

Article

Assessing Geological and Climatic Pressures on Human Settlements Through the Urban Geo-Climate Footprint (UGF): Application to 21 Regional Capital Italian Cities

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Abstract

Urban areas are increasingly affected by geological and climate-driven processes that influence their safety, functionality, and long-term resilience. Conventional sustainability indicators mainly focus on anthropogenic impacts on the environment, while the role of subsurface conditions and physical processes shaping urban vulnerability remains underrepresented. To address this gap, the Urban Geo-climate Footprint (UGF) introduced an inverse perspective, assessing how geological and climatic factors exert pressure on urban systems. The methodology is based on the classification of geological effects into five drivers: Geology, Deep Geological Processes, Surface Processes, Exogenous and Climatic Processes, and Subsurface Anthropogenic Pressure. These drivers, within the proposed framework, are articulated into 22 parameters evaluated using public datasets and expert judgment. These parameters are combined into a synthetic, standardised, reproducible and comparable index, the UGF Score Index (UGF-SI), ranging from 0 to >500 which enables direct comparison across cities and contexts. The application to 21 Italian cities highlights distinct spatial patterns, dominant drivers, and groups of cities facing similar geo-climatic challenges. The UGF framework constitutes a significant advancement in urban geoscience, supporting urban planning, risk awareness, and climate adaptation strategies by enhancing the understanding of subsurface-related pressures and promoting informed decision making.

Keywords: urban geology; climate change; urban subsurface; urban resilience; geological hazards; urban geo-climate footprint; UGF



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1. Introduction

Urban areas are complex systems whose development, functionality, and resilience are strongly conditioned by geological, geomorphological, and climatic factors [1,2]. While urban sustainability assessments increasingly rely on indicators such as carbon or water footprints, these approaches primarily quantify anthropogenic pressures on the environment [3]. Conversely, the influence of subsurface conditions and physical processes on

urban vulnerability remains underrepresented and often fragmented across sectoral analyses, thereby limiting the development of integrated planning strategies [4,5].

The Urban Geo-climate Footprint (UGF) methodology was developed to address this gap by providing a structured and operational framework that evaluates how geological and climatic processes influence urban systems. Rather than functioning as a multi-risk assessment tool, which is not its ambition, UGF aims to raise awareness of subsurface-related pressures and to support decision-makers, planners, and non-expert stakeholders in understanding geo-climatic constraints that affect cities [6].

This work presents the application of the UGF methodology [7] to 21 Italian regional capital cities (Figure 1) providing a testing framework for evaluating and refining several improvements to the original methodology. The analysis was conducted between 2025 and 2026 by researchers at the Geological Survey of Italy (ISPRA—Italian Institute for Environmental Protection and Research) in collaboration with local expert geologists from universities, municipalities, and private practice who peer-reviewed the results of each tested city.

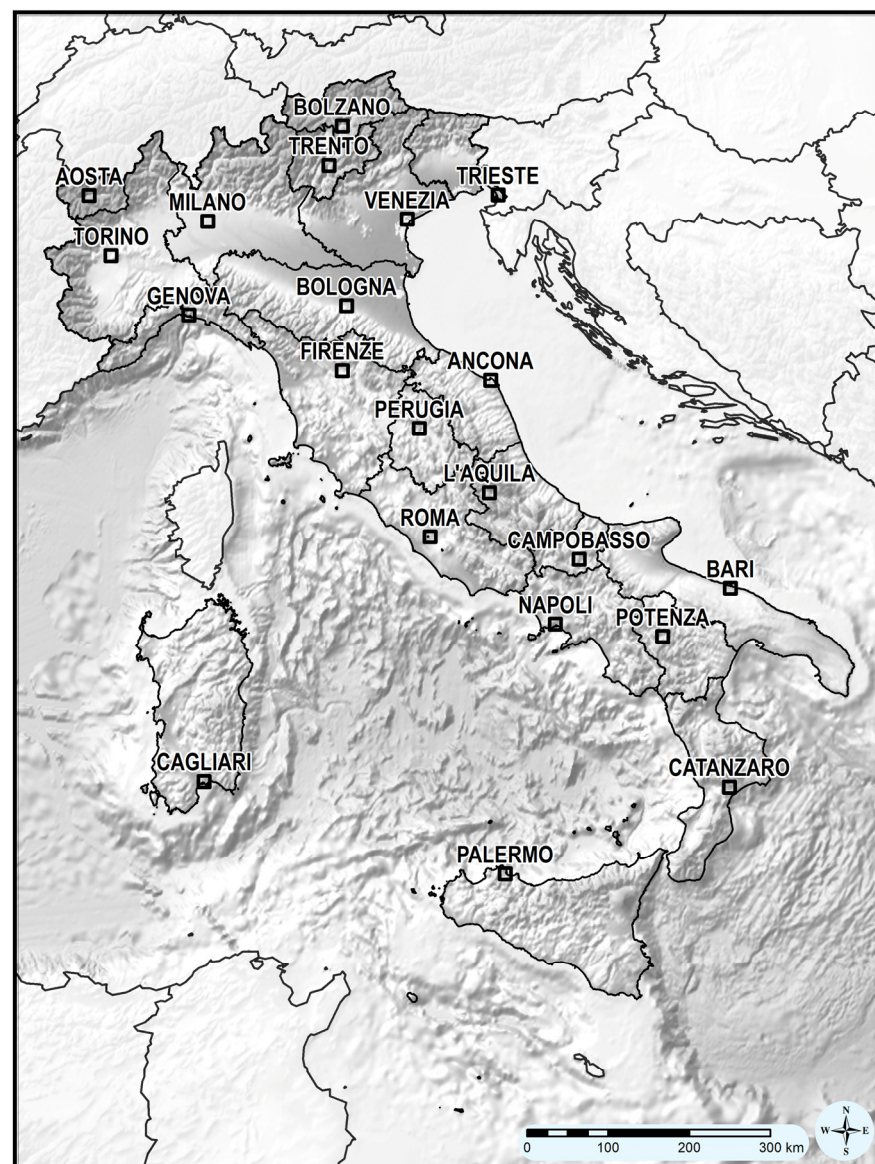


Figure 1. Location of the analysed cities.

This extensive nationwide testing aligns with an increasingly urgent body of international research aimed at bridging the gap between surface climate adaptation policies and urban subsurface strategic planning [8,9]. The underground three-dimensional space has been widely recognized as the hidden “engine room” of city development [10], whose geosystem services [11] and physical properties are crucial for mitigating compound global impacts such as urban flooding, groundwater degradation, and the subsurface urban heat island (SUHI) effect [12]. Consequently, assessing the interconnected pressures arising from geological constraints and climatic drivers at the city scale is no longer merely an academic exercise, but a prerequisite for fostering long-term geo-awareness and, therefore, enhancing urban resilience and sustainable underground management of underground urban space [13]. Within this global framework, Italy represents an exceptional natural laboratory due to the coexistence of multiple geohazards and diverse climate vulnerabilities. These conditions illustrate how different environmental pressures interact with highly heterogeneous geological settings and influence urban development and resilience.

1.1. Italy's Geological Framework

Italy exhibits a highly complex geological framework resulting from the convergence between the African and Eurasian plates, which led to the formation of the Apennines and the Alps [14]. This structural configuration has not only shaped the country's physical landscape but has also profoundly influenced the distribution and development of urban settlements throughout history. Mountain chains have acted both as natural barriers and corridors, influencing trade routes, defensive strategies, and cultural interactions.

