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Multi-hazard risk assessment methodology for European coastal cities

By

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for the degree of

Doctor of Philosophy in Civil and Environmental Engineering

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To my family.

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Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

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Nomenclature

AHHW	Annual Highest High Water
AI	Artificial Intelligence
ALOS	Advanced Land Observing Satellite
C3S CDS	Copernicus Climate Change Service Climate Data Store
CCAP	Climate Change Adaptation Plan
CCLL	Coastal City Living Lab
CMIP	Coupled Model Inter-comparison Project
CoSMoS	Coastal Storm Modelling System
CRediT	Contributor Roles Taxonomy
CSI	Coastal Sensitivity Index
CVI	Coastal Vulnerability Index
DEM	Digital Elevation Model
DIVA	Dynamic Interactive Vulnerability Assessment
DST	Decision Support Tool
EAD	Expected Annual Damage
EAPE	Expected Annual People Exposed
EC	European Commission
ECFAS	European Coastal Flood Awareness System
EDO	European Drought Observatory
EMI	European Multi-hazard Index
ENT	Environment and Management

ELSUS	European Landslide Susceptibility
ESG	Environmental, Social, and Governance
ESL	Extreme Sea Level
EU	European Union
GDP	Gross Domestic Product
GIS	Geographic Information System
GMES	Global Monitoring for Environmental Security
ICZM	Integrated Coastal Zone Management
IGOT-UL	Institute of Geography and Spatial Planning – University of Lisbon
IIGCC	Institutional Investors Group on Climate Change
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LAMMA	Environmental Monitoring and Modelling Laboratory for sustainable development
LAU	Local Administrative Unit
LECZ	Low Elevation Coastal Zone
LiDAR	Light Detection and Ranging
LULC	Land Use and Land Cover
MCL	Markov Cluster
MERIT DEM	Multi-Error-Removed Improved-Terrain Digital Elevation Model
MHA	Multi-Hazard Assessment
MHRA	Multi-Hazard Risk Assessment
ML	Machine Learning
MMU	Minimum Mapping Unit

MSL	Mean Sea Level
MSLR	Mean Sea Level Rise
NGO	Non-Governmental Organization
NUTS	Nomenclature of Territorial Units for Statistics
OSM	OpenStreetMap
PRI	Principles for Responsible Investment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCP	Representative Concentration Pathway
RFCT	Regional Functional Centre of Tuscany
SCORE	Smart Control of the Climate Resilience in European Coastal Cities
SDGs	Sustainable Development Goals
SIF	Sustainable Investment Forum
SPI	Standard Precipitation Index
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathway
TDDB	Turkish Disaster Data Bank
TWL	Total Water Level
UHI	Urban Heat Island
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VHR	Very High Resolution

VOS	Visualization of similarities
WCC-1	First World Climate Conference
WCRP	World Climate Research Program
WoS	Web of Science

Abstract

Multi-hazard risk assessment methodology for European coastal cities

by

Emilio Laíño Rebollido

The focus of this thesis is on the risk assessment of multiple climate-related hazards in European coastal cities, a crucial issue given the intensifying impacts of climate change. European coastal cities are particularly vulnerable to a variety of climate-related hazards, such as sea-level rise, coastal erosion, and extreme weather events, which are becoming more frequent and severe due to global warming. Despite the pressing nature of these risks, there has been a notable lack of comprehensive tools to evaluate and compare the risks faced by different cities. This research addresses that gap by developing a novel index-based methodology for climate risk assessment that is specifically tailored to European coastal cities.

One of the key features of the methodology developed in this thesis is its universality within the context of European coastal cities. Unlike other approaches that may be limited to specific types of hazards or localized contexts, this methodology encompasses a wide range of climate-related hazards, making it applicable to diverse coastal environments across Europe. This broad scope allows for a systematic and homogenized analysis of climate risks, which in turn facilitates direct comparisons between cities. Such comparative analysis is essential for informing policy decisions related to resource distribution and climate risk management. By identifying which cities face the greatest risks and which hazards are most prevalent, decision-makers can prioritize interventions and allocate resources more efficiently. Moreover, this

methodology can guide the development of coastal adaptation solutions by pinpointing areas of vulnerability that require immediate attention.

Another significant contribution of this thesis is the integration of local data through a participatory approach involving the innovative concept of Coastal City Living Lab (CCLL). This concept, developed as part of the EU-funded SCORE project (acronym of Smart control of the climate resilience in European coastal cities), allows for the incorporation of detailed local knowledge into the risk assessment process. The CCLLs engage local stakeholders—such as city planners, environmental scientists, and community members—in the data collection process, ensuring that the risk assessments are grounded in the specific conditions and needs of each city in order to cocreate innovative resilience-building solutions. This participatory approach not only enhances the accuracy of the risk assessments but also strengthens the practical relevance of the findings by ensuring that they are aligned with local priorities and realities.

The methodology developed in this thesis was tested and validated through its application on several European coastal cities. Furthermore, a detailed case study was conducted in Benidorm, Spain, where the methodology was applied to assess the risk of the city to climate-related hazards. The different case studies highlighted both the strengths and limitations of the proposed approach. On the one hand, the methodology proved effective in identifying key elements of risk and providing actionable insights for local policymakers. On the other hand, certain limitations were identified, such as the challenges of obtaining high-resolution data in some cities and the need for further refinement of the weighting of different indicators in the overall risk assessment.

The work presented in this thesis is supported by an extensive review, which includes both a literature review and two scientometric reviews. The literature review provides a comprehensive overview of the impacts of climate change on coastal cities, highlighting the gaps that this research aims to fill. The scientometric reviews, on the other hand, offer a more quantitative analysis of trends and patterns in the academic

literature, providing valuable insights into the evolution of the fields of climate impacts and indices regarding multiple climate-related hazards under climate change and the most influential studies and concepts. These reviews have helped to contextualize the findings of this thesis within the broader academic discourse on climate risk management and coastal adaptation.

In conclusion, this thesis makes a significant contribution to the field of climate risk assessment by developing a multi-hazard risk assessment methodology that is both comprehensive and adaptable to the specific challenges faced by European coastal cities. The ability to compare risks across different cities provides valuable insights for policymakers, while the integration of local data through the CCLLs ensures that the findings are grounded in real-world conditions. The case study in Benidorm demonstrates the practical applicability of the methodology and highlights areas for further refinement. As climate-related hazards continue to intensify, the tools and insights developed in this research will be critical for guiding future efforts in coastal adaptation and resilience planning.

Chapter 1.

Introduction

1.1. Climate change and climate-related hazards

Climate change is an ongoing and accelerating global phenomenon that has been widely studied and acknowledged, yet determining its precise impacts remains a formidable challenge [1–5]. The complexity of climate change stems from the intricate interactions between various natural systems—including the atmosphere, oceans, and biosphere—resulting in unpredictable and often compounding effects. These impacts are felt across ecosystems and human societies, with the most visible manifestations being the increasing frequency and severity of climate-related hazards, particularly in coastal regions [6–8]. Understanding these hazards and their implications is crucial as they threaten millions of lives and critical infrastructure worldwide, especially in densely populated coastal cities [9–12].

Climate-related hazards are defined as naturally occurring events or processes that are directly or indirectly influenced by changes in the Earth's climate [13–20]. These hazards can manifest as sudden-onset events, such as storms and floods, or as slow-onset phenomena, like sea-level rise and droughts [21–25]. Climate-related hazards are particularly disruptive because they can lead to cascading effects—one event can trigger others, creating compound hazards that exacerbate the overall impact on human and natural systems [26,27].

In the context of climate change, coastal hazards such as sea-level rise, coastal flooding, and coastal erosion are among the most significant concerns for coastal cities

[28–30]. These hazards are driven primarily by the thermal expansion of seawater, melting polar ice caps, and increased storm intensity due to warmer ocean temperatures. Coastal flooding occurs when high sea levels, storm surges, or waves inundate coastal land [3,31–37], while coastal erosion is the gradual removal of sediment from shorelines due to wave action, currents, and rising sea levels [12,38–41]. These hazards are particularly concerning for low-lying coastal areas, where populations and critical infrastructure are increasingly at risk.

However, climate-related hazards extend far beyond coastal hazards [42]. Extreme temperatures are one of the most prominent hazards exacerbated by climate change. Rising global temperatures are leading to more frequent and intense heatwaves, which have severe impacts on public health, agriculture, and energy systems and can lead to wildfires when combined with drought conditions [21,43,44]. Heatwaves can result in increased mortality, especially among vulnerable populations such as the elderly and those with pre-existing health conditions [45,46]. Conversely, some regions also experience cold spells—periods of unusually low temperatures that can disrupt ecosystems, damage infrastructure, and affect energy demand.

Droughts are another significant climate-related hazard, characterized by prolonged periods of insufficient rainfall that can lead to water shortages, reduced agricultural productivity, and ecosystem degradation [23,47,48]. Droughts are becoming more frequent and severe in many regions due to shifts in precipitation patterns driven by climate change [49–51]. Heavy precipitation events, on the other hand, are also becoming more common and intense, leading to pluvial flooding (surface water flooding) and river flooding when water bodies exceed their capacity [52–54]. The increase in heavy rainfall events can overwhelm drainage systems, cause landslides, and damage infrastructure, resulting in significant social and economic losses.

Landslides, which are often triggered by heavy precipitation or rapid snowmelt, pose a particular risk in mountainous or hilly regions [55–57]. These events can result in

the sudden displacement of large volumes of earth, rocks, or debris, causing destruction to property, infrastructure, and even loss of life. Climate change is increasing the likelihood of landslides by intensifying rainfall patterns and destabilizing slopes that have been weakened by changing environmental conditions [58].

Strong winds, including those associated with hurricanes, typhoons, and other storms, are another key climate-related hazard [59–63]. As global temperatures rise, the intensity of tropical cyclones is expected to increase, leading to more powerful storms that cause widespread damage to buildings, infrastructure, and ecosystems. The combination of high-velocity winds and heavy rainfall during such events further compounds the risks, leading to flooding, wind damage, and landslides.

Thus, compound hazards are an emerging area of concern, where multiple climate-related hazards occur simultaneously or in quick succession, leading to amplified impacts [4,64,65]. For example, a coastal city might experience a severe storm surge coinciding with heavy rainfall and strong winds, resulting in extensive flooding, infrastructure damage, and erosion. The interaction between different hazards can increase the overall risk and make it more difficult for communities to respond effectively.

In summary, climate-related hazards encompass a wide range of events, from rising sea levels and coastal flooding to extreme temperatures, droughts, heavy precipitation, landslides, strong winds, and wildfires. These hazards are becoming more frequent and severe due to the intensifying effects of climate change, and their impacts are often interconnected, leading to complex challenges for communities and decision-makers. Coastal cities, in particular, face significant risks from these hazards, which underscores the importance of developing robust risk assessment methodologies and adaptation strategies to mitigate the impacts of climate change on urban populations and infrastructure. This thesis aims to contribute to these efforts by focusing on multi-

hazard risk assessments for European coastal cities, which are among the most vulnerable to climate-related hazards.

1.2. Coastal cities in Europe

Coastal cities, which are home to a growing proportion of the world's population, are on the frontline of climate change [4,66–68]. Urbanization along coastlines continues to expand, exacerbating the risks posed by climate-related hazards. The development of coastal areas is progressing rapidly, while climate models predict that extreme events will become both more frequent and more intense as global temperatures rise [69–71]. Among the most concerning hazards for coastal cities are also extreme sea-level (ESL) events, which combine sea-level rise, storm surges, wave action and tidal variations to create significant flooding risks. The population exposed to these ESL events is projected to increase dramatically throughout the 21st century [11].

In European coastal cities, the impact of climate-related hazards is pronounced, with coastal flooding and coastal erosion as primary risks—driven by increasingly intense coastal storms. Coastal storms compound the effects of sea-level rise, storm surges, wave action, and tidal variations, causing widespread destruction and economic damage. For instance, a study by Abadie et al. (2016) identifies Istanbul, Odessa, Izmir, Rotterdam, and St. Petersburg as among the most vulnerable European coastal cities based on Expected Annual Damage (EAD) due to coastal flooding [72]. Without additional investments in coastal protection and adaptation, Europe's current annual EAD of €1.25 billion could increase significantly by 2100, with projections ranging from €93 billion to €961 billion [72]. Similarly, the Expected Annual Number of People Exposed (EAPE) to coastal flooding, estimated at 102,000, could surge to between 1.52 million and 3.65 million [72].

Further projections of ESL events underscore these risks. Along Europe's coastlines, the 100-year ESL could rise by 57 cm to 81 cm by 2100, depending on emissions

scenarios [7]. Regional studies provide similar estimates across Europe's coastal areas, with substantial ESL increases anticipated in the North Sea, followed by the Baltic Sea and the Atlantic coasts of the UK and Ireland, while lighter impacts are projected for southwestern Europe [7,73–78]. Under high-end warming (i.e., the RCP8.5 scenario), the current 100-year ESL could become a yearly event for five million Europeans, dramatically increasing the risk of coastal flooding [7]. The intensification of ESLs further amplifies coastal risks, accelerating coastal erosion and heightening exposure for urban and natural defences.

