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The Urban Geo-climate Footprint approach: Enhancing urban resilience through improved geological conceptualisation

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ABSTRACT

Urban resilience is critical to allow cities to withstand the challenges of the 21st Century. One factor that is often overlooked in such assessments is the role of the subsurface. A novel methodology called the Urban Geo-climate Footprint (UGF) has been developed to classify cities quickly and comprehensively from geological and climatic perspectives. The method operates on the fundamental assumption that cities with similar geological-geographical settings will face similar challenges, due to both common geological issues and associated climate impacts. The UGF approach has been applied to 41 European cities in collaboration with 17 Geological Surveys of Europe, the results of the UGF analysis are presented along with a regional classification of the geological resilience indicators. The UGF tool provides a semi-quantitative representation of the pressures driven by geological and climatic complexity for the cities presented, providing for a first time such classification of the urban environment. The advantage of this methodology lies in increasing awareness among non-experts and decision-makers of the interplay between geological settings, climate change pressures, and anthropogenic activities. Furthermore, it facilitates the exchange best practices among city planners to increase resilience, supporting knowledge based decision making to promote actions and policies, that enhance geoscience-informed climate justice.

1. Introduction

Global population growth and economic expansion is driving the demand for increased urban development and environmental resource utilisation. According to the 2022 United Nations World Population Prospect, the global population may reach 9.7 billion people by 2050, with nearly 70 % residing in urban areas (Esch et al., 2017; UN, 2022). Consequently, urban settings are becoming increasingly complex, this is compounded by geological and climate-related challenges associated with population growth, unequal resource distribution, and environmental exploitation (IPCC, 2012; Bricker et al., 2024).

The term "urban resilience," as defined by Meerow et al. (2016), refers to the capacity of an urban system—along with its socio-ecological and socio-technical networks—to maintain or rapidly recover desired functions, even when subjected to shocks (sudden events) and stresses. Building resilient cities can mitigate climate change impacts and associated effects (ESOTC, 2019; IPCC, 2012; Smol, 2022). However, any urban resilience strategy must prioritize safety by fostering understanding, raising awareness, facilitating knowledge transfer, promoting innovation, and enhancing education (Coaffee & Lee, 2016.)

Climate change mitigation and adaptation is a top priority for global policymakers. Initiatives like the European Green Deal (UNEP, 2009),

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the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015), the Sustainable Development Goals (UN., 2014; UN., 2016), the 2015 Paris Climate Agreement (UN, 2015a), and the 2016 New Urban Agenda (UN, 2015b; United Nations Habitat, 2017) set out the policy context for urgent action on urban sustainability and resilience. To protect human lives, health, environmental services and cultural heritage, cities must develop risk reduction plans (UNDP, 2015). Increasing awareness among citizens, as part of the city risk reduction plans, is considered a cost-effective preventive measure to protect human lives, health, environmental services and cultural heritage (UNDP, 2015).

Historically cities often lie in close proximity to natural resources and water communication routes such as riverine and coastal settings, and are shaped by their geological and geographical context.

Fostering global collaboration and raising citizens' awareness about the resources and threats associated with urban geology and climate change is therefore an essential component of urban resilience and climate action (Wachinger et al., 2013). By characterizing our urban environments geographically and geologically, we lay the foundation for resilient cities that can withstand future geological shocks and stresses. To address global challenges, a collective approach to knowledge is essential, requiring coordinated efforts from countries and cities alike (Rahman et al., 2021). One plausible solution involves classifying cities as complex systems, considering geological, subsoil-related climate impacts, environmental factors, and anthropic influences in a holistic manner (e.g., Wolniewicz, 2022; Brilha, 2016; Reynard et al., 2017).

In pursuit of this objective, we introduce the "Urban Geo-climate Footprint" (UGF) approach, a comprehensive tool for clustering and classifying cities (La Vigna et al., 2024; Lentini et al., 2021, 2022, 2024). Developed within the European context, the UGF builds on criterion proposed by La Vigna (2022) for classification of urban groundwater-related issues. The fundamental assumption is that cities can be classified based on their geological characteristics and that cities with similar geological-geographical characteristics and subsurface footprint, face comparable climatic challenges.

This assumption gains support from the growing demand for underground space—whether for groundwater, geo-energy, or construction—which if managed effectively can alleviates surface pressures and support resilience. By providing a classification tool for cities with similar challenges, the UGF becomes a starting point for a dialogue on city resilience and a platform to generate geologically sensitive interventions. It enhances citizens' awareness, improves city management, facilitates the exchange of best practices, and supports climate adaptation policies and cooperative geoscience efforts (Hollis et al., 2023) at both the European and global levels (Bricker et al., 2024).

While the Carbon Footprint quantifies gas emissions from human activities causing climate change (Wiedmann & Minx, 2008; Aichele & Felbermayr, 2012; Wright et al., 2011; Durojaye et al., 2020; Chen et al., 2021), the UGF's primary objective is to visually depict the impact of geo-climatic factors on urban settlements. It serves as a reference for investigating how cities can simultaneously enhance their resilience. Beyond visualizing exposure to hazardous geological and climatic processes, the UGF acts as a communication tool, revealing the invisible primary infrastructure—the ground itself—along with subsurface resources and geological functions and their associated benefits.

Other objectives of the UGF are:

- Develop methodology for comparison of different environmental urban contexts.
- Increase exchange good practices for urban' resilience across disciplines.
- Raise awareness for resources and threats linked to geology.
- Common toolbox for decision makers (e.g., urban planning, hazards prevention) to obtain a robust society.

The expected outcomes of the UGF analysis are:

- A classification based on geology and climatic challenges, as an administrative tool.
- A better understanding of geo-environmental processes and their potential interaction with urban subsurface and infrastructures, thus also encouraging and supporting cities' subsurface resilience for sustainable (future) growth.
- Support for the assessment of the 'economic' and 'social well-being' benefits (i.e. in terms of 'geological resilience') that could derive from urban planning associated with proper subsoil knowledge.
- A user-friendly factsheet referring to the geology of each city, to be progressively updated.

2. Materials and methods

The Urban Geo-climate Footprint comprises a tool available from the project website (http://ugf.isprambiente.it/) and in the Electronic Supplementary Materials.

Data of the different analysed European cities was derived through collaboration with 17 Geological Surveys of different countries within the Urban Geology Expert Group of EuroGeoSurveys (UGEG).

For the purposes of this work, the Degree of Urbanization (DEGURBA) classification system (Dijkstra et al., 2021) has been taken as a reference. However, the necessity to refer the analysis to a defined area led the authors to consider administrative boundaries as primary City identification. In the UGF tool the boundary of the cities is mainly based on the EU administrative classification adopted by EUROSTAT. This allows the analysis to be performed both as Local Administrative Units (LAUs) (Municipality level) or their relative NUTs3 (greater metropolitan areas) depending on the administrative fragmentation in the singular country. LAUs are used to divide up the territory of the EU for the purpose of providing statistics at a local level. They are low level administrative divisions of a country below that of a province, department, district, region or state. Not all countries classify their locally governed areas in the same way and LAUs may refer to a range of different administrative units, including municipalities, communes, parishes or wards. The Nomenclature of territorial units for statistics (NUTs3), is a geographical nomenclature subdividing the economic territory of the European Union (EU) into regions at three different levels (EuroStat, 2022); NUTs3 represent greater cities or metropolitan areas.

The analysed cities were chosen according to the following general criteria: i) at least one city per country, ii) at least the capital city of each country and/or, when possible, one more or more cities per country.

The UGF framework is defined by several factors (hereafter "drivers"): the geology pressure, the external climatic soil and subsoil-related pressures ("exogenous processes"), the deep geological processes pressure, the superficial processes pressure, and the anthropogenic (or human-induced) pressures on the subsurface ("subsoil anthropic pressure").

Each driver is articulated in quantitative and indexed parameters and weights, to define a final "UGF score INDEX" coming from the combination of all the drivers' specific scores explained in the next section. The higher this index value, the higher the geological and subsoil-related climatic complexity of the city.

Concepts and methods on which the tool is based are reported as follows.

2.1. The UGF concept

The UGF concept was born after a series of discussions and workshops between urban geology experts following a "trial & error" approach for three years, starting from very simple assumptions and adding complexity gradually (Hill & Tiedeman, 2006). Several challenges were faced in the concept development. The principal challenges were the heterogeneous data quality in different countries, and the heterogeneity in climate and geology as well.

To better understand the UGF concept both the underground extent of the city and the geological platform (the primary infrastructure cited in the Introduction) on which the city is built should be considered. This allows us to conceptualise the different pressures due to the geological characteristics of the city's foundations and consider them more coherently, as singular fingerprints. The combination of these pressures on the city represents the Urban Geo-climate Footprint (Fig. 1).

The cited pressures can be considered as drivers of the general framework of the UGF and can be described as follows:

2.1.1. *Geology (GEO)*

This driver describes and conceptualises the geological setting of the city. Physical aspects due to the geological structure (stratigraphy, groundwater, slope) and its complexity are considered here.

2.1.2. *Deep (geological) processes (DEE)*

This driver describes the active deep geological processes affecting the city. Aspects due to seismic and tsunami hazard, volcanic hazard, gas emissions and naturally occurring sinkholes are considered here.

2.1.3. *Superficial processes (SUP)*

This driver describes the geological processes and phenomena occurring on the city surface. Aspects due to ground instability (landslides and land subsidence), the interaction with surface water bodies (river floods), and the sea (coastal erosion) are considered here.

2.1.4. *Exogenous processes (EXO)*

This driver describes all those processes due to meteorological extreme events and climate change having an impact on the city's subsoil; processes such as heavy rains, droughts and sea level change are considered here.

2.1.5. *Subsoil anthropic pressure (SAP)*

This driver describes the effects on the city subsoil resulting from anthropic activities. This is the only driver whose concept is more conceptually similar to the ordinary footprints (e.g. carbon footprint), but its contribution to the UGF is crucial because geological problems can be triggered or exacerbated by human activity. The process of soil consumption and connected degradation and pollution (Ball et al., 2018), or sealing, which limits natural infiltration, reducing groundwater recharge and increasing urban runoff and exacerbating flood risk is considered here. Water stress and unmanaged or abandoned underground excavations are considered here as well.

There are three main assumptions that must be considered in the UGF concept and relative analysis:

1. The Urban Geo-climate Footprint is different than usual footprint concept (e.g. Carbon Footprint) and must be regarded as acting in reverse. In other words the UGF is not "of the city" rather than "on the city".
2. The parameters are designed so that the higher the value, the higher are the negative effects on the city by that parameter.
3. Cities can be compared because the parameters are evaluated according to the same general starting data set. Thus, parameters' values are generally referred to databases or maps available for the same considered context (currently the European continent). It is possible to downscale the analysis when a more detailed dataset is available, but every parameter assessment starts from the available general dataset.

