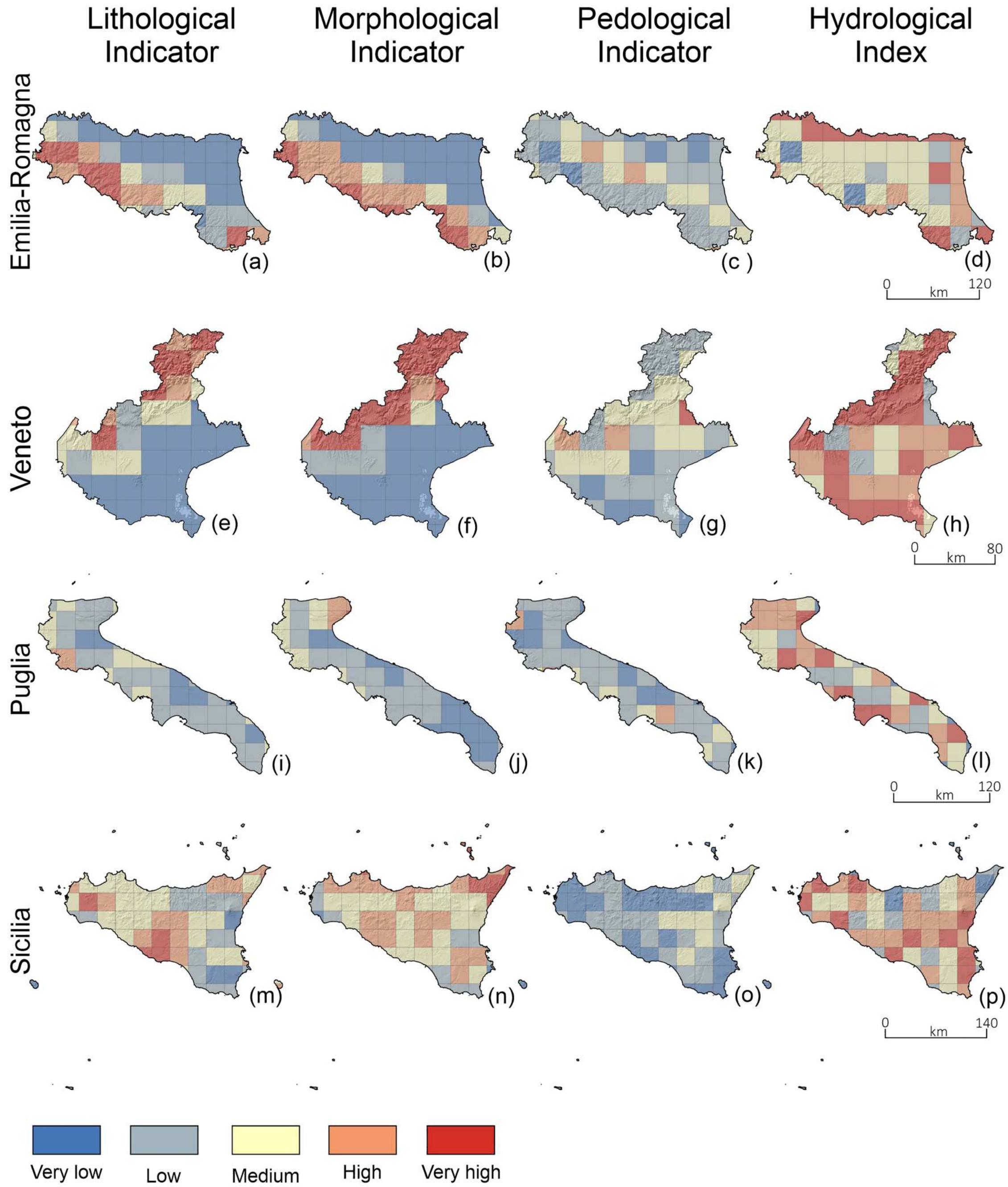

Figure 3. Maps of lithological, morphological, paedological indicators and hydrological indices for Italian Regions mainly characterised by very low and low Regional Geodiversity index (Main map, sketch map).

and in the northern sector for the presence of the Po River (Figure 3(d)).

Veneto Region has about 50% of its territory characterised by the very low geodiversity class, while the other classes have values of 8% (low and medium), 18% (high) and 20% (very high), respectively (histogram in Main Map). The low RGI value is due to the morphology of the region (Figure 3f), as about half of its territory falls within the Po Plain (Main Map), for which the same comments made for the Emilia Romagna region are valid. With regard to soils (Figure 3(g)), mountain regions show less variety than hill lands, which are characterised by more lithologically and climatically variable environments (Costantini et al., 2013). The hydrological index is high for a large part of the region as it is characterised by the presence of Alpine rivers, the Venice lagoon and access to marine resources (Figure 3(h)) (Alberico, Casaburi, et al., 2023).