Furthermore, heatwaves, droughts, and heavy precipitation events pose severe threats [79]. By 2100, such climate-related disasters could impact nearly two-thirds of Europe's population annually—an estimated 351 million people on average [79]. This marks a significant increase from the 5% affected yearly between 1981 and 2010, or around 25 million people [80]. Fatalities from these events could also rise sharply, from an average of 3,000 deaths per year during 1981–2010 to 152,000 by 2100 [79]. This substantial increase, driven largely by more frequent and intense heatwaves affecting southern Europe, underlines the need for mitigation and adaptation strategies to protect lives, infrastructure, and urban resilience [80].

In addition to direct climate impacts, human activities exacerbate coastal vulnerability, with urbanization, land reclamation, and agricultural runoff all contributing to coastal degradation. These anthropogenic factors disrupt sediment flows, elevate nutrient loads, and degrade coastal ecosystems, compounding the effects of climate-driven hazards. While this study focuses on climate-induced risks, recognizing the influence of these additional stressors helps illustrate the complexity of managing risk in coastal urban areas.

Despite strides in climate mitigation, European cities face mounting challenges in meeting Paris Agreement targets, necessitating greater efforts to mitigate these climate-induced risks [81,82]. The persistent gaps in adaptation emphasize the

urgency of proactive and well-coordinated resilience-building, particularly in coastal urban areas where exposure and vulnerabilities are highest.

Although significant research addresses specific climate-related hazards affecting urban areas [83–85], few studies adopt a comprehensive multi-hazard framework that encompasses both coastal and inland hazards. Literature reviews often focus on individual hazards, or case studies on specific urban areas [76,86,87]. However, a holistic approach that integrates inland hazards, such as droughts, heatwaves, landslides, and inland flooding, with coastal risks remains scarce [88]. Addressing this gap requires a multi-hazard framework capable of capturing the full spectrum of risks and supporting coordinated adaptation efforts across diverse urban and regional contexts.

1.3. Risk framework and Multi-Hazard Risk Assessment concept

In this thesis, the concept of risk is built on the widely recognized risk assessment framework developed by the Intergovernmental Panel on Climate Change (IPCC) [89]. This framework defines risk as a function of three interrelated components: hazard, exposure, and vulnerability.

Hazard refers to climate-related physical events or trends, such as extreme weather phenomena (e.g., storms, floods, and heatwaves) or longer-term shifts in climate patterns (e.g., sea-level rise or changing precipitation) [90,91]. These are naturally occurring or climate-change-induced events that have the potential to cause harm to human, environmental, or built systems.

Exposure denotes the presence of populations, ecosystems, or infrastructure in locations that could be negatively impacted by hazards [43,92,93]. This means that

even in areas prone to hazardous events, the risk is contingent on whether significant societal or environmental assets are present.

Vulnerability refers to the sensitivity and adaptive capacity of these exposed systems [94,95]. Vulnerability is influenced by both factors, such as the design and resilience of infrastructure, and socio-economic factors, including the wealth, education, and adaptive capacity of the affected populations.

In this framework, risk can be conceptualized as the overlap between a specific climate-related hazard and the degree of exposure and vulnerability of a particular system. As climate change intensifies, the interconnectedness of these components becomes more critical. Understanding this dynamic is essential for developing appropriate adaptation and mitigation strategies, particularly in coastal areas where the combination of hazards is especially complex.

As climate change impacts become more severe and widespread, there is a growing need for more comprehensive approaches to risk assessment. Traditionally, risk assessments have focused on individual hazards, analysing the potential effects of specific events such as a storm surge or a heatwave. However, this single-hazard approach often falls short of capturing the full spectrum of risks faced by a particular region or city, especially given the complex interactions between multiple hazards. In response, the multi-hazard risk assessment (MHRA) approach has emerged as a critical tool for understanding and mitigating the diverse threats posed by climate-related hazards [27,96–99].

The concept of multi-hazard assessment (MHA) was first introduced in the United Nations' Agenda 21 for sustainable development in 1992 (UNEP, 1992), and it has since become widely accepted. This approach recognizes that regions are often exposed to multiple hazards, which may occur simultaneously, sequentially, or interact with one another. These interactions can lead to compound hazards—when multiple hazards combine to create greater or more unpredictable risks—or cascading

hazards, where one event triggers subsequent hazards [26]. These types of interactions emphasize the necessity of considering not just individual hazards in isolation, but the cumulative and interrelated impacts of multiple hazards.

MHRAs thus involve the simultaneous evaluation of the risk posed by several hazards within a specific region, considering their potential to overlap or influence one another. This approach goes beyond merely assessing the likelihood and impact of each hazard independently; it evaluates how these hazards interact, amplifying their effects on exposed and vulnerable systems. By doing so, MHRA provides a more realistic and holistic understanding of the total risk a region faces, especially in complex environments like coastal cities [3,5].

Despite the growing recognition of the importance of multi-hazard approaches, there remain significant gaps in research, particularly regarding cross-regional methodologies that address the full range of climate-related hazards affecting coastal cities [99,100]. While there are numerous well-established methodologies for individual hazards, there are relatively few approaches that can account for the complexities of multiple, interacting hazards [27,99]. This is especially problematic for coastal cities, where the convergence of land-based and marine hazards creates unique challenges that are not fully addressed by existing models.

Furthermore, the lack of cross-regional comparative studies hinders the ability to benchmark risk levels across different coastal cities and to implement targeted, evidence-based interventions. A MHRA, when applied across regions, could provide valuable insights into which cities are most at risk and which specific hazards contribute the most to their vulnerability. This would allow for more efficient resource allocation and better-informed decision-making for climate adaptation.

In light of the increasing complexity of climate-related hazards, MHRAs have become essential for decision-makers seeking to manage risks in an effective and holistic manner. By accounting for multiple interacting hazards, MHRA offers a

comprehensive view of the risks facing a given area, enabling more informed policy decisions regarding urban planning, infrastructure investment, and emergency response.

In the context of coastal cities, MHRA serves as a critical decision support tool for identifying vulnerabilities and prioritizing interventions. By integrating data on hazards, exposure, and vulnerability, these assessments can provide stakeholders with clear insights into the most pressing risks and the potential consequences of inaction. Moreover, MHRA can serve as a foundation for detailed studies aimed at developing tailored adaptation strategies that address the unique dynamics of each city, ensuring that resources are allocated to the areas of highest need.

1.4. Index-based approaches and decision support tools

The assessment of risks posed by climate change in coastal cities involves a wide array of climate-related hazards. However, the complexity of these risks is further compounded by disparities in the availability and quality of data across different cities and regions [88,101]. These challenges make it difficult to conduct standardized and holistic MHRAs and limit the comparability of existing methodologies. In response, index-based approaches have emerged as a valuable solution for systematically evaluating baseline hazards, exposure, and vulnerability across cities in a standardized and robust manner [102].

Index-based approaches involve the use of aggregated indicators to quantify and compare various aspects of climate-related risks [103–106]. These approaches allow for a structured and consistent evaluation of multiple hazards across different geographical areas, making them particularly effective in addressing the data variability issue in climate risk assessments. By converting complex, multi-dimensional data into simplified indices, these methods offer decision-makers clear and actionable insights into the level of risk faced by different cities or regions.

In the context of MHRA, index-based approaches are often employed to evaluate risk as a function of hazard, exposure, and vulnerability, aligning with the IPCC's risk assessment framework [89]. This standardized structure ensures consistency across assessments, making it easier to draw comparisons and develop cross-regional insights. Various models and frameworks have been developed to operationalize these concepts, offering a range of methodologies to address the unique challenges of climate risk assessment [97,107].

Index-based approaches make it possible to quantify and rank the risks across regions, offering a standardized way to prioritize adaptation efforts. In practice, these indices rely on both climate data (e.g., temperature, precipitation, sea level) and socio-economic data (e.g., population density, economic activity) to paint a comprehensive picture of the risk landscape.

Several studies have successfully applied index-based methodologies to assess climate risks in Europe. One notable example is the work of Lung et al. (2013), who assessed regional-level impacts of multiple hazards, including heat-related events, river flooding, and forest fires [108]. Their framework integrates climate models with socio-economic data to provide a comprehensive analysis of risk distribution across Europe.

Crespi et al. (2020) conducted a comprehensive analysis of climate-related hazard indices across Europe [42]. They selected 32 indices, which draw on a variety of climate datasets, including data from the Copernicus Climate Change Service Climate Data Store (C3S CDS). This work is particularly noteworthy for its methodological rigor, as it systematically integrates climate reanalysis datasets such as E-OBS, ERA5, CMIP5, and CORDEX.

In a more recent example, Hincks et al. (2023) developed a typology of climate risk at the NUTS3 level (a geographic classification system in Europe) using K-means clustering [109]. This approach analysed 49 variables, including socio-economic and climatic data, to classify regions based on their varying climate change risks. The use

of cluster analysis in this study highlights the potential of index-based approaches to uncover patterns in vulnerability and resilience across different scales, from regional to local levels.

Index-based approaches are valuable for identifying preliminary hotspots of risk and serve as decision support tools (DSTs) for climate adaptation and mitigation strategies when complemented by detailed quantitative risk analysis [110]. By distilling complex climate risk data into simple, actionable indices, these approaches help policymakers, urban planners, and other stakeholders make informed decisions about where to allocate the often-limited resources and how to design effective climate adaptation measures.

One of the key advantages of using index-based approaches as DSTs is their ability to facilitate cross-comparisons between different regions or cities. In the context of European coastal cities, where climate risks can vary dramatically depending on geographic and socio-economic factors, index-based methods allow for standardized assessments. This cross-regional comparability enables stakeholders to identify areas of high risk, benchmark resilience levels, and tailor interventions to the specific vulnerabilities of each city or region [111–114].

The MHRA approach, when combined with index-based methodologies, provides an invaluable DST for coastal cities. These cities, which face a variety of interconnected climate-related hazards, require holistic solutions that go beyond the assessment of single risks. Index-based tools enable a more integrated approach, where the full spectrum of hazards, exposures, and vulnerabilities are considered in the formulation of risk management strategies. Additionally, the simplicity and clarity of index-based outputs allow for more efficient communication of risks to non-expert stakeholders, ensuring that climate action can be effectively prioritized and implemented.

1.5. Multi-Hazard Risk Assessment as foundation for resilience building and coastal city living labs

The increasing impacts of climate change on coastal cities call for comprehensive and adaptive strategies to enhance their resilience to various climate-related hazards [115,116]. MHRA methodologies provide a robust foundation for such resilience-building efforts, particularly when combined with participatory approaches that integrate both scientific and local knowledge [117]. By leveraging these methodologies, coastal cities can better understand the complexity of their vulnerabilities, exposures, and risks, and work collaboratively with stakeholders to develop sustainable adaptation strategies.

A critical aspect of MHRA is its ability to integrate diverse data sources, including climate models, socio-economic data, and local knowledge, into a coherent framework. This approach allows for the development of adaptive management strategies that can be updated as new data and insights become available. Continuous refinement of these assessments ensures that the risk evaluations remain relevant in the face of rapidly evolving climate conditions. Moreover, MHRA fosters collaborative decision-making, which is essential for identifying and implementing context-specific resilience measures. As noted by Curt (2021), these methodologies support proactive risk management, enabling cities to prepare for future climate scenarios and reduce their vulnerability to climate-related hazards [118].

MHRA also plays a central role in the development of coastal adaptation solutions, particularly when aligned with emerging frameworks such as Ecosystem-Based Approaches (EBA), Nature-Based Solutions (NBS), and digital innovations such as digital twins and real-time monitoring systems [101,119,120]. These concepts emphasize working with natural systems to mitigate risks, while also enhancing the resilience of human-built environments. For example, integrating EBAs into MHRA could involve the use of wetlands, dunes, or mangroves to reduce coastal flooding and

erosion, providing both ecological and protective benefits. Such strategies not only help manage climate risks but also contribute to broader sustainability goals by preserving biodiversity and ecosystem services.

The concept of CCLL builds on the traditional Living Labs model, which promotes innovation through collaborative, real-world experimentation among stakeholders [121,122]. The CCLL approach is particularly suited to coastal cities facing complex, multi-hazard risks. By engaging a wide range of actors—including scientists, policymakers, local communities, and private sector stakeholders—CCLL fosters innovation in both physical and virtual settings. This model encourages the co-creation of solutions tailored to the specific challenges of each coastal city, such as sea-level rise, coastal erosion, and extreme weather events.

Engaging local stakeholders in the risk assessment process is a key feature of the CCLL model. Local communities are often the first to experience the impacts of climate-related hazards, and their insights are invaluable for understanding the social, cultural, and economic dimensions of risk. By incorporating local knowledge into MHRA methodologies, CCLLs ensure that the resulting adaptation strategies are not only scientifically sound but also culturally appropriate and feasible within the local context (Figure 1.1). This approach enhances the overall resilience of communities by fostering a sense of ownership and responsibility for the adaptation measures, which can improve both their effectiveness and sustainability over time.