2.2. *Method for the UGF tool*

To have simple handling and ensure user-friendly compilation, the UGF tool (Electronic Supplementary Materials) has been developed in Microsoft Excel and its *.xlsx* file is organised in eight spreadsheets (Fig. 2) described in the Annex paragraph.

2.3. *Parameter calculation*

Depending on the parameter type, its calculation follows one of the three methods (quantitative, fixed-values, and percentage parameters) presented as follows.

2.3.1. *Quantitative parameters*

The quantitative parameters are those related to phenomena/characteristics for which there is an existing discretized map that allows a specific value for the considered city area. When the discretization is of higher resolution than the city area, it is necessary to consider the average value of the cells included in that area (e.g. average seismic ground acceleration). The value is considered with respect to its minimum and maximum and distributed on a scale from 0 to 100, where 0 represents the minimum and 100 is the maximum value, as shown in the following example.

e.g.: Driver "DEE"; Parameter "Earthquake related hazard".

Values gathered from Seismic hazard map (ESHM 20 – Danciu et al., 2021).

Minimum value <0.0002 g – Maximum value 0.8 g.

The Earthquake related hazard score is evaluated as follows:

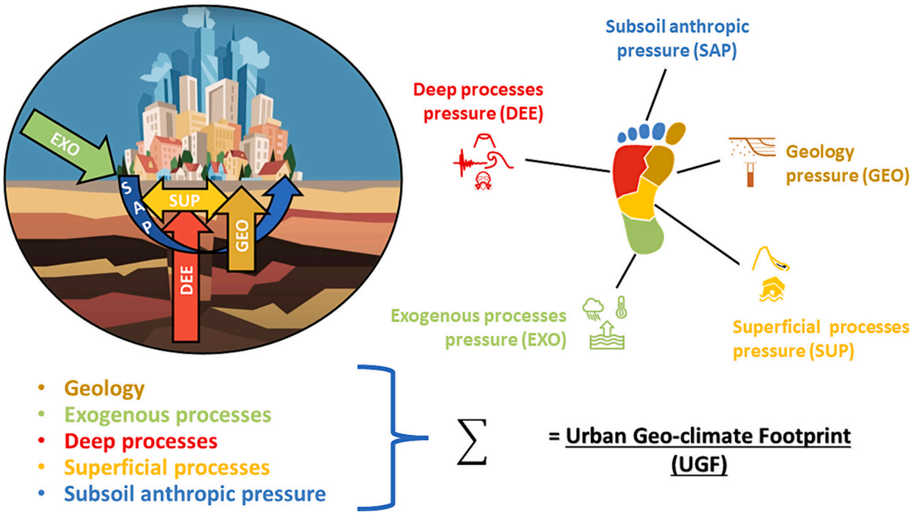

Fig. 1. Conceptualization of the Urban Geo-climate Footprint.

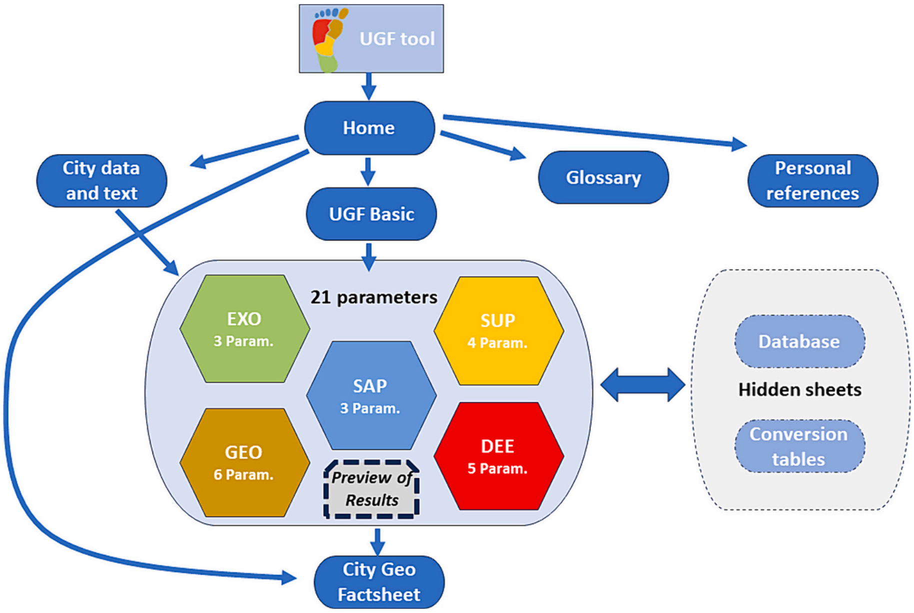

Fig. 2. Flowchart of UGF tool with the *.xlsx* structure organised in eight spreadsheets. The 21 parameters are grouped in the 5 drivers Geology (GEO), Superficial processes (SUP), Deep processes (DEE), Exogenous processes (EXO) and Subsoil anthropic pressure (SAP).

$$\text{Earthquake related hazard score} = \frac{\text{Seismic hazard value on the map}}{\text{Maximum value}} * 100$$

2.3.2. *Fixed-values parameters*

Fixed-values parameters are related to processes/characteristics for which there is a discretized map already organised in fixed categories or for which the analysis is approached more qualitatively and based on user expertise on the city area. These values can be also typical of processes or conditions that are commonly found just in some specific areas and places. Below are reported a couple of examples of the calculation for these types of parameters.

e.g.: Driver “SAP”; Parameter “Water stress”

Values gathered from Water Stress map (Luo et al., 2015; Reig et al., 2013; WRI, 2023).

Arid l. and NO DATA (Score = 0)

LOW (Score = 10).

LOW-MEDIUM (Score = 25).

MEDIUM (Score = 50).

MEDIUM-HIGH (Score = 75).

HIGH (Score = 100).

e.g.: Driver “SUP”; Parameter “Landslide hazard”

YES – Landslides occur over >30 % of the city area or on <30 %, but their propagation affects highly populated areas (Score = 100).

YES LOCALLY – Landslides are localised in specific parts of the city (Score = 50).

NEGLIGIBLE – Landslide phenomena are present but with negligible effects on the city (Score = 10)

NOT – There are no known landslides in the city area (Score = 0).

2.3.3. *Percentage parameters*

Percentage parameters are related to processes/characteristics that can be obtained from a dedicated map or from the analysis of the city area, as shown in the following example.

e.g.: Driver “SAP”; Parameter “Consumed soil – imperviousness”

The percentage value of the parameter is used as derived directly from the dataset expressed in percentage (European Copernicus Service, 2020.)

2.4. *Weight of the parameter values*

To weight the parameters both the expected extension of their effects and their relative behaviour as stress or shock are evaluated as follows:.

2.4.1. *Effect extension weight*

Some processes/characteristics can have an effect just in the “point” where they occur (e.g., a landslide), while others can have an effect on “widespread” areas or can affect the whole territory (e.g., an earthquake or land subsidence).

This weight is related to the effect extension that is considered for the process/characteristic, as follows.

e.g.: effect extension

Widespread effect process/characteristic (Weight = *1).

Point-effect process/characteristic (Weight = *0.5).

Weights (widespread or point effects) have predefined parameters, but they can be changed by the user in some specific conditions.

2.4.2. *Stress or shock weight*

Depending on the time needed for the process/characteristic to produce its effects on the city, any parameter is defined as a Stress or a Shock. A city stress is a slow process/phenomenon that occurs continuously and whose chronic effects are visible/can be felt over a long time and require continuous actions and investments, but it generally does not jeopardize people’s lives right away. A city Shock is a fast process/

phenomenon that occurs abruptly and whose effects are immediately visible/felt, it can endanger people's lives immediately and normally requires huge restoration costs.

Based on the above considerations, the stress and shock weight are assigned as follows.

e.g.: stress or shock

Shock process/characteristic (Weight = *1).

Stress process/characteristic (Weight = *0.5).

These weights (stress or shock) have predefined parameters but the user in some specific conditions can change them.

2.5. *Drivers score calculation*

Every parameter contributes to the drivers' score calculation. Considering the maximum obtainable value of the sum of the weighted parameters for each driver, the obtained values are returned as a percentage of it.

2.6. *Parameters*

The current version of the UGF tool (release 8.0) considers 21 parameters grouped in to 5 main drivers as previously defined. The list and calculation details of every parameter is reported in Table 1, while the parameters' meaning and description is reported in the Annex A. The terminology of the parameters is based on the UNDRR indications (UNDRR, 2017).

2.7. *Indexes calculation and city classification methods*

2.7.1. *UGF SCORE index and classes*

The sum of the percentage scores obtained for the different drivers represents the UGF SCORE INDEX (UGF-SI). It is a dimensionless value representative of the geological complexity beneath the city. As there are 5 drivers considered, each with a maximum singular score of 100, the maximum reachable UGF-SI is 500.

$$UGF\ SI = \frac{\sum_i GEO_i}{max(GEO)}*100 + \frac{\sum_i SUP_i}{max(SUP)}*100 + \frac{\sum_i DEE_i}{max(DEE)}*100 + \frac{\sum_i EXO_i}{max(EXO)}*100 + \frac{\sum_i SAP_i}{max(SAP)}*100$$

Table 1

- List of parameters with type of calculation, and their attribution as geohazard, point or widespread expected effects, shocks or stresses, and related references. The parameters' meaning and description is reported in the Annex A.