The Apennines display complex geological structures characterised by a wide variety of lithologies (limestone, shale, and sandstone) reflecting intense tectonic activity [15]. This diversity has directly affected settlement patterns: for instance, limestone-dominated areas are often associated with karst phenomena and limited surface water availability, historically constraining urban growth and water supply systems. In the southern sector (Calabria and northeastern Sicily), the geological domain is predominantly crystalline, with similar formations also dominating in Sardinia. These conditions have generally favoured more fragmented settlement systems, often adapted to less fertile soils.

In the Alps, compressional tectonics generated large recumbent folds (nappes) and major thrust systems derived from the former Alpine Tethys, which were displaced northward and stacked over one another [16]. Crystalline basement rocks, exposed in the highest central regions, form iconic peaks such as Mont Blanc and the Matterhorn, while sedimentary sequences dominate the southern and southeastern margins, including the well-known Dolomites. This geological setting has strongly influenced human occupation: glacially carved valleys and structurally controlled corridors have hosted settlements and transportation networks, whereas steeper and more unstable areas have remained sparsely populated. Interspersed among these major relief systems, particularly along coastal sectors, are plains of varying extent and thickness. Among them, the Po Plain stands out for both its size and hydrogeological importance. The fertility of its alluvial soils and the abundance of groundwater resources [17,18] have supported dense populations since antiquity and enabled the development of major urban centres, making it one of the country's principal economic cores to this day.

Another key feature of Italy's geological framework is the presence of active volcanoes, including Mount Vesuvius, the Phlegraean Fields and Ischia Island near Napoli, as well as Mount Etna and the Aeolian Islands in Sicily, all of which are expressions of the peninsula's active tectonic setting [19]. These volcanic systems have had a lasting impact on both landscape and human activities. While posing significant natural hazards that continue to

influence urban planning and risk management, they have also generated highly fertile soils [20], supporting agriculture and sustaining the growth of important settlements.

1.2. Geographical Context of Italian Regional Capitals

The geographical diversity of the Italian peninsula has historically acted as both a constraint and a catalyst for urban development, shaping settlement patterns that reflect centuries of adaptive responses to landscape, climate, and socio-political change. During the medieval period, the widespread preference for elevated terrain, particularly along the Apennine chain and its foothills, reflected the strategic importance of defence over agricultural productivity, giving rise to compact hilltop settlements whose spatial organisation remains visible in many contemporary urban centres. In contrast, the alluvial plains and river terraces of major drainage systems such as the Po, Arno, and Tiber provided fertile and stable ground that favoured the growth of early urban settlements, whose demographic and territorial expansion depended closely on the agricultural potential of the surrounding lowland areas.

The principal Italian cities analysed in this study (Figure 1) can be grouped into distinct geographical contexts, each reflecting not only a distinct altitudinal range but also a characteristic combination of geomorphological conditions, landform associations, and associated natural processes. In response to these conditions, human communities developed and applied different strategies of adaptation and landscape modification. This framework was developed drawing inspiration from the approach proposed by [21], whose work demonstrates the fundamental role of the underlying geology in shaping urban morphology and settlement dynamics. Four principal contexts were identified, as outlined below (Figure 2):

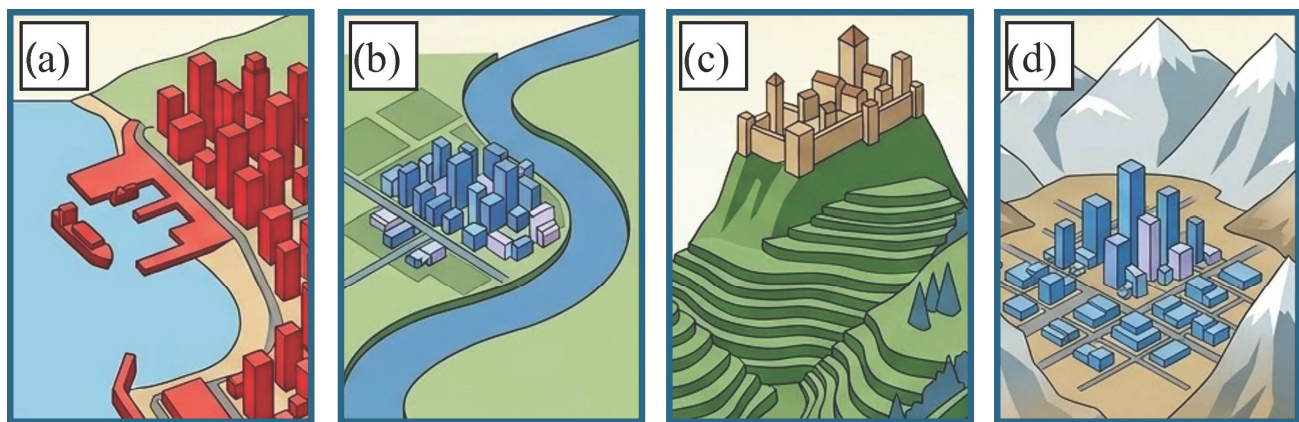


Figure 2. Schematic classification of urban settlement in four distinct geomorphological contexts: (a) coastal cities, (b) lowland cities, (c) upland cities, and (d) intermontane cities.

i. Coastal cities occupy low-relief terrain at or near the shoreline. Their urban development has been shaped by the interaction between marine, fluvial, and anthropogenic processes. Characteristic features include beach ridges, coastal plains, deltas, lagoons, and cliffed coastlines. Human intervention has historically involved port construction, land reclamation, and coastal-defence work.

ii. Lowland cities are situated on alluvial plains or river terraces, typically within major river basins. These settings are underlain by sedimentary deposits ranging from fine to coarse grain sizes, displaying significant lateral and vertical variability, low relief, and a dense hydrological network. Fluvial dynamics, including flooding, channel migration, and subsidence, have strongly influenced urban form and infrastructure development.

iii. Upland cities developed on hills or ridges, primarily within the Apennine system. This category encompasses a variety of geomorphological contexts, including structural ridges, erosional hills, and valley-side slopes. Gravitational processes, landsliding, and linear erosion represent the dominant active processes. Historically, elevated locations offered defensive and microclimatic advantages that guided settlement choices over agricultural or hydraulic considerations.

iv. Intermontane cities are located within enclosed mountain basins or confined valley floors, typically within the Alpine or highest Apennine systems. Their geomorphological setting is characterised by glacial and fluvioglacial landforms, steep valley sides, and active mass movement and alluvial fan processes. Urban development in these contexts has been strongly constrained by topographic confinement, constrained urban footprint, and significant exposure to natural hazards.

Nevertheless, cities have frequently developed within complex geographical systems, in which multiple simple systems overlap and interact. Representative examples include Genova, situated within a coastal setting where ridge morphology also plays a significant role, and Firenze, whose location along the Arno River valley floor is equally influenced by the surrounding hill system. The inherent complexity of such settings highlights the limitations of purely qualitative geographical classification. To address this issue, the UGF methodology provides a more comprehensive and quantitative framework for characterising the geo-climatic conditions of each urban centre, as described in the following sections. Table 1 presents a comprehensive classification scheme for the Italian regional capital cities.

Table 1. Synthesis of the geographical setting of each Italian regional capital city.