In addition to fostering community involvement, the CCLL framework enables the integration of advanced technologies such as real-time monitoring and data analytics into the risk assessment process [123]. The ability to track climate conditions and hazard impacts in real-time allows cities to respond more quickly and effectively to emerging threats. Furthermore, these technologies can facilitate the continuous updating of MHRA models, ensuring that cities are equipped with the most up-to-date information for decision-making.

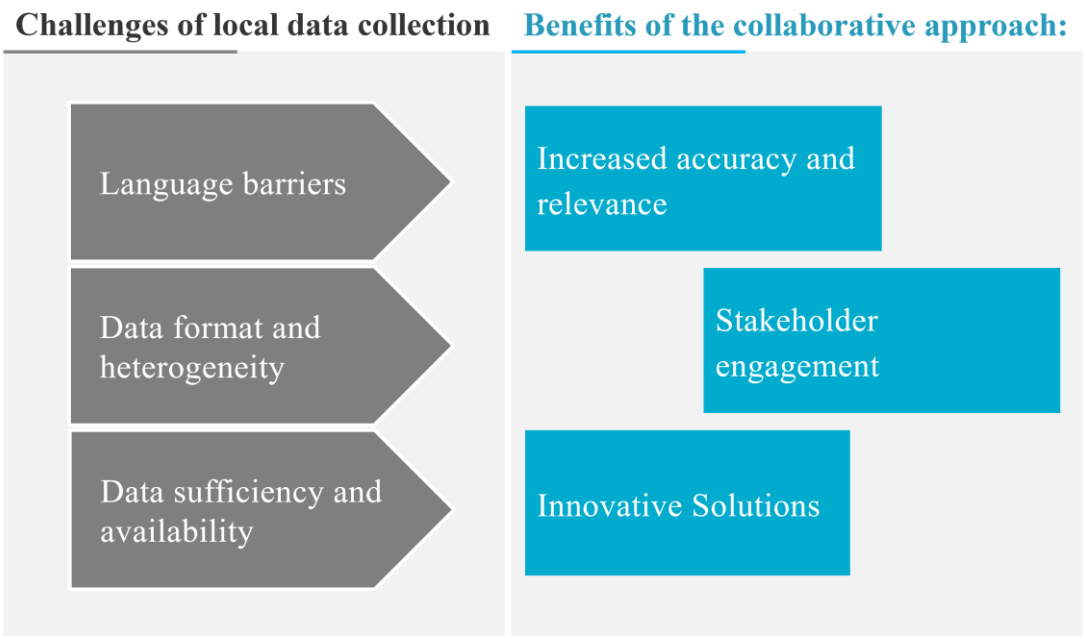


Figure 1.1. Challenges of local data collection and benefits of a collaborative approach involving local expertise.

The combination of MHRA methodologies and the CCLL concept offers a powerful foundation for resilience building in coastal cities. MHRA provides a rigorous, science-based framework for assessing the complex risks posed by multiple climate-related hazards, while the CCLL approach ensures that these assessments are informed by local knowledge and grounded in real-world conditions. Together, these tools provide coastal cities with an initial understanding of their baseline risks and impacts, and pave the way for the development of adaptation strategies that are both effective and socially relevant.

By integrating the MHRA framework with the CCLL model, cities can initiate a more comprehensive approach to climate adaptation. The inclusion of local expertise and context-specific knowledge can serve as a preliminary step for the cocreation of solutions that are not only technically feasible but also aligned with the cultural and social fabric of the community. Moreover, the collaborative nature of CCLLs promotes innovation, enabling stakeholders to experiment with novel solutions and technologies in a controlled, real-world environment. This iterative process of

experimentation and feedback is essential for developing adaptive strategies that can evolve in response to changing climate conditions. As an example, Figure 1.2 presents a conceptual scheme illustrating how the methodology developed in this work contributes to the climate-resilience-building framework of the SCORE project.

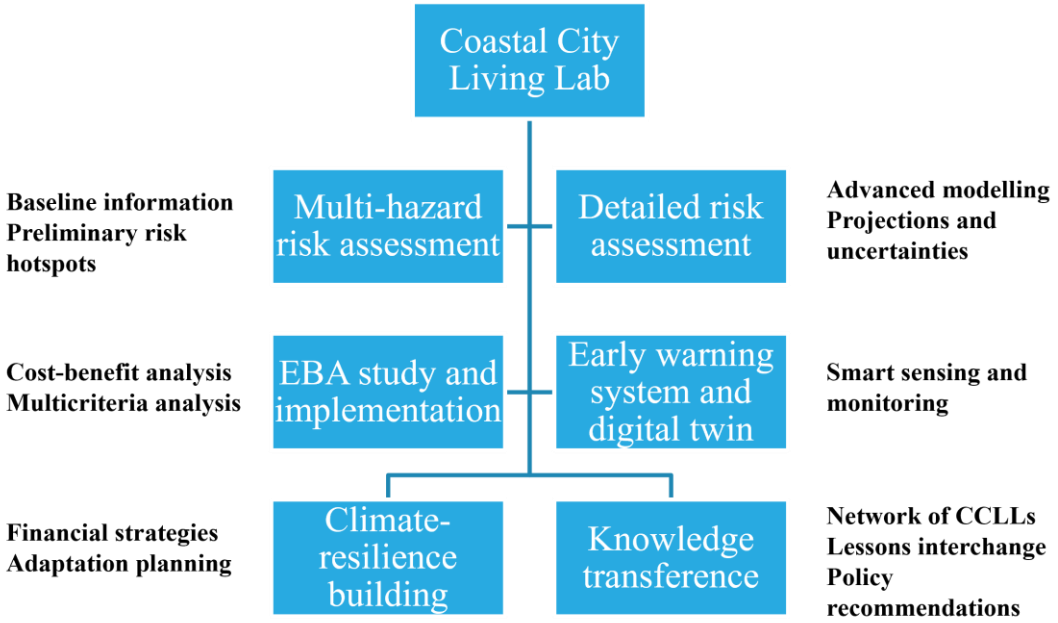


Figure 1.2. Conceptual example of the Multi-Hazard Risk Assessment methodology within a climate-resilience framework based on the Coastal City Living Lab concept.

1.6. Motivation and objectives

Despite the urgency of addressing climate risks, current methodologies for MHRA often fall short of providing a systematic and standardized framework that can be applied uniformly across different cities. European coastal cities are diverse in terms of their geographical characteristics, socio-economic profiles, and climate exposure. As a result, a comprehensive approach that allows for the comparative analysis of risks across multiple cities is currently lacking. This gap hinders the ability of policymakers and urban planners to effectively prioritize and implement climate adaptation measures based on a clear understanding of each city's unique vulnerabilities and exposures.

The motivation behind this work stems from the need to develop a novel MHRA methodology that addresses these limitations. By proposing a framework based on an index-based approach which integrates insights from diverse CCLLs (Figure 1.3), this study aims to provide a tool that enables the assessment of a wide variety of climate-related hazards in a standardized and comparative manner. This tool will serve as a critical resource for European coastal cities, providing insights into baseline risks while supporting the development of tailored coastal adaptation and resilience-building solutions.



Figure 1.3. Coastal City Living Labs supporting the development of the Multi-Hazard Risk Assessment methodology.

Thus, the objectives of this thesis are as follows:

I. Develop a MHRA methodology that integrates an index-based approach to evaluate risk as a function of hazard, exposure, and vulnerability across European coastal cities. This methodology will systematically leverage a comprehensive set of indicators to assess the complex interplay of climate-related hazards and their impacts on these urban environments.

II. Incorporate the CCLL framework to engage local stakeholders, ensuring that the development of the risk assessment process includes both scientific knowledge and local expertise. This participatory approach will enhance the practical relevance of the assessment and ensure that the potential adaptation strategies developed are socially and culturally appropriate for the communities they are intended to protect.

III. Enable cross-regional comparative analysis by applying the standardized MHRA framework to multiple European coastal cities. This will allow for the benchmarking of risk levels across cities, facilitating more efficient resource allocation and targeted interventions based on the severity of the risks each city faces.

IV. Provide a foundation for a decision-support tool designed for policymakers and urban planners, aimed at helping them prioritize coastal management actions. The tool will be designed to inform strategies for climate adaptation, infrastructure development, and resilience-building efforts, based on a clear understanding of baseline risks and vulnerabilities.

V. Pave the way for further development of coastal adaptation solutions by offering a comprehensive risk assessment that identifies critical areas of climate risk. The insights from this work will contribute to long-term resilience planning, helping cities better prepare for future climate scenarios and mitigate the impacts of climate change.

Ultimately, this study seeks to bridge the gap between existing climate risk assessment practices and the growing need for more integrative, systematic, and comparative methodologies (Figure 1.4). By focusing on European coastal cities, the proposed MHRA will enable decision-makers to take a more proactive and collaborative approach to managing climate risks, fostering resilience in the face of an increasingly uncertain and challenging climate future.



Figure 1.4. Principles behind the development of Multi-Hazard Risk Assessment methodology.

1.7. Thesis outline

This thesis is organized into nine chapters, each building on the previous to construct a comprehensive framework for assessing climate-related hazards in European coastal cities (Figure 1.5). Chapters 2 to 8 are structured to reflect a logical and progressive research trajectory. The literature reviews presented in Chapters 2, 3, and 4 provide the conceptual and methodological foundations of the work. These chapters identify critical knowledge gaps in existing climate risk assessments—particularly the lack of standardized, multi-hazard approaches tailored to the specific challenges of European coastal cities. These gaps directly informed the research questions and the subsequent development of the methodological framework. The initial stages of this development, described in Chapters 5 and 6, draw on collaborative inputs from ten European cities participating in the SCORE project, which serve as a reference for defining relevant hazards and indicators. As the methodology matures, its scope is expanded to include additional, diverse case studies across Europe in Chapters 7 and 8, enabling a more robust evaluation of the framework's adaptability and transferability.

Chapter 1	Introduction
Chapter 2	Global trends in climate-related hazards affecting coastal cities
Chapter 3	Climate-related hazards and impacts on European coastal cities
Chapter 4	State-of-the-Art in indices for multi-hazard climate risk assessment
Chapter 5	Identifying key climate-related hazards through Coastal City Living Labs
Chapter 6	Developing standardized indicators for comparative multi-hazard assessments
Chapter 7	The novel methodology for multi-hazard risk assessment
Chapter 8	Case study application of the multi-hazard risk assessment methodology
Chapter 9	Discussion, conclusions, and future research directions

Figure 1.5. Thesis structure.

Chapter 1, the introduction, establishes the background, motivation, and objectives of the study, as well as the need for a standardized MHRA methodology tailored specifically to European coastal cities. This chapter sets the foundation for the thesis, highlighting the urgency of addressing climate-related hazards in these highly vulnerable urban areas.

Chapters 2, 3, and 4 present an extensive literature review to contextualize the study within global and European perspectives. Chapter 2 opens with a scientometric review of global research on climate-related hazards affecting coastal cities, identifying worldwide trends and insights into the intensifying impacts of climate change on these regions. Chapter 3 narrows the focus to European coastal cities, conducting a systematic review to explore the unique climate impacts in this region. This chapter provides both a regional overview and a closer examination of ten European coastal cities, illustrating how climate-related hazards manifest in varied contexts across the continent. Chapter 4 then shifts to methodological considerations, providing a scientometric review of the indices used in multi-hazard climate risk assessments. This analysis reveals strengths and gaps in existing approaches, laying the groundwork for the new index-based methodology proposed in this thesis.

The thesis's methodological framework is developed progressively in Chapters 5 through 8, with each chapter building upon the previous. Chapter 5 identifies and characterizes key climate-related hazards through collaborative insights drawn from ten European CCLLs. This high-level hazard characterization offers an initial foundation for developing standardized indicators. Chapter 6 develops these hazard indicators in response to challenges identified in Chapter 5, presenting a systematic, homogeneous approach to assessing the hazard component of risk. Chapter 7 then completes the risk assessment framework by incorporating indicators for exposure and vulnerability, creating a comprehensive MHRA model. This framework is tested across six diverse European coastal cities, allowing for comparative analysis and benchmarking of climate risks across different urban settings. Chapter 8 focuses on

applying the full methodology within a single city, providing an in-depth evaluation of its reliability and adaptability. Here, each indicator is examined in detail, with risk results compared to other cities and existing studies to validate the framework's robustness.

Chapter 9 synthesizes the findings, discussing the strengths, limitations, and overall implications of the methodology. The chapter concludes with suggestions for future research and potential refinements to the MHRA approach, supporting the development of resilient and adaptive coastal city strategies. This progression from global perspectives to a focused case study builds a clear pathway to achieving the thesis objectives, advancing a robust, standardized framework for assessing multi-hazard climate risks in European coastal cities.

1.8. Publications

Seven publications were produced as a direct result of the research conducted in this thesis. The research of the following journal papers was included in this thesis:

Laino, E., and Iglesias, G. Scientometric review of climate-change extreme impacts on coastal cities. Ocean & Coastal Management, 2023. 242: p.106709.