Driver	Parameter	Type of calculation	Geohazard	Point or wide effects	Shock or Stress	Type of dataset	General Reference
Geology (GEO)	Surface geology	Percentage		Widespread	Stress	(Local / EU / Global)	Local data /Asch, 2005
	Shallow geological setting – consolidation state <50 m	Fixed-values		Widespread	Stress	Local	Local data /user expertise
	Complexity of the geological setting	Fixed-values		Widespread	Stress	Local	Local data /user expertise
	Anthropogenic deposits >5 m thickness	Fixed values		Widespread	Stress	Local	Local data /user expertise
	Groundwater interference with urban fabric/environment	Fixed-values		Widespread	Stress	Local	Local data /user expertise
	Terrain gradient	Fixed-values		Widespread	Stress	Global	ASTER GDEM (Nasa Meti) Abrams et al., 2020
Deep processes (DEE)	Earthquake related hazard	Quantitative parameters	✔	Widespread	Shock	European	Giardini et al., 2014; ESHM20 (Danciu et al., 2021)
	Volcanic related hazard	Fixed-values	✔	Widespread	Shock	Global	Smithsonian Institution-Global Volcanism Program, 2023
	Tsunami hazard	Fixed-values	✔	Widespread	Shock	European	NEAMTHM18Basili et al., 2018 (Basili et al., 2021)
	Non volcanic gas hazard	Fixed-values	✔	Widespread	Stress	Local	Local data
	Sinkhole hazard	Fixed-values	✔	Point	Shock	Local	Local data
Superficial processes (SUP)	Landslide hazard	Fixed-values	✔	Point	Shock	European	Pan-European landslide susceptibility mapping: ELSUS Version 2, 2018 (European Commission – JRC), (Günther et al., 2014)
	Flood hazard	Fixed-values	✔	Widespread	Shock	European	River flood hazard maps for Europe and the Mediterranean Basin region, 2022, (European Commission – JRC), (Dottori et al., 2021)
	Land Subsidence	Fixed-values	✔	Widespread	Stress	Global	(Herrera-García et al., 2021)
	Coastal hazard	Fixed-values	✔	Widespread	Stress	Local	Local data
Exogenous processes (EXO)	Heavy winter and summer precipitation change (%) max value between summer and winter	Quantitative parameters	✔	Widespread	Shock	European	The Copernicus Interactive Climate Atlas (Copernicus, 2024)
	Drought risk	Quantitative parameters	✔	Widespread	Shock	European	European Drought Observatory, 2020 (European Commission-JRC)
	Projected in relative Sea Level rise /City coastline percentage	Quantitative parameters	✔	Widespread	Stress	European	European Environment Agency, 2024

(*continued on next page*)

Table 1 (*continued*)

Driver	Parameter	Type of calculation	Geohazard	Point or wide effects	Shock or Stress	Type of dataset	General Reference
Subsoil anthropic pressure (SAP)	Consumed soil - Imperviousness	Quantitative parameters		Widespread	Stress	European	European Environment Agency, 2022
	Water stress	Quantitative parameters		Widespread	Stress	Global	WRI (aqueduct), 2023; Luo et al., 2015; Reig et al., 2013
	Consumed subsoil - unmanaged underground caves and quarries	Fixed-values		Widespread	Stress	Local	Local data

Depending on the UGF-SI value the analysed cities are categorised in the following 4 classes with relative descriptions. Cities with highest classes are expected to experience more geological-related issues than those with lower classes.

- UGF-1 (UGF-SI < 150): Low geological impact on settlements, but some areas may have issues for which citizens should be aware. Some knowledge of the urban geology and climate change effects by urban planners can help in the city management.
- UGF-2 (UGF-SI $= 151 \div 225$): Moderate geological impact on settlements, with several areas facing challenges. Planners and managers must understand urban geology and climate change effects, and citizens must be aware.
- UGF-3 (UGF-SI $= 226 \div 300$): High geological impact on settlements, with many issues in the city. Understanding urban geology and climate change effects is vital for citizens, and mandatory for planners and managers.
- UGF-4 (UGF-SI > 300): Potential catastrophic geological impact on settlements. Knowledge of urban geology and climate change effects, along with citizens and planners' awareness, is crucial.

2.7.2. UGF classification

As the UGF classification is related just to the natural geological and climatic conditions of the city, the proportional magnitude of four drivers (GEO, DEE, SUP, EXO) is compared excluding the driver Subsoil anthropic pressure (SAP) which doesn't depend on the above-mentioned parameters and local climate. The comparison is made by a radar graph of the four considered drivers (see Fig. 8 later in the text). The two drivers with the highest score define categories of cities by type of dominant processes.

2.7.3. Geohazard index

It is a dimensionless value representative of the geohazard level of the analysed urban area. It is evaluated by the sum of all those parameters of the tool identified as geohazards (Table 1). In this regard, it is important to underline that this index does not refer to, nor does it replace, a detailed hazard assessment (and/or risk analysis) but it is intended as a summary descriptive index, as largely described in the previous sections.

$$Geohazard\ Index = \frac{\sum_i geohazard_i}{max(geohazard)} * 100$$

2.7.4. Shock/Stress ratio

As previously described, parameters are classified as stress or shock (Table 1). The ratio between the sum of all shock parameters and the sum of all stress parameters is representative of the type of phenomena/setting of the city. A ratio close to 1 or >1 indicates cities with a greater propensity to be affected by sudden events.

$$\text{shock} - \text{stress ratio} = \frac{\sum_i \text{shock}_i}{\sum_j \text{stress}_j}$$

2.7.5. Subsoil anthropic pressure

This index simply represents the sum of the scores related to the driver Subsoil anthropic pressure (SAP). It was decided to display it separately as it is not considered in the UGF classification.

$$Subsoil\ anthropic\ pressure = \frac{\sum_i SAP_i}{max(SAP)} * 100$$

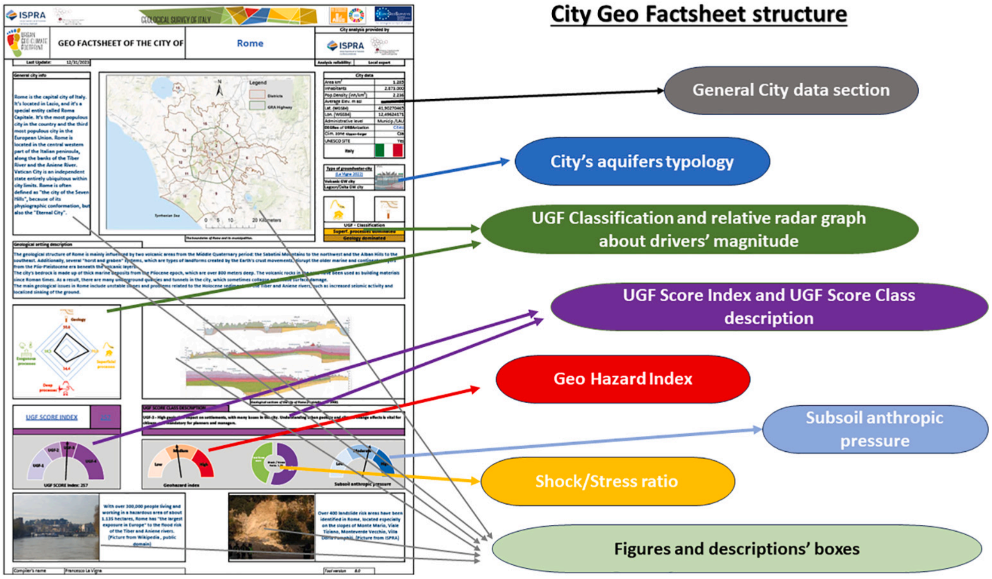

Fig. 3. The main result of the UGF city analysis is the "City Geo Factsheet, a "user-friendly" document to be used to share the knowledge about the city's geological setting.

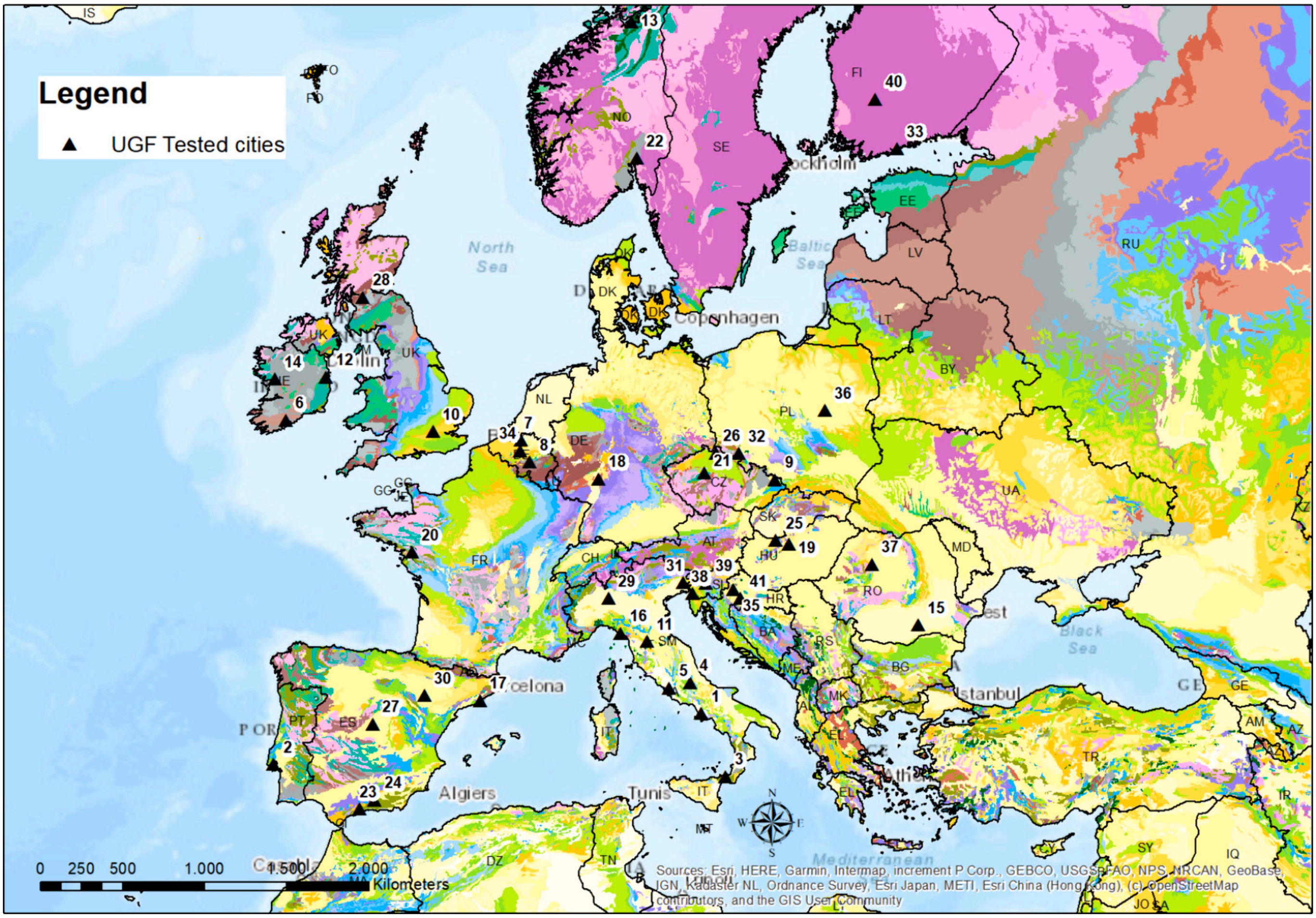

Fig. 4. UGF's analysed cities VS the 1:5 million International Geological Map of Europe and Adjacent Areas (source: EGDI platform) (Asch, 2005). Labels are relative to the position in Table 2.