Geographical Setting	Cities
Coastal cities	Ancona (AN) [Adriatic coast] Bari (BA) [Adriatic low coast] Cagliari (CA) [Gulf of Cagliari] Genova (GE) [Ligurian steep coast] Napoli (NA) [Gulf of Napoli] Palermo (PA) [Tyrrhenian coast] Trieste (TS) [Gulf of Trieste] Venezia (VE) [Venetian lagoon]
Lowland cities	Bologna (BO) [Reno plain] Milano (MI) [Po plain] Roma (RM) [Tiber plain] Torino (TO) [Po plain] Firenze (FI) [Arno river valley]
Upland cities	Campobasso (CB) [Southern Apennine ridge] Catanzaro (CZ) [Southern Apennine ridge] Perugia (PG) [Tiber valley hilltop] Potenza (PT) [Southern Apennine ridge]
Intermontane cities	Aosta (AO) [Aosta valley] Bolzano (BZ) [Adige-Isarco river confluence] L'Aquila (AQ) [Gran Sasso intermontane basin] Trento (TN) [Adige river valley]

2. Materials and Methods

The Urban Geo-climate Footprint (UGF) method assesses the influence of geological and climatic conditions on urban areas through a novel semi-quantitative, driver-based methodology previously described in earlier works [7,22,23] and summarised in Figure 3. Compared with the version of the UGF tool adopted in the reference study [7] (release 8.0),

this work employs a more recent version (release 10.2), whose main improvements are described later in this section.



Figure 3. UGF concept and methodological framework and its fitting inside the UGF tool. The UGF integrates five geo-climatic drivers into a semi-quantitative index (UGF-SI; 0 ->500) to classify urban areas by geo-climatic complexity.

The approach systematically evaluates pressures exerted by subsurface characteristics and physical processes on urban infrastructure, safety, and territorial planning.

The UGF framework is organised around five main drivers, each representing a coherent set of phenomena capable of exerting pressure on urban systems:

1. **Geology (GEO)**—This driver describes the physical structure of the urban area, including physiography, unconsolidated deposits and bedrock, groundwater occurrence and interaction with urbanization, and anthropogenic fill materials.
2. **Deep Geological Processes (DEE)**—This driver includes phenomena linked to deep Earth processes, such as seismic hazard, tsunami hazard, volcanic activity, natural gas emissions, and natural sinkholes.
3. **Surface Processes (SUP)**—This driver encompasses surface-related hazards, including landslides, floods, subsidence, and coastal hazards.
4. **Exogenous and Climatic Processes (EXO)**—This driver addresses only climate-driven pressures with clear ground-effects such as changes in extreme rainfall, drought risk, and projected sea-level rise (all refereed to the RCP 8.5 scenario).
5. **Subsurface Anthropogenic Pressure (SAP)**—Although not strictly natural, this driver accounts for anthropogenic pressures affecting the subsurface, including soil sealing, contaminated sites, groundwater stress, and abandoned underground cavities.

Together, these drivers provide an integrated and multiscale representation of the geo-climatic pressures acting on urban areas. The five drivers are articulated into 22 parameters. The additional parameter—Ground and/or Groundwater Contamination Sites—compared with the tool version previously presented in [7] and reported in Table 2, was calculated using three different approaches:

- Quantitative parameters, derived from measurements or numerical models;
- Fixed-value parameters, based on expert classifications or thematic maps;
- Percentage-based parameters, calculated as proportions of the urban area.

Table 2. Overview of the 22 parameters constituting the UGF methodology. For each parameter, the table details the reference driver, type of calculation and dataset—for specific descriptions, see ESM UGF Tool Glossary.

Driver	Parameter	Type of Calculation	Type of Dataset
Geology (GEO)	Surface geology	Percentage	(Local/EU/Global)
	Shallow geological setting—consolidation state < 50 m	Fixed-values	Local
	Complexity of the geological setting	Fixed-values	Local
	Anthropogenic deposits > 5 m thickness	Fixed-values	Local
	Groundwater interference with urban fabric/environment	Fixed-values	Local
	Terrain gradient	Fixed-values	Global
Deep processes (DEE)	Earthquake related hazard	Quantitative parameters	European
	Volcanic related hazard	Fixed-values	Global
	Tsunami hazard	Fixed-values	European
	Non volcanic gas hazard	Fixed-values	Local
	Sinkhole hazard	Fixed-values	Local

Table 2. *Cont.*

Driver	Parameter	Type of Calculation	Type of Dataset
Superficial processes (SUP)	Landslide hazard	Fixed-values	European
	Flood hazard	Fixed-values	European
	Subsidence	Fixed-values	Global
	Coastal hazard/City coastline percentage	Fixed-values	Local
Exogenous processes (EXO)	Heavy precipitation change (%) max value (RCP 8.5)	Quantitative parameters	European
	Drought risk/Projection drought events frequency (RCP 8.5)	Quantitative parameters	European
	Projected in relative Sea Level rise (RCP 8.5)/City coastline percentage	Quantitative parameters	European
Subsoil anthropic pressure (SAP)	Consumed soil—Imperviousness	Percentage	European
	Ground and/or groundwater contamination sites	Fixed-values	Global
	Water stress	Quantitative parameters	Local
	Consumed subsoil—unmanaged underground caves and quarries	Fixed-values	Local

Each parameter is normalised to a score between 0 and 100, where higher values indicate greater geological complexity and/or potential criticality. The normalization procedure ensures comparability across different urban contexts and geographical settings. Most parameters rely on publicly available datasets at national, European, or global scales, while selected parameters are based on expert judgment and local geological knowledge.

For the Italian case study, national datasets were used for parameters related to surface and subsurface geology, seismic hazard, gas emissions, sinkhole susceptibility, landslide and flood hazards, coastal hazard, soil consumption, and contaminated sites.

Each parameter is weighted according to three main criteria:

1. Spatial extent of the phenomenon, with widespread processes (e.g., subsidence and flooding) weighted more heavily ($\times 1$) than localised ones ($\times 0.5$), such as isolated landslides;
2. Nature of the process, distinguishing between sudden events (shocks), such as earthquakes or volcanic eruptions ($\times 1$), and gradual processes (stresses), such as soil consumption or coastal erosion ($\times 0.5$);
3. Historical Events (HE), considering documented events that caused damage, injuries, or fatalities. This weighting criterion ($\times 2$) was introduced in the last version of the UGF tool used in this study and may result in parameter scores (and consequently driver scores) exceeding the standard normalised range of 0–100. These criteria ensure that the index reflects both physical characteristics and historical evidence of impacts, thereby grounding the UGF-SI in empirical evidence rather than solely on theoretical hazard assessments. The weights 1 and 2 are mainly assigned by default in the tool depending on the parameter typology and left user-definable in only few cases; therefore, not all parameters can reach the total theoretical score of 100.

The combination of parameter scores produces the UGF Score Index (UGF-SI), a dimensionless value ranging from 0 to >500. Values exceeding the nominal maximum score of 500 are theoretically possible, although no such cases have yet been documented. This may occur where high scores are recorded across multiple drivers in combination with significant Historical Impact Events.

The UGF-SI is obtained by summing the normalised scores of the five drivers each having a theoretical maximum value of 100, although higher values may occur where Historical Impact Events trigger score amplification. This additive structure ensures transparency and reproducibility, allowing users to identify the contribution of each driver to the final score.

Based on UGF-SI, cities are classified into four classes:

- UGF-1: low complexity
- UGF-2: moderate complexity
- UGF-3: high complexity
- UGF-4: very high complexity

In addition to UGF-SI, cities are classified according to the pair of drivers with the highest scores, enabling the identification of groups of cities characterised by similar geo-climatic conditions and challenges.

The UGF methodology also includes complementary indices:

- Geohazard Index, aggregating all parameters related to geological hazards;
- Shock–Stress Ratio, indicating the relative dominance of sudden versus gradual processes;
- SAP Index, highlighting anthropogenic pressures affecting the subsurface;
- Geo-Benefits Index, a semi-qualitative assessment of geological resources, including geo-heritage, groundwater productivity, and shallow geothermal potential.