Laino, E., and Iglesias, G. Extreme climate change hazards and impacts on European coastal cities: A review. Renewable and Sustainable Energy Reviews, 2023. 184: p.113587.

Laino, E., Paranunzio, R., and Iglesias, G. Scientometric review on multiple climate-related hazards indices. Science of The Total Environment, 2024. 945: p.174004.

Laino, E., and Iglesias, G. High-level characterisation and mapping of key climate-change hazards in European coastal cities. Natural Hazards, 2024. 120(4): p.3623-3659.

Laino, E., and Iglesias, G. Multi-hazard assessment of climate-related hazards for European coastal cities. Journal of Environmental Management, 2024. 357: p.120787.

Laino, E. and Iglesias, G. Beyond coastal hazards: A comprehensive methodology for the assessment of climate-related hazards in European coastal cities. Ocean & Coastal Management, 2024. 257: p.107343.

Laino, E., Toledo, I., Aragonés, L. and Iglesias, G. A novel multi-hazard risk assessment framework for coastal cities under climate change. Science of The Total Environment, 2024. 954: p.176638.

For each article, the role of the first author (i.e., the thesis author) is specified according to the CRediT (Contributor Roles Taxonomy) [124] at the end of the corresponding chapter.

Chapter 2.

Global trends in climate-related hazards affecting coastal cities

This chapter corresponds to: Laino, E., and Iglesias, G. Scientometric review of climate-change extreme impacts on coastal cities. Ocean & Coastal Management, 2023. 242: p.106709.

ABSTRACT

The generalised sea level and temperature rise, along with the increasing frequency and intensity of storms and temperature extremes, trigger a variety of climate-change-related impacts on coastal communities, such as coastal flooding and erosion, pluvial and river flooding, heat waves, cold spells, droughts, and landslides. These events can rapidly cascade into additional challenges and have a profound impact on the coastal zone. Many studies have focused on the causes and consequences of climate change for coastal cities in the past decades. As a result, the number of forecasts, risk assessments, literature reviews, and methodologies has increased. This comprehensive review comprises the key findings of a systematic analysis of the scientific literature on extreme impacts of climate change on coastal cities. After a bibliometric analysis, which yields 2321 papers in 470 journals from 1976 to 2021, a scientometric analysis is carried out. There is wide geographical diversity, with publications from 97 countries. In terms of numbers and nationalities, the USA was followed by China, UK, Australia, and Indonesia. The scarcity of papers from developing countries is apparent. “Storm” and “risk assessment” are the top keywords regarding frequency of occurrence and relationships with other keywords. The main research areas for this

topic are risk assessment, climate-change-related hazards and their drivers, modelling tools, disaster control and prevention measures, climate change policies and urban planning. Finally, research gaps are identified, and future research directions proposed, e.g., emerging integrated coastal zone management tools and the impacts on climate change on developing countries.

2.1. Introduction

The development of coastal cities continues to grow around the world [69], whereas the frequency and severity of extreme events are increasing as a result of climate change [70,71]. As the population exposed to mean and ESL events is expected to grow significantly throughout the 21st century [11], there is a continuous increase of studies focused on climate change and its consequences to coastal populations [9–12].

Research on climate change impacts at global scale dates back approximately to 1970s [125]. Since its roots, the literature on this topic has grown exponentially and is quite well established nowadays. The growth in Environmental, Social, and Governance (ESG) investment, and in particular climate change, have caused more funds to be channelled to the scientific research in recent years and therefore may have contributed to the acceleration in the scientific production. Today, institutional investors participate in a wide-ranging number of initiatives and organizations to address climate-related risks in their portfolios, such as Climate Action 100+, the Montreal Carbon Pledge, the Ceres Investor Network on Climate Risk, UN Principles for Responsible Investment (PRI), Global Sustainable Investment Forums (SIFs), UNEP FI, Institutional Investors Group on Climate Change (IIGCC), and many others. For instance, the G20 Financial Stability Board's Task Force on Climate-related Financial Disclosures released recommendations in June 2017, which highlighted the importance of using scenario analysis to assess climate change-related impacts within the financial sector (“Task Force on Climate-related Financial Disclosures”). Also, the

European Commission has recently (March 2018) published a series of measures to enhance the ESG transparency of benchmark methodologies and an initiative to put forward standards for the methodology of low-carbon benchmarks in the Union, in alignment with its action plan *Financing Sustainable Growth*.

Nevertheless, ESG investment by corporations is not the only reason behind the boom of climate-change-related publications. A large set of milestones regarding the fight against climate change may have contributed to the social conscience: from the creation of the IPCC in 1988, bringing together thousands of scientists to assess scientific evidence on climate change and its impacts, and the signature of the United Nations Framework Convention on Climate Change (UNFCCC) by countries around the world in 1992 to the ratification of the European Green Deal in 2020 and the publication of the 6th Assessment Report on Climate Change between 2021 and 2022.

There has not been found a publication analysing the former sources together. In this context, the purpose of this article is to develop a bibliometric and scientometric analysis of the literature regarding extreme climate change impacts on coastal cities, with a particular focus on sea level rise, coastal flooding and coastal erosion, in order to (i) review the spatial and temporal evolution of research, (ii) identify the major themes of current research, (iii) summarize and compare research through meta-analysis and qualitative review, and (iv) suggest future research directions. It is expected that the scientific literature on climate change and coastal cities had grown rapidly in recent decades, reflecting the increasing recognition of the risks and challenges posed by climate change to urban coastal areas. A scientometric analysis of this literature can reveal the patterns, trends, and gaps in research on this topic, providing insights into the knowledge structure and evolution of the field and facilitating evidence-based policy and decision-making.

The increase in the frequency and intensity of storms, in addition to the incessant sea level rise, are the main drivers behind the increase in the number and severity of ESL,

coastal flooding and coastal erosion episodes [91,127–129]. Information on past events and studies is of interest in assessing the evolution of the problem. In this regard, literature and bibliographic reviews, risk assessments (including hazard, vulnerability and exposure assessments [130]), climate change reports, and climate projections are valuable information sources.

In general, social, economic, and environmental losses due to the destruction of land, damage to urban assets, seawater intrusion, harmful biological blooms, and pollution are some of the main impacts facing coastal cities and communities. These impacts may stem from either global warming (climate change), human activities, or a combination of both (Figure 2.1). However, in this study we will exclude those impacts related exclusively to anthropogenic action.

On the one hand, the extreme impacts enhanced by climate change include heatwaves, cold spells, droughts, heavy precipitation, pluvial floods, river floods, coastal flooding and coastal erosion in general terms [131]. Moreover, more than one of the extreme events above may occur simultaneously, leading to compound events. Certain impacts are of particular concern to coastal communities, such as coastal flooding, coastal erosion, saltwater intrusion and any others that may affect coastal ecosystems [2,28,132,133]. In this context, coastal flooding is defined as a temporary inundation of a terrestrial area that is not normally submerged and is caused by the combination of Relative Sea Level Rise (RSLR), tides, storm surge and wave setup at the shoreline [3,31–37]. Coastal erosion may be defined as the net removal of material from one coastal location to another [1,134]. It is driven by many natural factors including storm surge, changes in wave energy, sediment supply and sea level rise [12,38–41]. Coastal erosion is generally accompanied by shoreline retreat, which may occur as a gradual process (e.g., due to sea level rise) or as an episodic event due to ESLs or coastal flooding [36,135].

On the other hand, as a consequence of socioeconomic development, certain human-related drivers may produce a number of impacts on coastal systems related to sediment delivery, nutrient loads, and hypoxia [136]. Human activities in drainage basins and coastal plains impact the coastal zone by changing the delivery of sediment to the coast [137,138]. Shoreline changes as a result of urbanisation, construction of ports, sediment trapping behind dams, water diversion for irrigation, sand and gravel mining in river channels, and soil erosion due to land use changes all affect sediment delivery. Besides, riverine discharge of nutrients (nitrogen, phosphorus) onto coastal areas as a result of fertilizer use in agriculture and fossil fuel emissions may impact coastal ecosystems [139]. Indeed, excessive concentrations of nutrients in coastal waters, which cause eutrophication and the subsequent decomposition of organic matter, are the primary cause of decreased oxygen concentration (hypoxia), thereby posing a serious threat to marine life [140,141]. How the anthropogenic action affects coastal systems is a complex field, and its analysis is out of the scope of this work.

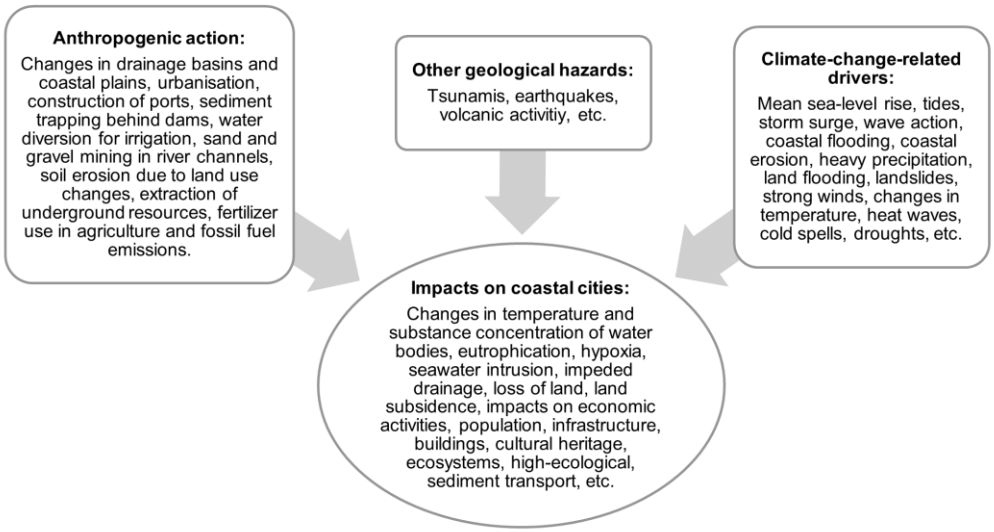


Figure 2.1. Summary scheme of the impacts on coastal cities and their drivers.

The sub-domain of this field of research focusing on extreme impacts exacerbated by climate change is developing fast, and the analysis in this work will illustrate its momentum. In Data collection, processing and analysis method, we discuss the

methodology used to obtain the relevant bibliometric data. In the Results section the meta-analysis of this literature will show that, within the last two decades, the number of scientific studies on the topic has grown exponentially, with the hot topics continually evolving and the geographical distribution of publications retaining the aforementioned diversity. The Discussion section elaborates on these findings and identifies certain topics which are currently underrepresented and may warrant further attention by the research community.

2.2. Materials and methods

Bibliographic details of the scientific literature on climate change extreme impacts on coastal cities in general and extreme sea levels, coastal flooding and coastal erosion in particular were identified and retrieved from Scopus, one of the main databases of academic publication records [142].

Scopus encompasses a broad range of scientific literature, including journals, conference papers, books, and patents. It covers multiple subject areas, making it a valuable resource for multidisciplinary research. Complementarily, Scopus allows users to track citations, analyse citation patterns, and measure the impact of scholarly works through metrics such as the h-index and citation counts. However, it may not include all journals and publications worldwide, and some niche or regional publications may be underrepresented or absent from the database. Citation data may not capture all forms of scholarly communication, such as preprints, non-peer-reviewed publications, or works outside the Scopus database.

Advanced search capabilities, allowing users to conduct complex queries and refine search results based on various criteria are offered in Scopus. It provides access to abstracts, full-text articles, and bibliographic details. However, the search algorithms and indexing process may occasionally result in false positives or missed relevant articles, necessitating careful selection and interpretation of search results. Moreover,

while Scopus indexes open access journals and publications, not all content in the database is freely accessible. Some articles may be behind paywalls or require individual subscriptions, making it challenging for users without institutional access or subscriptions to retrieve full-text versions of certain publications.

While Scopus provides a wealth of bibliographic information, it may lack certain types of data that researchers might require (e.g., detailed experimental data, raw datasets, or supplementary materials associated with publications may not be readily available through Scopus). Although Scopus includes publications from various languages, its coverage is biased toward English-language literature. This language bias may result in the underrepresentation of research published in other languages, limiting access to non-English sources. In addition, as with any bibliographic database, Scopus may be subject to inherent biases in publication patterns, citation practices, and author demographics. These biases can impact the representation of research from certain regions, disciplines, or research communities.

To obtain the reference database for the previous topics, the following combination of search terms was used in a title-abstract-keyword search: *TITLE-ABS-KEY(climate AND change AND extreme AND impact OR event AND coastal OR coast AND city OR town) OR TITLE-ABS-KEY(extreme AND sea OR water AND level AND city OR town) OR TITLE-ABS-KEY(coastal OR coast AND flooding OR flood AND city OR town) OR TITLE-ABS-KEY(coastal OR coast AND erosion AND city OR town)*. The search for establishing the dataset used in this article was last updated in December 2021, considering only texts in English. A total of 3811 results were initially obtained. After screening out the scientific publications which were not relevant to the study – unrelated topics, publications with blank bibliographic fields, and studies regarding human-related drivers exclusively, as mentioned in the Introduction – the final dataset was reduced to 2321 results. The bibliographic details of the reference database, including the list of authors, title, year of publication, source title, volume, issue, page numbers, author affiliations, abstracts, author keywords, index keywords, list of

references, document type and some other details, were exported and analysed using scientometric methods.

