land

MDPI

Article

Multi-Hazards and Existing Data: A Transboundary Assessment for Climate Planning

Alessandra Longo *, Chiara Semenzin and Linda Zardo

Department of Architecture and Arts, University IUAV of Venezia, S. Croce 191, 30135 Venice, Italy;
csemenzin@iuav.it (C.S.); lzardo@iuav.it (L.Z.)
* Correspondence: alongo@iuav.it

Abstract: Many regions worldwide are exposed to multiple omnipresent hazards occurring in complex interactions. However, multi-hazard assessments are not yet fully integrated into current planning tools, particularly when referring to transboundary areas. This work aims to enable spatial planners to include multi-hazard assessments in their climate change adaptation measures using available data. We focus on a set of hazards (e.g., extreme heat, drought, landslide) and propose a four-step methodology to (i) harmonise existing data from different databases and scales for multi-hazard assessment and mapping and (ii) to read identified multi-hazard bundles in homogeneous territorial areas. The methodology, whose outputs are replicable in other EU contexts, is applied to the illustrative case of Northeast Italy. The results show a significant difference between hazards with a 'dichotomous' spatial behaviour (shocks) and those with a more complex and nuanced one (stresses). The harmonised maps for the single hazards represent a new piece of knowledge for our territory since, to date, there are no comparable maps with this level of definition to understand hazards' spatial distribution and interactions between transboundary areas. This study does present some limitations, including putting together data with a remarkable difference in definition for some hazards.

Keywords: multi-hazard adaptation; climate-related hazards; transboundary mapping; spatial planning; existing datasets; homogeneous territorial areas

check for updates

Received: 3 February 2025
Revised: 27 February 2025
Accepted: 1 March 2025
Published: 5 March 2025

Citation: Longo, A.; Semenzin, C.; Zardo, L. Multi-Hazards and Existing Data: A Transboundary Assessment for Climate Planning. *Land* **2025**, *14*, 548. https://doi.org/10.3390/land14030548

1. Introduction

Christopher Alexander [1] argued that the method we adopt to read reality is not the method by which reality happens. Applying this thesis to the semantic field of hazards, we can say that although science tends to study hazards—their drivers and their effects—one by one, in reality, territories suffer them as a whole. The need to take a holistic approach in multi-hazard assessments is widely discussed in the literature because of the complex interactions and interdependencies among hazards reflected in compound and nonlinear effects [2–4]. Indeed, hazards can occur over time in a simultaneous, cascading or cumulative way, as reported in the definition provided by the United Nations Office for Disaster Risk Reduction (UNDRR) [5]. Although, worldwide, many regions are affected by complex hazard landscapes characterised by their omnipresence, hazards are typically studied in isolation [6]. That assumes greater significance when considering the transboundary issue, where administratively different territories are exposed to the same hazards in the immediate future and may, therefore, also share after-effects [7]. Thus, considering hazards as a 'holistic complex' can promote knowledge advancement and improve climate adaptation and resilience building [8,9]. In this work, we draw on the definition proposed by the UN-Habitat programme that (urban) resilience is 'the ability of any urban system and its inhabitants to maintain continuity through shocks and stresses while adapting and transforming toward sustainability' [7] (p. 2), with particular attention to the City Resilience Planning (CityRAP) Tool process. Urban resilience has become a central concept in promoting sustainable development, especially in contexts jointly affected by increasing urbanization and climate change effects [10]. In this sense, a better understanding of the interactions between multiple hazards can promote the sustainable management of society [11].

The Mediterranean region is one of the 'hot spots' of climate change, with warming exceeding the global average increase by 20%, and a reduction in rainfall. In Italy, the statistics indicate that the average temperature is increasing, and that there is a general increase in the intensity of rainfall events [12], while a large part of the country shows low disaster resilience and the effects of a changing climate might be devastating for people and infrastructure; in this regard, adaptation to climate change and local resilience building are desirable [12].

Spatial planning is crucial for promoting adaptation approaches from regional to local scale. However, at present, only a limited number of spatial plans and adaptation measures account for current knowledge [13]. Enhancing the resilience of cities and territories implies strengthening urban and territorial systems against adverse events and building flexible and elastic structures to make them less vulnerable while supporting their capacity for positive transformation [14]. Adaptation to climate change requires greater synergies between planning instruments and cross-sectoral cooperation [15]. Integrating climate adaptation issues and knowledge into planning processes appears necessary, enabling the inclusion of effective and multi-purpose resilience tools in existing instruments and plans. Indeed, assessing and mapping flooding, drought, hydrogeological risk, and soil erosion allow for effective management of these issues. Building resilient territories requires truly integrated planning strategies that involve and broaden the expertise in decision-making processes, promote horizontal and vertical synergies, from regional strategies to local planning instruments, and enable spatial governance bodies to address climate challenges in a cohesive and synergetic manner. In the attempt to build resilient territories, the role of the information base and the ability to consider collectively the complexity of hazards in the assessment to support spatial planning is part of the function [6].

However, even though the relevance of multi-hazard analyses for climate change adaptation has been largely recognised in the last decades, it represents an aspect that is still mostly confined to scientific debate. Conversely, current planning practices are often based on consolidated methods and procedures for single hazard analyses [16,17]. Moving towards multi-hazards assessment requires a radical change in perspective: multi-hazards assessment should be 'spatial-centred', starting from the selection of a geographical area to identify, firstly, the multiple hazards it is prone to, as well as to chained or coupled ones [17,18].

Galderisi and Limongi [17] identified a set of gaps preventing the inclusion of multi-hazards assessment in the planning practice. Among the shortcomings deriving from hazard-assessment-related knowledge, they list:

- Fragmented knowledge bases developed by different authorities in charge of individual hazards;
- Data and information provided at different geographical scales and not always up-to-date;
- Frequent lack of adequate platforms to collect, synthesise, and share existing data and information;

- The need for aggregate indexes to select the areas characterised by the highest multi-hazard levels, and disaggregate and detailed information at different scales to define adequate climate change adaptation strategies.

An aspect underpinning all these shortcomings is the issue represented by transboundary areas. Thus, administrative boundaries are rarely coincident with natural ecological boundaries, such as ecosystems and hazards' impacts or drivers [19–22]. While it seems unavoidable to consider the specific conditions of local social-ecological systems [23], those landscapes fragmented by borders are reflected in equally fragmented and weak governance landscapes, in which sovereignty, responsibility, ownership, and jurisdiction barriers emerge [19,24]. Indeed, when dealing with transboundary hazards, governance cannot operate in separate silos [25], even though, to date, strategic adaptation responses remain confined to sectors and local boundaries [26].

On top of ecological and governance aspects, the availability of reliable, spatially explicit and comparable data and their scale or aggregation also represent a topic when discussing regional planning and transboundary systems [25,27]. Thus, the analysis of hazards derived from different sources (regional or province-level databases) often requires using distinct methodologies and spatial scale resolution. The consequence of such inherent differences is that even the metrics commonly adopted to measure the hazard are very different and hardly directly comparable [28]. It is true that national models that allow for the estimation and representation of hazards already exist [29]. However, the scale of analysis for local transboundary assessments, tailored to the needs of the regional and provinces for acting, may be quite smaller than that used in the bigger scale models [28]. Results of national hazards assessment transferred to smaller regional/local spatial scales may therefore be of lower interest and less useful for planners and decision-makers. Despite some progress made by recent studies [30–36], multi-hazard assessment in transboundary areas at the local scale is urgently required.

A concluding remark when identifying shortcomings in the effective inclusion of multi-hazard assessment for climate change adaptation planning and resilience building is the lack of proper information in a relevant and manageable format for planning and decision-making at the local scale. That spans from the final outputs that are too complex to be included in a planning process to information adopting a non-user-friendly lexicon, such as ecology terms or hydraulic wording for guiding spatial planners [37].

This work aims to enable spatial planners to include multi-hazard assessment into their climate change adaptation measures, by providing them with both synthetic and disaggregated information obtained from existing data deriving from different single-hazards datasets and different regional datasets. Through this, we aim to support multi-purpose responses for regional and local planning to increase the resilience of territories to the multiple challenges they face. In this paper, we focus on developing (i) a harmonised methodology for multi-hazards assessment and mapping, and (ii) a shared methodology for identified multi-hazards bundles in homogeneous territorial areas (see Section 3.4), to translate the outputs in a format which can be relevant and ready-to-use for decision-makers, which allows identifying multi-needs deriving from multi-hazards in an area (to design multi-purpose solutions) and similar systems which can learn one from the other.

More in detail, this work does not address gaps not filled by other studies. On the contrary, our approach aims to treat them differently from the responses previously found by others and that, from our perspective, are time-consuming or not addressed due to the often-limited administrative expertise. That is the case, for instance, with modelling that is too complex to be easily replicated and updated.

Our work is structured following the red thread of two research questions:

RQ1: How can we combine existing data from different single-hazard datasets and regional datasets to obtain single-hazard maps with homogenous data for different territories, and a synthetic multi-hazard overall picture?

RQ2: How can we transform the above-mentioned results into relevant information for spatial planners, to be included in climate change adaptation planning?

In this research, we focus on a set of hazards and apply our methodology to the illustrative case of Northeast Italy—consisting of two regions and two provinces sharing challenges—where we attempt to support their sharing of understanding and solutions. Our approach results from the effort to combine knowledge from different disciplines and existing data to contribute to this purpose. The methodology is replicable in other contexts in the EU.

2. Case Study

This study focuses on the Triveneto area (Figure 1), comprising the two regions of Veneto and Friuli Venezia Giulia and the two autonomous provinces of Trento and Bolzano. Triveneto is the subject of the iNEST—Interconnected Northeast Innovation Ecosystem—a research project working, among many other topics, on strategies for the sustainable transformation of the built environment [38]. The reason for investigating the Triveneto macro-region relies upon its national relevance for its territorial fragility and socio-economic value [39].

The Triveneto macro-region is located in the northeast Italian peninsula and offers a geographical section from the Adriatic coast to the Alpine arc. The sandy coastal arc faces the Adriatic Sea, including the Venice and Grado Lagoons. On the other hand, a rich mountain system in the north covers the highest percentage of the territory which is differentiated between the system of Alpine valleys, including the Dolomites, and the lower foothills. Between these two extremes lies part of the Po Valley. The area contains almost the entire drainage basins of river axes such as the Adige, the Brenta, the Piave, the Tagliamento and a large part of the Isonzo, and hosts the wide Po Delta. The anthropic impact on the entire area has been high since ancient times and involved, for example, the significant river diversions carried out to maintain the Venice lagoon and the transformations of the agrarian landscapes employed by the Roman centurions that are still visible. In modern times, the plains have been characterised by a high degree of urban sprawl, to the extent that centres follow one another without interruption in the diffuse city. Differently, the mountain centres have gradually been depopulated. In addition to the rich geographical variability, Triveneto is an interesting case from an administrative point of view for transboundary comparison. Although it lies within a single country, it consists of three regions to which four different administrative units correspond, all with independent databases. Furthermore, Friuli Venezia Giulia, Trento, and Bolzano are autonomous regions and provinces.

The precariousness of the territory is highlighted by the increasingly frequent damage caused by natural and catastrophic events. Damage has been recorded across much of the territory in the last few years alone: from storm Vaia in 2019 [40], which wiped out hectares of forest, to the increasingly numerous floods [41,42] that, in addition to the extraordinarily high water [43] in Venice, are affecting large portions of the Veneto plain with regrettable frequency [39]. In addition to the extreme events in the national and foreign news, there are heat waves, increasingly uncertain harvests due to water shortages and torrential rains, landslides, and mudslides that lead to the urgent need to analyse the territory in the light of the risks to which it is exposed.