Geo-benefits do not influence the UGF-SI but contribute to a broader understanding of urban geo-climatic contexts and represent a distinctive feature of the UGF framework, acknowledging the positive role that geological resources can play in urban systems. As the primary objective of this study is to assess pressures affecting Italian cities, the Geo-Benefits results are not presented or discussed further. The methodology is implemented through a freely available Microsoft Excel-based tool composed of multiple worksheets, including a glossary and user guide. The core worksheet, UGF Basic, hosts parameter input and index calculation functions. The analysis must be conducted by expert users (e.g., geologists or technical professionals) and may follow three progressive levels of detail: bibliographic analysis, expert local analysis, and peer-reviewed analysis.

The main output is the City Geo Factsheet, a concise and visual summary designed for non-expert users. This study was carried out using UGF tool release 10.2, available at the ISPRA website [23].

3. Results

The application of the UGF methodology to 21 Italian regional capitals (Table 3 and Figure 4) reveals a wide spectrum of geo-climatic complexity. Cities range from low-complexity contexts (UGF-1), such as Trento and Campobasso, to very high complexity (UGF-4), represented by Napoli and Genova.

The distribution of UGF classes highlights the combined influence of geological structure, climate exposure, and anthropogenic pressure. Higher UGF-SI values are typically associated with the simultaneous presence of deep geological processes, surface hazards, climate-driven pressures, and intensive subsurface use, confirming that geo-climatic complexity is rarely driven by a single factor but rather by the convergence of multiple pressures.

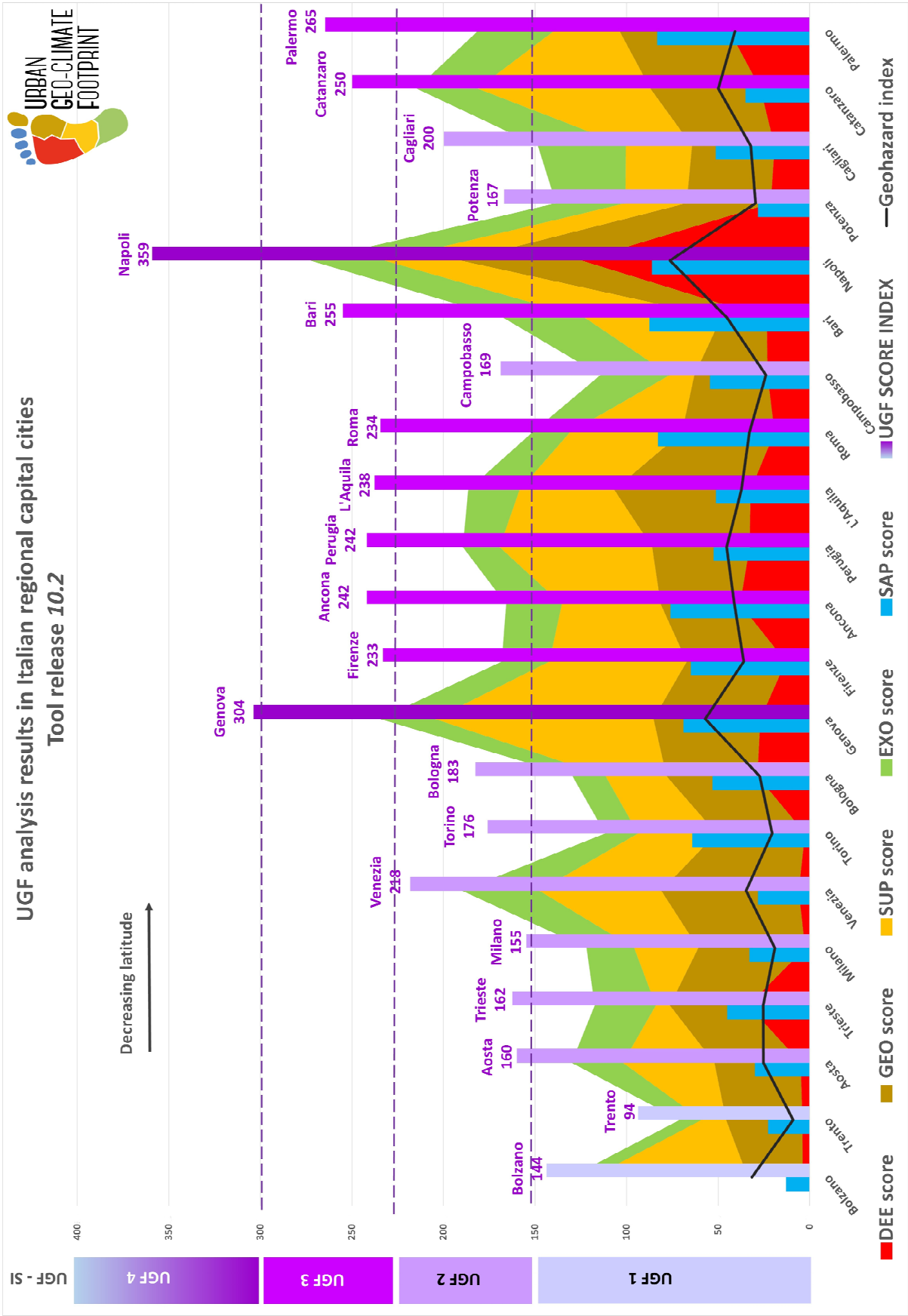


Figure 4. UGF analysis results on the 21 Italian regional capital cities.

Table 3. Data results of the UGF analysis of the 21 Italian regional capitals (see also Figure 4).

City	Inhabitants	GEO Score	SUP Score	DEE Score	EXO Score	SAP Score	UGF SI	UGF CLASS	Geohazard Index	UGF CLASSIFICATION
Bolzano (BZ)	106,177	30.0	85.0	3.8	12.0	12.9	144	UGF-1	32	SUP-GEO
Trento (TN)	119,122	41.7	13.3	4.0	12.0	22.7	94	UGF-1	9	GEO-SUP
Aosta (AO)	33,176	47.0	50.0	5.0	28.0	29.9	160	UGF-2	25	SUP-GEO
Trieste (TS)	200,630	42.8	7.7	33.5	33.4	45.0	162	UGF-2	25	GEO-DEE
Milano (MI)	1,372,355	58.3	35.0	2.5	26.0	32.9	155	UGF-2	19	GEO-SUP
Venezia (VE)	256,083	75.0	66.7	6.0	42.3	28.3	218	UGF-2	35	GEO-SUP
Torino (TO)	857,917	48.3	42.9	2.5	18.0	64.2	176	UGF-2	21	GEO-SUP
Bologna (BO)	391,484	49.7	33.3	28.5	18.0	53.1	183	UGF-2	27	GEO-SUP
Genova (GE)	562,422	58.3	119.4	27.0	30.1	68.9	304	UGF-4	57	SUP-GEO
Firenze (FI)	367,150	54.2	75.0	13.0	26.0	64.9	233	UGF-3	36	SUP-GEO
Ancona (AN)	99,377	43.3	54.0	38.0	30.5	76.1	242	UGF-3	41	SUP-GEO
Perugia (PG)	162,099	53.3	83.3	32.8	20.0	52.4	242	UGF-3	45	SUP-GEO
L'Aquila (AQ)	69,560	74.5	51.7	32.3	28.0	51.2	238	UGF-3	37	GEO-SUP
Roma (RM)	2,873,000	50.5	61.3	19.3	20.6	82.9	234	UGF-3	33	SUP-GEO
Campobasso (CB)	47,261	40.0	13.3	23.0	38.0	54.4	169	UGF-2	24	GEO-EXO
Bari (BA)	315,625	24.8	74.5	23.5	44.5	87.6	255	UGF-3	45	SUP-EXO
Napoli (NA)	940,940	66.2	41.7	124.5	40.5	86.2	359	UGF-4	76	DEE-GEO
Potenza (PZ)	65,770	46.0	33.3	21.3	38.0	28.2	167	UGF-2	29	GEO-EXO
Cagliari (CA)	149,974	45.0	36.2	19.3	48.0	51.3	200	UGF-2	32	EXO-GEO
Catanzaro (CZ)	83,247	60.0	94.4	27.0	33.3	35.1	250	UGF-3	50	SUP-GEO
Palermo (PA)	637,885	60.0	36.1	43.8	41.5	83.2	265	UGF-3	41	GEO-DEE

3.1. Spatial Patterns and Dominant Drivers

A latitudinal trend emerges, with UGF-SI generally increasing towards southern Italy. This pattern reflects the stronger influence of seismicity, volcanism, coastal dynamics, and Mediterranean climate stressors in southern regions of the country. Coastal cities tend to exhibit higher SUP and EXO scores, whereas large metropolitan areas generally show elevated SAP values highlighting the distinct geo-climatic footprints associated with different urban typologies.