For the described dataset, scientometric methods are applied in Results to obtain high-level insights into the development of these research domains. Apart from elementary statistics and standard visualization graphs, we apply the VOSviewer software [143]. This open-access tool implements the visualization of similarities approach (VOS) [144] and is widely used to map clustered networks of authors, journals, collaborating countries, and co-citations. The VOS clustering methodology employed involves a two-step process: the similarity calculation and the clustering. VOSViewer calculates similarities between pairs of documents using either co-citation or co-occurrence data. Co-citation similarity measures the degree of overlap in the articles cited by two documents, indicating their relatedness. Co-occurrence similarity, on the other hand, quantifies the extent to which two documents share common terms or keywords, reflecting their thematic similarity. These similarity measures serve as the basis for subsequent clustering. Once the similarity matrix is generated, VOSViewer applies clustering algorithms to group similar documents together. The software employs a variant of the MCL (Markov Cluster) algorithm, which is an unsupervised clustering method based on graph theory. The MCL algorithm simulates stochastic flow in a graph, identifying clusters of highly interconnected nodes or documents. The resulting clusters represent groups of documents with significant similarities in terms of citation patterns or thematic content. Finally, three visualizations referred to as the *network* visualization, the *overlay* visualization, and the *density* visualization can be constructed from the results.

The outputs include (i) rankings on the most cited and prolific publishers, the most cited articles, and the most important journals; (ii) visualization graphs illustrating the distribution of scientific publications over the years, and the geographical distribution of both the citations and articles produced using the ArcGIS Pro software; and (iii) the results from the application of the VOSviewer software on the research topic showing

the authors network, the countries heat-map network, and heat-maps networks of frequently-occurring terms in the dataset.

Moreover, the relationship between the main milestones on the fight against climate change (Table 2.1) and the evolution of the number of publications regarding climate change extreme impacts on coastal cities is analysed in Discussion.

Table 2.1. Milestones to climate change fight which may be contributed to the social conscience on the matter.

Year	**Milestone**
1979	First World Climate Conference (WCC-1), as “a world conference of experts on climate and mankind”.
1980	Establishment of the World Climate Research Program (WCRP), to help to coordinate global climate research.
1988	Intergovernmental Panel on Climate Change (IPCC) foundation, bringing together thousands of scientists to assess scientific evidence on climate change and its impacts.
1990	IPCC First Assessment Report.
1992	Establishment of the United Nations Framework Convention on Climate Change (UNFCCC), as an international environmental treaty to combat "dangerous human interference with the climate system".
1995	WCRP Coupled Model Intercomparison Project, a collaborative framework designed to improve knowledge of climate change. IPCC Second Assessment Report.
1997	The UNFCCC adopts the Kyoto Protocol, the world’s first greenhouse gas emissions treaty.
1998	Launch of the Global Monitoring for Environmental Security (GMES), the EU's Earth monitoring initiative.
2001	IPCC Third Assessment Report.
2005	C40 Cities Climate Leadership Group foundation, a global network of cities fighting climate change. The EU launches its Emissions Trading System.
2007	IPCC Fourth Assessment Report. The EU adopts its 2020 climate and energy package, with three key targets: reduce EU greenhouse gas emissions by 20 % compared to 1990; increase the share of renewables to 20 % of EU energy use; and improve energy efficiency by 20 %.

2009	UN climate change conference in Copenhagen ends without an overall agreement on binding emissions cuts.
2014	IPCC Fifth Assessment Report. Establishment of the Copernicus programme (previously known as GMES)
2015	The Paris Agreement is agreed and entering into force on 4th November 2016. Launch of SDGs.
2017	China launches its carbon emission trading market.
2018	The European Commission (EC) launches a series of measures to enhance the ESG. Countries agree on the detailed rules and guidelines to make the Paris Agreement work in practice across the world.
2020	European Green Deal is approved on the goal to make the EU climate-neutral by 2050.
2021/2022	IPCC Sixth Assessment Report.

2.3. Results

The yearly distribution of publications from 1976 to 2021 is illustrated in Figure 2.2. The first publication, “Effects of Hurricane Eloise on beach and coastal structures, Florida Panhandle”, was published by R.A. Morton in the United States in 1976 [145]. Until 1989, when a relative peak of 13 publications was reached, the scientific production regarding extreme climate change impacts on coastal cities remains low. Thereafter, and between 1989 and 1997, the number of publications is not higher than 15 (1991) and significant trends are not observed. However, the graphic starts to show a general uptrend practically at the end of the century. In general, the analysis indicates an increasing research trend in recent years. In fact, the cumulative number of publications from 1976 to 2016 (1024) is less than the number of works published within the last five years (1297). Exceptionally, the number of publications decreased substantially in 2016 compared to 2015. The surge of studies in the last five years (2017-2021) appears to be the most pronounced of all by far.

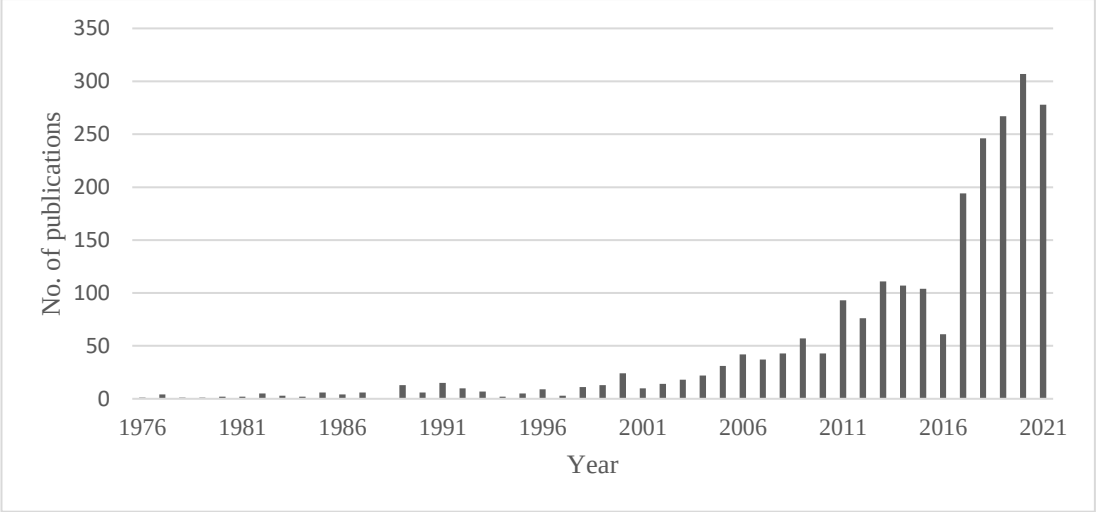


Figure 2.2. Evolution of publications on climate-change extreme impacts in coastal cities between 1976-2021.

Despite the boom registered during the last lustrum, most of the articles accumulating the highest numbers of citations were published before 2015. In Table 2.2, the publications accumulating more than 200 total citations in the dataset are sorted. Information on the authors, title, year of publication, source title, number of citations, and document type are also provided. They are 13 in total, of which 10 were published between 2008 and 2014. In the article "Future flood losses in major coastal cities [146]", published in the journal *Nature Climate Change* in 2013, S. Hallegatte, C. Green, R. Nicholls, et J. Corfee-Morlot provide a quantification of present and future flood losses in the 136 largest coastal cities, accumulating up to 1034 citations at the moment of writing these results and ranking the highest in the dataset. The following articles in the list have also a great number of citations – ranging between 459 and 204 –, although substantially lower than the top. Most of the publications included in the table are related to the increasing flood risk in the coastal cities.

An analysis of the sources may provide guidance to identify reputable scholarly journals for publication. The 2231 documents included in the analysis dataset were published in 1271 scientific sources (470 journals), indicating a wide dissemination. The top 20 journals by citations in the field of climate change extreme impacts on

coastal cities are presented in Table 2.3. The top five consists of the journals *Natural Hazards*, *Water (Switzerland)*, *Journal of Coastal Research*, *Ocean and Coastal Management* and *Sustainability (Switzerland)*, with 66, 43, 41, 35 and 28 publications respectively, accounting for the 17 % of the published work, approximately. The *h*-index according to Google Scholar and the Impact Factors on Web of Science (WoS) and Scopus are also included in the table. The data have been retrieved from the SCI Journal database and the values were last measured in 2020 (SCI Journal). The five journals with the highest *h*-indices are *Science of the Total Environment* (244), *Journal of Hydrology* (226), *Water Resources Research* (217), *Climatic Change* (188), and *Journal of Environmental Management* (179). The previous journals are also the top five regarding the Scopus and WoS Impact Factors, although the order is slightly different: *Science of the Total Environment* (7.937; 6.551), *Journal of Environmental Management* (7.058; 5.647), *Journal of Hydrology* (6.002; 4.500), *Water Resources Research* (5.549; 4.309), and *Climatic Change* (5.248; 4.134), with the Scopus and WoS Impact Factors indicated respectively in the brackets. However, it has been observed that some of the most impactful articles had been published in other relevant journals, e.g., *Nature*, *Nature Communications*, *Nature Climate Change* and *Science*.

Table 2.2. Articles accumulating more than 200 citations in Scopus (December 2021).

Authors	**Title**	**Year**	**Source title**	**Citation**
Hallegatte, S.; Green, C.; et al.	Future flood losses in major coastal cities	2013	*Nature Climate Change*	1,034
Sallenger, A; Doran, K.; and Howd, P.	Hotspot of accelerated sea-level rise on the Atlantic coast of North America	2012	*Nature Climate Change*	459
Hanson, S.; Nicholls, R.; et al.	A global ranking of port cities with high exposure to climate extremes	2011	*Climatic Change*	408
Reid, C; O'Neill, M; et al.	Mapping community determinants of heat vulnerability	2009	*Environmental Health Perspectives*	359

Douglas, I.; Alam K.; et al.	Unjust waters: Climate change, flooding and the urban poor in Africa	2008	*Environment and Urbanization*	359
Kunkel, K.E.; Pielke Jr., R.A.; and Changnon, S.A.	Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review	1999	*Bulletin of the American Meteorological Society*	355
E. Balica. et al.	A flood vulnerability index for coastal cities and its use in assessing climate change impacts	2012	*Natural Hazards*	326
Balica, S.F.; Wright, N.G.; and van der Meulen, F.	Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction	2013	*Remote Sensing of Environment*	286
Vitousek, S.; Barnard, P.L.; et al.	Doubling of coastal flooding frequency within decades due to sea-level rise	2017	*Scientific Reports*	268
Clark, G.E.; Moser, S.C.; et al.	Assessing the vulnerability of coastal communities to extreme storms: The case of reverse, MA., USA	1998	*Mitigation and Adaptation Strategies for Global Change*	260
Aerts, J.C.J. H.; Botzen, W.J.W.; et al.	Evaluating flood resilience strategies for coastal megacities	2014	*Science*	258
Gornitz, V.	Global coastal hazards from future sea-level rise	1991	*Palaeogeography, Palaeoclimatology, Palaeoecology*	215
Revi, A.	Climate change risk: An adaptation and mitigation agenda for Indian cities	2008	*Environment and Urbanization*	204

Table 2.3. Twenty journals with the highest number of publications of the dataset, including the scholarly metrics of h-index (from Google Scholar) and Impact Factor (from Web of Science and Scopus) retrieved from the SCI Journal database (https://www.scijournal.org/). Note that some values of the Impact Factor were not available for the Web of Science browser.

Journal	**Number of publications**	***h*-index (Google Scholar)**	**Impact Factor (WoS)**	**Impact Factor (Scopus)**
Natural Hazards	66	105	2.427	3.494
Water (Switzerland)	43	55	*Not available*	3.287
Journal of Coastal Research	41	90	0.793	0.885
Ocean and Coastal Management	35	84	2.482	3.581
Sustainability (Switzerland)	28	85	2.576	3.659
International Journal of Disaster Risk Reduction	19	45	2.896	5.145
Science of the Total Environment	17	244	6.551	7.937
Journal of Hydrology	15	226	4.500	6.002
Coastal Engineering	14	110	4.119	5.078
Journal of Coastal Conservation	14	39	1.374	1.823
Natural Hazards and Earth System Sciences	14	99	3.102	4.202
Arabian Journal of Geosciences	13	48	1.327	1.958
Environmental Earth Sciences	13	118	2.180	2.851
Journal of Flood Risk Management	13	36	3.066	3.641
Climatic Change	11	188	4.134	5.248
WIT Transactions on Ecology and the Environment	11	24	*Not available*	0.43
Environmental Monitoring and Assessment	10	109	*Not available*	2.805
Journal of Environmental Management	9	179	5.647	7.058

Water Resources Management	9	100	2.924	3.825
Water Resources Research	9	217	4.309	5.549

Altogether, the network of countries associated with publications on climate-change extreme impacts on coastal cities from VOSviewer (showing countries with a minimum of five publications) and the standard graphs illustrating the geographical distribution of the number of citations and publications show that the countries where the research is more productive include the United Stated of America, United Kingdom, China, France, Netherlands, Australia, Italy, India and Indonesia. Figure 2.3 illustrates the most active countries in the research domain and their cooperation, including 44 countries (amongst 135 identified in the dataset) with at least 10 publications and 50 citations, and excluding countries that did not have a cooperation relation. The node sizes, colours, and connecting lines in the cooperation network reflect the number of publications, collaboration clusters, and strength of collaborations, respectively. Figures 2.4 and 2.5 show the complete geographical distribution of the number of publications and citations by country, respectively. The United States of America dominates the scene with 631 works published and 11362 citations, whereas the second and third place are occupied by the United Kingdom and China, with 5030 and 2551 citations, respectively.