3. Results

The main result of the UGF tool for each analysed city is a "user-friendly" factsheet named "City Geo Factsheet" (Fig. 3), which automatically shows the previously described indexes and the city classification by infographics, together with some simple descriptions and pictures reported by the user (City Geo Factsheets of the analysed cities are available in the Annex B).

To date, 41 cities of the European continent have been analysed through the UGF tool covering several geological contexts. The cities' location is shown in Fig. 4 while the list with relative values of the single drivers is shown in Table 2. The city collection is still in progress and in the current work only its first stage is presented.

The UGF analyses results are reported (Table 2; Fig. 5) for each considered city, along with the final UGF score Index obtained (approximate integer digits) by the sum of the five single driver scores. Also, the mean and median values have been calculated for each driver at the base of each column. It can be observed that the higher mean value pertains to the GEO driver with the value of 50, other drivers being close to 40 except for the DEE one, barely reaching the value of 15. The UGF Score Index (sum of drivers' scores), namely the first and most simple parameter to rank cities, varies considerably, spanning from 120 points for Sisak (Croatia) to 315 points for Naples (ITA). This latter, according to the well-known Tukey fences method (Tukey, 1977) represents the only outlier of the dataset (k = 1.5), as depicted in the boxplot in Fig. 5, where preliminary statistical analysis referred to the present dataset are shown. Again, with reference to the UGF score, the median value is at 183,6 points while the mean value is at 190,2 points.

Regarding the 21 parameters underlying the 5 main drivers, a frequency distribution analysis was conducted considering the dataset for the 41 cities (Fig. 6). As 16 parameters provide a known outcome through predefined classes (e.g., 0, 25, 50), only on 5 remaining parameters was it possible to analyse the frequency distribution in more detail: Surface geology (GEO), Shallow geological setting (GEO), Earthquake related hazard (DEE), Sea level rise (EXO), and Consumed soil - Imperviousness (SAP). As can also be seen from the graphs in Fig. 6, none of these five parameters follows a normal distribution, as demonstrated by the Shapiro-Wilk Test performed, which examines if a variable is normally distributed in some population (Shapiro & Wilk, 1965).

4. Discussion

The scores assigned to the 5 drivers were considered both individually and jointly to rank the cities. One of the easiest ways is to consider the rankings that can be obtained from each driver, while also respecting the UGF score index as the sum of the driver scores. This allows the immediate and clear identification of which specific driver(s) or, combination of drivers is influencing the city most. It can, when geo-climate area is also considered allow a city to be compared to other cities. It allows also to assess which drivers or pressures are most dominant for European cities by considering different datasets, and whether this changes as the sample size of cities analysed grows. Several cities might have a similar score but have a very different geo-climatic factors, so refined assessment of the underlying factors for the different cities is needed.

Table 2-
Resulting drivers' and UGF index scores for the tested cities and related country (coded according to ISO 3166-1 alpha-3). According to Fig. 1 the drivers are: GEO (brown) = Geology, DEE (red) = deep processes, SUP (yellow) = Superficial processes, EXO (green) = Exogenous processes and SAP (blue) = Subsoil anthropic pressures as described above in materials.

POSITION	CITY NAME	COUNTRY	GEO	DEE	SUP	EXO	SAP	UGF SCORE
1	Naples	ITA	66,2	66,9	60,0	34,3	87,6	315
2	Lisbon	PRT	43,7	39,1	70,0	49,2	86,7	289
3	Messina	ITA	55,2	50,9	85,0	38,1	39,1	268
4	L'Aquila	ITA	80,8	25,0	62,0	38,0	51,8	258
5	Rome	ITA	55,8	34,4	70,0	39,3	57,7	257
6	Cork	IRL	66,7	37,5	70,0	36,6	22,4	233
7	Antwerp	BEL	41,7	4,7	70,0	53,5	56,7	227
8	Namur	BEL	51,7	16,4	30,0	48,5	76,7	223
9	Ostrava	CZE	39,2	12,5	40,0	54,0	73,3	219
10	London	GBR	42,0	12,5	50,0	53,1	58,3	216
11	Florence	ITA	51,7	14,1	50,0	36,0	64,0	216
12	Dublin	IRL	56,7	25,0	70,0	30,8	31,8	214
13	Trondheim	NOR	56,7	1,6	100,0	40,6	13,0	212
14	Galway	IRL	55,0	31,3	50,0	40,1	21,9	198
15	Bucharest	ROU	50,0	18,8	30,0	46,0	51,7	196
16	La Spezia	ITA	25,8	25,9	82,0	32,1	29,6	195
17	Barcelona	ESP	54,0	9,1	50,0	28,4	53,2	195
18	Darmstadt	DEU	78,3	10,9	40,0	20,0	43,3	193
19	Budapest	HUN	76,7	4,7	32,0	54,0	25,0	192
20	Nantes	FRA	33,8	1,6	60,0	62,3	30,5	188
21	Prague	CZE	70,0	6,3	30,0	54,0	23,3	184
22	Oslo	NOR	56,7	14,1	40,0	46,0	25,0	182
23	Malaga	ESP	35,5	30,0	40,0	32,8	38,0	176
24	Granada	ESP	64,7	7,5	10,0	34,0	59,9	176
25	Tata	HUN	60,8	7,8	24,0	54,0	28,3	175
26	Liberec	CZE	38,3	12,5	30,0	38,0	53,7	173
27	Madrid	ESP	27,0	0,6	30,0	48,0	64,7	170
28	Glasgow	GBR	56,7	0,0	40,0	13,7	56,7	167
29	Milano	ITA	58,3	6,3	30,0	46,0	26,0	167
30	Zaragoza	ESP	41,7	13,4	50,0	46,0	12,0	163
31	Udine	ITA	50,0	16,9	22,0	38,0	34,1	161
32	Wałbrzych	POL	35,3	6,3	20,0	46,0	51,0	159
33	Helsinki	FIN	53,3	0,3	40,0	41,4	20,0	155
34	Brussels	BEL	58,3	3,9	10,0	36,0	36,0	144
35	Zagreb	HRV	44,5	12,5	30,0	36,0	20,0	143
36	Warsaw	POL	31,7	0,0	40,0	54,0	14,7	140
37	Cluj-Napoca	ROU	38,3	3,1	30,0	26,0	41,7	139
38	Trieste	ITA	34,3	22,8	6,0	40,0	34,2	137
39	Ljubljana	SLO	33,3	8,6	30,0	44,0	20,0	136
40	Tampere	FIN	44,0	0,3	20,0	44,0	18,3	127
41	Sisak	HRV	50,0	9,4	20,0	26,0	15,0	120
mean			50,3	15,2	43,0	40,9	40,7	190,2
median			51,7	12,5	40,0	40,1	36,0	183,6

One simple classification consisted in grouping cities according to the couple of most dominant drivers (Fig. 7) excluding the SAP, focusing thus the attention on the geo-climatic drivers only. According to this clustering four categories were defined for the analysed cities, that are discussed as follows.

4.1. Group 1 | GEO-EXO

This category predominantly includes cities situated within river valleys or alluvial plains, notable examples being Milan, Bucharest, Budapest, Prague, and Zagreb. These cities are partially or entirely situated upon soft detrital sediments that house alluvial aquifers. Many of them are enclosed by topographical features or occupy elevated terrains, contributing to an aesthetically pleasing cityscape and often serving as a reservoir of construction materials utilized in the city's architecture. Among the challenges faced by cities of this type, extreme climatic events tend to have the most pronounced impact. A distinctive outlier within this category is Helsinki. Positioned along the coast, this city occupies a particularly unique locale characterised by a dominance of islands and rocky coastlines made by granitic rocks. This distinctive geographical and geological setting sets Helsinki apart from the typical attributes associated with the group, although the city faces the same problems with climatic phenomena. The UGF score index of the cities included in this group usually score in medium values, except for those cities exposed to great threats such as earthquakes in the case of Bucharest or impacted by mining activities as in the case of Namur.

4.2. Group 2 | EXO-SUP

This category encompasses cities of medium to large size situated across a variety of fluvial landscapes. These landscapes range from hilly terrains adjacent to river valleys, as exemplified by Madrid, to estuarine settings seen in cities like Antwerp and Nantes. Additionally, the category spans alluvial plains traversed by major rivers, much like the urban areas of London or Warsaw. While sharing geological traits akin to those in Group 1, cities within this category possess a distinct feature: a soft subsoil extended deeply that is well-suited for the construction of subsurface infrastructures. The most prominent threat faced by cities in this group is flooding, which ranks as their primary Superficial Processes driver. Among the cities in this group, Madrid stands out due to certain distinctive characteristics. It is exposed to a broader spectrum of phenomena, including subsidence and climatic events like droughts. Within this group, the UGF score index demonstrates medium to elevated scores, except for Warsaw. These high values can be attributed to a