Puglia Region points out a very low and low geodiversity classes for 52% and 30% of the territory, respectively (histogram in Main Map). The low geodiversity is to be found in the low morphological (Figure 3(j)), lithological (Figure 3(i)) and paedological variety (Figure 3(k)) due to the presence of the 'Tavoliere delle Puglie', the largest Italian Plain after the Po Plain (Main Map). The medium and high value of geodiversity is attributable to the hydrological

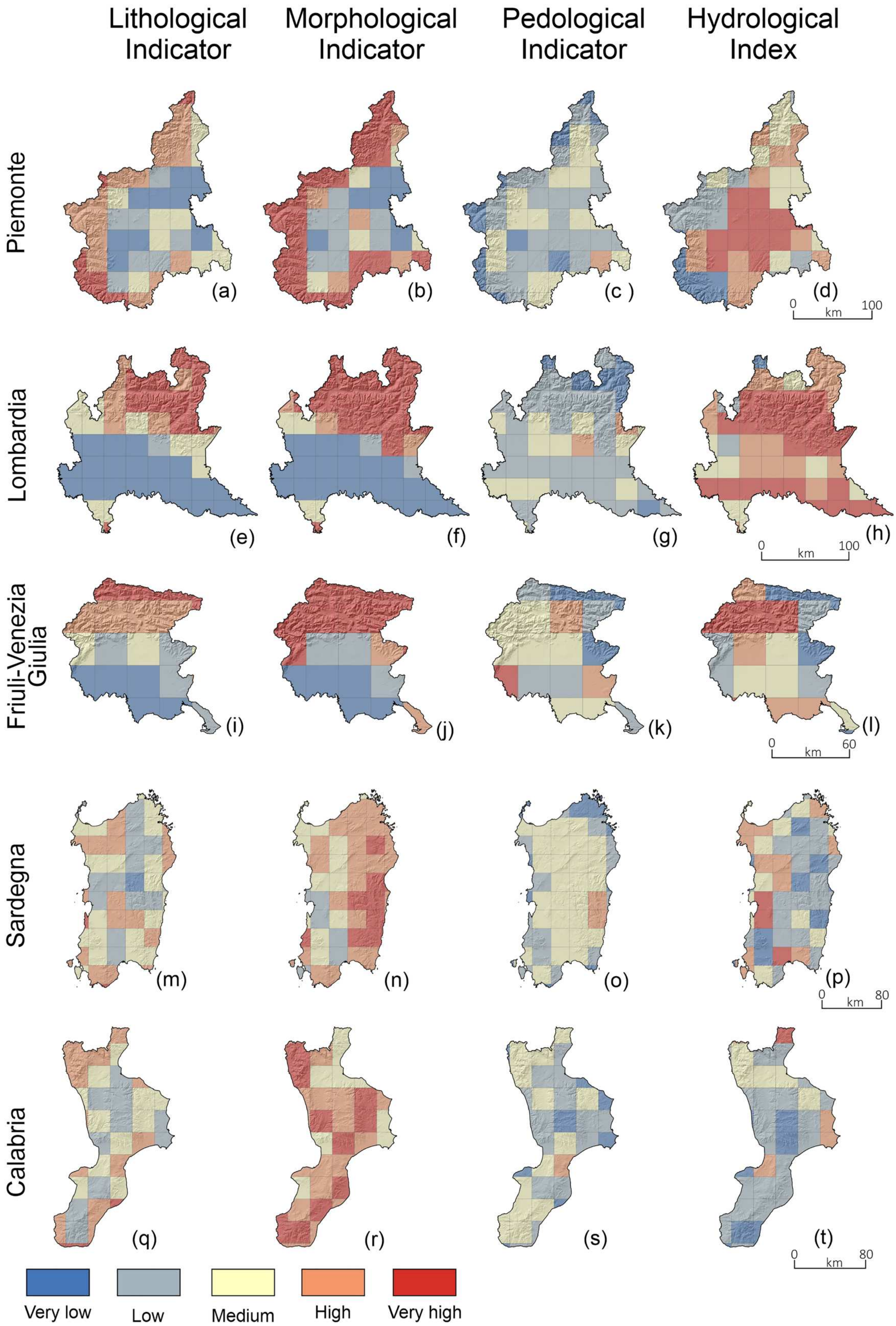

Figure 4. Maps of lithological, morphological, paedological indicators and hydrological indices for Italian Regions mainly characterised by medium Regional Geodiversity index (Main map, sketch map).

index, it is mainly due to the presence of wetlands and areas facing the sea (Figure 3(l)).

Sicily Region is characterised by the absence of a very high geodiversity class and the medium-high classes, representing 56% of territory, typify the zones with the maximum lithological (Figure 3(m)) and morphological variety (Figure 3(n)) (histogram in the Main Map). The hydrological index points out medium to high values especially in the more permeable areas and coastal zones (Figure 3(p)).