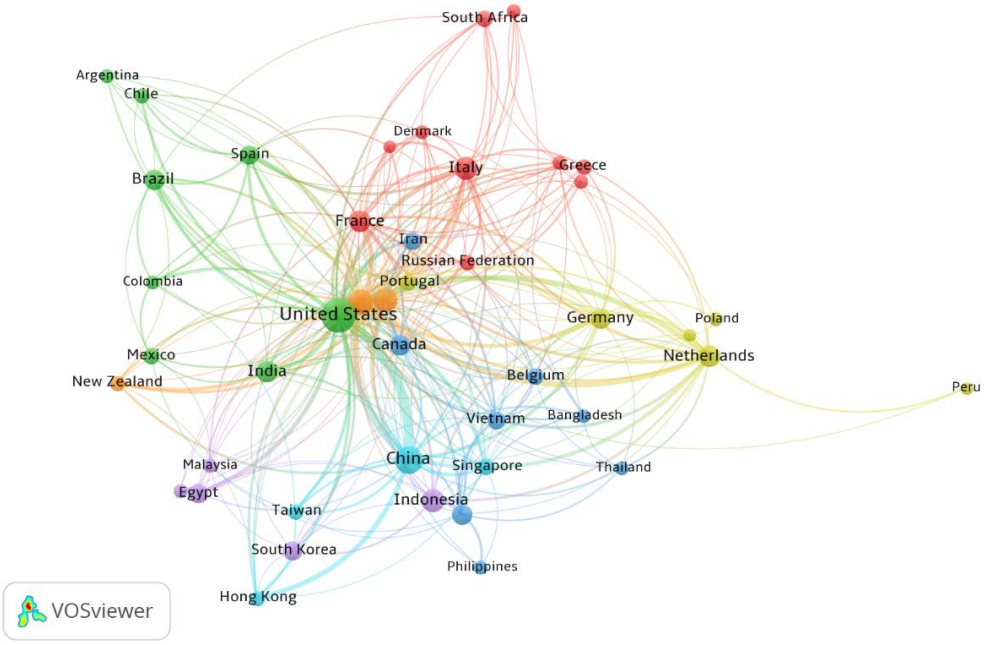


Figure 2.3. Network visualization of countries/regions associated with publications regarding climate-change extreme impacts on coastal cities.

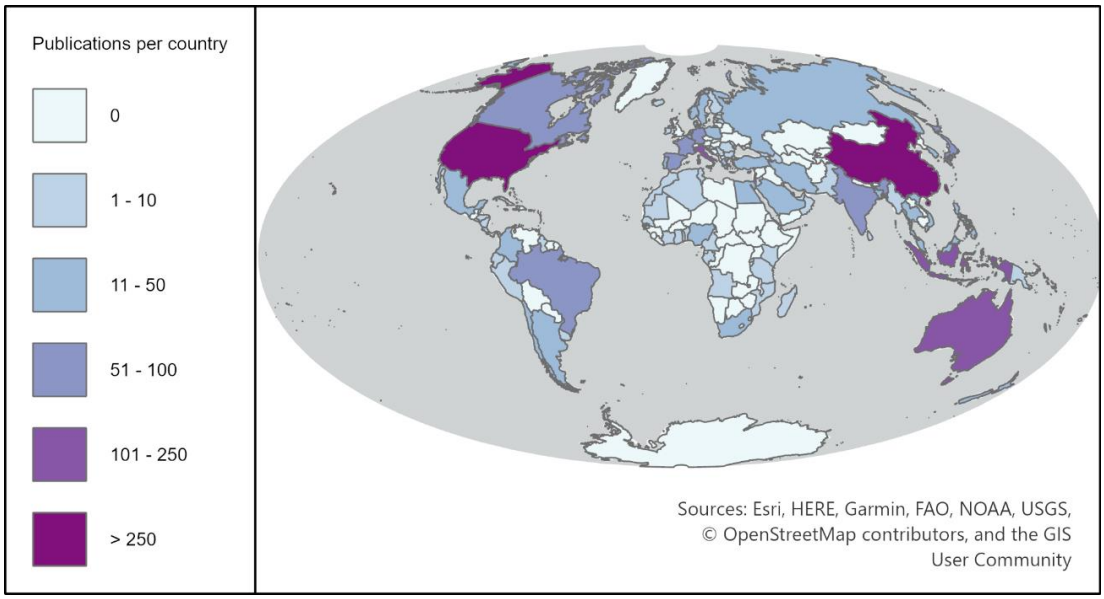


Figure 2.4. Geographical distribution of publications.

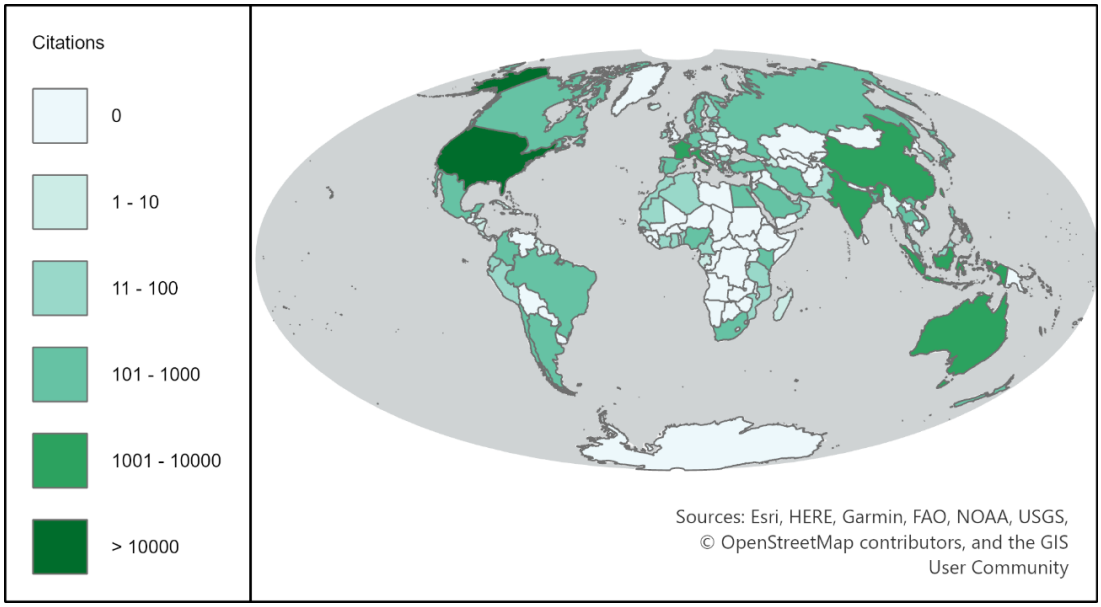


Figure 2.5. Geographical distribution of citations.

Similarly, Figure 2.6 shows the network of authors who have written at least 3 publications and accumulated at least 15 citations. Out of the 6863 authors included in the dataset, 216 meet the threshold. However, the largest set of related authors included 127 of them, represented in the figure. As in the previous graph, the node sizes, colours, and connecting lines in the network reflect the number of publications, collaboration clusters, and strength of collaborations, respectively. The author who has accumulated more publications in the research topic is Mohammad Karamouz, from the University of Tehran, with 22 published documents, including articles related to coastal flooding resilience [148,149], coastal flooding modelling [150,151], climate change impacts on coastal flood vulnerability [152], and coastal flooding risk management [153], for instance. Ning Lin (Princeton University) has worked on impactful articles studying extreme storms and their consequences on the rainfall; extreme sea levels; and coastal flooding [154–158]. Xiuquan Wang (University of Prince Edward Island) has developed his research on, *inter alia*, regional changes in temperature and precipitation (and other climatic variables) extremes through downscaling methods [159–162] and occurrences of droughts under climatic change [163]. Robert J. Nicholls (University of East Anglia) has worked on a number of global

studies regarding the impacts of climate change on coastal systems, e.g., coastal zones [164], coastal cities [146], wetlands [165,166], and the adaptation costs, among other topics [167]. Last, but not least, Zahra Zahmatkesh (McMaster University) has delved into the effects of climate change on urban storm water runoff and their mitigation [168,169].

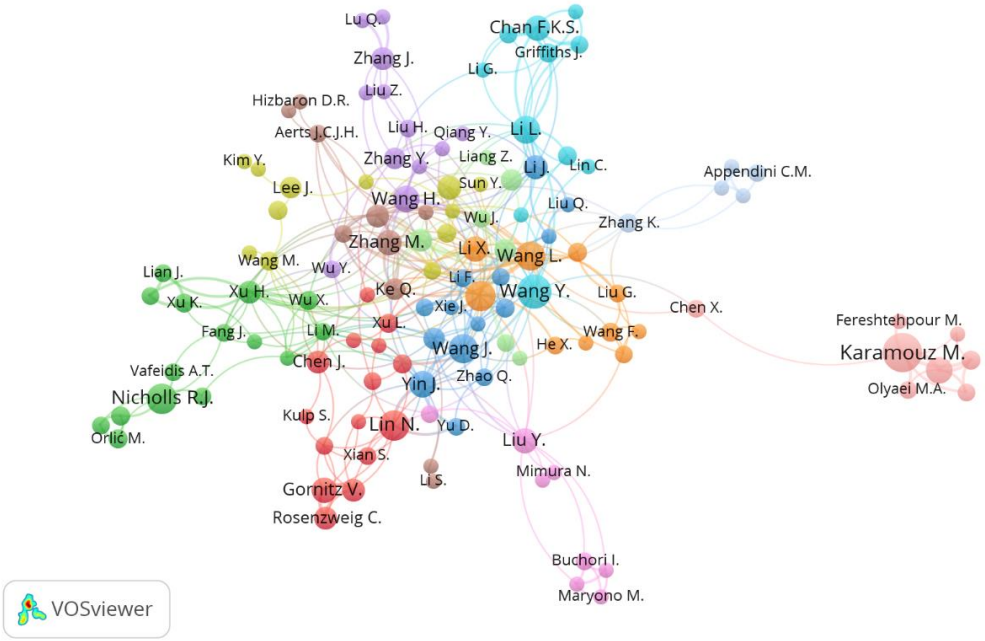


Figure 2.6. Network visualization of the authors associated with publications regarding climate-change extreme impacts on coastal cities.

A meta-analysis of the keywords included in the scientific publications may be used to reveal the "hot topics". In this vein, Figure 2.7 shows the network of keywords associated with publications on climate change extreme impacts on coastal cities, and Figure 2.8, the corresponding heatmap. Only the keywords which appeared in at least 15 publications of the dataset are showed in the graph, representing 356 out of the 12142 terms included in the dataset. As previously, the node sizes, colours, and connecting lines reflect the number of keywords, relationship clusters, and strength of the links in the network, respectively. Some of the most recurring terms and their occurrences are presented in Table 2.4. The analysis of the clusters identified shows how the research topics may be classified within six categories. The largest cluster

(red) incorporates a variety of keywords related to policy making and planning (e.g., climate change adaptation, mitigation, adaptative management, sustainable development, urban planning, resilience, water management, regional planning, decision making, risk assessment, strategic approach). "Rivers", "catchments", "water supply", "groundwater", "runoff", "river discharge", "urban flood", "aquifers", "hydrology" and other water-related terms are covered by the green cluster. The third cluster (dark blue) includes keywords corresponding to coastal erosion and coast morphology, such us "accretion", "barrier island", "beach erosion", "beach nourishment", "breakwaters", "coastal engineering", "coastal management", "land reclamation", "satellite imagery", "sediment" and "shoreline change", *inter alia*. Topics related to climatology and meteorology are well covered by the yellow cluster: "air temperature", "climate models", "extreme event/precipitation/rainfall", "forecasting", "frequency analysis", "precipitation", or "return period" are some examples of this. The cluster coloured in light blue is apparently related to climate-related hazards and risk in the USA, as it includes, for example, "coastal flooding", "embankments", "Florida (USA)", "hurricanes", "Hurricane Sandy", "Hurricane Katrina", "levees", "New York", "New Orleans", "storm surge" and "United States". The last cluster (violet) of research hot terms does not seem to focus on any topic in particular and may be understood as a cluster connecting the remaining part of the network.