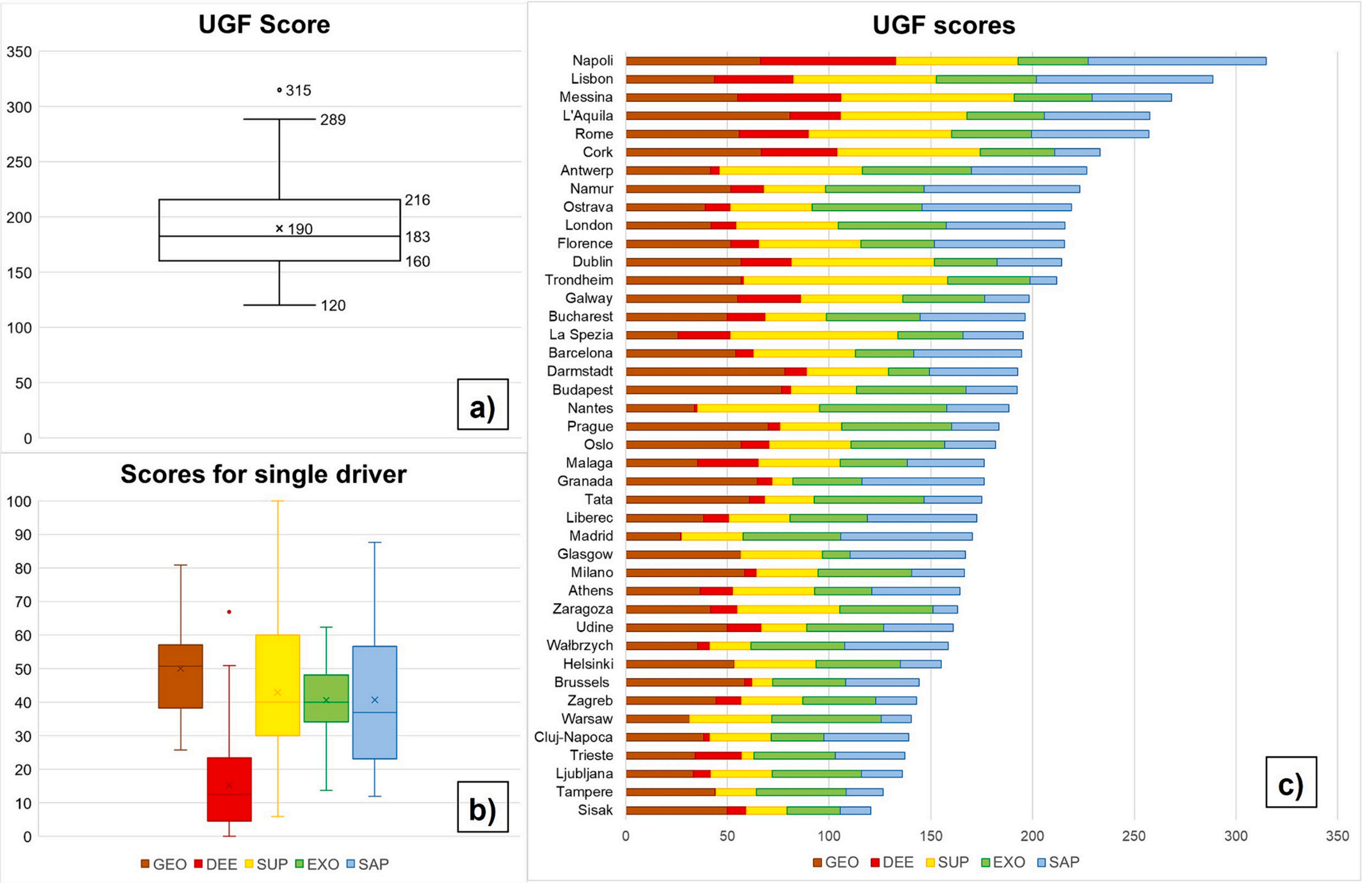

Fig. 5. Descriptive graphs of the UGF results about the analysed cities across Europe. a) Box-plot distribution of the UGF score; b) Distribution of the scores for each single driver, where GEO (brown) = Geology, DEE (red) = deep processes, SUP (yellow) = Superficial processes, EXO (green) = Exogenous processes and SAP (blue) = Subsoil anthropic pressures as described above in materials; c) Stacked bar chart for single city used to highlight the role of the SAP driver. The colour for each driver is reflected in the city geo factsheet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

combination of factors, including the substantial influence of flood hazards, susceptibility to detrimental climatic occurrences, and the significant anthropogenic pressures exerted on the subsoil within these urban zones. It is important to pay close attention to cities in estuarine contexts because those assessed have the highest scores in this group. In these cases, the coastal floods enhanced by sea level rise is the main phenomenon that increased the index value.

4.3. Group 3 | GEO-SUP

Group 3 stands out as highly diverse in terms of the geological and geomorphological settings of the cities it encompasses. The common denominator of these cities is the complex subsoil condition. However, this complexity is diverse through the group. Coastal cities or those situated near coastlines are predominant, most of them having relatively thin surficial deposits laying on a bedrock composed of hard rock types. Additionally, within this primary group, two smaller to medium-sized cities located in river valleys, etched into bedrocks with special characteristics, conform to the overall characteristics of the group – these cities are Darmstadt and Cluj-Napoca. The overall complex geological conditions of the cities contribute significantly to the high Geology driver scores observed within this group. Moreover, various surface-related phenomena resulting from these conditions play a role in yielding elevated scores in the Superficial Processes driver category. The latter include landslides in cities with relatively high local relief or with lithology prone to these phenomena: sinkholes due to rock dissolution or human excavations, subsidence related to compactable soils and fluvial or coastal floods. These processes are totally linked to the geological setting of the city. Climatic-related processes, although they can influence the frequency of these processes, are not crucial for their development. The important relationship of the city with its geological setting makes that UGF score index value reach high scores in most of the group. In this sense, the UGF index describes well the relationship of the city with its geological setting and the importance of considering it in the city management of the members of this group.

4.4. Group 4 | GEO-DEE

In this group, the city assessed with the deepest links to the geosphere stands out. Among the assessed cities, Naples is the only representative of this category right now, although it is plausible to expect that an extension of the assessment to other cities - whether in Sicily, Iceland or other parts of the world - would certainly populate this group further. Naples scores remarkably high in the category of Deep Processes drivers. This high index score is mainly due to its location within an active volcanic region, constantly exposed to risks related to eruptions and degassing. In addition, the city is located in an active geodynamic region, making it susceptible to seismic hazards such as earthquakes and tsunamis. Add to these dynamics the densely built-up urban fabric of the city, its Mediterranean climatic context and its extensive historical past, which contribute to a legacy of subsoil excavations. These multifaceted elements lead Naples to achieve the highest UGF score index value among the cities assessed. In few words, the city of Naples has a unique convergence of natural and urban attributes that makes it an extreme example where the fate of the city is linked to its geo-climatic context.

The classification scheme proposed herein warrants further

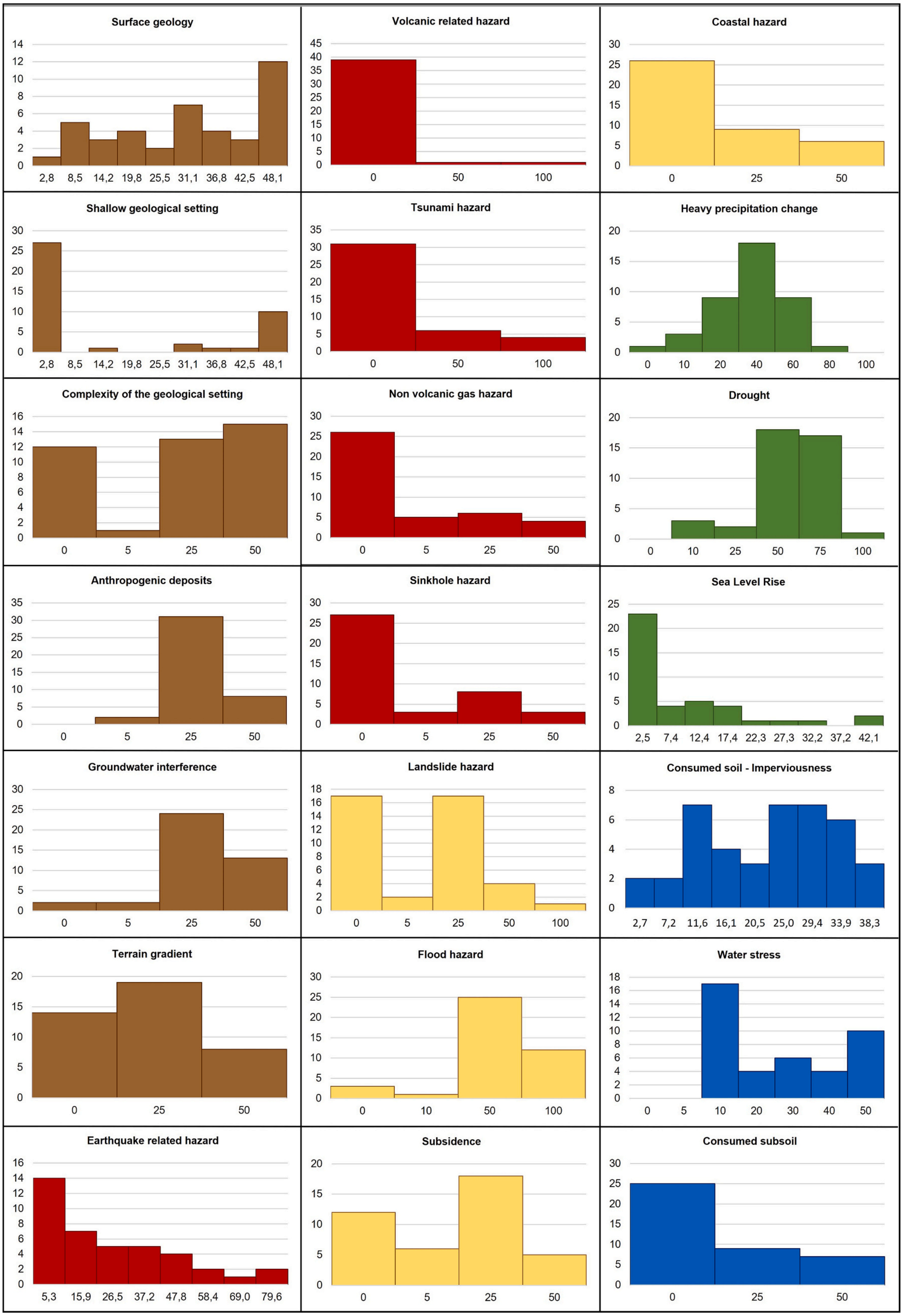

Fig. 6. Frequency distribution of the 21 parameters considered, grouped into 5 main drivers as previously defined (GEO: brown, DEE: red, EXO: green, SUP: yellow, SAP: blue). For each chart, the x-axis represents the categories (fixed classes for known outcomes, 9 classes for infinite possible outcomes) and the y-axis is the frequency density. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