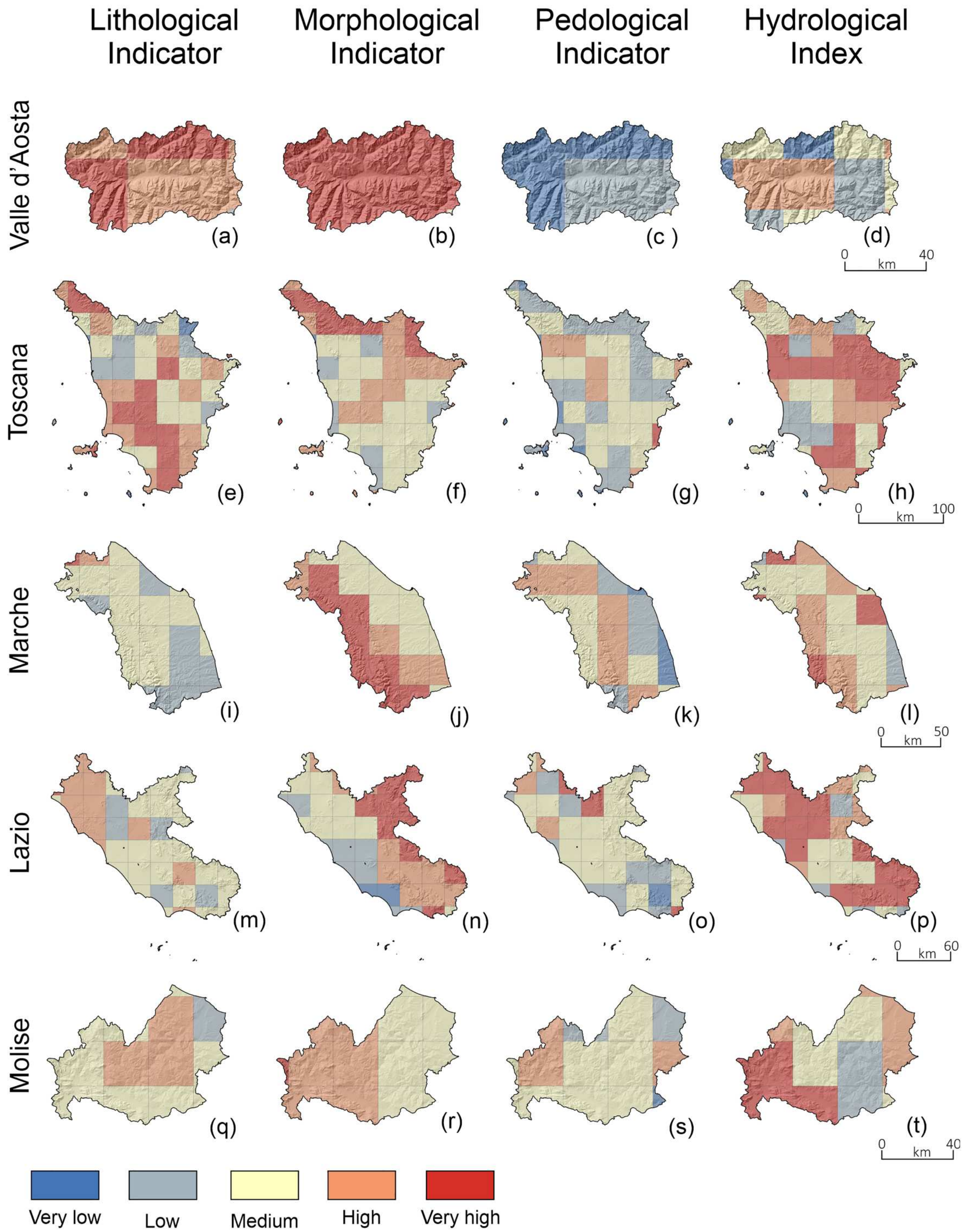

Figure 5. Maps of lithological, morphological, paedological indicators and hydrological indices for Italian Regions mainly characterised by high Regional Geodiversity index (Main map, sketch map).

Piemonte, Lombardia, Friuli-Venezia Giulia, Sardegna and Calabria are the Regions with medium RGI (RGI map in Main Map). The first three regions share a high percentage of very low and low geodiversity classes whose sum is about 33%, 51% and 56%, respectively (histogram in Main Map). As in the other regions of northern Italy, these classes are due to the presence of the Po Plain characterised by a low spatial variability of both geological (Figure 4(a,e,i)) and morphological features (Figure 4(b,f,j)). The soil indicator is medium-low in relation to the lower climatic variety of the lowland and mountainous areas compared to the Apennine chain (Figure 4(c,g,k)). The hydrological indicator is high and very high due to the presence of lakes, glaciers and important rivers. The contribution of the coastline, i.e. the possibility of access to marine resources, characterises only Friuli Venezia Giulia (Figure 4(d,h,l)).