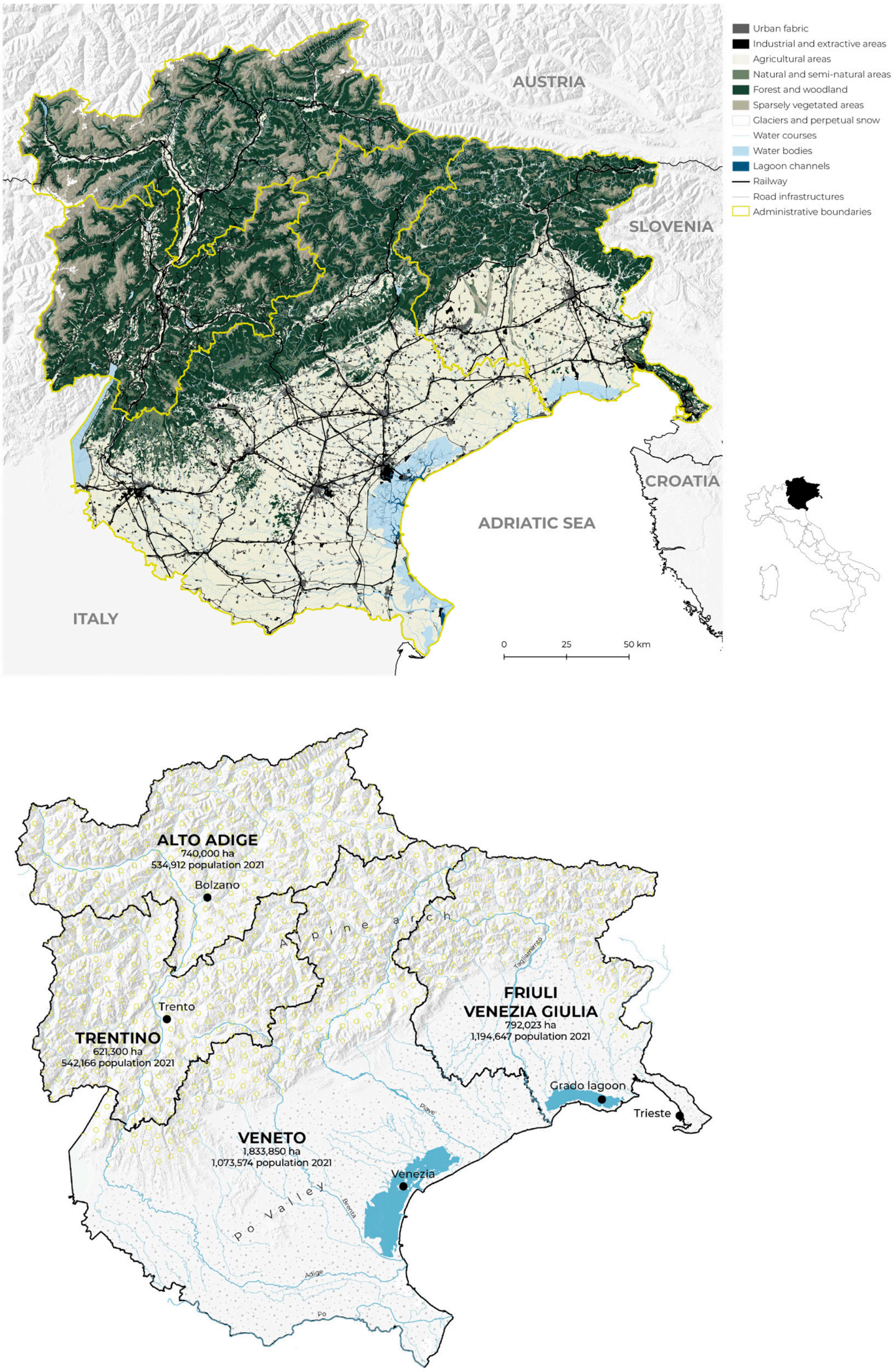


Figure 1. (**top**) Map and localisation of case study area. (**bottom**) Focus on key areas of interest outlined and main statistics (surface and population).

Over the years, the increasing detection of climate anomalies and recording of extreme weather events has led administrations to equip themselves with appropriate tools to regulate and prevent such phenomena. Looking at the four administrative areas in the Triveneto region, both regions and provinces are committed to adapting to climate change. The Veneto region concluded the consultation phase in July 2024 and is now proceeding with the approval process of the Regional Climate Change Adaptation Strategy. A preliminary document is already available pending this final approval [44]. The Friuli Venezia Giulia region is engaged in several project initiatives for climate change adaptation, which flank and complement the institutional pathway started with the Regional Law ‘FVGreen’ (L.R 4/2023). The law provides for drafting the Regional Climate Change Mitigation and Adaptation Strategy, which will be implemented through the subsequent Regional Climate Plan [45]. The Autonomous Province of Trento approved the ‘Trentino Climate 2021–2023’ work program on 7 August 2021, defining the pathway to the Provincial Climate Change Mitigation and Adaptation Strategy. Subsequently, the adaptation measures identified in the Strategy will then be integrated into sector plans and programs [46] Finally, the Autonomous Province of Bolzano approved the final document of the South Tyrol Climate Plan 2040 in July 2024, an integral part of the ‘Everyday for Future’ Sustainability Strategy and a tool for achieving climate neutrality by 2040 [47]. Inside, the field of action ‘resilience and adaptation’ aims to develop a climate change adaptation strategy, with further drafting of strategic plans of sector priorities by the end of 2025.

3. Materials and Methods

The research workflow (Figure 2) was developed in four successive steps, each with its method. The first step identifies relevant climate-related hazards and indices (Section 3.1). The second step selects suitable indicators for hazards assessments and collects existing geolocalised data to map hazards (Section 3.2). The third step harmonises data for all relevant hazards to build comparable information and provide both a synoptic view of single hazards and cross-sectoral reading of them (Section 3.3). Finally, the fourth step defines minimum reading units (in this work called ‘homogenous territorial areas’) for the study area within which to assess spatial interactions between hazards to provide planners with an operational decision-making tool (Section 3.4). Except for step 1, which builds on an analysis of the existing literature, the other three steps relate to the case study. However, steps 3 and 4 also present methods that can be replicated in different contexts. Respectively, we used ArcGIS Pro and QGIS 3.26 Buenos Aires software for spatial elaborations and layer styling and layouts.

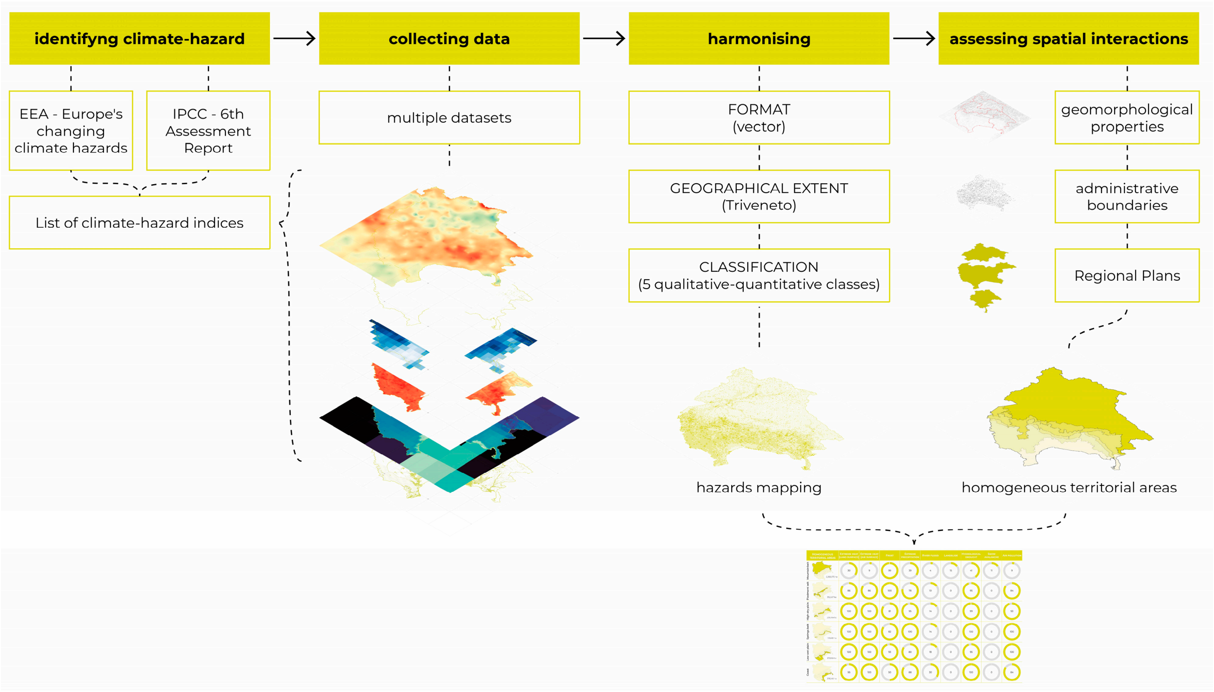


Figure 2. Workflow illustrating four-step methodology.

3.1. Identifying Relevant Climate-Related Hazards and Indices

The section aims to identify the most relevant hazards related to climate change and useful indices for their mapping (individual hazards) and assessment (multi-hazard). We adopted two main references from the grey literature referring to international reports on this issue, namely the 'Climate Change 2021: The Physical Science Basis' published by the Intergovernmental Panel on Climate Change (IPCC) [48] and the 'Climate-related hazard indices for Europe' published by the European Environment Agency (EEA) [49]. We performed a content analysis [50] to identify the most recurring hazards. The final list of hazards is the result of combining the climatic impact-drivers (CIDs) identified by IPCC (see Table 12.1 in 'Chapter 12: Climate Change Information for Regional Impact and for Risk Assessment' [48]) with the climate-related hazards identified by EEA (see Table 4.1 in [49]), which was itself a reworking of the IPCC CIDs. Specifically, we compared IPCC's CIDs categories with EEA hazard types and obtained a final list of relevant hazards to be investigated.

We derived the priority in the choice of indicators from the 'confidence' identified for the Mediterranean Region by the IPCC (see Table 12.7 in [48]) and the 'priority' identified by the EEA (see Table 4.1 in [49]). We then compared the priorities highlighted by studies on a European and Mediterranean scale with the recurrence of extreme events recorded locally, with a 139% increase between 2021 and 2024, according to Legambiente's National City Climate Observatory [51].

3.2. Selecting Indicators and Collecting Existing Geolocalised Data for Hazard Mapping

Based on the content analysis carried out in Section 3.1, we chose the most representative hazards for the Triveneto context, i.e., those to which it has been and tends to be most exposed (see Section 2 Case Study). We then selected one suitable indicator—according to priority—from those identified as possible key indicators in the reports by the IPCC and EEA for mapping and assessing each hazard. Moreover, according to national and local scientific studies, we integrated these indicators with specific and available ones for the study area. At this point, we collected data matching the selected indicators for the entire extension of the Triveneto.

The administrative organisation of this territory into two regions (Veneto and Friuli Venezia Giulia) and two autonomous provinces (Trento and Bolzano) made it difficult to collect uniform data. Hence, the data collection started by searching for common data for the entire area available at a European or national level and descriptive of phenomena at the sub-municipal scale. Where no single source was available, we used sources with a smaller spatial extent and spatially merged the data. Concerning common databases, primary European sources were the Copernicus Climate Data Store [52] and the EEA datahub [53]. The Higher Institute for Environmental Protection and Research (Istituto superiore per la protezione e la ricerca ambientale, ISPRA) provided most of the data at the national scale [54]. Finally, the North-East Climate Platform by the Regional Agencies for Environmental Protection of Veneto (ARPAV) and Friuli Venezia Giulia (ARPA FVG) [55] was used at the sub-national level. When we could not draw on common databases, we collected the data separately for the four administrative areas and combined them into one layer. In such cases, we searched for the same indicators within the databases of the different agencies to collect data that were as similar and consistent as possible to each other.

To provide an example, for frost and extreme precipitation, data collected presented a resolution difference between the two regions (Veneto and Friuli Venezia Giulia) and the two autonomous provinces (Trento and Bolzano) that we could not bridge, so we merged them by maintaining a higher approximation in the latter.

3.3. Harmonising and Comparing Diverse Existing Data

There are several analytical techniques for assessing interactions among multiple hazards in one single administrative area, as well as and/or for assessing a single hazard merging different areas [28,56,57]. When methodologies exist to assess multiple hazards in different administrative regions, they require modelling or the collection of new data, which is often too costly and time-consuming. In this section, we aim to propose a methodology for data harmonisation to address the lack of availability of multi-hazards assessments in different administrative regions using existing data.

The data collected from various databases in the second step (Section 3.2) differ in geographical extent, format (vector or raster), statistical range, and classification (quantitative or qualitative). In this section, we harmonised data by choosing common technical parameters and transforming data to be comparable. We adopted the works by [58–61] to build the methods for this section.

Going into details of the technical parameters, the collected data were mainly in raster format (6 compared to 3 in vector format). Nevertheless, the vector format is considered more practical for processing and is therefore chosen. Each raster is reclassified into five classes—adjusted from ArcGIS Pro default classification to make them more likely, thus reducing the loss of relevant information—and transformed into a polygon.

In terms of geographical extent, we joined layers for hazards with disaggregated data, i.e., composed of information from different datasets.

Finally, the third element to be standardised was classification and, consequently, statistical ranges. Data collected in raster format had a range of numerical values for each pixel, while vector data had a qualitative classification. To standardise the hazards, we proposed a qualitative-quantitative classification of 5 classes, related to what, from here on, will be called ‘hazard level’: 0—null, 1—low, 2—moderate, 3—medium, 4—high, and 5—very high. Null values correspond to the absence of the data, a situation that occurs when the spatial extent of data does not reach that of the Triveneto. In that situation, we reconstructed the datum by uniting the hazard layer with the study area boundary layer in the GIS environment. Then, we assigned a value of 0—null in the empty fields, i.e., without value. For numerical ranges (raster), we used the five classes obtained from the reclassification procedure that precedes the transformation of the data into a polygon. Regarding the data originally in vector format, we matched each class back to the closest class of the proposed classification. This means that some classes of the new classification remain empty for those starting classifications with fewer than 5 classes.