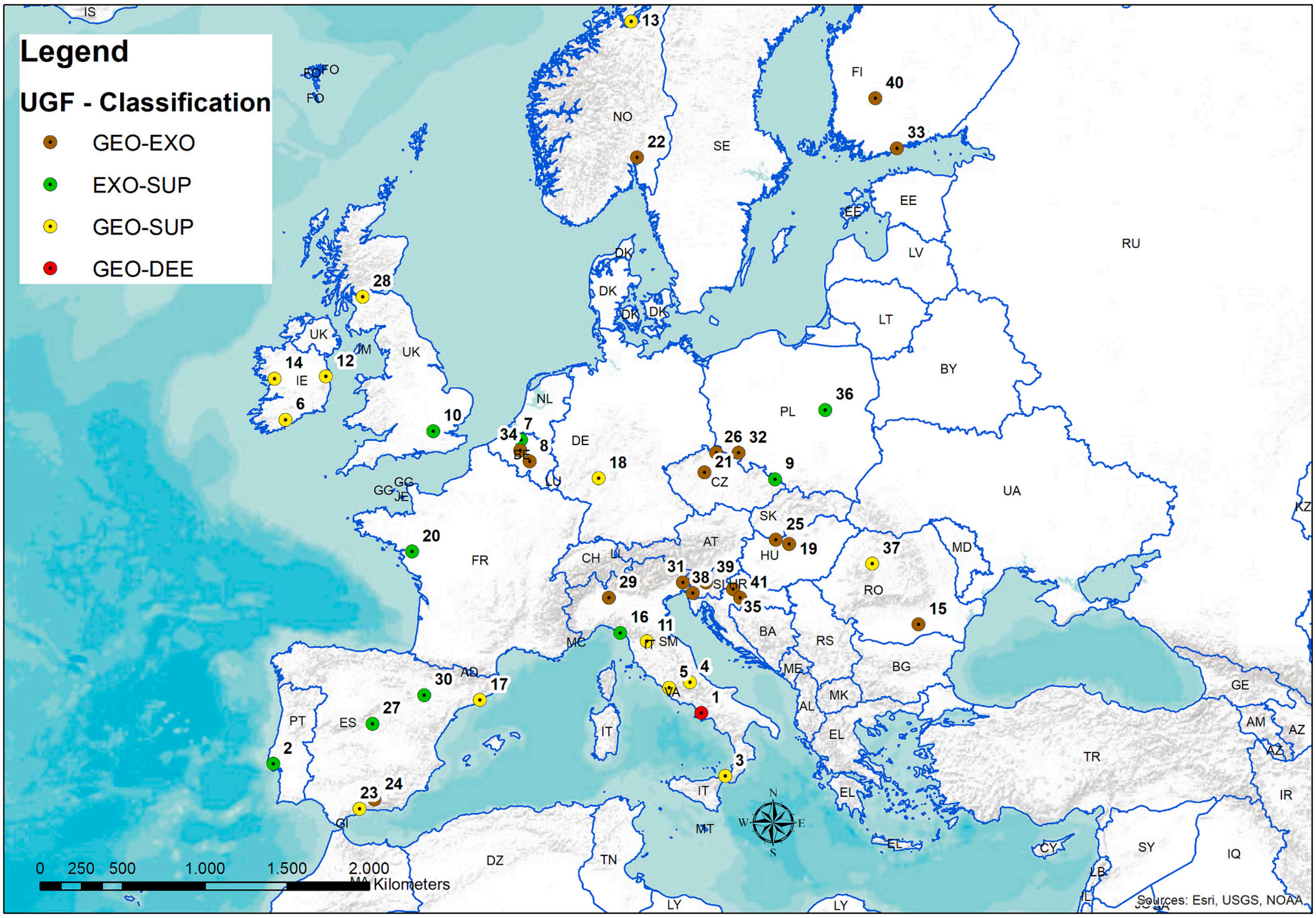

Fig. 7. Resulting UGF city classification by coupling the two greater drivers. Labels are relative to the position in Table 2.

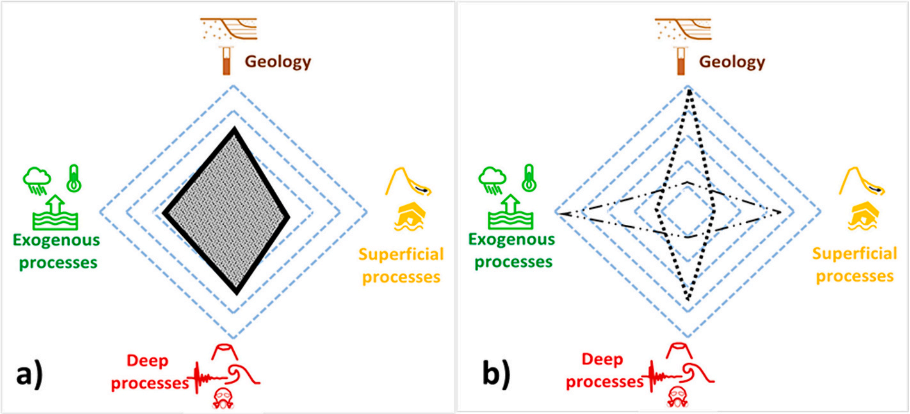

Fig. 8. Ranking parameters derived from the graphical expression of UGF classification: 1) the magnitude of the area enclosed in the 4-coordinates polygon (a) and 2) the shape of the area when different strong drivers occur (b) for cities having the same area value (dotted polygons).

refinement, as evidenced by the emergence of discernible subgroups within the above-described primary categories. Specifically, within the EXO-SUP group, two principal subgroups are apparent: coastal cities in estuarine settings and those situated on fluvial plains. Similarly, the GEO-SUP category is characterised by a high degree of diversity. While a primary distinction between coastal and inland cities is observed, further differentiation is feasible based on additional contextual attributes. Nevertheless, all cities within this group share the commonality of complex subsurface geology, which serves as a unifying characteristic. This aspect underscores the necessity for detailed future investigations to better understand the implications of such diversity and to refine the classification framework accordingly. From a geological perspective, the significance of geology in the cities of GEO-SUP group is pronounced, playing a pivotal role in their future development. Consequently, a nuanced approach to analysing this group will be imperative to fully appreciate the geological factors influencing urban development in these cities.

Another way to visualize the different magnitude of drivers of each city is to look at the graphical representation (4-coordinate graph / radar graph) for the UGF classification, always focusing attention on the geo-climatic drivers only (Fig. 8); this UGF classification represents geometrically the "size/shape of the geo-climate footprint". Such polygons can have, different shapes depending on the score of each driver; moreover, due to the possible occurrence of strong drivers, the graph can be very different while the area of the polygon remains the same, as depicted in Fig. 8. Possible asymmetry of the shape can occur also when one driver dominates respect to the others. In this case, the attention is focused to the value of the ratio between the two main axes of the graph (H/V), to help in differentiating and, thus, in clustering cities mostly suffering from superficial process pressures and climate pressures (Exogenous processes), compared to those cities where the deep geological processes and geological complexity are predominant. To substantiate this approach, statistical analyses were conducted to assess possible correlations between the coupled drivers: exogenous (EXE) with superficial processes (SUP) and deep processes (DEE) with geology (GEO). The latter show a Pearson correlation coefficient of $r = 0.4$ (p-value $= 0.02$) indicating a moderate strength and positive association of correlation. Concerning to EXE and SUP drivers, no Pearson correlation analysis was conducted since not all the foreseen preconditions were verified (normal distribution of variables). By considering the ratio described above, the analyses can be performed regardless of the size of the footprint.

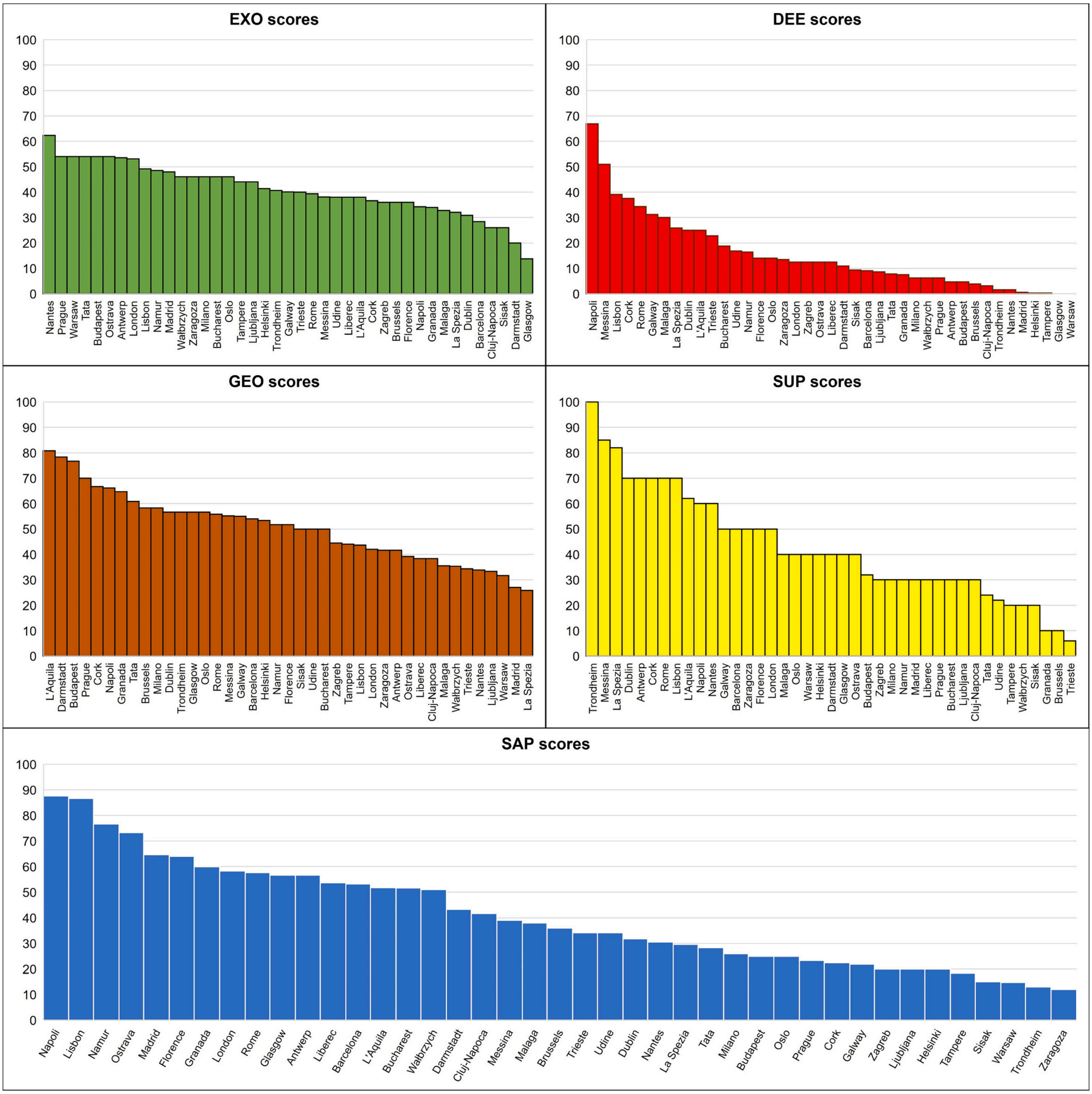

Fig. 9. Ranks of cities considering different drivers. GEO (brown) = Geology, DEE (red) = deep processes, SUP (yellow) = Superficial processes, EXO (green) = Exogenous processes and SAP (blue) = Subsoil anthropic pressures as drivers described above in materials and methods section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It is interesting to note that cities with a combination of pressures from Exogenous and Superficial processes (high horizontal to vertical ratio) are strongly predominant and, conversely, few cities are strongly influenced by the Geologic and Deep drivers as highlighted in the previously presented grouping. Considering information deriving from the polygon area of the radar graph and the axes ratio values is illustrative of how drivers can be informative if jointly considered. For some cities the overall size of their UGF score index is rather different being at the opposite of the ranking, but based on their H/V shapes, they are suffering the same combination of pressures and therefore they could share actions/policies that may be beneficial regardless of the position in the overall ranking based on the total UGF score (Table 2).