Sardegna and Calabria, even if they belong to the same RGI class, have different geodiversity characteristics. The medium class (48% of territory) prevails in Sardinia and the low class (43% of territory) in Calabria, while the

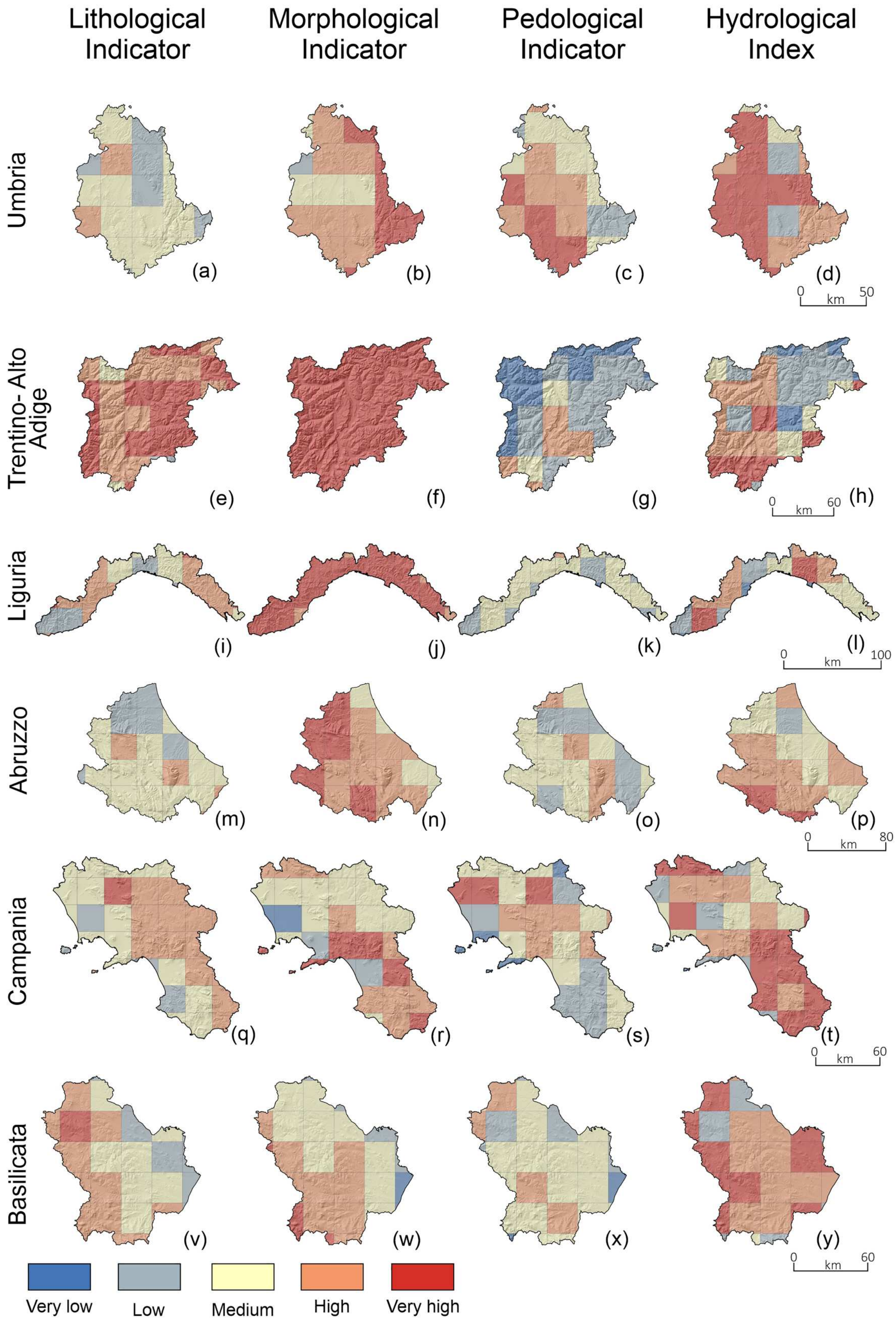

Figure 6. Maps of lithological, morphological, paedological indicators and hydrological indices for Italian Regions mainly characterised by very high Regional Geodiversity index (Main map, sketch map).

very low and high geodiversity classes are comparable (Main Map). For both regions, morphological variety is the factor that makes the greatest contribution to geodiversity (Figures 4(n,r)) and for Sardinia, the contribution of the hydrological index (Figure 4(p)) due to the presence of wetlands and water bodies near the coast also emerges.

Valle d'Aosta, Tuscany, Marche, Lazio and Molise Regions are the regions characterised by high *RGI* class. The Valle d'Aosta region is marked by the same percentage of medium and high geodiversity classes, the only two that characterise the entire region (Main Map), For this mountainous region, the greatest contribution to geodiversity is due to lithological (Figure 5(a)) and morphological variety (Figure 5 (b)). The soil variety is lower than hilly lands which are the most lithologically and climatically variable environments (Costantini et al., 2013) (Figure 5(c)). The hydrological index has medium and high variety in areas with glaciers and watercourses (Figure 5(d)).