3.2. City Group Classification

The GEO driver remains consistently significant across the analysed cities, reflecting Italy's high geocomplexity, which is associated with both recent depositional environments and ancient sedimentary sequences affected by tectonic processes. The SUP driver also shows a consistently important contribution across the study area. The comparatively greater contribution of GEO and SUP drivers is clearly visible in Figure 5, where each city is represented through a 2D vector-based projection of normalised driver scores. Specifically, for each city, the four drivers were first normalised and then projected onto orthogonal axes by computing the difference between opposing components (SUP–EXO for the x-axis and GEO–DEE for the y-axis). Consequently, each point reflects the relative dominance of the four drivers. The average relative importance of the drivers is additionally represented using the radar-chart configuration adopted by the UGF tool. The Geohazard Index closely follows SUP and DEE drivers, confirming their major contribution in urban geological risk.

Based on dominant driver pairs, four groups of cities are identified (Figure 6):

- GEO–SUP, characterised by strong interaction between geological complexity and surface processes;
- GEO–EXO, dominated by geological complexity and climate-driven pressures;
- GEO–DEE, marked by the influence of seismic and volcanic processes;
- EXO–SUP, dominated by climate and surface processes.

This classification supports comparative analysis and facilitates the exchange of good practices among cities facing similar challenges.

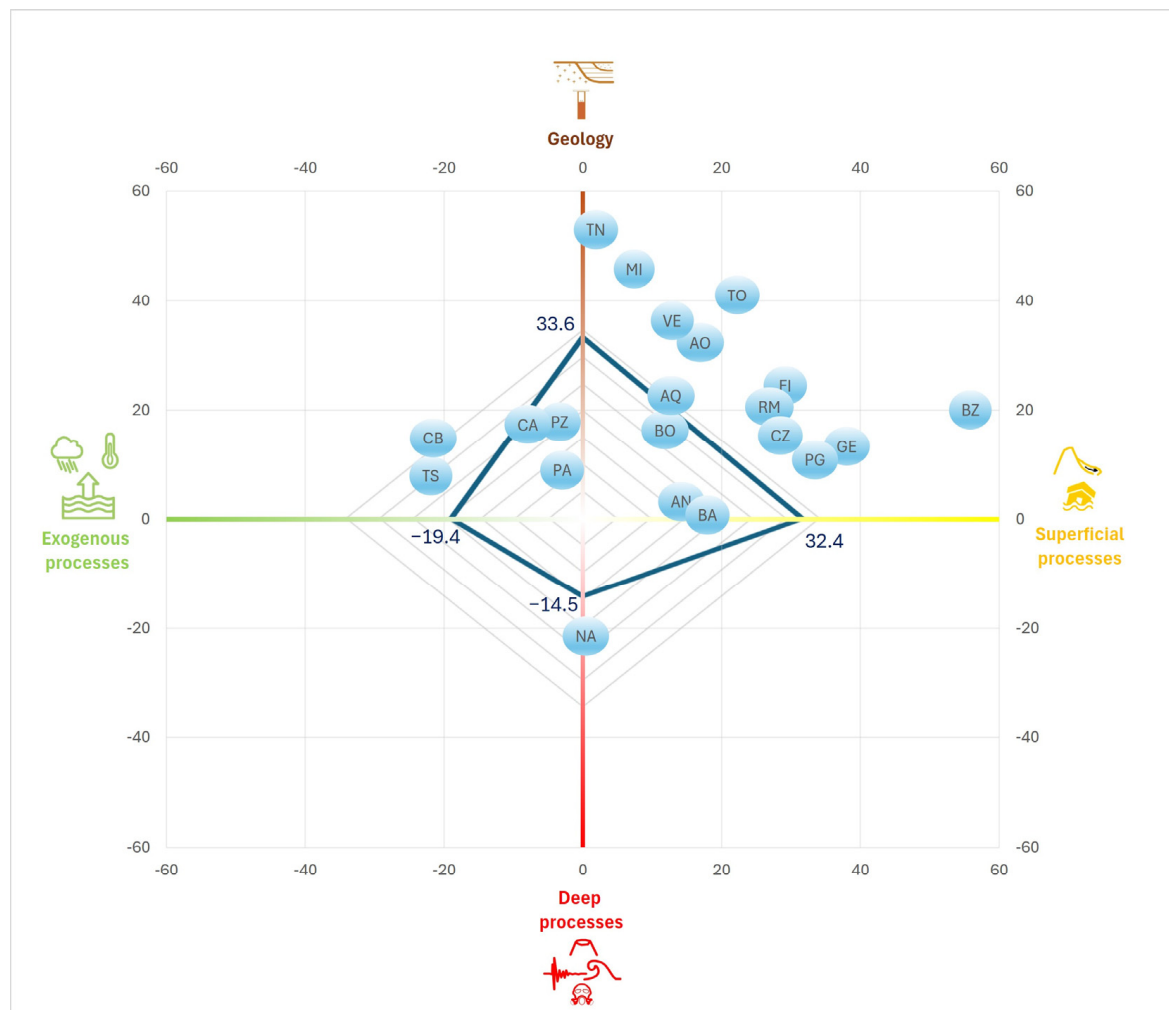


Figure 5. 2D vector-based projection of normalised driver scores for the analysed cities. Each point reflects the relative dominance of the four drivers, computed as differences between opposing components (SUP–EXO and GEO–DEE). The radar diagram shows the average driver importance across all cities.