Table 2.4. Most frequent keywords of the publications on climate-change extreme impacts on coastal cities.

Keywords	**Number of occurrences**
Floods	652
Climate change	584
Storms	314
Risk assessment	200
Coastal zone	275
Flood control	252
Sea-level rise	230

Vulnerability	226
United States	207
Storm surge	199
Urban area	165
Erosion	159
Rain	142
Hurricanes	137
Disasters	137

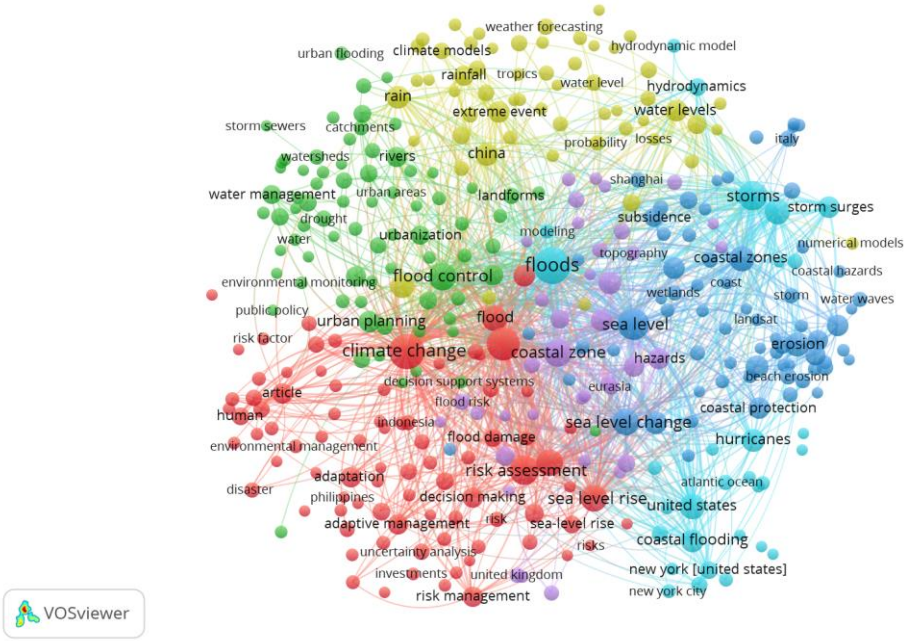


Figure 2.7. Network of keywords of publications on climate-change extreme impacts on coastal cities.

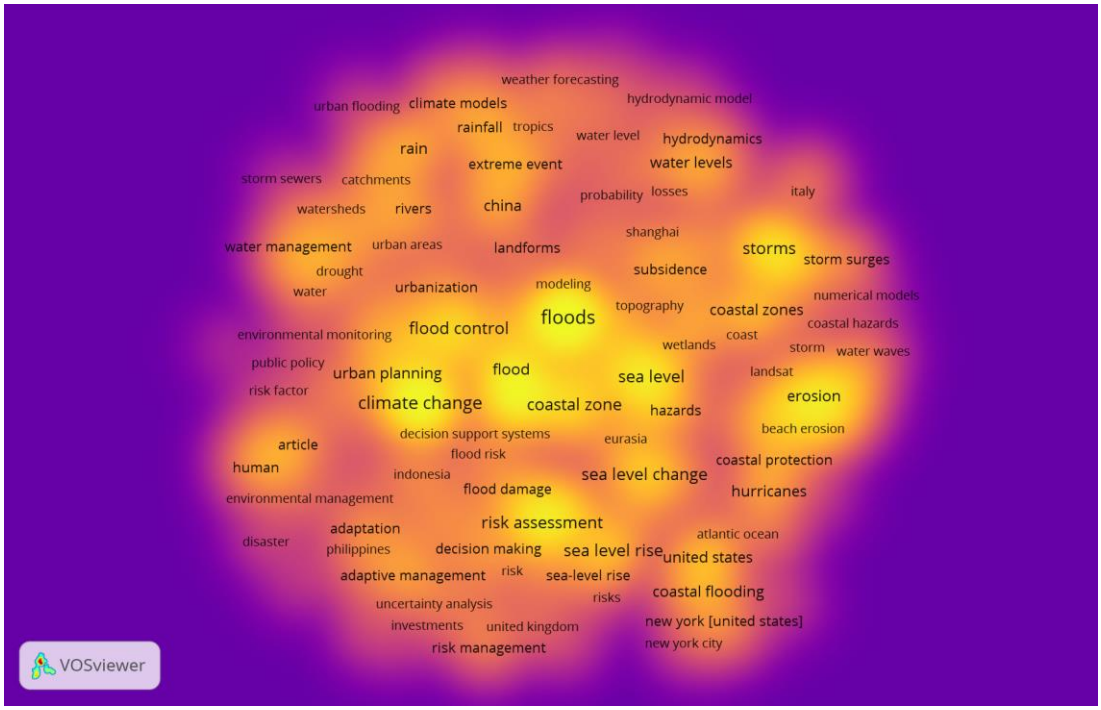


Figure 2.8. Heatmap of keywords of publications on climate-change extreme impacts on coastal cities.

Finally, it has been observed how the research topics have evolved between 1976-1991, 1992-2001, 2002-2006, 2007-2011, 2012-2016 and 2017-2021 (Figure 2.9). In the first period (1976-1991), the most recurrent terms are mainly associated to the domain of coastal erosion (e.g., "coastal engineering", "shore protection", "tides", "beach erosion", "coastal processes", "beach", "dune" and "barrier islands"), but also to the study of storms and floods ("meteorology- storms", "water waves", "flood control", "flood protection" and "storm surges") and the study cases of the Venice Lagoon (Italy) and Ocean City (Maryland, USA). The second period (1992-2001) introduces a number of new topics related to climate change ("greenhouse", "global warming", "climate", "meteorology", "pollution control" and "anthropogenic effect"). In the third period (2002-2006), keywords related to the USA and natural disasters are strongly linked, reflecting the impact of Hurricane Katrina ("United States", "New Orleans", "North America", "natural disasters", "hurricanes" and "disaster planning"). Furthermore, other topics related to probabilistic analysis and hazard modelling ("computer simulation", "joint probability", "extreme event", "geographic

information systems" and "GIS") and large geographical areas ("world", "Far East", "Asia", "South America", "Eurasia", "Africa", "Europe", "western hemisphere") are also of relevance in this period. Although the term "risk assessment" was present in the heatmap, it is in the period (2007-2011) when this keyword is most recurrent, including some related topics ("risk management", "vulnerability", "risk perception", and "risk factor"). The last two periods (2012-2016) and (2017-2021) do not show the boom of a new group of keywords as in the previous cases. Instead, the heatmaps are very similar to the one corresponding to the period (2007-2011), although the number of publications per year had significantly grown. This may reflect a period of knowledge consolidation during the last decade.

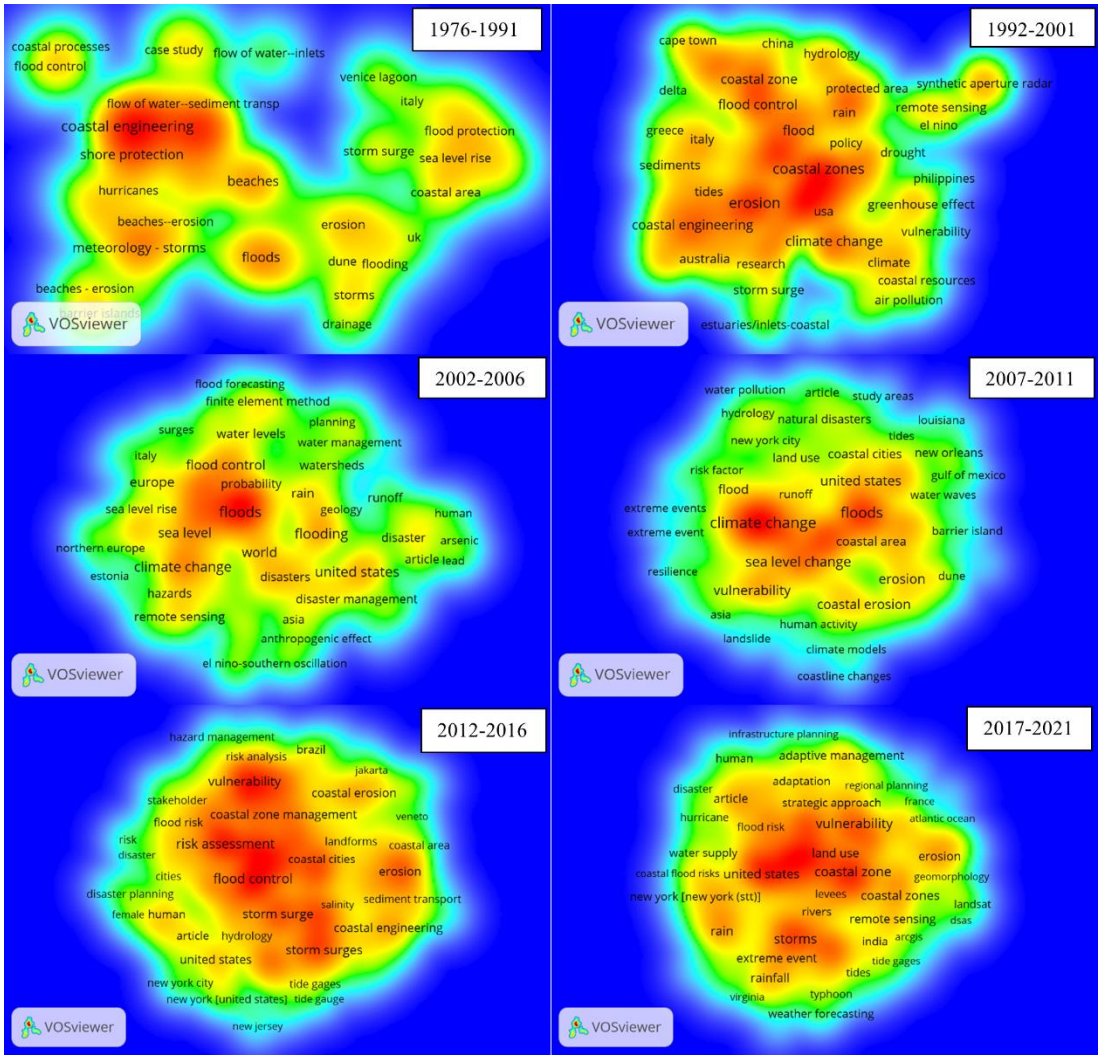


Figure 2.9. Temporal evolution of heatmaps of keywords of publications on climate-change extreme impacts on coastal cities.

2.4. Discussion

The understanding of the impacts of climate change on coastal systems has continuously evolved since the first published studies regarding this matter. In this sense, the chronological alignment of certain milestones and the corresponding variations in the number of publications suggest a connection worth exploring. For example, the relative peak in the number of publications reached in 1989 coincides with the foundation of the IPCC in 1988, which brought together numerous scientists to assess scientific evidence on climate change and its impacts. This correlation could

potentially be attributed to a shift in research focus towards collaboration with the IPCC, leading to a temporary increase in publications specifically related to coastal cities. Another noteworthy association is observed around the year 1997 when the UNFCCC adopted the Kyoto Protocol as the world's first greenhouse gas emissions treaty. This milestone is followed by an increase in the number of publications for subsequent years. The adoption of the Kyoto Protocol likely drew attention to the impacts of climate change, including those on coastal cities, prompting researchers to intensify their investigations and publish findings related to this crucial area. Similarly, in subsequent years, as the adoption of the UN SDGs and agreements such as the Paris Agreement gained prominence between 2015 and 2016, the number of publications related to the impacts of climate change on coastal cities exhibited an upward trend, especially between 2017-2021. This suggests that global climate change agreements and initiatives served as catalysts for increased research focus on the specific challenges faced by coastal cities and their vulnerability to climate change, leading to the establishment of cities as relevant actors in the global climate change regime [170]. It is important to note that while these observations indicate a general relationship between the milestones and the publication trends, they do not establish a direct cause-and-effect relationship. Numerous other factors, including regional research priorities, funding availability, and evolving scientific paradigms, can also influence publication patterns. Additionally, the number of publications alone does not capture the depth or quality of the research conducted.

In the literature, an event is generally considered extreme if the value of a certain variable exceeds a threshold. The boundary between non-extreme and extreme events is usually defined based on the consequences that these extreme values may trigger (e.g., health impacts, irreversible damage to goods and property, biodiversity loss) [171]. In this vein, a large number of keywords are closely related with the definition of extreme events and their consequences. For example, keywords from yellow and light blue clusters may reflect that much research is oriented towards these topics.