The other regions show a similar distribution of geodiversity classes. Medium and high classes have a value between 31% and 38% and the very high class between 10% and 18% (histograms in Main Map). Tuscany shows greater lithological variety than the other regions (Figure 5(e)) while morphological, paedological and hydrological variety is similar in all regions except for Molise dominated by the medium and high morphological variety classes (Figure 5(q–t)).

Umbria, Trentino Alto Adige, Liguria, Abruzzo, Campania e Basilicata Regions are the regions characterised by the very high *RI* class (Main Map). Umbria is the Italian region with the highest geodiversity. The very high and high classes characterise 40% and 33% of the territory, respectively (histograms in Main Map). The geological variety of this region pertain to the medium class (6a) while the morphological and paedological variety, due to the Apennine chain that crosses the region, is high (Figure 6(b,c)). The very high variety of the hydrological index is due to the presence of the Tiber River, Lake Trasimeno and very permeable lithologies (Figure 6(d)).

Trentino Alto Adige and Liguria Regions, which are entirely mountainous, are characterised by a high morphological (Figure 6(f,j)) and geological (Figure 6(e,i)) variety. The variety of soils is low for Trentino Alto Adige with the exception of the area corresponding to the Adige River valley and medium for the Liguria Region characterised by a greater altitude variety in the mountainous area (Figure 6(k)). Hydraulic variety is mainly medium-high for the presence of river in both regions and of glaciers and lakes in Trentino Alto Adige and of access to sea for the Liguria Region (Figure 6(h,l)).

Abruzzo Region has 53% of its territory with a high geodiversity (histogram in Main Map). The medium class of lithological and paedological variety characterises a large part of the region (Figure 6(m,o)). The classes of morphological and hydrological indices are high and very high, respectively (Figure 6(n,p)) due to the presence of the Apennine chain and its climatic variability, as well as the high permeability of its lithologies. Liguria has medium-high (Figure 6(i)) and very high (Figure 6(j)) geological and morphological variety, respectively. Soil variety is medium (Figure 6 (k)), while the hydrological index is high in the coastal area, along river courses and in areas with higher permeability (Figure 6(l)).

Campania and Basilicata Regions are characterised by very high geodiversity, which encompasses approximately 25% –30% of their territory (histograms in Main Map). Both regions show medium to high values of the lithological index (Figure 6(q,v)). The morphological and paedological indices show values ranging from very low in the coastal plains to very high in the Apennine chain for the Campania Region (Figure 6(r,s)) while Basilicata presents medium-high values for most of the territory (Figure 6 (w,x)). For both regions, the hydrological index is very high in the zone close to the Apennine chain, where extremely permeable lithologies outcrop, to the main rivers (Sele, Liri-Garigliano, Bradano) and along the Tyrrhenian and Ionian coasts (Figure 6(t,y)).

4. Discussion and conclusive remarks

The first geodiversity map of Italy at 1:1.000.000 scale is proposed in this work. The adopted methodology made it possible to process raster and vector data source with different scales preserving the main features of the Italian territory (Alberico, Casaburi, et al., 2023).

Lithology, geomorphology, pedology and hydrology have been considered the main abiotic features of environmental system to define geodiversity. In detail, the spatial variety of the first three features and the presence of water resources were used to define the geodiversity map (Main Map), ranked from ‘Very low’ (in dark blue colour) to ‘Very high’ (in red colour). From this Map clearly emerges the distribution of high and very high geodiversity classes along the Alpine and the Apennine mountain chains and of very low and low classes in the coastal and alluvial plains. Morphological variability plays a key role in GI distribution, in which the highest values are shown for Alps (Central and Eastern Alps in particular) and Apennines Mountain. On the contrary, the coastal and floodplains display very low values of *GI* as can be noticed for the wide Po Plain and the Apulian region. Furthermore, *RGI* index map (sketch map, in Main Map), ranking the Italian regions from ‘Very low’ to ‘Very high’ classes, made it possible to rapidly visualise the Regions with higher values of geodiversity. It is important to note that GI and RGI do not indicate absolute geodiversity values but have a comparative significance. In this regards, regions such as Apulia and Veneto are less geo-diverse than other Italian regions, as they are characterised by wide plains (the Po Valley and the Tavoliere delle Puglie) dominated by alluvial deposits and a less variable morphology.

The geodiversity map of Italy presented in this paper can be considered the first output of a geodiversity geodatabase. It has a flexible structure that can be supplemented with other abiotic data and geological resources in order to provide a better description of Italian territorial features. In this frame, geodiversity hotspots and potential geosites, useful to highlight places characterised by both a peculiar geodiversity and a relevant scientific value, will be firstly implemented. These sites are considered particularly important for lowland areas, in order to integrate the national geodiversity map with important landforms and geological sections (Bollati & Zerboni, 2021; Filippo et al., 2019), which can only be detected at a detailed working scale. Furthermore, the database is conceived as modular, i.e. capable of integrating and processing data of diverse nature (e.g. physical environmental parameters air temperature; mean radiant temperature; air speed; relative humidity) according to the specific goals to be achieved and to generate maps at different scales.