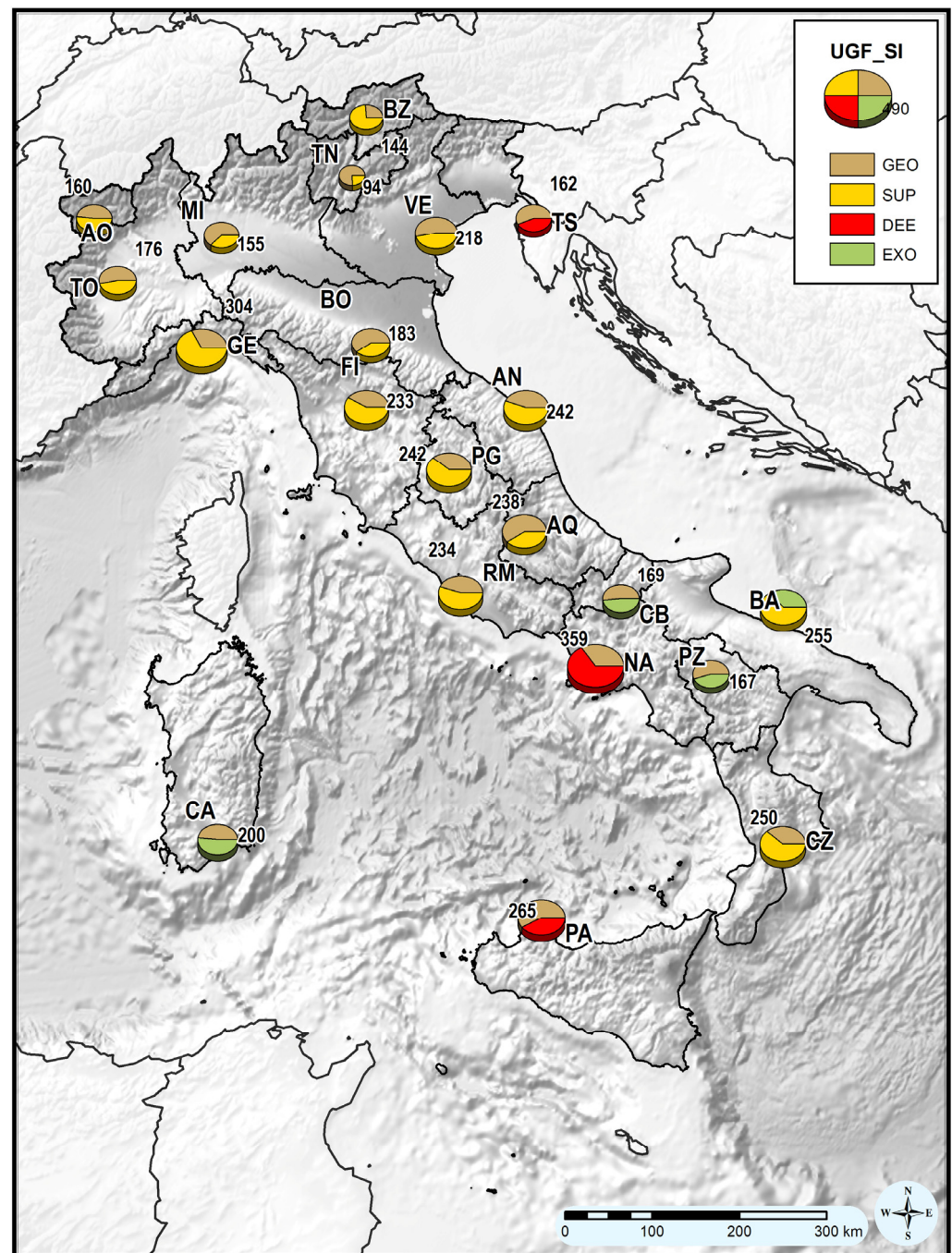


Figure 6. UGF city clusters. Cities' indicators are shown with only the pair of major resulting drivers determining the 4 groups. Cities' acronyms are listed in Table 3.

4. Discussion

The application of the UGF to the 21 Italian regional capitals provides a rich and comprehensive overview of the geological and climatic variability of Italy. The selection of these cities, representative of the country's main geographical, climatic, and structural settings, made it possible to test the methodology across the different geographical contexts described in the Introduction, ranging from Alpine systems to coastal areas, and including the volcanic regions of southern Italy.

4.1. Distribution of UGF Classes

The results (Figure 4, Table 3) reveal a broad spectrum of conditions, with cities such as Trento and Bolzano exhibiting relatively low levels of geo-climatic complexity and pressure (UGF class 1), whereas cities such as Genova and Napoli fall within UGF-4 due to a unique combination of strong exposure to surface and anthropogenic processes in the former, and seismicity, active volcanism, and anthropogenic subsidence phenomena in the latter.

The distribution of UGF classes is as follows:

- UGF-4: 2 cities (Genova, Napoli)
- UGF-3: 8 cities (Firenze, Ancona, Perugia, L'Aquila, Roma, Bari, Catanzaro, Palermo)
- UGF-2: 9 cities (Aosta, Trieste, Milano, Venezia, Torino, Bologna, Campobasso, Potenza, Cagliari)
- UGF-1: 2 cities (Bolzano, Trento)

As expected from the structure of the UGF methodology, cities with higher UGF-SI values are generally characterised by the simultaneous interaction of deep geological processes (e.g., seismicity and volcanism), surface processes (e.g., landslides, flooding, and subsidence), climate-related pressures (e.g., extreme rainfall and drought), and intense anthropogenic pressures on the subsurface (e.g., land consumption, soil sealing, and groundwater contamination). In the case of Napoli, the DEE driver dominates the framework with exceptionally high scores, reflecting the presence of the active volcanic complexes of the Phlegraean Fields and Mount Vesuvius, together with elevated seismicity and geological complexity (GEO). Conversely, Venice represents a case where vulnerability is primarily associated with the SUP driver, although EXO factors also play an important role. Natural and anthropogenic subsidence, projected sea-level rise, recurrent flooding, and the complex interaction between the lagoon environment and coastal morphology, all contribute substantially to Venice's UGF profile. It is important to emphasize that UGF classes do not constitute a "ranking" of cities according to their degree of disadvantage. Rather, they represent a tool for increasing awareness of potential critical issues, many of which are already addressed to mitigation and planning measures but may not be fully recognised by the wider public.

4.2. Latitudinal Trends and Regional Geo-Climatic Variations

Analysis of the drivers reveals a geographical differentiation highlighted in Figure 4, where cities are sorted by decreasing latitude. With a few exceptions, UGF-SI values generally increase towards southern Italy. This pattern reflects the combined effect of several factors. On the one hand, the peninsular sector of the country is more strongly affected by marine-related dynamics. On the other hand, the contribution of deep processes increases owing to higher seismic activity along the Apennine chain and the presence of active volcanic districts. Furthermore, Italy's position within the central Mediterranean increases exposure to climate change impacts including drought and desertification processes, compared with other continental European regions. The Mediterranean area is widely recognised as a climate change hotspot, as recently confirmed by international studies [24]. This pattern is also reflected in EXO driver scores, which show a slight increase in southern Italian cities, with some exceptions. Moreover several SUP parameters, including landslides, flooding, and coastal dynamics are themselves influenced by climate change and contribute to increasing scores across Italian cities.

At lower latitudes, cities located closer to the Apennine chain tend to exhibit higher DEE values, particularly due to seismicity, active volcanism, and, in some coastal cases, potential tsunami hazard. Coastal cities generally display relatively higher SUP and EXO scores due to coastal erosion, storm surges, and sea-level rise.

One driver that remains comparatively consistent across most cities is GEO, reflecting the country's overall geological complexity.

Large cities predictably exhibit high SAP scores, mainly associated with significant land consumption, soil and groundwater pollution, and, in some cases, unmanaged underground cavities that may compromise surface stability. This driver sometimes contributes significantly to the total UGF-SI, as observed in cities such as Genova, Ancona, Bari, Napoli, and Palermo.

The Geohazard Index, represented by the black line in Figure 4, closely follows the behaviour of the SUP and DEE drivers, confirming their major contribution to geo-climatic pressures and geological hazard exposure.

4.3. Urban Clustering Based on Dominant Geo-Climatic Drivers

Considering the four city groups presented in the results (Figure 6), it should be emphasised that this classification is not “absolute” but rather relative. As previously described, the methodology assigns each city to a group based on the two drivers with the highest scores compared to the others. This system is highly effective when differences between drivers are substantial but becomes less representative when the remaining driver values differ only slightly from the top two.

A further aspect to consider is the sensitivity of this classification approach. Since the assignment depends on the relative magnitude of the two highest driver scores, small variations in parameter values, normalization procedures, or weighting schemes may lead to changes in the identified dominant pair, particularly in cases where driver scores are close. This sensitivity reflects the semi-quantitative nature of the UGF methodology and implies that the resulting groups should be interpreted as indicative rather than rigid categories.