Appendix A: Data harmonisation presents the reclassification of hazards. For each, we indicated the reference ranges and the new classes to which they correspond. Raster data reference ranges are subdivided into two columns for the start and end of the range. This type of subdivision was not necessary for vector data, for which we reported text classes. To provide an example, in the case of snow avalanches, we had to combine data from four different datasets (one per administrative area) but with very similar content. First, we reconstructed the classification by placing the classes in the hazard level they were closest to. Subsequently, we merged the four shapefiles into a single one. Since the avalanches were localised only in mountainous areas, most of the Triveneto territory was empty. Therefore, we merged this new layer with the Triveneto boundary and associated the new class—which appeared empty—with the value 0—null.

We used the new data to produce single hazard maps which are comparable.

Once all harmonisation operations were made, we dissolved the individual vectors to obtain one geometry for each newly defined hazard class and calculated the areal extent. To increase the readability of maps, we constructed a grid of points that we then superimposed on each hazard, where the more intense the colour, the higher the hazard level (value equal to 5—very high).

3.4. Assessing Spatial Hazard Interactions in Homogeneous Territorial Areas

This last step of the methods aims at translating results produced so far in a format and in a way that enables decision-makers and planners to integrate such information into adaptation strategies and plans. More specifically, we reorganised all the information produced in Section 3.3 by defining minimum reading units describing the major geomorphological properties of the Triveneto macro-region, i.e., the homogeneous territorial areas. Hence, the objective of this section is to assess spatial hazard interactions—that means, how many and which hazard combinations are preponderant—in each homogeneous territorial area. This operation allows for connecting multi-hazard and transboundary data to support decision-making.

Following the description given in Section 2 Case Study, we recognised six homogeneous territorial areas from north to south: (i) the mountain belt, (ii) the piedmont belt, (iii) the high dry plain, (iv) the springs belt, (v) the low wet plain, and (vi) the coast. Bertin et al. [39] initially theorised these areas as part of the iNEST project. Thus, the terminology is the same, while the spatialisation is the contribution this work makes to their theorisation. We evaluated several alternatives but preferred to continue the reasoning they started within the iNEST project to maintain consistency and advance in the same line of research (see pages 265–267 in [39] for further details). In addition, this distinction describes the geomorphological richness of the area.

We reconstructed this level of information from three main data: the landscape areas of the Friuli Venezia Giulia Regional Landscape Plan [62], the valley communities of the Autonomous Province of Trento, and the district communities of the Autonomous Province of Bolzano. Landscape areas identify morphologically similar realities and were therefore used to define the main vocation of the area. For the Veneto region, we used the datum of 'territorial reference elements' designated by the Regional Territorial Coordination Plan [63] available in the regional database. For the springs belt, we downloaded the data from the respective geoportals of the Veneto region and the Friuli Venezia Giulia region. For the latter, the datum was in polyline format, so we had to create a buffer to transform it into a polygon.

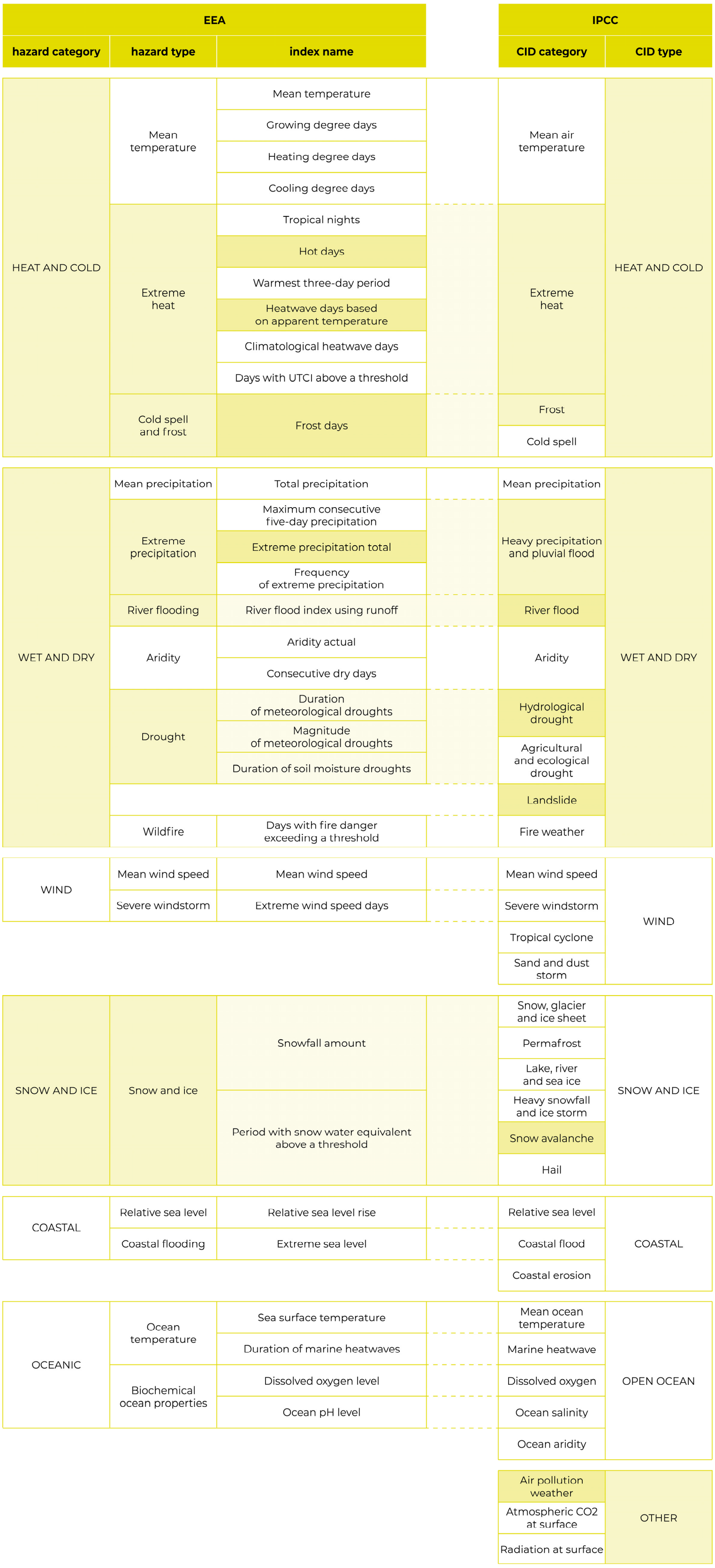
To assess the interactions, we intersected each hazard with the homogeneous territorial areas layer in the GIS environment. Then, we calculated the percentage of land occupied by the first out of the total extension of the areas. Specifically, we considered only hazard levels from medium to very high (i.e., 3 to 5).

4. Results

4.1. Identifying Relevant Climate-Related Hazards and Indices

Figure 3 re-elaborates what emerges from the content analysis of the reference studies, i.e., the macro categories of hazards, hazards typologies and hazard indices, highlighting correspondences between EEA and IPCC. Yellow boxes indicate the elements we have chosen. In particular, the darker shade refers to the indices we selected to describe the hazards.

The comparison between EEA's hazard categories and IPCC's CID type led to the selection of four groups of hazards, which in this study will be referred to as 'hazard categories': Heat and Cold, Wet and Dry, Snow and Ice, and Other. Inside, we identified the eight relevant hazards of extreme heat, frost, extreme precipitation, river flood, hydrological drought, landslide, snow avalanche, and air pollution weather for the Triveneto context. Among the indices proposed by the EEA, we identified the following as significant: hot days, heatwave days based on apparent temperature, frost days, and extreme precipitation total. Concerning IPCC, the selected hazards also refer to indices we further investigated. This difference explains why we looked at more than one reference.



EEA			IPCC	
hazard category	**hazard type**	**index name**	**CID category**	**CID type**
HEAT AND COLD	Mean temperature	Mean temperature	Mean air temperature	HEAT AND COLD
		Growing degree days		
		Heating degree days		
		Cooling degree days		
	Extreme heat	Tropical nights	Extreme heat	
		Hot days		
		Warmest three-day period		
		Heatwave days based on apparent temperature		
		Climatological heatwave days		
		Days with UTCI above a threshold		
	Cold spell and frost	Frost days	Frost	
			Cold spell	
WET AND DRY	Mean precipitation	Total precipitation	Mean precipitation	WET AND DRY
	Extreme precipitation	Maximum consecutive five-day precipitation	Heavy precipitation and pluvial flood	
		Extreme precipitation total		
		Frequency of extreme precipitation		
	River flooding	River flood index using runoff	River flood	
	Aridity	Aridity actual	Aridity	
		Consecutive dry days		
	Drought	Duration of meteorological droughts	Hydrological drought	
		Magnitude of meteorological droughts		
		Duration of soil moisture droughts	Agricultural and ecological drought	
			Landslide	
	Wildfire	Days with fire danger exceeding a threshold	Fire weather	
WIND	Mean wind speed	Mean wind speed	Mean wind speed	WIND
	Severe windstorm	Extreme wind speed days	Severe windstorm	
			Tropical cyclone	
			Sand and dust storm	
SNOW AND ICE	Snow and ice	Snowfall amount	Snow, glacier and ice sheet	SNOW AND ICE
			Permafrost	
			Lake, river and sea ice	
		Period with snow water equivalent above a threshold	Heavy snowfall and ice storm	
			Snow avalanche	
			Hail	
COASTAL	Relative sea level	Relative sea level rise	Relative sea level	COASTAL
	Coastal flooding	Extreme sea level	Coastal flood	
			Coastal erosion	
OCEANIC	Ocean temperature	Sea surface temperature	Mean ocean temperature	OPEN OCEAN
		Duration of marine heatwaves	Marine heatwave	
	Biochemical ocean properties	Dissolved oxygen level	Dissolved oxygen	
		Ocean pH level	Ocean salinity	
			Ocean aridity	
			Air pollution weather	OTHER
			Atmospheric CO2 at surface	
			Radiation at surface	

Figure 3. Relevant hazards according to IPCC and EEA. Hazards and indices selected in this work are highlighted in yellow.

We did not consider the Wind hazard category due to the lack of data on strong wind storms in the Triveneto area and because this hazard has little influence in the area compared to the international references.

For Coastal and Oceanic/Open Ocean hazard categories, we initially recognised relative sea level and ocean salinity as relevant to the study area. However, they were not taken into account due to the lack of sufficiently detailed datasets for their spatialisation. The same happened in the Snow and Ice category, particularly for hail, for which there was still not enough useful data.

All those hazards and indices that were less impactful due to their extension or insignificant frequency and those lacking in data were not dealt with but left for future studies.

To summarise, the final list of four hazard categories and eight hazards used for mapping and assessment is presented:

- Heat and Cold: extreme heat, frost;
- Wet and Dry: extreme precipitation, river flood, landslide, hydrological drought;
- Snow and Ice: snow avalanche;
- Other: air pollution.

4.2. Selecting Indicators and Collecting Existing Geolocalised Data for Hazard Mapping

Table 1 presents the list of hazards resulting from the content analysis and related indicators—including indicator description, the reference justifying data reliability and relevance, and data source—according to the data search performed in various databases at the European, national, and sub-national level. We interpreted a few hazard names when more than one term was used and there was no direct correspondence from the EEA to the IPCC. Moreover, we interpreted and detailed some indicators based on data availability. That is the case of, for example, Extreme heat, which appears twice. We decided to decline the hazard by emphasising the difference between air (which is present in the reference reports) and land surface temperature (which is not directly mentioned), due to the relevance to the case study. Cities in the Triveneto context are characterised by dense urban fabric which tends to be exposed to the urban heat island effect, especially during the summer period [64,65], widely measured through land surface temperature (LST) [66,67]. In those cases, the land surface temperature is generally warmer than the air temperature [66], highlighting the need to consider this aspect.

Regarding the sources, we used the EEA datahub only for air pollution. All other information levels were too coarse-grained for the study scale. Even at the national scale, no common climate-related hazard database is available. However, we identified two databases covering the entire study area for some of the indicators searched. ISPRA provided data for river flood, landslide and hydrological drought, and the North-East Climate Platform by ARPAV and ArpaFVG presented data for extreme heat (air surface), frost, and extreme precipitation. For the latter, it should be noted that data were divided into four layers according to seasons, thus we chose spring and autumn as relevant for the case study area, we merged them through the 'combine multiple rasters' command in ArcGIS Pro, and finally calculated their average. For the snow avalanche indicator, we collected and merged data from four databases, corresponding to the administrative areas that make up the Triveneto macro-region. In this case, the four administrative units provided similar data but with slight differences in detection and mapping. Merging the databases required an approximation of these differences.

Table 1. Data and indicators to assess single hazards.