The position of each city along the ranking obviously changes when the different drivers are considered (Fig. 9). Moreover, deep processes (i.e., the DEE driver) seem to have a very different distribution within the sampled cities, as about 75 % of the tested localities have a score below 20, while it increases almost exponentially for the top 5 positions and eventually triples for the first one. The distribution of the GEO driver is also notable, this is also the only driver exceeding 50 points for the 60 % of cities, that is, representing a non-negligible factor for the development of a city, at least for the present dataset. If the city ranking changes by considering different drivers, this is not an issue, since different classifications can help identify which cities can share actions/policies to reduce the impact of specific driver or combination of drivers.

The current leading position for Naples (IT) between the analysed cities was rather expected, given this urban area is characterised by a very complex geological setting, while also suffering historically from geohazards (Orsi et al., 2003). However, looking at the boxplots in Fig. 5b, it should be also noted the dispersion of the SAP values for Naples, clearly higher than that of other drivers: the effect of the SAP values on classification should be carefully considered, as for many cities the final position could be very different not just depending on natural conditions but also on human pressures. This is consistent with the base concepts of the driver definition given in the introduction and method section, and we can thus consider two kinds of UGF scores, the total UGF Score INDEX and the UGF Rough (excluding SAP).

It is important to consider for instance, that, based on the first four (geo-climate) drivers, Messina (IT), Naples (IT), Cork (IE), L'Aquila (IT), Lisbon (PT), Rome (IT) and Trondheim (NO) have comparable final "UGF Rough" scores (229–199), but Naples and Lisbon clearly emerge only if the SAP (Subsoil anthropogenic pressures) driver is introduced (see the stacked bar-chart in Fig. 5c). In addition, the SAP score represents the higher values for 32 % of tested cities (about 1 out of 3) and this deviates the analysis of the results when they need to be used to classify the cities only by their geo-climate features. This is the reason why the SAP driver is omitted in the presented geo-climate classification, but not in the total UGF Score Index quantification.

5. Conclusions

The results presented and discussed in this paper, show that the Urban Geo-climate Footprint tool is currently capable of providing a semi-quantitative representation of the pressures driven by geological and climatic complexity in the analysed cities. The city data collection is ongoing, but the current distribution of analysed cities could be considered representative at European scale.

With the wide application of this methodology to several cities in Europe with contrasting geological settings, it will be possible to cluster them by city typology and deliver different benefits as follows.

- The general awareness of non-experts about the link between geological setting and the increase in pressures due to climate change and anthropogenic activity.
- Cities with similar UGF classification will be able to exchange best practices with each other to solve or mitigate typical common issues.
- European institutions will be able to look at the whole member states' cities together, to generally evaluate the differences between the expected impact of geology and subsoil-related climatic effects on the life of citizens and be helped in decision processes to define and differentiate policies and actions.

The upcoming developments of the tool will drive to collect more city data, to perform a detailed comparison methodology of the analysed results, and finally to extend the applicability of the tool also out of the European context, to define a worldwide city geo-climate clustering.

Given the dynamic nature of this new approach, it would also be possible that, based on more cities available, some parameters, weights and indexes calculations will be revised in the future, following a "data-driven" approach, without prejudice to the basic assumptions presented here.

The annexes to this paper are the Glossary Tab (Annex A) of the UGF Tool (ESM) and the City Geo Factsheets (Annex B) of the analysed cities. The structure of the UGF Tool (Microsoft Excel file, ESM) is described as follows: The "*Home*" spreadsheet is a resume and cover page allowing the user to move to the other sheets. The most important input data and calculation for the UGF analysis of the city are the "*City data and text*", and the "*UGF BASIC*", while the "*City Geo Factsheet*" represents the result of the analysis. The "*City data and text*" sheet is a simple table where the user must insert some city general data such as the name of the city, the county, the extent of the city area, the coordinates, population data, etc. The "*UGF BASIC*" sheet is the core of the tool. In this spreadsheet, all single parameter values of the city are indicated and the predefined routines inside the cells automatically assign a score to every parameter. The scores are weighted, summarised, and then combined to obtain several indicators that are further explained in the next section. The city analysis results are reported in the "*City Geo Factsheet*". This is predefined table that automatically reports all graphs and results in a user-friendly way. In this sheet, there are also some boxes where descriptive texts and details related to specific geological issues/characteristics of the city can be added. There are also two guidance sheets that are the "*Glossary*" and the "*Personal references*"; in the first one, all parameters and concepts of the tool are explained, while in the second, the user can report any specific references, different from those proposed as default, used in its city analysis. Furthermore, two hidden spreadsheets named "*Database*" and "*Conversion tables*" are present (Fig. 2). The first one is a repository of different values assignable to the different parameters or obtainable by the calculations in some cells; the second one allows some parameters to be converted into the scores according to predefined functions. Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2024.105287.

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CRediT authorship contribution statement

Azzurra Lentini: Writing – original draft, Validation, Methodology, Investigation, Data curation. **Jorge Pedro Galve:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Beatriz Benjumea:** Writing – review & editing, Data curation. **Stephanie Bricker:** Writing – review & editing, Data curation, Conceptualization. **Xavier Devleeschouwer:** Writing – review & editing, Data curation, Conceptualization. **Paolo Maria Guarino:** Validation, Data curation, Conceptualization. **Timothy Kearsey:** Writing – review & editing, Data curation, Conceptualization. **Gabriele Leoni:** Validation, Supervision, Data curation, Conceptualization. **Luca Maria Puzzilli:** Validation, Data curation, Conceptualization. **Saverio Romeo:** Writing – original draft, Supervision, Software, Methodology, Investigation, Data curation. **Guri**

Venvik: Writing – review & editing, Data curation, Conceptualization. **Francesco La Vigna:** Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization, Project coordintation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Disclaimer

The UGF Tool doesn't provide in any way a multi-hazard analysis of the city and is not a planning instrument, therefore, its results must be used just as a communication instrument for citizens, planners and policy makers.

The tool is in continue evolution and, even if the basic assumptions and setting are always the same, during the time the releases can change. To use the latest version of the tool please visit the project website http://ugf.isprambiente.it or contact the authors.

References

Abrams, M., Crippen, R., & Fujisada, H. (2020). ASTER global digital elevation model (GDEM) and ASTER global water body dataset (ASTWBD). *Remote Sensing, 12*, 1156. https://doi.org/10.3390/rs12071156.

Aichele, R., & Felbermayr, G. (2012). Kyoto and the carbon footprint of nations. *Journal of Environmental Economics and Management, 63*(3), 336–354. ISSN 0095-0696. https://doi.org/10.1016/j.jeem.2011.10.005

Asch, K. (2005). *IGME 5000: 1: 5 million international geological map of Europe and adjacent areas*. Hannover: BGR.

Ball, B. C., Hargreaves, P. R., & Watson, C. A. (2018). A framework of connections between soil and people can help improve sustainability of the food system and soil functions. *Ambio, 47*, 269–283. https://doi.org/10.1007/s13280-017-0965-z

Basili, R., Brizuela, B., Herrero, A., Iqbal, S., Lorito, S., Maesano, F. E., … Oueslati, F. (2018). NEAM Tsunami Hazard model 2018 (NEAMTHM18): Online data of the probabilistic Tsunami Hazard model for the NEAM region from the TSUMAPS-NEAM project. *Instituto Nazionale di Geofisica e Vulcanologia (INGV)*. 10.13127/tsunami/neamthm18.

Basili, R., Brizuela, B., Herrero, A., Iqbal, S., Lorito, S., Maesano, F. E., … Zaytsev, A. (2021). The making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18). *Frontiers in Earth Science*. https://doi.org/10.3389/feart.2020.616594

Bricker, S., Jelenek, J., Van der Keur, P., La Vigna, F., O'Connor, S., Ryzynski, G., … Venvik, G. (2024). Geoscience for cities: Delivering Europe's sustainable urban future. *Sustainability, 16*, 2559. https://doi.org/10.3390/su16062559

Brilha, J. (2016). Inventory and quantitative assessment of Geosites and geodiversity sites: A review. *Geoheritage, 8*, 119–134. https://doi.org/10.1007/s12371-014-0139-3

Chen, R., Zhang, R., & Han, H. (2021). Where has carbon footprint research gone? *Ecological Indicators, 120, 106882*. https://doi.org/10.1016/j.ecolind.2020.106882. ISSN 1470-160X https://www.sciencedirect.com/science/article/pii/S1470160X20308207.

Coaffee, J., & Lee, P. (2016). *Urban resilience: Planning for risk, crisis and uncertainty*. Palgrave Macmillan: Macmillan Publishers.

Copernicus Interactive Climate Atlas: guide to the powerful new C3S tool. https://climate.copernicus.eu/copernicus-interactive-climate-atlas-guide-powerful-new-c3s-tool.

Danciu, L., Nandan, S., Reyes, C., Basili, R., Weatherill, G., Beauval, C., Rovida, A., Vilanova, S., Sesetyan, K., Bard, P.-Y., Cotton, F., Wiemer, S., & Giardini, D. (2021). The 2020 update of the European Seismic Hazard Model: Model overview. In *EFEHR technical report 001, v1.0.0*. https://doi.org/10.12686/a15

Dijkstra, L., Florczyk, A. J., Freire, S., Kemper, T., Melchiorri, M., Pesaresi, M., & Schiavina, M. (2021). Applying the degree of urbanisation to the globe: A new harmonised definition reveals a different picture of global urbanisation. *Journal of Urban Economics, 125*, Article 103312. https://doi.org/10.1016/j.jue.2020.103312

Dottori, F., Alfieri, L., Bianchi, A., Skoien, J., & Salamon, P. (2021). *River flood hazard maps for Europe and the Mediterranean Basin region*. European Commission, Joint Research Centre (JRC). https://doi.org/10.2905/1D128B6C-A4EE-4858-9E34-6210707F3C81. PID: http://data.europa.eu/89h/1d128b6c-a4ee-4858-9e34-6210707f3c81.