This limitation is partially mitigated by the transparency of the UGF framework, which provides full access to the individual driver scores and parameter-level information. In addition, the classification reported in individual city sheets (see Supplementary Materials) also includes the four highest-scoring parameters, allowing for the representation of specific critical issues regardless of the assigned group. An illustrative example is the city of L'Aquila (UGF3—UGF-SI 238). Although it is classified within the GEO–SUP group, its highest individual parameter is seismic hazard. This occurs because, despite the very high seismic hazard score, the absence of other contributing deep processes (DEE) results in a relatively moderate overall DEE value (32.3 out of 100).

From a methodological perspective, alternative data-driven approaches such as clustering techniques (e.g., k-means or hierarchical clustering) could be applied to the same dataset to identify groups of cities based on overall similarity across all drivers, rather than only the dominant pair. These approaches may provide a more stable classification framework, as they consider the full multidimensional structure of the data and are less sensitive to marginal differences between individual drivers.

However, the dominant-pair approach adopted in this study was intentionally selected for its interpretability and communicative effectiveness. It allows non-expert users and decision-makers to easily identify the primary geo-climatic pressures affecting each city, which is a key objective of the UGF framework. In this sense, the classification should be viewed as a simplified but transparent representation of complex interactions rather than as a strict clustering outcome. Future developments of the UGF methodology may explore the integration of clustering techniques as a complementary tool, enabling a systematic comparison between rule-based and data-driven classifications and further strengthening the robustness of the framework.

As follows, comments on the four identified city clusters:

- **GEO–SUP:** the largest group, with 14 cities, characterised by a strong interaction between geological complexity and surface processes. As previously noted, due to the overall geological complexity of Italy, the GEO driver is relatively consistent and significant across cities, making it one of the two dominant drivers in three out of four groups identified. Moreover, some GEO parameters relate to the lithological nature of the bedrock, assigning higher weight—and thus higher scores—to alluvial deposits, which often characterize the subsurface of cities historically developed along riverbanks. Surface processes (SUP) are also a constant in Italian cities, often for the same reasons, but also due to coastal phenomena affecting 5 of the 14 cities in this group, as well as landslides and subsidence. Comparing this cluster with the geographical contexts listed in the introduction, all Lowland and Intermontane cities are included within this group. This is probably related to the close association of Lowland cities with river systems and floodplain environments, and to the shared high relief energy and significant exposure to natural hazards that characterise Intermontane cities.
- **GEO–EXO:** 3 cities, characterised by geological complexity and exogenous processes. This group includes Campobasso, Potenza, and Cagliari, which differ in typology and geographical location but all fall within UGF class 2. A common feature of the EXO driver is susceptibility to drought events, rated as “medium-high” in all three cities. Since these cities generally have low UGF-SI values, the contributing parameters are of moderate importance. In Cagliari, a coastal city, potential sea-level rise also plays a significant role.
- **GEO–DEE:** 3 cities, characterised by geological complexity and deep processes. Only three cities fall into this group, including Napoli, which currently has not only the highest UGF-SI value nationally (359) but also among the cities analysed at the European scale. The other cities are Palermo (UGF-SI 265) and Trieste (UGF-SI 162). This group clearly illustrates the difference between UGF-SI score classes and UGF classification based on the relative importance of drivers. Although belonging to the same group, these cities fall into three different UGF classes. The concentration of deep processes in Napoli represents a unique case at national, European, and even global scales. Palermo shows DEE-related criticalities linked to seismic hazard, potential tsunamis, and possible natural sinkholes due to carbonate substrata in some areas. Trieste exhibits relatively high seismic hazard due to its proximity to active Alpine structures and past significant events; however, in the absence of other major criticalities and with geological complexity comparable to other cities, its overall UGF-SI remains relatively low. A common feature among all three cities is the presence of anthropogenic underground cavities that may lead to surface subsidence.
- **EXO–SUP:** 1 city, characterised by exogenous and surface processes. The only city in this group is Bari (UGF-SI 255). Flood hazards and historically significant events, together with coastal dynamics, contribute substantially to the SUP driver score, while exposure to drought episodes and projected sea-level rise account for the relatively high EXO score. Although not exhibiting particularly high values in other natural drivers, Bari shows a high level of anthropogenic pressure on the subsurface, which contributes significantly to its overall UGF-SI.

4.4. Socio-Economic Implications and Risk Correlation

Figure 7a clearly illustrates the latitudinal gradient in the UGF Score Index across Italian cities, with values generally increasing towards lower latitudes (i.e., from Northern to Southern Italy), consistent with the pattern discussed above. This trend suggests a growing prevalence of geological and geo-climatic criticalities, such as slope instability, seismic exposure, and climate-related stressors, in southern urban contexts. When this pattern

is compared with the GDP per capita of the corresponding provinces of the considered cities [25], an exploratory inverse spatial association emerges (negative correlation). The linear trend of GDP shows a general decrease along the same North–South gradient, opposing the upward trend of the UGF Score Index. In other words, higher UGF values, indicating greater environmental and geological vulnerability, seem to coincide with relatively lower levels of economic output. This spatial co-occurrence may be consistent with findings from regional geo-hazard assessments showing that geological risk and economic development exhibit significant spatial correlations, albeit in different geographic contexts [26]. These two variables (UGF-SI and GDP per capita) were also analysed through a scatter plot correlation graph (Figure 7b) and the Pearson’s correlation coefficient to assess the linear association between them.

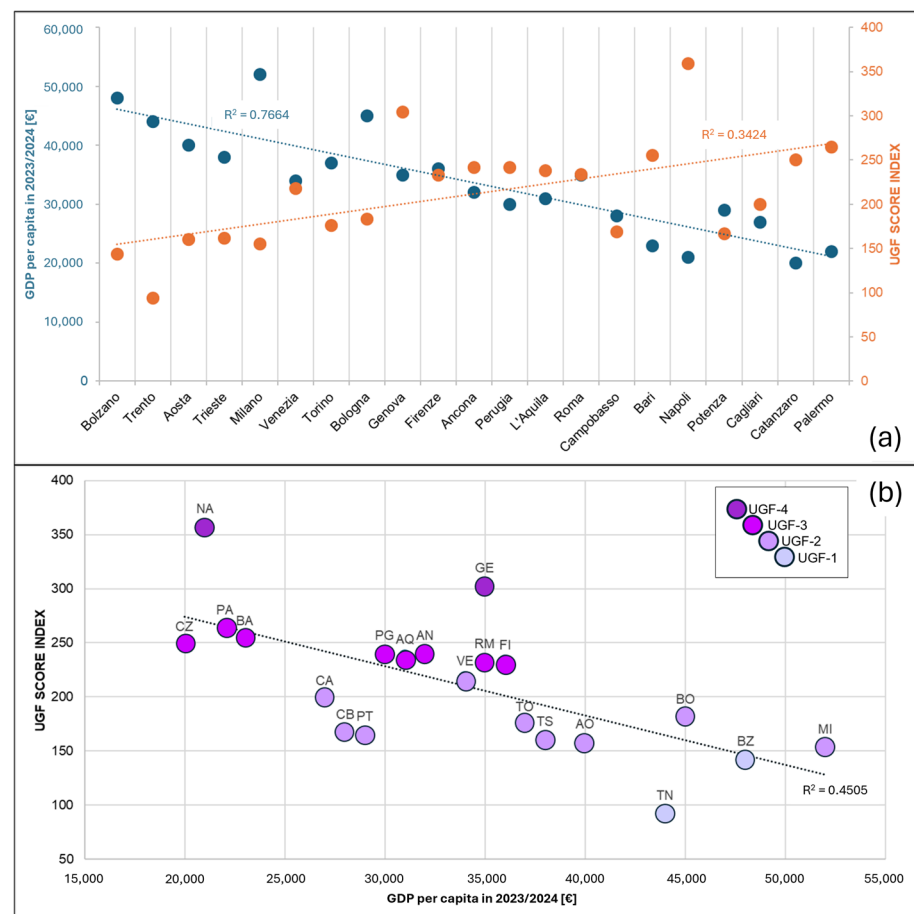


Figure 7. (a) Graph showing the UGF-SI variation vs. the average GDP per capita of the relative provinces of the 21 capital cities; (b) scatter plot correlation graph of UGF-SI vs. GDP per capita (cities are reported as acronyms and coloured by UGF classes).