Hazard	Indicator	Description	Reference	Data Source	Metrics	Year
		DETECTION				
Extreme heat (land surface)	Land Surface Temperature (LST)	The measurement of LST, the radiative skin temperature of the land derived from infrared radiation, is an affordable method to assess UHI effects and its spatially varying intensity at large spatial and temporal scales.	Longato and Maragno, 2023 [66]	Landsat 8	Magnitude [T]	2024
Hydrological drought	Standardised Precipitation Index (SPI-12)	The 12-month Standardised Precipitation Index (SPI) provides an assessment of hydrological drought conditions, obtained using precipitation data. SPI represents the relationship between the amount of precipitation falling in a time interval and its climatology. The 12-month aggregation time step chosen for the SPI assessment is the one that best describes the effects of drought (precipitation deficits) on river discharge, reservoir recharge, and water availability in the aquifers.	Mariani et al., 2018 [68]	ISPRA	Frequency	2023
Snow avalanche	Carte di Localizzazione Probabile delle Valanghe (CLPV)—Probable Avalanche Location Maps	Map of avalanche sites identified both in situ based on eyewitness and/or archival evidence and by analysis of the permanent parameters that distinguish an area prone to avalanche fall, inferred from stereoscopic aerial photographs.	Trigila and Iadanza, 2016 [69]	Autonomous Region Friuli Venezia Giulia, ARPAV, Autonomous Province of Bolzano, Autonomous Province of Trento	Frequency	2011–2023
Air pollution	PM10	Concentrations for the air pollutants PM10 at grid level combining monitoring air quality data and the observational values of the air quality monitoring stations used in the interpolation	PM10, European air quality data (2024) [70]	EEA	Magnitude [$\mu g/m^3$]	2023

Table 1. *Cont.*

Hazard	Indicator	Description	Reference	Data Source	Metrics	Year
PROJECTION						
Extreme heat (air surface)	Number of hot days	Number of days over a certain time interval with daily maximum temperature above 30 °C (1). The indicator accounts the change of number of hot days in 2021–2050 projection.	Crespi et al., 2020 [49]	ClimaArpa	Magnitude [days]	2013–2023
Frost	Number of frost days	Number of days over a certain period with daily minimum temperature below 0 °C. The indicator accounts the change of number of frost days in 2021–2050 projection.	Crespi et al., 2020 [49]	ClimaArpa	Magnitude [days]	1976–2005
Extreme precipitation	Extreme precipitation total	Total sum of daily precipitation over a certain period exceeding the 99th percentile of the reference interval. The indicator accounts the average between the sum of daily precipitation in spring and autumn seasons.	Crespi et al., 2020 [49]	ClimaArpa	Magnitude [mm]	1976–2005
River flood	Mosaic of the flood hazard zones	Areas of high hazard and flood risk, defined as temporary flooding of areas that are habitually not covered with water, mapped by the River Basin District Authorities according to the one identified pursuant to Art. 5 of D.Lgs. 49/2010. Flooding is defined as temporary flooding of areas that are not usually covered with water. This includes flooding caused by rivers, mountain streams, temporary watercourses, and marine flooding of coastal areas, and may exclude flooding caused by sewage systems.	Lastoria et al., 2021 [71]	ISPRA	Frequency	2020

Table 1. *Cont.*

Hazard	Indicator	Description	Reference	Data Source	Metrics	Year
Landslide	Mosaic of the landslide hazard zones	Areas of landslide hazard of the Rivers Basin Plan (PAI), including landslides that have already occurred, areas of possible evolution of the phenomena and areas potentially susceptible to new landslides. Landslide hazard is the probability of occurrence of a potentially destructive phenomenon of a given intensity at a given time and in a given area.	Trigila et al., 2021 [72]	ISPRA	Frequency	2021

4.3. Harmonising and Comparing Diverse Existing Data

Figure 4 shows the mappings of individual hazards resulting from the data harmonisation: the more intense the colour, the higher the hazard level (value equal to 5—very high). These maps are accompanied by related statistics presented in Figure 5, which describes, by hazard level, the percentage of land occupied by each hazard out of the total Triveneto area. In general, it can be seen from the maps that the investigated hazards tend to be concentrated either on the mountainous belt to the north (frost, landslide, and hydrological drought) or on the remaining part of the south-central territory (extreme heat (land surface), extreme heat (air surface), hydrological drought, and air pollution), which includes the foothills, plains and coastal belt. Exceptions are the hazards of extreme precipitation, partially present in both areas, and river flood, which follows river courses from source to mouth.

The highest values (classes 4 and 5) occupy more than 30% of the territory in extreme heat (land surface), extreme heat (air surface), extreme precipitation, hydrological drought, and more than 50% in frost. In detail, the greatest presence of the very high hazard level is found in extreme heat (air surface), with a weight of 31% of the Triveneto total, while the lowest presence of this level is found in landslide.

Conversely, the null value is widely present (>80%) in river flood, landslide, and hydrological drought hazards, which correspond to the three source data in vector format. However, the null class is at or around zero for all other hazards. Thus, the values tend to skew in one or two hazard levels, and only rarely do they appear rather evenly distributed, as in the case of hydrological drought.

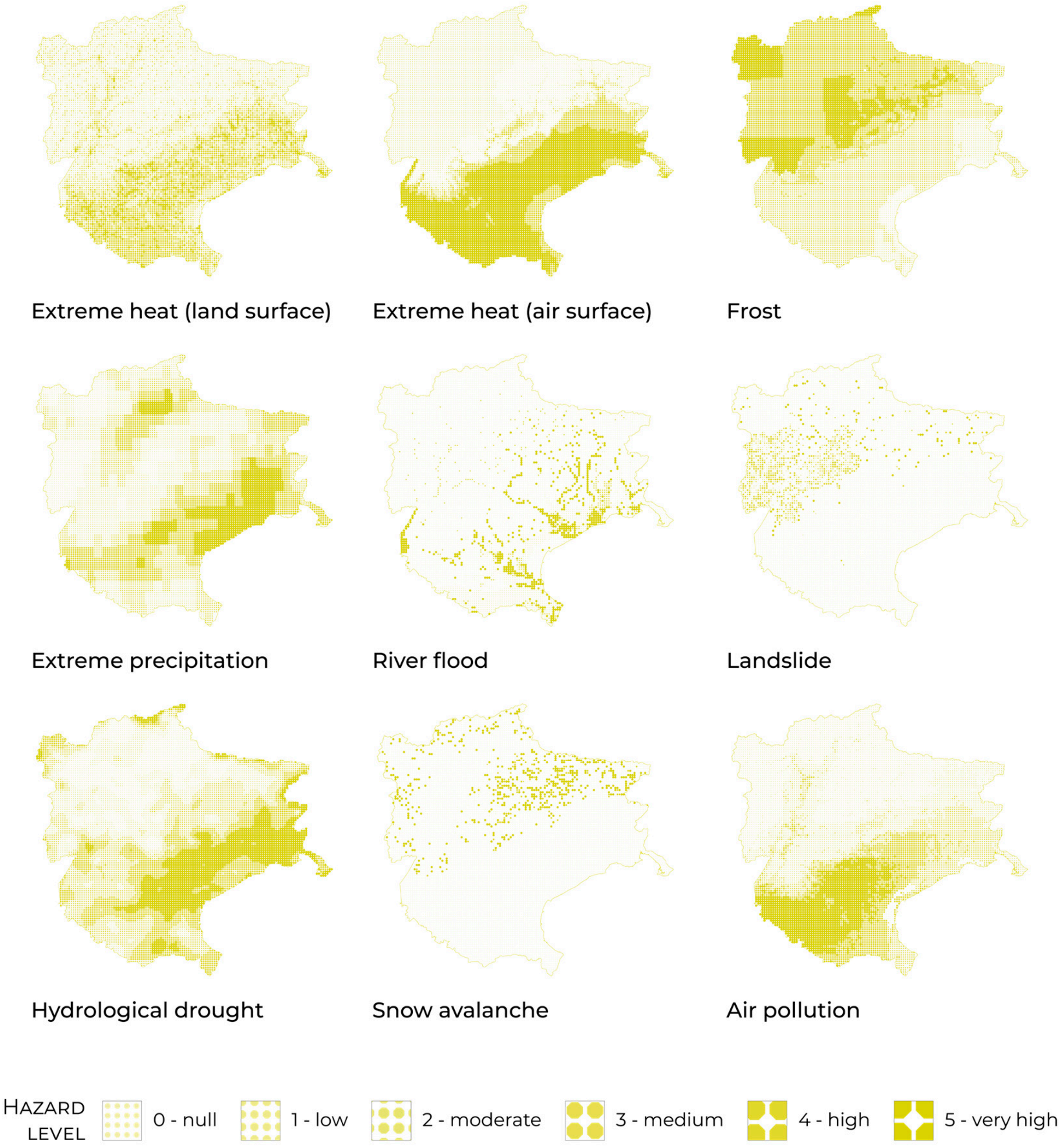
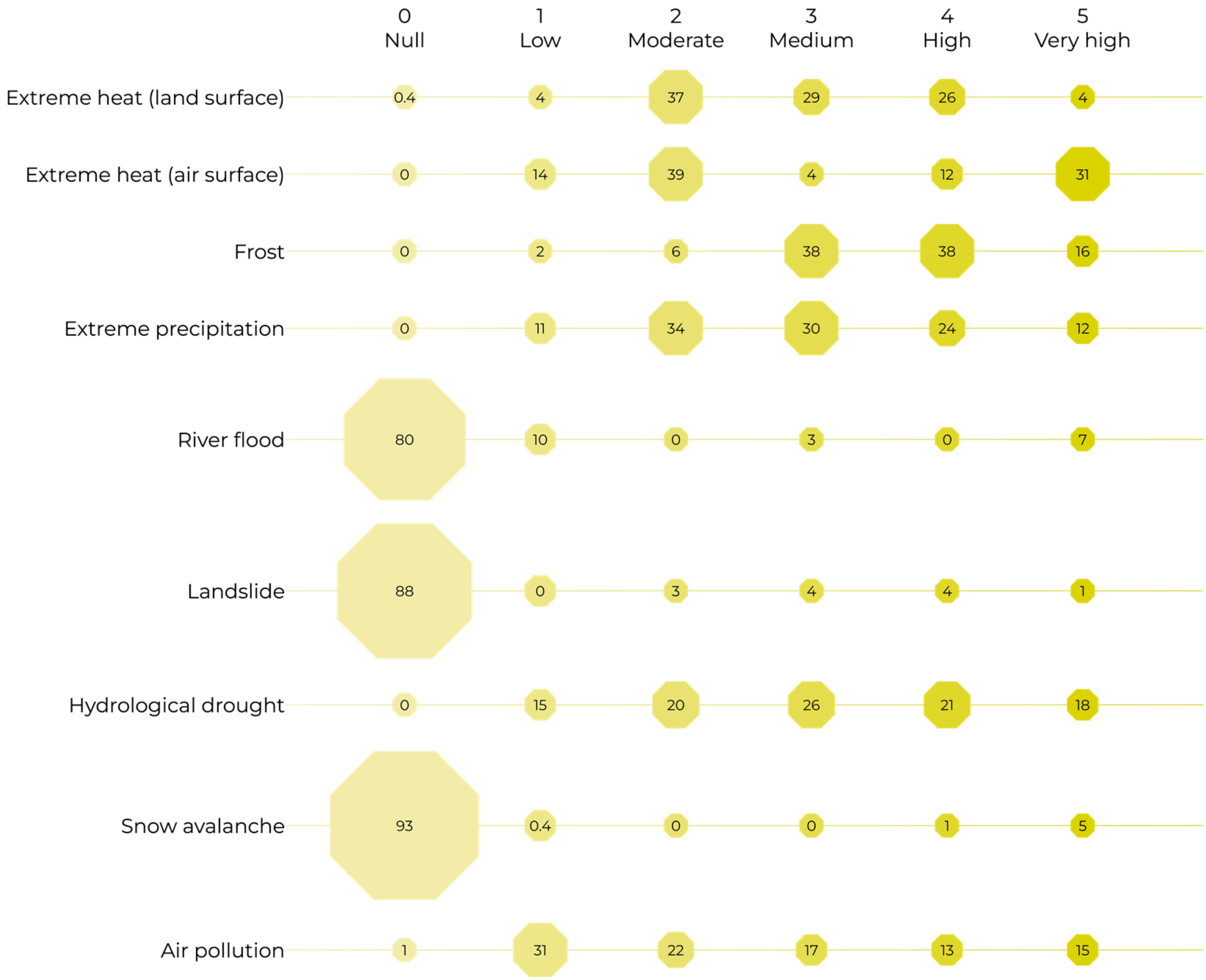


Figure 4. Mapping of nine hazards in Triveneto study area according to harmonised classification.



	0 Null	1 Low	2 Moderate	3 Medium	4 High	5 Very high
Extreme heat (land surface)	0.4	4	37	29	26	4
Extreme heat (air surface)	0	14	39	4	12	31
Frost	0	2	6	38	38	16
Extreme precipitation	0	11	34	30	24	12
River flood	80	10	0	3	0	7
Landslide	88	0	3	4	4	1
Hydrological drought	0	15	20	26	21	18
Snow avalanche	93	0.4	0	0	1	5
Air pollution	1	31	22	17	13	15

Figure 5. Quantification of percentage of land occupied by each hazard out of total extent of study area, according to hazard level, i.e., 0—null to 5—very high.

4.4. Assessing Spatial Hazard Interactions in Homogeneous Territorial Areas

Figure 6 illustrates the mapping of the six homogeneous territorial areas defined in the methods (Section 3.4).