At a time when environmental sustainability is the primary goal of society, the geodiversity database could be used to identify the environmental assets and ecosystem services to be preserved for future generations. Furthermore, it will be necessary to assess the anthropogenic impact on geo-resources in order to define procedures for their proper management in terms of use and conservation.

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Software

The indicator, index and geodiversity maps were processed with the spatial analysis algorithms available in the Geo-graphic Information System ArcGis® 10.8.2 (ESRI) software. CorelDraw Graphic Suite 2022 was used for final production of the map in pdf format.

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Appendix 1

Table A1. Description of lithological classes (Bucci et al., 2022 – modified).

	Description		Description
	Alluvial deposits: alluvial, lacustrine, swamp and marine deposits. Eluvial and colluvial deposits		*Intrusive rocks*: acid (granites, quartz-diorites, quartz-monzonites), intermediate (diorite, monzonite, syenite),and basic (gabbros and peridotites) plutonics. Ophiolite structures are included into basic plutonic except for basalt and serpentinite.
	Anthropogenic deposits: include Roman and modern landfills, drainage channel excavations and archaeological remains		*Lakes and Ice*: lakes, rivers, ice and glaciers on some Alpine mountains. However, the coverage is not representative for a lake or ice extent, as the priority of this map is on lithology.
	Beaches and coastal deposits: include beaches and coastal deposits.		*Lavas and basalts*: volcanic rocks including acid (rhyolites, trachytes or dacites), intermediate (andesites) and basic (basalt-type rocks, tephrites, tholeites and lamprophyres) volcanics
	Carbonate rocks: carbonate-dominant sedimentary rocks. Limestone, dolomite and marl can be associated but in a clear minority with respect to limestone. *Marlstone*: includes mostly marly rocks with a composition ranging from calcareous marls to clayey limestones.Typically, it contains marly sediments of cartographic importance associated with Carbonatic rocks or Siliciclastic sedimentary rocks		*Mixed sedimentary rocks*: sediments where carbonate is mentioned but not dominant. The class encompasses mixed sedimentary rocks that are usually a combination of different rock types (e.g. interlayered sandstone and limestone, or shaley marl with interlayered subordinated calcilutite beds or radiolarite). Mixed pelagic sediments as well as calcareous turbidites are included in the SM class.
	Chaotic – mélange: include chaotic terrains with a predominantly clay matrix and olistostromes composed by mixed sedimentary rocks (SM class). Fragments of ophiolite structures can be locally included in the Cm class.		*Non-schistose metamorphic rocks*: metamorphics where schistose fabric can be present but not dominant. It contains gneiss, amphibolite, quartzite, meta-conglomerate, and marble. Schistose metamorphic rocks: 'broad' lithological class that encompasses a wide variety of rocks from fillade to schist, including association of schist and paragneiss. Ophiolite derived rocks that show a certain degree of metamorphism and schistosity (e.g. Serpentinite) are included in this class.
	Consolidated clastic rocks: clay, sand, debris, conglomerates with a varied origin, usually of Neogene and Quaternary age, which have undergone consolidation or secondary cementation phenomena.		*Pyroclastic rocks*: sediments of volcanic origin. Typical pyroclastics are tuff, volcanic breccias, ash, slag, pozzolane, pumice.
	Evaporite: contains substantial amounts of evaporitic rocks. The typical encountered evaporite rock was gypsum, but also anhydrite and halite. If a map unit was interpreted as dominated by evaporites, it was classified as E, regardless of other mentioned rocks. This implies that E class may additionally contain, e.g. carbonates.		*Siliciclastic sedimentary rocks*: sandstone, mudstone and greywacke. Where carbonate was named in the rock description of the mapped unit, the lithological classes Cr or SM was used, so siliciclastic sedimentary rocks are without mapped carbonate influence. Note that in some cases the carbonate presence (e.g. as matrix) may not be named in the rock description, and siliciclastic sediments may still contain carbonate in nature.
	Glacial drift: include moraines and other related deposits.		*Unconsolidated clastic rock*: young, not yet consolidated and/or weathered sediments, usually of Neogene and Quaternary age. It comprises all grain sizes with a heterogeneous origin loosely arranged and not cemented together. Examples of unconsolidated sediments are clay soil, sand, not cemented breccia, loose debris and conglomerate. Significant regional differences in the distribution of lithologies exist.

Table A2. Relation between slope range, landform and processes (from Steinke et al., 2016).