The analysis showed a moderate-to-strong negative correlation ($r = -0.671$), which was highly significant (p -value = 0.0009; $p < 0.001$). As a control analysis, Spearman’s correlation (a non-parametric test) was used, which confirmed and reinforced Pearson’s result, suggesting that the relationship is robust and does not depend on assumptions of normality ($\rho = -0.718$, p -value = 0.0002). The linear regression ($R^2 = 0.45$) indicates that GDP per capita explains 45% of the variance in the UGF index within the sample. This negative correlation offers several interesting points for discussion, although it does not imply any causal link. First, it highlights a spatial overlap where geophysical constraints and regional economic disparities coexist, potentially representing a dual challenge for infrastructure resilience, investment attractiveness, and long-term development capacity in more vulnerable areas as

already highlighted by several authors [27,28]. Second, the coexistence of higher risk and lower economic resources in southern regions constitutes a combination of factors that can complicate the operational context for local administrations called to effectively mitigate or adapt to environmental hazards, as already well documented in the literature [29,30]. This spatial intersection is also observed in broader studies on disasters and inequality, which note that hazard-prone areas and economically disadvantaged contexts frequently overlap, characterizing a complex territorial dynamic [31].

Finally, these findings point to the need for targeted policy interventions that integrate risk reduction with economic development strategies, prioritizing investments in resilience, land management, and climate adaptation in areas where vulnerability and economic disadvantage overlap most strongly.

4.5. Limitations

Notwithstanding the interesting results, it is important to highlight that the UGF methodology has several limitations that should be considered when interpreting the findings.

- (a) Spatial scale and intra-urban variability. The analyses are conducted at the municipal administrative scale, which may include uninhabited or peri-urban areas, potentially diluting the signal of highly exposed urban cores. Municipal-scale averaging masks intra-urban variability, meaning that localized hotspots of geo-climatic indexes may not be captured by the composite index.
- (b) Sensitivity to weighting and normalization choices. The equal weighting assigned to each of the five drivers reflects a transparent baseline in the absence of an established empirical consensus on their relative dominance. However, different weighting schemes or normalization procedures could alter city rankings and class assignments. Sensitivity analyses testing alternative configurations are identified as a priority for future work.
- (c) Indicator selection, driver categorization, and scoring thresholds involved expert judgment without formal inter-rater reliability checks. It should be noted, however, that the assessment of each city involved a peer review process engaging local experts, providing a consistency check, reducing the risk of systematic bias in the scoring. Future iterations should nonetheless incorporate structured expert elicitation protocols to further improve reproducibility and reduce subjectivity.
- (d) Static nature of the index. The UGF-SI is a static index that does not capture temporal dynamics such as urban growth or the evolving intensity of climate-driven hazards. By design, the assessment represents a snapshot of the city's geo-climatic conditions at the time of data collection, reflecting the state of available information at that specific moment. However, this limitation can be partially addressed through scheduled periodic updates, allowing the index to be revised as new data become available and urban conditions evolve. Incorporating more systematic temporal dimensions into future versions would further enhance its utility for long-term urban planning and risk monitoring.
- (e) Parameter dependence. Some parameters within the UGF methodology are naturally interdependent. Examples include *Earthquake related hazard*, *Surface geology* and *Shallow geological setting (consolidation state < 50 m)* as well as *Terrain gradient*, *Landslide hazard*, *Flood hazard*, and *Projected changes in heavy precipitation*. Disentangling the individual contribution of each parameter is methodologically challenging. For the sake of simplicity, parameter interdependence is not currently considered in the calculation procedure.

- (f) Absence of empirical validation. Given the novelty and multidisciplinary nature of the UGF approach, identifying an appropriate validation approach represents a significant methodological challenge in itself. Unlike single-hazard or risk-oriented frameworks, the UGF-SI integrates heterogeneous geo-climatic drivers across different disciplinary domains, making it difficult to identify a single, universally applicable reference. Developing robust validation strategies, whether through expert consensus, cross-comparison with independent indices, or field-based assessments, remains a crucial next step for consolidating the scientific credibility of the framework. At present, only a consistency check is addressed through a peer-review process involving local geological experts for each evaluated city.
- (g) Data sources and transferability. Some parameters rely on European or global datasets, which may vary in spatial resolution and temporal coverage across different national contexts. The methodology should therefore be regarded as a screening and prioritization tool rather than a substitute for detailed site-specific analyses.
- (h) The classification based on dominant driver pairs may be sensitive to small variations in scores, particularly when driver values are similar. Future work may explore the use of clustering techniques to assess the robustness and stability of the identified groups.

5. Conclusions

The Urban Geo-climate Footprint (UGF) is not a multi-hazard or multi-risk assessment methodology, but it provides a novel and communicative framework for assessing how geological and climatic conditions influence urban systems.

The UGF methodology provides insights that are often overlooked by traditional urban indicators. By focusing on subsurface conditions and physical processes, UGF supports strategic planning, climate adaptation, and risk awareness. Importantly, UGF classes do not represent a ranking of “unfortunate” cities but rather a diagnostic tool that highlights priorities and context-specific challenges.

By shifting the analytical focus from environmental impacts generated by cities to the pressures exerted by subsurface and physical processes on urban environments, the methodology fills a critical gap in urban sustainability and resilience assessments. This perspective aligns with empirical and historical evidence demonstrating how geological substrates and geohydrological constraints have fundamentally shaped and dictated human settlement patterns and urban configurations over the long term, e.g., [32–34].

The application to Italian cities demonstrates the ability of the UGF to capture spatial variability, identify dominant geo-climatic drivers, and group cities according to shared challenges rather than absolute levels of risk. This makes the UGF particularly suitable as a decision-support and awareness-raising tool for urban planners, local authorities, and stakeholders.

Although the methodology does not replace detailed multi-risk analyses, it offers a complementary perspective that emphasizes the strategic role of subsurface conditions as a primary urban infrastructure. The UGF framework is transferable to different geographical contexts, provided that appropriate datasets and expert knowledge are available. Its integration into urban regeneration, climate adaptation, and long-term planning strategies can foster more resilient and geologically informed cities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/urbansci10070400/s1>, UGF Tool release 10.2, The 21 city geo factsheets of the analysed cities which references quoting are listed as follows [35–58], following the cities’ order.

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Abbreviations

The following abbreviations are used in this manuscript:

UGEG	Urban Geology Expert Group of EuroGeoSurveys
UGF	Urban Geo-climate Footprint
UGF-SI	UGF Score Index
GEO	Geological pressure driver
DEE	Deep processes driver
SUP	Superficial processes driver
EXO	Exogenous and climatic processes driver
SAP	Subsoil anthropic pressure
GDP	Gross Domestic Product
SUHI	Subsurface Urban Heat Island

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