Figure 7 presents a synoptic view of multi-hazard bundles in each homogeneous territorial area. In particular, we displayed the weight (percentage value) of the area occupied by every hazard out of the total extent of the individual homogeneous territorial area. The latter is indicated in hectares below each spatialization in the first left column. We considered only medium, high, and very high hazard levels. In general, it is immediately apparent that some hazards have a decisive weight in certain portions of the territory, while others are almost absent for the selected hazard levels.

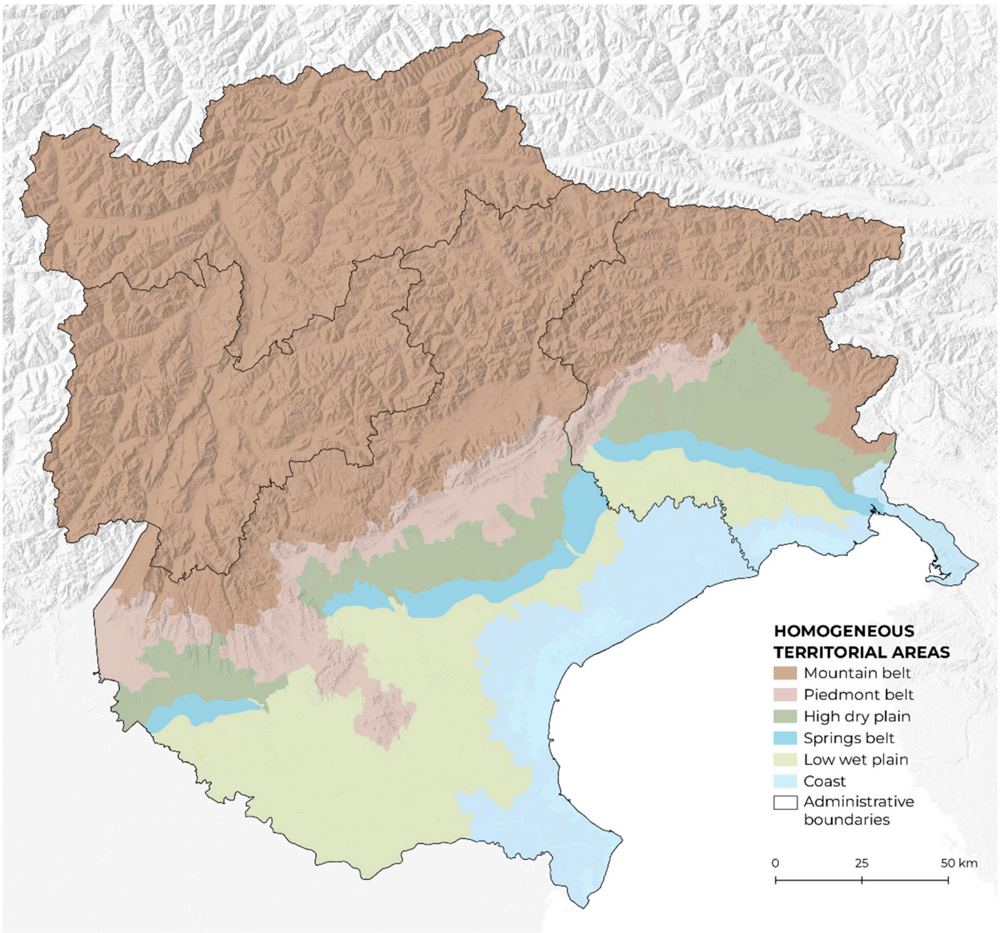
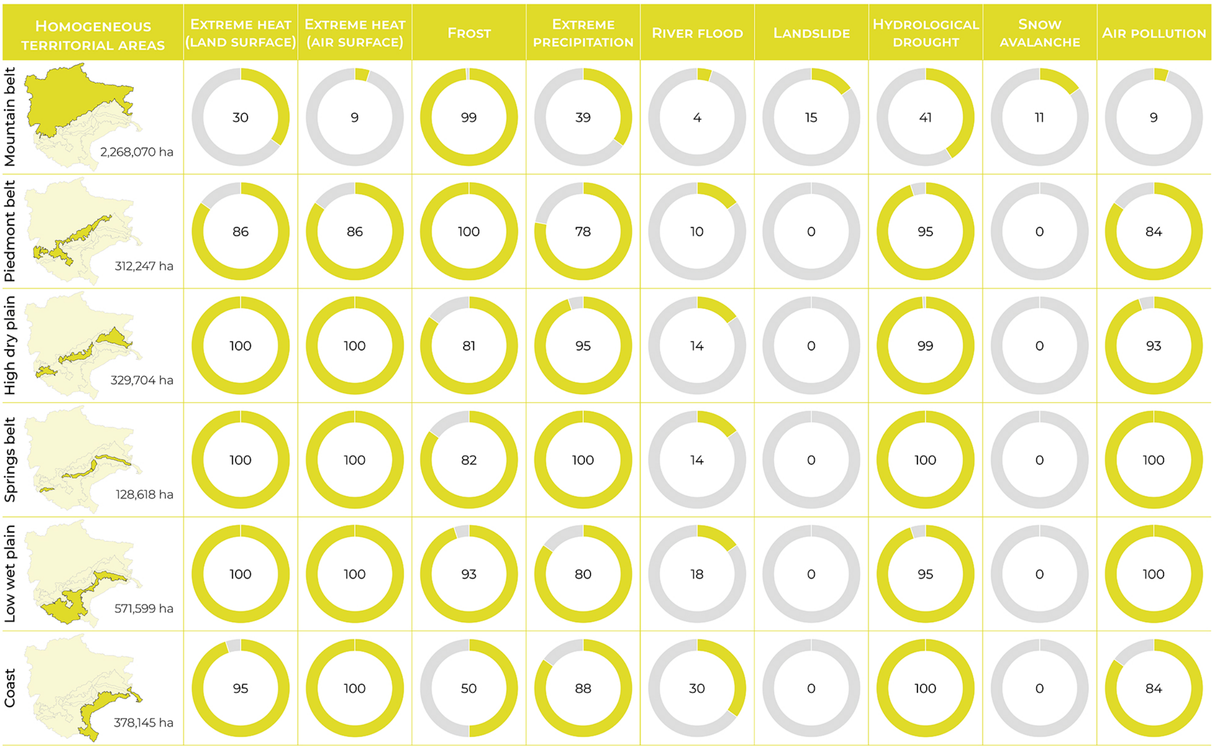


Figure 6. Proposed spatialisation of homogeneous territorial areas for Triveneto study area.



Homogeneous Territorial Areas	Extreme Heat (Land Surface)	Extreme Heat (Air Surface)	Frost	Extreme Precipitation	River Flood	Landslide	Hydrological Drought	Snow Avalanche	Air Pollution
Mountain belt 2,268,070 ha	30	9	99	39	4	15	41	11	9
Piedmont belt 312,247 ha	86	86	100	78	10	0	95	0	84
High dry plain 329,704 ha	100	100	81	95	14	0	99	0	93
Springs belt 128,618 ha	100	100	82	100	14	0	100	0	100
Low wet plain 571,599 ha	100	100	93	80	18	0	95	0	100
Coast 378,145 ha	95	100	50	88	30	0	100	0	84

Figure 7. Multi-hazard matrix by homogeneous territorial area. Graphs show percentage of land occupied by each hazard in the different areas, according to hazard levels from medium to very high.

Reading the figure from top to bottom, i.e., by hazard, we observed similar behaviours in the hazard pair of extreme heat (air surface) and air pollution, in the group of extreme heat (land surface), extreme precipitation, and hydrological drought, and in the pair of landslide and hydrological drought, from which river flood in the coast deviates slightly. Only frost has areal percentages greater than or equal to 50% in all homogeneous territorial areas.

Conversely, reading the figure from left to right, that is, by homogeneous territorial area, we noticed that five of them exhibit similar behaviours for the hazards of extreme heat (land surface), extreme heat (air surface), frost, extreme precipitation, hydrological drought and air pollution, with percentages around or above 80%, except for frost in the specific context of the coast. Thus, the mountain belt differs from the other areas, as it reports a 99% for frost, percentages around 30–40% for extreme heat (land surface), extreme precipitation, and Hydrological drought, and values of 15% or less for all other hazards.

In addition to the proposed overlap between the single hazard and the homogeneous territorial areas, Figure 8 shows the overlap between all analysed hazards. In particular, we depicted the intersection between the average values per hazard level. The highest hazard levels (medium to very high) are concentrated in the coastal and lowland areas (low wet plain, springs belt, and high dry plain), which coincide with the river axes. On the other hand, we find lower hazard values (low and moderate) in small, concentrated portions of the mountain.

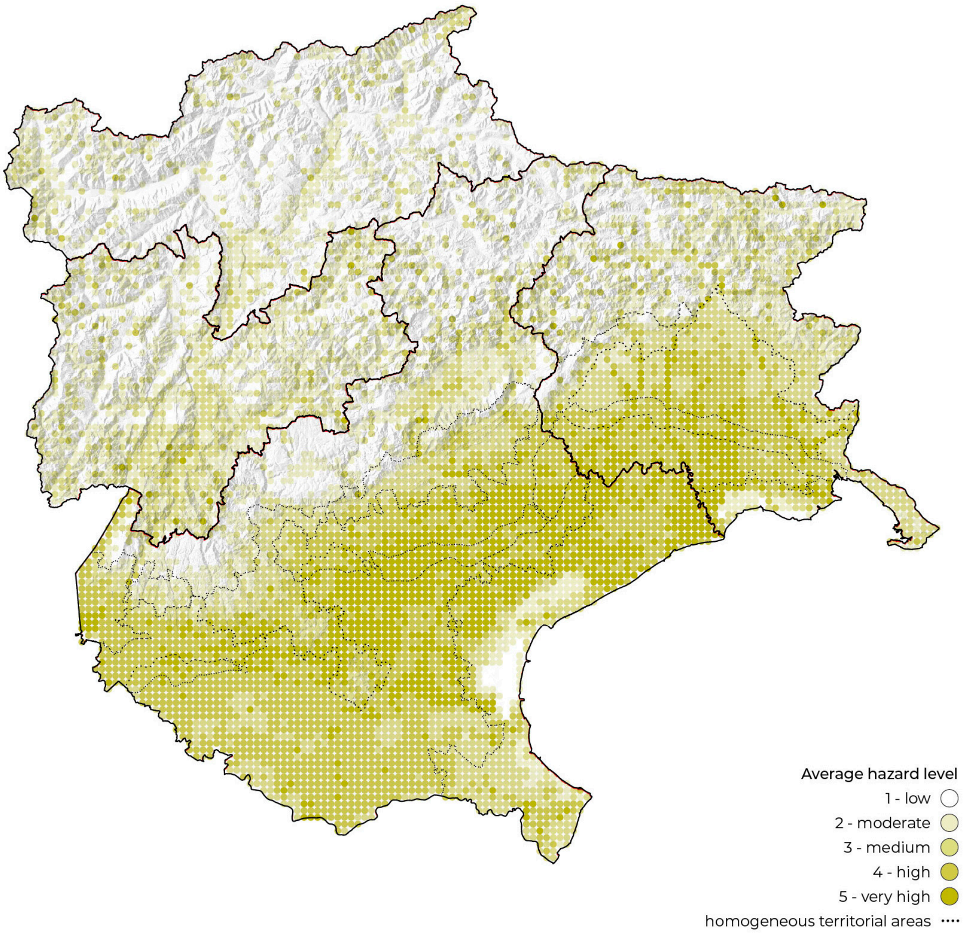


Figure 8. Overlapping hazards. Map shows average of each selected climatic hazard correlated to homogeneous territorial areas.

5. Discussion and Conclusions

The inclusion of multi-hazard assessment in spatial planning for climate adaptation at the regional and local levels is crucial for enhancing the resilience of our territories [13]. Despite a common agreement among the scientific literature and practitioners on this, multiple gaps prevent the inclusion of multi-hazard assessment in practice (for example, the fragmentation of hazard-specific knowledge, the lack of common and synthetic data and datasets, and the heterogeneity of information to address multiple hazards, as we all have different administrative areas for transboundary maps and assessments).

The work presented here contributes to responding to the above-mentioned gaps through what we call the 'building new knowledge through existing data' approach. With our research, we aimed to capitalise on existing data to maximise what we can do with what we already have and create a fertile ground for decision-makers, who could access existing knowledge and information to integrate existing data in their planning processes for climate adaptation. In particular, this work contributes to enabling spatial planners to include multi-hazard assessment in their climate change adaptation measures by providing them with synthetic and disaggregated information from existing data, different single-hazard datasets and different regional datasets.

The novelty of this piece of research is the methodology for harmonising existing data and transforming them into new comparable information, on the one hand, and on the other hand on the work undertaken around the concept of homogeneous territorial areas. Thus, while more precise methods to assess single hazards exist, and alternative ways of obtaining multiple-hazards maps through modelling circulate already, the effort to get a bundle of relevant multiple-hazards per homogeneous territorial areas represents a new brick for bridging the 'scientific' assessment world to the worlds of the practitioners. Indeed, these can take action, and understand the set of multiple-hazards affecting a specific portion of territories with common physical features. Landscapes are an ensemble of heterogeneous spatial units constituted by different ecosystems and are considered the appropriate scale for examining the impact of human activities on natural capital [73]. By identifying the relevant multiple-hazards for a portion of territories with similar physical features (the homogeneous territorial areas), this work on the one hand enables the design of multi-purpose solutions (instead of solutions for floods or for drought, nature-based solutions addressing more challenges at the same time), and on the other hand, promotes the mutual learning of territories sharing similar challenges (hazards) and similar opportunities (their territories' specificities).