	Class	Slope Angle	Landform	Process Erosion
	1	0°–2°	Floodplains, terraces, and surface erosion	Minimal soil loss and no landslides
	2	2.1°–5°	Soft ripples, valley bottoms, and tabular surfaces.	Start of solifluction, diffuse and laminar flow; furrows.
	3	5.1°–15°	On hillsides, monoclines, and structural reliefs.	Mass movements, creeping laminar flow, landslides, furrows, and ravines.
	4	15.1°–25°	Mountainous slopes, escarpment failures and terraces.	Strong linear erosion, soil destruction, landslides and falling blocks.
	5	25.1°–35°	Hogback-type structural relief, coastal cliffs, and ridges.	Strong linear erosion, destruction of soil, landslides, falling blocks, and avalanches.
	6	>35°	Walls and cliffs in canyons or very enclosed valleys, and cornices.	Mass falls, landslides, and collapses.

Table A3. Description of main soil types in Italy (Costantini, 2012).

	Codice	Description
	0	Urbanised areas and water bodies
	1	Gleyic, Calcaric, Mollic e Dystric Endogleyic Fluvisol; Rendzic Leptosol
	2	Haplic Calcisol, Calcaric Regosol, Haplic Luvisol (Cutanic)
	3	Leptic, Rendzic e Haplic Phaeozem; Rendzic Leptosol; Dystric e Eutric Cambisol
	4	Calcaric e Rendzic Leptosol; Dystric Endoskeletic Cambisol; Leptic, Skeletic Regosol (Humic, Gelic) e Eutric Colluvic Regosol (Humic); Calcaric Phaeozem
	5	Dystric, Eutric e Hypereutric Endoleptic Cambisol
	6	Calcaric Endoleptic Cambisol; Rendzic Leptosol; Rendzic Phaeozem; Haplic Luvisol (Cutanic)
	7	Albic, Umbric, Entic e Haplic Podzol (Skeletic); Dystric Cambisol; Umbric e Dystric Hyperskeletic Leptosol; Calcaric Skeltic Phaeozem; Fibric Histosol; Skeletic Regosol (Humic, Gelic); Leptic e Turbic Cryosol
	8	Sapric Histosol; Skeletic Phaeozem; Eutric Fluvic Skeletic Cambisol; Haplic Luvisol (Cutanic, Dystric); Pellic Vertisol
	9	Haplic Calcisol; Calcaric Cambisol
	10	Calcaric e Eutric Fluvic Cambisol; Luvic Phaeozem
	11	Rendzic Leptosol; Calcaric e Skeletic Endoleptic Phaeozem; Calcaric Skeletic Regosol; Calcaric Cambisol
	12	Leptic e Calcaric Endoleptic Phaeozem; Chromic Luvisol; Dystric Endoleptic Cambisol
	13	Haplic e Leptic Umbrisol (Humic); Rendzic Leptosol; Calcaric, Calcaric Leptic, Eutric e Dystric Skeletic Cambisol; Haplic Podzol
	14	Calcaric, Eutric e Eutric Skeletic Cambisol; Calcaric Regosol; Calcaric Leptosol; Haplic Calcisol
	15	'Haplic Luvisol (Cutanic, Profondic); Calcaric Cambisol'
	16	Haplic Calcisol; Calcaric Regosol; Calcaric Cambisol
	17	Calcaric, Eutric e Vertic Cambisol; Calcaric Regosol
	18	Calcic, Calcaric, Mollic e Eutric Gleysol (Anthraquic); Gleyic Cambisol; Haplic Calcisol (Hypercalcic, Siltic)
	19	'Dystric Cambisol; Chromic Luvisol; Haplic Alisol (Cutanic) e (Cutanic, Fragic)'
	20	Calcic, Calcic Hyposalic e Haplic Vertisol; Haplic Calcisol; Vertic Cambisol
	21	Hypercalcaric Regosol (Humic); Calcaric Episkeletic e Calcaric Regosol (Escalic); Skeletic, Calcaric, Calcaric Fluvic e Chromic Cambisol; Haplic Luvisol (Cutanic)
	22	Chromic, Haplic, Gleyic, Skeletic e Calcic Skeletic Luvisol; Haplic Luvisol (Dystric); Eutric Vertic, Dystric, Gleyic, Stagnic e Calcaric Cambisol
	23	Haplic Calcisol (Endogleyic) e (Hypercalcic); Calcaric e Calcaric Fluvic Cambisol; Calcaric Fluvisol
	24	Calcaric, Skeletic, Fluvic Gleyic e Calcaric Cambisol (Bathicalcic); Calcaric Gleyic Arenosol; Mollic Fluvisol (Arenic) e Thapthohistic Thionic Fluvisol (Humic)
	25	Chromic e Haplic Luvisol; Calcaric, Leptic e Stagnic Cambisol; Skeletic Endoleptic Regosol
	26	Haplic, Calcic e Pellic Hyposodic Vertisol; Eutric, Calcaric, Vertic, Gleyic e Calcaric Endoleptic Cambisol; Calcaric Skeletic Regosol; Haplic Calcisol (Endogleyic)
	27	Haplic Calcisol; Calcaric Cambisol; Calcaric Regosol
	28	Calcaric, Eutric, Calcaric Gleyic, Calcaric Endoleptic e Vertic Cambisol; Calcic Chernozem; Haplic, Leptic, Vertic e Calcaric Phaeozem; Calcaric Regosol; Haplic Calcisol; Calcic Kastanozem
	29	Haplic e Leptic Umbrisol (Arenic, Humic); Dystric Cambisol; Umbric Leptosol; Silandic Andosol
	30	Eutric, Calcaric, Dystric, Stagnic, Fluvic, Vertic e Leptic Cambisol; Calcaric Regosol; Calcaric Leptosol; Haplic Luvisol (Profondic)
	31	Chromic Luvisol; Dystric Leptic Cambisol; Eutric e Lithic Leptosol; Eutric Fluvisol