Durojaye, O., Laseinde, T., & Oluwafemi, I. (2020). A descriptive review of carbon footprint. In T. Ahram, W. Karwowski, S. Pickl, & R. Taiar (Eds.)*, Vol. 1026. Human systems engineering and design II. IHSED 2019. Advances in intelligent systems and computing*. Cham: Springer. https://doi.org/10.1007/978-3-030-27928-8_144.

Esch, T., Heldens, W., Hirner, A., Keil, M., Marconcini, M., Roth, A., … Strano, E. (2017). Breaking new ground in mapping human settlements from space. The global urban footprint. *ISPRS Journal of Photogrammetry & Remote Sensing, 134,30-42*. https://doi.org/10.1016/j.isprsjprs.2017.10.012. ISSN 0924-2716 https://www.sciencedirect.com/science/article/pii/S0924271617301880.

European Copernicus Service. (2020). *Imperviousness Density 2018*.

European Drought Observatory (EDO). (2020). *EDO Combined Drought Indicator*. European Commission, Joint Research Centre (JRC). PID, available at: http://data.europa.eu/89h/e83b19ce-08c2-4e0c-b93a-5fd62be21e5e.

European Environment Agency. (2022). Imperviousness and imperviousness change in Europe. Available at: https://www.eea.europa.eu/en/analysis/indicators/imperviousness-and-imperviousness-change-in-europe (last access August 2024).

European Environment Agency. (2024). *Global and European sea level rise* (last access August 2024) Available at: https://www.eea.europa.eu/en/analysis/indicators/global-and-european-sea-level-rise/.

European State of the Climate (ESOTC). (2019). Copernicus climate change service, full report. Available online at: https://climate.copernicus.eu/ESOTC/2019/about-european-state-climate-2019.

EuroStat. (2022). Statistical regions in the European Union and partner countries NUTS and statistical regions 2021. *European Union*. https://doi.org/10.2785/321792

Giardini, D., Wössner, J., & Danciu, L. (2014). Mapping Europe's seismic Hazard. *Eos Trans. AGU, 95*(29), 261. https://doi.org/10.1002/2014EO290001.

Global Volcanism Program. (2023). *St. Helens (321050) in [Database] Volcanoes of the World (v. 5.1.0; 9 Jun 2023)*. Distributed by Smithsonian Institution, compiled by Venzke, E. https://doi.org/10.5479/si.GVP.VOTW5-2023.5.1.

Günther, A., Van Den Eeckhaut, M., Malet, J.-P., Reichenbach, P., & Hervás, J. (2014). Climate-physiographically differentiated Pan-European landslide susceptibility assessment using spatial multi-criteria evaluation and transnational landslide information. *Geomorphology, 224*, 69–85. https://doi.org/10.1016/j.geomorph.2014.07.011.

Herrera-García, G., Ezquerro, P., Tomás, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., Mateos, R. M., Carreón-Freyre, D., Lambert, J., Teatini, P., Cabral-Cano, E., Erkens, G., Galloway, D., Hung, W., Kakar, N., Sneed, M., Tosi, L., Wang, H., & Ye, S. (2021). Mapping the global threat of land subsidence. *Science, 371* (6524), 34–36. https://doi.org/10.1126/science.abb8549.

Hill, M. C., & Tiedeman, C. R. (2006). *Effective groundwater model calibration: With analysis of data, sensitivities, predictions, and uncertainty*. John Wiley & Sons.

Hollis, J., Pizzocolo, F., La Vigna, F., Piessens, K., Tulstrup, J., Wall, P., & Dancy, T. (2023). Applications of the European geological data infrastructure to support policy and cooperative geoscience. *European Geologist Journal* (under review). (issue 56: Geoscience in policy making: past experience, current practice and future opportunities).

IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change* (pp. 1–582). Cambridge, UK; New York, NY, USA: Cambridge University Press.

La Vigna, F. (2022). Review: Urban groundwater issues and resource management, and their roles in the resilience of cities. *Hydrogeology Journal, 30*, 1657–1683. https://doi.org/10.1007/s10040-022-02517-1

La Vigna, F., Lentini, A., Galve, J. P., Benjumea-Moreno, B., Bricker, S., Devleeschouwer, X., Guarino, P. M., Kearsey, T., Leoni, G., Romeo, S., & Venvik, G. (2024). Decoding the urban geo-puzzle: Navigating geological issues and global challenges through the lens of the Urban Geo-climate Footprint. In *EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24–20428* (p. 2024). https://doi.org/10.5194/egusphere-egu24-20428

Lentini, A., Benjumea-Moreno, B., Bricker, S. H., Chiessi, V., Devleeschouwer, X., Galve, J. P., Guarino, P. M., Kearsey, T., Leoni, G., Puzzilli, L. M., & La Vigna, F. (2021). Preliminary activities aimed to cluster EU cities by a geological point of view: The Urban Geo Footprint tool. In *90° Congresso della Società Geologica Italiana SGI (Trieste 14th–16th september 2021)*. https://doi.org/10.3301/ABSGI.2021.03

Lentini, A., Benjumea-Moreno, B., Bricker, S. H., Chiessi, V., Xavier, D., Galve, J. P., Giordano, G., et al. (2022). Clustering urban areas by a geological point of view: The Urban Geo Footprint tool. In *EGU General Assembly Conference Abstracts* (pp. EGU22–12453). https://ui.adsabs.harvard.edu/abs/2022EGUGA..2412453L/abstract. https://doi.org/10.5194/egusphere-egu22-12453.

Lentini, A., Galve, J. P., Benjumea, M. B., Bricker, S., Devleeschouwer, X., Guarino, P. M., Kearsey, T., Leoni, G., Saverio, R., Venvik, G., & La Vigna, F. (2024). Current status of the Urban Geo-climate Footprint project. In *EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24–20648* (p. 2024). https://doi.org/10.5194/egusphere-egu24-20648

Luo, T., Young, R., & Reig, P. (2015). Aqueduct projected water stress country rankings. *Technical Note, 16*.

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and urban planning., 147*, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Orsi, G., de Vita, S., Di Vito, M. A., Isaia, R., Nave, R., & Heiken, G. (2003). Facing volcanic and related hazards in the Neapolitan area. In G. Heiken, R. Fakundiny, & J. Sutter (Eds.), *Earth science in the City: A reader*. Wiley.

Rahman, M. M., Bodrud-Doza, M., Shammi, M., Md Towfiqul Islam, A. R., & Moniruzzaman Khan, A. S. (2021). COVID-19 pandemic, dengue epidemic, and climate change vulnerability in Bangladesh: Scenario assessment for strategic management and policy implications. *Environmental Research, 192*, Article 110303. https://doi.org/10.1016/j.envres.2020.110303

Reig, P., Maddocks, A., & Gassert, F. (2013). *World's 36 most water-stressed countries*.

Reynard, E., Pica, A., & Coratza, P. (2017). Urban geomorphological heritage. An overview. *Quaestiones Geographicae, 36*(3), 7–20. https://doi.org/10.1515/quageo-2017-0022, 3917.

Shapiro, S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika, 52*(3–4), 591–611. https://doi.org/10.1093/biomet/52.3-4.591. December 1965.

UNDRR. (2015). Sendai framework for disaster risk reduction 2015–2030. In *UN world conference on disaster risk reduction. Sendai, Japan. Geneva: United Nations Office for Disaster Risk Reduction. March 14–18*. http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf.

Smol, M. (2022). Is the green deal a global strategy? Revision of the green deal definitions, strategies, and importance in post-COVID recovery plans in various regions of the world. *Energy Policy, 169*, Article 113152. https://doi.org/10.1016/j.enpol.2022.113152

Tukey, J. W. (1977). *Exploratory data analysis*. Reading, Mass. — Menlo Park, Cal., London, Amsterdam, Don Mills, Ontario, Sydney: Addison-Wesley publishing company. https://doi.org/10.1002/bimj.4710230408, 1977, XVI, 688 S.

UN. (2014). Open working group proposal for sustainable development goals, document a/68/970. In *New York: Open Working Group of the United Nations General Assembly on Sustainable Development Goals*.

UN. (2015a). Framework convention on climate change. In *Adoption of the Paris agreement, 21st conference. of the parties*. Paris: United Nations.

UN. (2015b). Transforming our world: The 2030 Agenda for Sustainable Development United Nations General Assembly21 October 2015. A/RES/70/1. https://www.refworld.org/docid/57b6e3e44.html.

UN. (2016). New Urban Agenda. New York: United Nations Geneal Assembly 2016. http://habitat3.org/the-new-urban-agenda/.

UN. (2022). *World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO*. United NationsDepartment of Economic and Social Affairs, Population Division.

UNDP. (2015). The Sendai framework for disaster risk reduction 2015-2030. In *Third United Nations world conference on disaster risk reduction*. Japan: The United Nations Development Programme(Sendai).

UNDRR. (2017). *Terminology of disaster risk reduction*. United Nations Office for Disaster Risk Reduction. https://www.unisdr.org/we/inform/terminology.

UNEP. (2009). A global green new deal. In *Report prepared for the Green Economy Initiative of. United Nations Environment Programme*. https://sustainabledevelopment.un.org/.

United Nations Habitat. (2017). *Action framework for implementation of the new urban agenda*. New York: United Nations. http://nua.unhabitat.org/AFINUA19thApr.pdf.

Wachinger, G., Renn, O., Begg, C., & Kuhlicke, C. (2013). The risk perception paradox—Implications for governance and communication of natural hazards. *Risk Analysis, 33*(6), 1049–1065. https://doi.org/10.1111/j.1539-6924.2012.01942.x

Wiedmann, T., & Minx, J. (2008). A definition of "Carbon Footprint". In *C. C. Pertsova, ecological economics research trends: Chapter 1* (pp. 1–11). Hauppauge NY, USA: Nova Science Publishers. https://www.novapublishers.com/catalog/product_info.php?products_id=5999.

Wolniewicz, P. (2022). Classification and quantification of urban geodiversity and its intersection with cultural heritage. *Geoheritage, 14*, 63. https://doi.org/10.1007/s12371-022-00693-w

World Resources Institute, Aqueduct. (2023). https://www.wri.org/applications/aqueduct/water-risk-atlas.

Wright, L. A., Kemp, S., & Williams, Y. (2011). 'Carbon foot printing': Towards a universally accepted definition. *Carbon Management, 2*(1), 61–72. https://doi.org/10.4155/cmt.10.39