Results for the identification of relevant hazards and the indicators needed to assess them (Sections 4.1 and 4.2) can be adopted for other regional and local works in the European contexts.

Regarding results from the collection of the data needed for assessing the case study (Section 4.2), and from the building of the maps through GIS (Section 4.3), outputs are context-specific, but the harmonisation process proposed in Section 4.3 can be adapted to other Italian and European local contexts.

The choice of working on the available data for each indicator identified entailed using significantly different databases in terms of quality and robustness. For some indicators, it was possible to draw on solid databases in terms of the level of definition and accuracy of the information, as in the case of Landsat 8, ISPRA and partly EEA, which are unique sources that can be extended to the national and European scale while maintaining a high level of detail. In the case of EEA's air pollution data, the scale of the data is less detailed. However, it constitutes a valid reference thanks to its equal distribution over the entire European territory. The data collected by ClimaArpa and snow avalanche are less robust as they were elaborated by local databases with different methods. Nevertheless, they still constitute a valid reference for the analysed case study.

The harmonised maps for the single hazards (Section 4.3) represent a brand-new piece of knowledge for our territory. Thus, to date, no comparable maps exist with this level of definitions to understand differences and similarities in the spatial distribution and hazard level among different regions and hazards with such a level of detail. Specifically, we carried out the harmonisation process in two ways, i.e., within the same hazard, in which we merged data from different datasets to construct a single hazard, and between hazards, which involved the construction of criteria to make different hazards comparable.

From a critical and overview reading of the ensemble of single hazard maps (Figure 4), an important difference emerges between hazards with a 'dichotomous' spatial behaviour (either there is or is not) and hazards with a more complex and nuanced spatial behaviour. We can associate hazards with 'dichotomous' spatial behaviour with those close to the definition of shocks and related to territory specificities. Hazards such as river floods depend on the presence of a river, landslides and snow avalanches of the mountain. The other types of hazards, on the other hand, with a more 'nuanced' distribution in space represent the so-called 'stresses', which more or less intensely affect the entire territory. These are: extreme heat (land surface), extreme heat (air surface), frost, extreme precipitation, hydrological droughts, and air pollution. Extreme precipitation is a bridging situation between the two groups, as the so-called 'flash floods' have a 'shock' effect but the alteration of precipitation is a phenomenon that affects (with different levels of severity) the whole territory.

If, on the other hand, we look at the quantitation of the areas affected by each hazard (Figure 5), it should be noted that the value 0 (absence of hazards) tends to appear more for 'dichotomous' or shock hazards, and when particularly high values are seen in the picture, they are related to the absence of hazards, not to hazards. This does not mean that there are no relevant hazards, yet, but rather that we have high-level hazards in small portions of land (where, however, settlements and infrastructure are often concentrated and where the impact can therefore be terrible).

High-level hazards are 'few' among the hazards (of nine hazards, only extreme precipitation (air surface)). Hazards on average show medium to medium–high levels. Often the real problem is related, if not to the level, then to the accumulation of these medium to medium–high hardships over time.

If the maps represent indeed a precious and innovative output for our territory, the real contribution of Sections 3.3 and 4.3 is made by harmonising the methodology to obtain such maps and that can enable other territories to use existing data to build multi-hazards and transboundary assessments (as mentioned above).

The results of Section 4.4 bring us a reading of the bundle of relevant hazards for each homogeneous territorial area. The reconstruction of this information level facilitates the organization of the information and the consequent reading of the results. Moreover, it enables the distribution of the analysed hazards and the study of how they interact with and on the territory (Figure 7), and with each other (Figure 8). However, a clarification needs to be made. The proposed approach analyses the possible spatial co-occurrence between hazards, thus lacking a deeper analysis of the complex interrelationships and co-dependencies between hazards, which is a gap that still poses challenges in multi-hazard assessments [74].

From this last block of results, it emerges that the mountain belt enjoys a better condition (having less co-presentation of hazards) than the rest of the territory. The mountain belt differs, in particular, from the patterns of the other areas that show consistently high hazard levels for temperature, drought, and pollution. As far as 'gradual' or stress hazards are concerned, here too, the mountains tend to be ‘unloaded’ where the other areas are always loaded. It should be noted, however, that of the three ‘territorial’ or dichotomous hazards, two are in the mountains (avalanches and landslides). What does it mean that it is unloaded? It has little area affected by high hazard levels. But maybe this is very serious (in fact these data are only for medium–high and very high). Moreover, the small percentage of level probably coincides with inhabited valleys.

On the contrary, the most exposed or with the worst hazard levels is the central area of Triveneto, which includes stretching from the high dry plain to the coast. Reading the related statistics (Figure 7), we reconfirm the categorisation between two main spatial behaviours of hazard types already described in the results of Section 4.3.

To summarise, in general, the results obtained in this work, particularly the last ones just discussed (Section 4.4), can practically inform planning decisions by facilitating prioritising those areas most exposed to multiple hazards. That makes it possible to recognise areas in which to intervene in the short term while reasoning from a long-term strategic and preventive perspective. Moreover, defining bundles of hazards per homogeneous territorial area enables designing a common and adaptive response strategy for geomorphologically different but adjacent territories.

This study presents some limitations. First, obviously, due to the challenge of the work (harmonising data from different datasets), for some hazards we had to put together data with an important difference in definition. For example, the data for the Autonomous Province of Trento and the Autonomous Province of Bolzano were sometimes taken from European/national datasets with a higher definition because data at the same scale as those available for the Veneto Region and the Friuli Venezia Giulia Region (which are much more detailed) were missing. A further limitation is omitting significant land hazards for the Triveneto context, such as wind and sea level rise, due to a lack of data. Again, due to the use of different datasets, another limitation is that we imagine that some hazards have been mapped much more accurately in some regions than in others (e.g., the landslide hazard in Trentino is very well defined and seems higher, but it is likely that in the other regions it has simply been mapped with less accuracy, not that the hazard level is lower). These limitations, in any case, impact the case study maps (specific output), not the methodology proposed as replicable and are likely, with variations, to be limitations present in other national and European contexts. Another issue to be raised is the fact that the value ‘0’ in the maps corresponds not only to a low or absent level of hazard but also to a lack of data. This suggests that, rather than thinking that where we see the value 0 (lighter tones in the maps) is a safe zone, where we see high values (darker tones in the maps) we certainly have high levels of hazard. A final issue we would like to highlight is the current lack of a layer presenting settlements. Indeed, we believe that an overlay of the hazard maps with the map of the spatial distribution of settlements would allow further fundamental reasoning to build knowledge useful for resilience. However, we reserve this step for future steps in this research.

As mentioned, we live in a complex world, and to address the urgent challenges we face, it is necessary to find synoptic ways of reading the totality of phenomena and the relationships between multiple causes and effects, between impacts and impacted territories, and so on. This article proposes two main and replicable outputs: the first is the methodology to harmonise different data (from different administrative datasets, but also datasets for individual hazard species) to address the gaps mentioned in the introduction, using the fragmented existing data. The second is the reading of hazards by homogeneous units of territory. The latter brings two great benefits: on the one hand, it breaks down the wall dividing hazard specialists from planners, uniting the two semantic heads; on the other hand, it allows the identification of groups of hazards that each territory (with its specific characteristics, opportunities, and problems) has to cope with. This cross-reading is also replicable, with a greater effort requiring the identification of minimum reading units for the area in which it is to be replicated.

Let us now turn more specifically to replicability. The first step is fully replicable in other European regions, as it uses international sources (IPCC and EEA) to identify climate hazards and indices. One difference lies in the relevance given during identification, as it must be adapted to the most interesting hazards for the analysed area. This varies from case to case, as it depends on the information/material already available, e.g., previous national or local climate assessments, preliminary analyses to the multi-hazard assessment, newspaper reports, and database of hazard events. From the second step onwards, the approach we adopted becomes replicable for its rationale, namely (i) for the procedural logic through which the data to describe the locally relevant hazards are selected and collected, (ii) for the harmonisation methodology that may vary but already suggests a method and starting issues, (iii) for the construction or use of an existing intermediate level of reading (homogeneous territorial areas) and, finally, (iv) for the assessment in the latter of the interactions between multiple hazards. The proposed methodology is, therefore, flexible in that it serves as a guideline in an assessment process that must be detailed and adapted to local specificities, but at the same time encompasses a series of steps that may also be valid in a context other than the one in which we tested it.

Here, we provide some suggestions and recommendations to be addressed in future research. The challenge of harmonisation lies in constructing a robust and valid final datum. Our advice is to strike a balance between resolution and extent of the datum, i.e., to find one that reaches the extent of the analysed area at a resolution that makes it meaningful. That can involve foregoing more detailed data at the local level but allows for building a common knowledge base. In our view, there is an underlying problem with data production, as often there is a lack of coordination between the different administrative units and a shared and replicated mapping method. Co-production of guidelines to collect data at the local level by different territorial authorities could be valuable, at least for some aspects, such as the urgency of preparing a joint climate adaptation response.

That does not mean we suggest a new layer of bureaucracy to oversee this aspect. On the contrary, our effort to work on existing data intends to show those involved in hazard-related responses what elements they already have to build cross-cutting knowledge. Nowadays, there is a tendency to create new data for the 'occasion' of a specific task, project or study; however, when addressing this scale, which includes transboundary areas, there is a need to adopt a different approach and not to add extra elements that may be redundant and time-consuming. Therefore, from now on, we believe that the central elements in strengthening and improving transboundary governance for hazard management are shared knowledge and international and inter-country cooperation.

The previously discussed limitations on the use of collected data could be resolved in future studies by the adoption of machine learning approaches, which have proven to be a valuable tool for assessing geomorphological susceptibility [75], natural hazards [76,77], and multi-hazards [78,79], particularly landslides, floods, drought, and wildfires [80,81]. These have been recognised as accurate techniques for land use planners [82], generally used in combination [83,84]. Among their abilities are handling large amounts of data, dealing with uncertainty and making predictions [85,86].

Also interesting in future research steps would be superimposing the hazard mapping with the different 'urban textures' [10] for more detail on the cities and human systems, always keeping the transboundary view.

Our work aims to contribute to bridging theory and practice, as well as different fields of knowledge, such as the specific studies of single hazards, assessment and mapping, and spatial planning and policy design for climate resilience. We believe that the challenges that we are facing do not only require multiple-discipline knowledge, but interdisciplinary tools to integrate different fields. Further research is needed in this direction and joining forces is crucial.

Author Contributions: Conceptualization, A.L., C.S. and L.Z.; methodology, A.L., C.S. and L.Z.; software, A.L. and C.S.; validation, L.Z.; formal analysis, A.L. and C.S.; investigation, A.L. and C.S.; data curation, A.L. and C.S.; writing—original draft preparation, A.L., C.S. and L.Z.; writing—review and editing, A.L., C.S. and L.Z.; visualization, A.L. and C.S.; funding acquisition, A.L., C.S. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded under the iNEST Interconnected Northeast Innovation Ecosystem research program, from the resources of the National Recovery and Resilience Plan (NRRP), M4C2—Investment 1.5. Creation and strengthening of 'Innovation Ecosystems for Sustainability', funded by the European Union, NextGenerationEU, CUP F43C22000200006.

Data Availability Statement: The original contributions presented in this study are included in the article and Appendix A. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ARPA FVG	Regional Agency for Environmental Protection of Friuli Venezia Giulia
ARPAV	Regional Agency for Environmental Protection of Veneto
CID	climatic impact-drivers
EEA	European Environment Agency
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Institute for Environmental Protection and Research

Appendix A

Table A1. Data harmonization. The table presents the transition from the previous statistical range (start-end) to the new classification for each hazard. For some cases, values are to be interpreted in reverse order; for example, for hydrological drought, where negative values gradually correspond to increasingly severe drought. Abbreviations refer to the terminology used in the attribute table of individual shapefiles. Therefore, we decided to translate the class names but report the abbreviations as they are to facilitate consultation and eventual use of these data.