(*Continued*)

Table A3. Continued.

	Codice	Description
	32	Leptic Umbrisol; Dystric Leptic Cambisol; Eutric Regosol; Mollic Leptosol (Vitric); Mollic Vitric e Silandic Andosol
	33	Dystric Leptic e Eutric Leptic Cambisol; Eutric e Lithic Leptosol; Eutric Regosol
	34	Mollic, Eutrisilic, Vitric e Silandic Andosol; Rendzic Leptosol; Eutric, Skeletic, Calcaric e Fluvic Cambisol Haplic Luvisol (Andic)
	35	Chromic, Calcic e Haplic Luvisol; Haplic, Calcic, Chromic e Hyposodic Vertisol; Haplic Calcisol; Calcaric e Eutric Cambisol; Calcaric Regosol; Calcaric Phaeozem
	36	Eutric, Calcaric, Vertic e Fluvic Cambisol; Haplic Calcisol; Calcaric Regosol; Haplic, Luvic, Leptic e Skeletic Phaeozem; Luvic Kastanozem; Chromic e Cutanic Luvisol
	37	Vitric, Leptic, Mollic e Melanic Andosol; Vitric Cambisol
	38	Haplic Calcisol (Hypercalcic); Vitric Andosol; Haplic Luvisol (Vitric)
	39	Chromic e Haplic Luvisol (Cutanic, Vitric); Vitric e Umbric Andosol; Dystric Andic Cambisol
	40	Leptic Luvisol; Luvic, Haplic e Calcaric Phaeozem; Calcaric Leptosol; Dystric Andic e Calcaric Cambisol
	41	Eutric Leptosol; Andic, Eutric e Thaptoandic Cambisol; Haplic Luvisol (Vitric); Vitric Andosol; Tephric e Eutric Regosol (Humic)
	42	Rhodic, Chromic, Leptic e Calcic Luvisol; Rendzic Leptosol
	43	Calcic, Sodic, Gypsic e Haplic Vertisol; Fluvic e Calcaric Cambisol; Calcic Luvisol; Gypsiric Regosol; Calcic e Haplic Gypsisol
	44	Leptic e Luvic Phaeozem; Leptic e Chromic Luvisol; Haplic Calcisol; Calcic Chernozem; Calcaric Regosol; Calcaric Cambisol; Calcic Kastanozem; Calcaric Leptosol; Calcaric Arenosol
	45	Leptic, Stagnic, Rhodic e Ferric Endostagnic Luvisol; Calcaric Cambisol
	46	Eutric Planosol (Sodic);Brunic e Calcaric Arenosol;Gleyic Solonchak;Luvic e Calcaric Phaeozem;Chromic e Leptic Luvisol;Eutric Fluvisol (Arenic);Eutric e Sapric Histosol;Mollic e Calcaric Gleysol;Gleyic Vertic Cambisol;Salic Sodic e Chromic Vertisol (Grumic)
	47	Haplic e Petric Calcisol;Calcic,Chromic e Skeletic Luvisol;Calcaric e Luvic Phaeozem; Calcaric Fluvisol; Haplic e Calcic Vertisol; Calcic Kastanozem;Eutric,Fluvic,Endogleyic e Calcaric Cambisol;Vitric Andosol;Calcaric Regosol;Calcaric Arenosol

Table A4. Permeability classes derived from the lithological classes.

	Permeability Class	Lithological Units
	Impermeable	Schistose Metamorphic Rocks
	Very low	Chaotic – Mélange; Evaporite
	Low	Glacial Drift; Intrusive Rocks; Non-Schistose Metamorphic Rocks
	Low-Medium	Alluvial Deposits; Marlstone; Pyroclastic Rocks
	Medium	Beaches And Coastal Deposits; Mixed Sedimentary Rocks; Siliciclastic Sedimentary Rocks; Unconsolidated Clastic Rock
	Medium-High	Consolidated Clastic Rocks
	High	Carbonate Rocks; Lavas And Basalts; Mass Wasting Material