Hazard	Classification Range		
	Start	End	New
Extreme heat (land surface)	−12.073	20	1
	20	27.5	2
	27.5	35	3
	35	40	4
	40	70.26	5
Extreme heat (air surface)	−0.013	2.702	1
	2.702	7.12	2
	7.12	11.939	3
	11.939	16.132	4
	16.132	24.693	5

Table A1. *Cont.*

Hazard	Classification Range		
	Start	**End**	**New**
Frost	−42.567	−25.5	5
	−25.5	−22.083	4
	−22.083	−17.417	3
	−17.417	−12.4	2
	−12.4	−8.087	1
Extreme precipitation	2	15	1
	15	24	2
	24	32	3
	32	40	4
	40	54	5
River flood	low		1
	medium		3
	high		5
Landslide	Areas of Attention AA		No Data
	Moderate P1		2
	Medium P2		3
	High P3		4
	Very high P4		5
Hydrological drought	−3.941	−2.486	5
	−2.486	−1.962	4
	−1.962	−1.455	3
	−1.455	−0.88	2
	−0.88	0.372	1
Snow avalanche	*Veneto Region*		
	1—avalanche site		5
	2—danger zone at partial discharges		4
	3—possible continuations and linking of avalanche sites		3
	4—presumed dangerous zone		2
	Bolzano Province		
	Avalanche—Very high hazard level (H4)		5
	Avalanche—High hazard level (H3)		4
	Avalanche—Medium hazard level (H2)		3
	Avalanche—Examined and not dangerous		No Data
	Trento Province		
	Ordinary hazard classes:		
	H4—high		5
	H3—medium		3
	H2—low		1
	H1—negligible		No Data
	Extraordinary hazard classes:		
	HP—potential		1
	HR4—high residual		5
	HR3—medium residual		3
	HR2—low residual		1
	Friuli Venezia Giulia Region		
	Avalanche		5
	Dangerous areas		4
Air pollution	3.14	8.692	1
	8.692	14.76	2
	14.76	20.828	3
	20.828	25.992	4
	25.992	36.062	5

References

1. Alexander, C. A City Is Not a Tree. 1965. Available online: https://en.wikipedia.org/wiki/A_City_Is_Not_a_Tree (accessed on 20 December 2024).
2. Van Wyk de Vries, M. All hazards are multihazards, few of them are natural. *npj Nat. Hazards* **2025**, *2*, 18. [CrossRef]
3. Arosio, M.; Martina, M.L.V.; Figueiredo, R. The whole is greater than the sum of its parts: A holistic graph-based assessment approach for natural hazard risk of complex systems. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 521–547. [CrossRef]
4. IPCC. Climate Change 2022—Impacts, Adaptation and Vulnerability. In *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., et al., Eds.; Cambridge University Press: Cambridge, UK, 2022. [CrossRef]
5. United Nations General Assembly. Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction: Note/41p. 2016. Available online: http://digitallibrary.un.org/record/852089 (accessed on 20 December 2024).
6. Pourghasemi, H.R.; Gayen, A.; Edalat, M.; Zarafshar, M.; Tiefenbacher, J.P. Is multi-hazard mapping effective in assessing natural hazards and integrated watershed management? *Geosci. Front.* **2020**, *11*, 1203–1217. [CrossRef]
7. Zardo, L.; Alonso, C.; Angelone, S.; Straus, F.; Spaliviero, M. Transboundary hazards and governance: Sub-regional and national implications. In *Regional Assessment on Urban Vulnerability and Resilience in Southern African Development Community Member States*; Briggs, S., Maseland, J., Eds.; Università Iuav di Venezia: Venice, Italy, 2022; ISBN 978-92-1-132889-9.
8. Pescaroli, G.; Alexander, D. Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework. *Risk Anal.* **2018**, *38*, 2245–2257. [CrossRef]
9. Gohil, M.; Mehta, D.; Shaikh, M. An integration of geospatial and fuzzy-logic techniques for multi-hazard mapping. *Results Eng.* **2024**, *21*, 101758. [CrossRef]
10. UN-Habitat. Breaking Cycles of Risk Accumulation in African Cities. United Nations Human Settlements Programme (UN-Habitat). 2020. Available online: https://unhabitat.org/breaking-cycles-of-risk-accumulation-in-african-cities (accessed on 20 December 2024).
11. Pourhashemi, S.; Zangane Asadi, M.A.; Boroughani, M. Multi-hazard susceptibility mapping in the Salt Lake watershed. *Environ. Chall.* **2025**, *18*, 101079. [CrossRef]
12. De Montis, A.; Ledda, A.; Serra, V.; Calia, G. Green Infrastructure and Adaptation to Climate Change in Marginal Areas: A Reference Scheme for Implementation Guidelines in Italy. *Sustainability* **2024**, *16*, 8641. [CrossRef]
13. Ledda, A.; Kubacka, M.; Calia, G.; Bródka, S.; Serra, V.; De Montis, A. Italy vs. Poland: A Comparative Analysis of Regional Planning System Attitudes toward Adaptation to Climate Changes and Green Infrastructures. *Sustainability* **2023**, *15*, 2536. [CrossRef]
14. Kabisch, S. Urban Transformations to Pursue Sustainability Through Resource Efficiency, Quality of Life and Resilience: A Conceptual Approach. *Geogr. Tech.* **2019**, *14*, 98–107. [CrossRef]
15. Longo, A.; Zardo, L.; Maragno, D.; Musco, F.; Burkhard, B. Let's Do It for Real: Making the Ecosystem Service Concept Operational in Regional Planning for Climate Change Adaptation. *Sustainability* **2024**, *16*, 483. [CrossRef]
16. de Ruiter, M.C.; Couasnon, A.; van den Homberg, M.J.; Daniell, J.E.; Gill, J.C.; Ward, P.J. Why We Can No Longer Ignore Consecutive Disasters. *Earth's Future* **2020**, *8*, e2019EF001425. [CrossRef]
17. Galderisi, A.; Limongi, G. A Comprehensive Assessment of Exposure and Vulnerabilities in Multi-Hazard Urban Environments: A Key Tool for Risk-Informed Planning Strategies. *Sustainability* **2021**, *13*, 9055. [CrossRef]
18. Graff, K.; Lissak, C.; Thiery, Y.; Maquaire, O.; Costa, S.; Medjkane, M.; Laignel, B. Characterization of elements at risk in the multirisk coastal context and at different spatial scales: Multi-database integration (normandy, France). *Appl. Geogr.* **2019**, *111*, 102076. [CrossRef]
19. Cui, B.; Zhang, Y.; Wang, Z.; Gu, C.; Liu, L.; Wei, B.; Gong, D.; Rai, M.K. Ecological Risk Assessment of Transboundary Region Based on Land-Cover Change: A Case Study of Gandaki River Basin, Himalayas. *Land* **2022**, *11*, 638. [CrossRef]
20. Boas, I.; Farbotko, C.; Bukari, K.N. The bordering and rebordering of climate mobilities: Towards a plurality of relations. *Mobilities* **2024**, *19*, 521–536. [CrossRef]
21. Zhang, T.; Gibson, L.; Ma, J.; Sreekar, R.; Lindenmayer, D.; Liu, J. Global patterns of border protected areas reveal gaps in transboundary conservation efforts. *One Earth* **2025**, 101206. [CrossRef]
22. Dallimer, M.; Strange, N. Why socio-political borders and boundaries matter in conservation. *Trends Ecol. Evol.* **2015**, *30*, 132–139. [CrossRef]
23. Schirpke, U.; Tasser, E. Potential impacts of climate change on ecosystem services in Austria. *Ecosyst. Serv.* **2024**, *68*, 101641. [CrossRef]
24. Harris, K.; Lager, F.; Jansen, M.K.; Benzie, M. Rising to a New Challenge: A Protocol for Case-Study Research on Transboundary Climate Risk. *Weather Clim. Soc.* **2022**, *14*, 755–768. [CrossRef]

25. Anisimov, A.; Magnan, A.K. (Eds.) The Global Transboundary Climate Risk Report. 2023. Available online: https://adaptationwithoutborders.org/knowledge-base/adaptation-without-borders/the-global-transboundary-climate-risk-report/ (accessed on 20 December 2024).
26. Talebian, S.; Benzie, M.; Harris, K.; Jarząbek, Ł.; Magnuszewski, P.; Carter, T.R.; Obermeister, N. A conceptual framework for responding to cross-border climate change impacts. *Environ. Sci. Policy* **2025**, *163*, 103949. [CrossRef]
27. Aall, C.; Leander, E.; Menk, L.; Meyer, M.; Dale, B.; Lückerath, D.; Nyadzi, E.; Rome, E.; Rudolf, F.; Goosen, H.; et al. *Methods for Climate Change Risk Assessments: An International Knowledge Review*; Aall, C., Ed.; Norwegian Research Board: Oslo, Norway, 2020. Available online: https://www.vestforsk.no/sites/default/files/2021-01/D1.1-knowledge%20review%20final2%20(1).pdf (accessed on 20 December 2024).
28. Polese, M.; Tocchi, G.; Babič, A.; Dolšek, M.; Faravelli, M.; Quaroni, D.; Borzi, B.; Rebora, N.; Ottonelli, D.; Wernhart, S.; et al. Multi-risk assessment in transboundary areas: A framework for harmonized evaluation considering seismic and flood risks. *Int. J. Disaster Risk Reduct.* **2024**, *101*, 104275. [CrossRef]
29. Cremen, G.; Galasso, C.; McCloskey, J. Modelling and quantifying tomorrow's risks from natural hazards. *Sci. Total Environ.* **2022**, *817*, 152552. [CrossRef] [PubMed]
30. Rahayu, H.P.; Zulfa, K.I.; Nurhasanah, D.; Haigh, R.; Amaratunga, D.; Wahdiny, I.I. Unveiling transboundary challenges in river flood risk management: Learning from the Ciliwung River basin. *Nat. Hazards Earth Syst. Sci.* **2024**, *24*, 2045–2064. [CrossRef]
31. Booth, L.; Fleming, K.; Abad, J.; Schueller, L.A.; Leone, M.; Scolobig, A.; Baills, A. Simulating synergies between Climate Change Adaptation and Disaster Risk Reduction stakeholders to improve management of transboundary disasters in Europe. *Int. J. Disaster Risk Reduct.* **2020**, *49*, 101668. [CrossRef]
32. Garrick, D.E.; Schlager, E.; De Stefano, L.; Villamayor-Tomas, S. Managing the Cascading Risks of Droughts: Institutional Adaptation in Transboundary River Basins. *Earth's Future* **2018**, *6*, 809–827. [CrossRef]
33. Clegg, G.; Haigh, R.; Amaratunga, D.; Rahayu, H. Transboundary River Governance Practices for Flood Risk Reduction in Europe: A Review. In *Multi-Hazard Early Warning and Disaster Risks*; Amaratunga, D., Haigh, R., Dias, N., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 291–302.
34. Mavlyanova, N.G.; Lipatov, V.A.; Yuldashev, O.R. Transboundary Problems of Overcoming Natural Disasters for International Regional Organizations in the Eurasian Region. *Stud. Russ. Econ. Dev.* **2018**, *29*, 322–328. [CrossRef]
35. Polese, M.; Tocchi, G.; Dolsek, M.; Babič, A.; Faravelli, M.; Quaroni, D.; Borzi, B.; Prota, A. Seismic risk assessment in transboundary areas: The case study on the border between Italy and Slovenia. *Procedia Struct. Integr.* **2023**, *44*, 123–130. [CrossRef]
36. Bignami, D.F.; Ambrosi, C.; Bertulessi, M.; Menduni, G.; Pozzoni, M.; Zambrini, F. Governance strategies and tools towards the improvement of emergency management of natural disasters in transboundary areas. *Int. J. Disaster Risk Reduct.* **2024**, *111*, 104704. [CrossRef]
37. Zardo, L.; Geneletti, D.; Pérez-Soba, M.; Van Eupen, M. Estimating the cooling capacity of green infrastructures to support urban planning. *Ecosyst. Serv.* **2017**, *26*, 225–235. [CrossRef]
38. Consorzio iNEST. Interconnected Nord-Est Innovation Ecosystem. Available online: https://www.consorzioinest.it/ (accessed on 30 January 2025).
39. Bertin, M.; Pisciella, S.; Revellini, R.; Ruggeri, D.; Semenzin, C.; Zardo, L.; Zatta, E. Verso la neutralità climatica: Progettare una transizione sostenibile ed equa. In *Primo Volume dello Spoke 4 Città, Architettura e Design Sostenibile*, 1st ed.; Anteferma: Conegliano, Italy, 2024. [CrossRef]
40. Giovannini, L.; Davolio, S.; Zaramella, M.; Zardi, D.; Borga, M. Multi-model convection-resolving simulations of the October 2018 Vaia storm over Northeastern Italy. *Atmos. Res.* **2021**, *253*, 105455. [CrossRef]
41. Bernello, G.; Mondino, E.; Bortolini, L. People's Perception of Nature-Based Solutions for Flood Mitigation: The Case of Veneto Region (Italy). *Sustainability* **2022**, *14*, 4621. [CrossRef]
42. Barbi, A.; Cagnati, A.; Cola, G.; Checchetto, F.; Chiaudani, A.; Crepaz, A.; Delillo, I.; Mariani, L.; Marigo, G.; Meneghin, P. Atlante Climatico del Veneto. Precipitazioni—Basi Informative per L'analisi delle Correlazioni tra Cambiamenti Climatici e Dinamiche Forestali nel Veneto. 2013. Available online: https://www.arpa.veneto.it/arpavinforma/pubblicazioni/atlante-climatico-del-veneto-precipitazioni-basi-informative-per-l2019analisi-delle-correlazioni-tra-cambiamenti-climatici-e-dinamiche-forestali-nel-veneto (accessed on 20 December 2024).
43. Cavaleri, L.; Bajo, M.; Barbariol, F.; Bastianini, M.; Benetazzo, A.; Bertotti, L.; Chiggiato, J.; Ferrarin, C.; Trincardi, F.; Umgiesser, G. The 2019 Flooding of Venice and Its Implications for Future Predictions. *Oceanography* **2020**, *33*, 42–49. [CrossRef]
44. Regione del Veneto. Strategia Regionale di Adattamento ai Cambiamenti Climatici: Documento Preliminare. 2024. Available online: https://www.regione.veneto.it/web/ambiente-e-territorio/documento-preliminare (accessed on 20 December 2024).
45. ARPAFVG. Segnali dal clima in FVG. Cambiamenti, impatti, azioni. 2024. Available online: https://www.meteo.fvg.it/clima/clima_fvg/03_cambiamenti_climatici/07_GRUPPO_DI_LAVORO_CLIMA_FVG_e_Segnali_dal_Clima/SegnaliDalClimaFVG2024_HD.pdf (accessed on 20 December 2024).

46. Agenzia Provinciale per la Protezione dell'Ambiente Della Provincia Autonoma di Trento. Verso la Strategia Provinciale di Mitigazione e Adattamento ai Cambiamenti Climatici. 2024. Available online: https://www.appa.provincia.tn.it/Documenti-e-dati/Documenti-tecnici-di-supporto/Verso-la-Strategia-provinciale-di-mitigazione-e-adattamento-ai-cambiamenti-climatici (accessed on 20 December 2024).
47. Provincia Autonoma di Bolzano. Piano Clima Alto Adige 2040. 2023. Available online: https://assets-eu-01.kc-usercontent.com/6d9c060a-0054-014c-abec-f2b3f9a8afeb/feb8c942-7ab6-4f43-bad2-04a2cb3aeeae/Piano%20Clima%20Alto%20Adige%202040.pdf (accessed on 20 December 2024).
48. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021—The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2023. [CrossRef]
49. Crespi, A.; Terzi, S.; Cocuccioni, S.; Zebisch, M.; Berckmans, J.; Füssel, H.-M. Climate-related hazard indices for Europe. In *European Environment Agency, European Topic Centre Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) Technical Paper 2020/1*; European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA): Bologna, Italy, 2020. Available online: https://doi.org/10.25424/cmcc/climate_related_hazard_indices_europe_2020 (accessed on 20 December 2024).
50. Hsieh, H.F.; Shannon, S.E. Three approaches to qualitative content analysis. *Qual. Health Res.* **2005**, *15*, 1277–1288. [CrossRef]
51. Legambiente. Osservatorio Nazionale Città Clima. Available online: https://cittaclima.it/mappa/ (accessed on 26 February 2025).
52. European Union. Copernicus Climate Data Store. Available online: https://cds.climate.copernicus.eu/ (accessed on 30 January 2025).
53. European Environment Agency. EEA Datahub. Available online: https://www.eea.europa.eu/en/datahub?size=n_10_n&filters[0][field]=issued.date&filters[0][type]=any&filters[0][values][0]=All%20time (accessed on 30 January 2025).
54. Istituto superiore per la protezione e la ricerca ambientale, I. ISPRA Database. Available online: https://www.isprambiente.gov.it/it/banche-dati (accessed on 30 January 2025).
55. ARPAV,; ARPAFVG. North-East Climate Platform. Available online: https://clima.arpa.veneto.it/proiezioni-avanzata?climatological_variable=tas&climatological_model=model_ensemble&scenario=rcp85&measure=anomaly&time_window=tw1&aggregation_period=30yr&year_period=winter&data_series=no&archive=forecast (accessed on 30 January 2025).
56. Hochrainer-Stigler, S.; Šakić Trogrlić, R.; Reiter, K.; Ward, P.J.; de Ruiter, M.C.; Duncan, M.J.; Torresan, S.; Ciurean, R.; Mysiak, J.; Stuparu, D.; et al. Toward a framework for systemic multi-hazard and multi-risk assessment and management. *IScience* **2023**, *26*, 106736. [CrossRef] [PubMed]
57. Tilloy, A.; Malamud, B.D.; Winter, H.; Joly-Laugel, A. A review of quantification methodologies for multi-hazard interrelationships. *Earth-Sci. Rev.* **2019**, *196*, 102881. [CrossRef]
58. Olteanu, I.; Crenganiș, L.M.; Diac, M.; Precul, A.M. Sustainable Approach of a Multi-Hazard Risk Assessment Using GIS Customized for Ungheni Areal Situated in the Metropolitan Area of Iasi. *Sustainability* **2024**, *16*, 4485. [CrossRef]
59. Cappucci, S.; Pollino, M.; Farrace, M.G.; Della Morte, L.; Baiocchi, V. Infrastructure Impact Assessment through Multi-Hazard Analysis at Different Scales: The 26 November 2022 Flood Event on the Island of Ischia and Debris Management. *Land* **2024**, *13*, 500. [CrossRef]
60. Poggi, V.; Parolai, S.; Silacheva, N.; Ischuk, A.; Abdrakhmatov, K.; Kobuliev, Z.; Ismailov, V.; Ibragimov, R.; Karaev, J.; Ceresa, P.; et al. Harmonizing seismicity information in Central Asian countries: Earthquake catalogue and active faults. *Nat. Hazards Earth Syst. Sci.* **2024**, *24*, 2597–2613. [CrossRef]
61. Schmidt-Thomé, P. Natural and technological hazards and risks affecting the spatial development of European regions. In *Special Paper of the Geological Survey of Finland (Issue 42)*; Geological Survey of Finland: Espoo, Finland, 2006.
62. Regione Autonoma Friuli Venezia Giulia. Piano Paesaggistico Regionale (PPR-FVG). 2018. Available online: https://www.regione.fvg.it/rafvg/cms/RAFVG/ambiente-territorio/pianificazione-gestione-territorio/FOGLIA21/ (accessed on 20 December 2024).
63. Regione del Veneto. Piano Territoriale Regionale di Coordinamento (PTRC). 2020. Available online: https://www.regione.veneto.it/web/ptrc/ptrc-2020 (accessed on 20 December 2024).
64. Semenzato, P.; Bortolini, L. Urban Heat Island Mitigation and Urban Green Spaces: Testing a Model in the City of Padova (Italy). *Land* **2023**, *12*, 476. [CrossRef]
65. Musco, F. (Ed.) *Counteracting Urban Heat Island Effects in a Global Climate Change Scenario*; Springer International Publishing: Cham, Switzerland, 2016. [CrossRef]
66. Longato, D.; Maragno, D. Mapping the vulnerability to urban heat island combining satellite and ecosystem service data: A case study in Udine (Italy). *Contesti. Città Territ. Progett.* **2023**, *2*, 128–149.
67. Falco, E.; Garda, E.; Zardo, L.; Cortinovis, C. Learning from Two Early Brownfield Redevelopment Projects in Italy: Soil Desealing, Cooling Effects, and Implementation of Nature-Based Solutions Through Traditional Planning Tools. *Land* **2024**, *13*, 1700. [CrossRef]

68. Mariani, S.; Braca, G.; Romano, E.; Lastoria, B.; Bussettini, M. Linee Guida Sugli Indicatori di Siccità e Scarsità Idrica da Utilizzare Nelle Attività Degli Osservatori Permanenti per gli Utilizzi Idrici. 2018. Available online: https://www.isprambiente.gov.it/pre_meteo/idro/Osservatori/Linee%20Guida%20Pubblicazione%20Finale%20L6WP1_con%20copertina_ec.pdf (accessed on 20 December 2024).
69. Trigila, A.; Iadanza, C. Indicatore Sulle Valanghe in Italia. 2016. Available online: https://www.isprambiente.gov.it/files/suolo/rapporto_indicatore_valanghe_ispra_luglio_2016.pdf (accessed on 20 December 2024).
70. European Environment Agency. PM10, European Air Quality Data, (Interpolated Data). 6 June 2024. Available online: https://sdi.eea.europa.eu/catalogue/srv/api/records/abc66a42-b595-4e0f-9772-b862dc454e9f (accessed on 20 December 2024).
71. Lastoria, B.; Bussettini, M.; Mariani, S.; Piva, F.; Braca, G. Rapporto Sulle Condizioni di Pericolosità da Alluvione in Italia e Indicatori di Rischio Associate. Istituto Superiore per la Protezione e la Ricerca Ambientale, Rapporti 353/21. 2021. Available online: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-sulle-condizioni-di-pericolosita-da-alluvione-in-italia-e-indicatori-di-rischio-associati (accessed on 20 December 2024).
72. Trigila, A.; Iadanza, C.; Lastoria, B.; Bussettini, M.; Barbano, A. Dissesto idrogeologico in Italia: Pericolosità e indicatori di rischio. 2021. Available online: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/dissesto-idrogeologico-in-italia-pericolosita-e-indicatori-di-rischio-edizione-2021 (accessed on 20 December 2024).
73. Khoroshev, A. Landscape-Ecological Approach to Spatial Planning as a Tool to Minimize Socio-Ecological Conflicts: Case Study of Agrolandscape in the Taiga Zone of Russia. *Land* **2020**, *9*, 192. [CrossRef]
74. Dunant, A.; Robinson, T.R.; Densmore, A.L.; Rosser, N.J.; Rajbhandari, R.M.; Kincey, M.; Li, S.; Awasthi, P.R.; Van Wyk de Vries, M.; Guragain, R.; et al. Impacts from cascading multi-hazards using hypergraphs: A case study from the 2015 Gorkha earthquake in Nepal. *Nat. Hazards Earth Syst. Sci.* **2025**, *25*, 267–285. [CrossRef]
75. Gayen, A.; Pourghasemi, H.R.; Saha, S.; Keesstra, S.; Bai, S. Gully erosion susceptibility assessment and management of hazard-prone areas in India using different machine learning algorithms. *Sci. Total Environ.* **2019**, *668*, 124–138. [CrossRef]
76. Bordbar, M.; Aghamohammadi, H.; Pourghasemi, H.R.; Azizi, Z. Multi-hazard spatial modeling via ensembles of machine learning and meta-heuristic techniques. *Sci. Rep.* **2022**, *12*, 1451. [CrossRef]
77. Javidan, N.; Kavian, A.; Pourghasemi, H.R.; Conoscenti, C.; Jafarian, Z.; Rodrigo-Comino, J. Evaluation of multi-hazard map produced using MaxEnt machine learning technique. *Sci. Rep.* **2021**, *11*, 6496. [CrossRef]
78. Youssef, A.M.; Mahdi, A.M.; Al-Katheri, M.M.; Pouyan, S.; Pourghasemi, H.R. Multi-hazards (landslides, floods, and gully erosion) modeling and mapping using machine learning algorithms. *J. Afr. Earth Sci.* **2023**, *197*, 104788. [CrossRef]
79. Zhang, T.; Wang, D.; Lu, Y. Machine learning-enabled regional multi-hazards risk assessment considering social vulnerability. *Sci. Rep.* **2023**, *13*, 13405. [CrossRef]
80. Choubin, B.; Jaafari, A.; Mafi-Gholami, D. A spatially explicit multi-hazard framework for assessing flood, landslide, wildfire, and drought susceptibilities. *Adv. Space Res.* **2025**, *75*, 2569–2583. [CrossRef]
81. Nachappa, T.; Ghorbanzadeh, O.; Gholamnia, K.; Blaschke, T. Multi-Hazard Exposure Mapping Using Machine Learning for the State of Salzburg, Austria. *Remote Sens.* **2020**, *12*, 2757. [CrossRef]
82. Yousefi, S.; Pourghasemi, H.R.; Emami, S.N.; Pouyan, S.; Eskandari, S.; Tiefenbacher, J.P. A machine learning framework for multi-hazards modeling and mapping in a mountainous area. *Sci. Rep.* **2020**, *10*, 12144. [CrossRef] [PubMed]
83. Rahmati, O.; Yousefi, S.; Kalantari, Z.; Uuemaa, E.; Teimurian, T.; Keesstra, S.; Pham, T.; Tien Bui, D. Multi-Hazard Exposure Mapping Using Machine Learning Techniques: A Case Study from Iran. *Remote Sens.* **2019**, *11*, 1943. [CrossRef]
84. Surbhi Singh, S.; Jeganathan, C. Using ensemble machine learning algorithm to predict forest fire occurrence probability in Madhya Pradesh and Chhattisgarh, India. *Adv. Space Res.* **2024**, *73*, 2969–2987. [CrossRef]
85. Pourghasemi, H.R.; Kariminejad, N.; Amiri, M.; Edalat, M.; Zarafshar, M.; Blaschke, T.; Cerda, A. Assessing and mapping multi-hazard risk susceptibility using a machine learning technique. *Sci. Rep.* **2020**, *10*, 3203. [CrossRef]
86. Dahim, M.; Alqadhi, S.; Mallick, J. Enhancing landslide management with hyper-tuned machine learning and deep learning models: Predicting susceptibility and analyzing sensitivity and uncertainty. *Front. Ecol. Evol.* **2023**, *11*, 1108924. [CrossRef]