The frequency and intensity of some climate change extreme events are increasing due to climate change. Climate-change extreme impacts may refer to the harmful effects of short-duration climate-change extreme events which produce a certain level of damage – usually on the economy, society, environment, urbanisation or geomorphology. Climate-change extreme impacts are usually driven by severe storms, which lead to strong winds, high sea levels, intense rainfall, coastal flooding and coastal erosion episodes, loss of ecosystems, salinisation of soils, ground and surface water, and impeded drainage. Moreover, light changes in some magnitudes may also lead to large impacts on fragile coastal systems. Changes in temperature, precipitation, substance concentration or pH may produce large-scale effects, such as droughts and eutrophication, leading to impacts on ecosystems, soil characteristics and water availability, or even forest fires, algal blooms and fish kills [140]. On the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities, the capacity of the urban drainage systems to absorb storm water, the construction of renewable energy infrastructure, and critical infrastructures such as transportation, ports, and naval bases [172,173]. Furthermore, some results and conclusions from research on inland cities may be applied to coastal cities.

Climate change effects do not take place alone. More often than not, the impacts on cities are caused by a combination of climate change effects and human drivers. For instance, the transformation of the coast due to human action (e.g., keywords related to coastal protection schemes, ports and urbanization) modifies the development of climate change extreme events and determines the exposure and vulnerability of nearby cities. Moreover, other geohazards not necessarily related to climate change, such as earthquakes, tsunamis and volcanic eruptions, may increase the harmful potential of climate-change-related hazards (e.g., flood risk [174]) as a result of extensive changes in the terrain level, the coastal morphology and the built

environment of cities. In addition, the eventual failure of protection systems, e.g., breakwaters, levees and dams, may be expected to increase damage levels.

Conversely, certain human actions, such as beach nourishment to control erosion or, in particular, ecosystem-based approaches (e.g., restoration of vegetation in dune and mangrove habitats) contribute to the resilience of cities to climate change [175]. However, in the scientometric analysis it is readily seen how most of the publications focus on the characterisation of hazards and assessment of risks, whereas the number of publications relating to the development of coastal adaptation solutions is far smaller. One possible explanation is the complex nature of coastal adaptation solutions. Crafting effective strategies that can withstand the dynamic nature of coastal ecosystems and the multifaceted challenges they face often requires a multidisciplinary approach and extensive collaboration among researchers, policymakers, and stakeholders. The absence of substantial research in this area may suggest a need for enhanced collaboration and interdisciplinary efforts to tackle the intricate issues posed by coastal adaptation. Moreover, it is plausible that the limited availability of funding and resources might be a contributing factor. Research endeavours aimed at developing viable adaptation solutions in coastal regions often demand substantial financial investment and logistical support. The comparatively smaller number of publications in this domain may reflect the challenges that researchers face in securing the necessary resources to undertake comprehensive studies and develop practical solutions. Notwithstanding, the societal conscience is gradually evolving to apprehend new concepts that have emerged in the urban planning and policy-making landscape in recent years, such as climate-change adaptation, climate resilience, adaptative management, sustainable development, or disaster prevention, inter alia [176–178].

Climate change has sound impacts on coastal societies and greatly attracts the interest of the scientific community and governments, resulting in a frenetic scientific production. Although the number of publications that relate climate change and its

impact on coastal systems is high, as can be deduced from this work, no publication has been found that performs a holistic meta-analysis of said works, in order to understand their momentum. The novelty of this work lies in the unified and systematic meta-analysis of how the study of climate change has developed and evolved from its roots to today throughout the world, by means of a scientometric and bibliometric approach. Due to its complexity, the study of the impact of anthropogenic action on coastal systems has been left aside. Its analysis would complement to that developed here to finish understanding the evolution of the main challenges that coastal cities face.

2.5. Conclusions

The results shows that scientometric analysis can provide a valuable tool for understanding the research landscape on climate change and coastal cities, including the key themes, contributors, and impacts of the research, as well as the gaps and opportunities for further research.

Scopus offers researchers a powerful tool for accessing, exploring, and analysing scholarly literature. It provides a wide range of features and functionalities for citation tracking, search, and retrieval. However, researchers should be aware of its limitations, including incomplete coverage, language bias, data limitations, and potential biases in the database.

The research interest in extreme impacts of climate change is high, as evidenced by the number of publications, authors and citations. The results show in which manner authors collaborate, and how the keywords analysed are directly related to concepts of sea-level rise and extreme events. The research topics associated to coastal flooding, coastal erosion and sea level rise were covered, and the trending topics and those less pursued so far were indicated. Hot topics of research are mainly related to the

assessment of climate-related hazards and risks, policy making and planning, water-related topics, coastal management, climatology and meteorology.

The most relevant publications, authors and research topics have been identified and analysed. The journals Ocean and Coastal Management, Journal of Coastal Research, Natural Hazards, Water (Switzerland) and Sustainability (Switzerland) were the venue for the highest number of documents and considerable scholarly metrics. The five authors who have accumulated more publications in the research topic are Mohammad Karamouz (University of Tehran), Ning Lin (Princeton University), Xiuquan Wang (University of Prince Edward Island), Robert J. Nicholls (University of East Anglia) and Zahra Zahmatkesh (McMaster University). Some of the most impactful publications encompassing the different research areas identified include “Future flood losses in major coastal cities”, “Hotspot of accelerated sea-level rise on the Atlantic coast of North America”, “A global ranking of port cities with high exposure to climate extremes”, “Mapping community determinants of heat vulnerability” and “Unjust waters: Climate change, flooding and the urban poor in Africa” [46,92,146,179,180].

Regarding the geographical coverage, works tend to concentrate in a few regions, and there is a serious scarcity of studies published in English in developing countries. USA, China, UK, Australia and Indonesia are the countries which concentrate most of the research. Many of the publications do not focus on coastal cities exclusively but on long coastal fringes where cities are included.

The results show how climate-change extreme impacts on coastal cities are scoped by research, but also how the concepts and disciplines in the study of these impacts are related to each other through the different keywords and clusters which arose from the scientometric analysis. The number of scientific studies has evolved alongside the growing societal conscience of the need to combat climate change over the last fifty years, since the foundation of the IPCC up to the ratification of the European Green

Deal, with an unprecedented surge in the last five years. Many of the keywords and clusters raised are closely related with the characterisation of climate-related extreme events and hazards, rather than with coastal adaptation measures or the development of integrated coastal zone management tools.

The synthesis carried out in this work by means of a bibliometric and scientometric analysis on climate-change extreme impacts on coastal areas contributed to documenting and understanding the momentum of the research to date, but also to helping scientists spot research gaps which might otherwise be missed or to orientating new investigation. The study of emerging integrated coastal zone management tools (e.g., nature-based solutions, ecosystem-based approaches, coastal city living labs, digital twins and smart-sensing technologies) and the impacts of climate change on developing countries are possible opportunities to extend current research. Moreover, key events and agreements in the global climate change fight appear to have influenced research interest and output in studying the effects of climate change on coastal cities. Further investigation and analysis are necessary to ascertain the precise nature and extent of this relationship.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 3.

Climate-related hazards and impacts on European coastal cities

This chapter corresponds to: Laino, E., and Iglesias, G. **Extreme climate change hazards and impacts on European coastal cities: A review**. Renewable and Sustainable Energy Reviews, 2023. **184**: p.113587.

ABSTRACT

The intensification of extreme events due climate change and sea-level rise are major challenges to be urgently addressed by Europe's coastal cities. Coastal hazards have the potential to cause significant damage to coastal communities. Nevertheless, various other climate-related hazards also pose imminent threats. This review paper examines the impacts of climate change on ten European coastal cities by means of a participatory process involving the coastal cities and the review of existing literature. Local expertise is included through the novel concept of Coastal City Living Lab (CCLL). The study also leverages bibliometric analysis of the Scopus and Web of Science databases, along with a desk review of climate-change related institutions and agencies at international, national, regional and local levels. By combining scientific literature analysis with insights from local experts, this research provides a comprehensive overview of the current situation of these diverse cities in relation to multiple climate-related hazards, which can be extrapolated to other cities. There is a scarcity of scientific data for some of the cities, hence collaboration with the CCLLs

was crucial. Results serve as a valuable baseline for future works, introducing detail studies focusing on various climate-related challenges. This paper not only contributes novel insights by including the perceptions of local partners but also offers a unique perspective on the complex nature of climate change impacts at city level.

3.1. Introduction

Climate-related hazards are expected to increase in frequency and intensity in Europe, notably those related to heat waves, droughts and heavy precipitation events [79]. Climate-related disasters could affect about two-thirds of the European population annually by the year 2100 (351 million EAPE on average) compared to 5% between 1981-2010 (25 million EAPE on average) [80]. Likewise, the number of fatalities related to these events could increase from 3,000 (1981-2010) to 152,000 (2100) deaths per year on average, mainly through a rise in the frequency of heatwaves, with the highest changes affecting southern Europe [80]. While progress has been made in addressing climate change, numerous European cities still face challenges in meeting the targets outlined in the Paris Agreement, necessitating increased efforts to mitigate the most severe impacts [81,82].

In the case of coastal cities, coastal storms can be considered as the main climate-related hazard, as these lead to destructive ESLs, coastal flooding and coastal erosion [28–30]. A climate risk assessment performed by Abadie et al. (2016) [72] estimated the EAD for main European coastal cities, with Istanbul, Odessa, Izmir, Rotterdam and St. Peterburg ranking highest. In the absence of additional investments in coastal adaptation measures in Europe, the current EAD of €1.25 billion is projected to experience a substantial increase by the end of the century, ranging between €93 and €961 billion. Similarly, the present EAPE to coastal flooding, currently at 102,000, is anticipated to rise significantly to 1.52-3.65 million EAPE by 2100.

The ESL associated to the 100-year return period along Europe's coastlines is projected to increase on average by 57 cm and 81 cm by 2100 under the RCP4.5 and RCP8.5 scenarios, respectively [7]. These findings align with other regional assessments conducted for coastal flooding in the German Bight [73,181], UK [74], Portugal [182], Adriatic Sea [76], Baltic Sea [77] and Balearic Sea [78]. The North Sea region is anticipated to experience the most substantial rise in ESLs, followed by the Baltic Sea and the Atlantic coasts of the United Kingdom and Ireland, whereas light changes along the Southwestern Europe coast are expected [7,182,183]. In this vein, the current 100-year ESL could become the 1-year ESL for five million Europeans by the end of the century under high-end warming, increasing coastal flooding risk significantly [7]. Without doubt, the increases in storm severity would also mean the enhancement of their potential to erode coasts.

A number of articles review the impacts of climate change in general [82,83], or regarding specific topics related to cities (e.g., weather [84,85], renewable energy [184,185], energy consumption [186], infrastructure [187,188], cultural heritage [189], health [63], tourism [190], or research momentum [191]). Numerous historical reviews examining the impacts of climate-related hazards on European cities can be found within the literature. For example, studies have investigated past extreme weather events and flooding episodes in Copenhagen, Denmark [86], historical patterns of ESL in Venice, Italy [76], or historic storms across various European coastal areas (i.e.: Belgium, Bulgaria, France, Italy, Netherlands, Poland, Portugal, Spain and the United Kingdom) [87]. However, holistic literature reviews combining coastal hazards, but also other climate-related hazards, such as droughts, heat waves, landslides or land flooding are significantly scarcer. Indeed, scientific results are not always available and new approaches can be considered.

This work aims to shed light on the impacts of climate-change-related hazards on European coastal cities, with a particular focus on ten representative cities. What sets this research apart is the incorporation of local expertise achieved by means of a

collaborative process involving the authors and city partners, through the novel concept of CCLL under the umbrella of the EU-funded SCORE project. The expansion of the Living Labs concept to encompass coastal cities and settlements results in the establishment of a CCLL. In essence, CCLLs represent both physical and virtual urban environments situated along coastlines, where individuals, as well as public and private entities, collaborate in order to jointly devise and implement innovative solutions to address various local challenges arising from sea-level rise, coastal erosion, and extreme climate-related hazards. The goal of SCORE is to enhance the climate resilience of ten coastal cities by developing Ecosystem-Based Approaches and advanced digital technologies in collaboration with the CCLLs [116,192,193]. The ten coastal cities include Sligo (Ireland), Dublin (Ireland), Vilanova i la Geltrú (Spain), Benidorm (Spain), Oarsoaldea (Spain), Oeiras (Portugal), Massa (Italy), Piran (Slovenia), Gdańsk (Poland) and Samsun (Türkiye).

As a first step forwards, this article delves into the review process on the current effects of extreme climate-related events and sea-level rise for these coastal cities, maintaining future climatic projections out of the scope. The review process includes the analysis of local information obtained from liaison with the CCLLs, a systematic review of scientific and technical publications, data from climate-change-related agencies and institutions and non-technical media sources (newspapers, news portals, etc.). By embracing this approach, the study provides a holistic and comprehensive methodology to contribute understanding the complex interplay between climate change and local vulnerabilities that can be extrapolated to other coastal cities. Lastly, the intention is also to produce a baseline that paves the way for more detailed studies considering multiple climate-related hazards.

3.2. Materials and methods

To ensure a comprehensive assessment, this review employs a multifaceted methodology. Firstly, a desk review was performed to gather information from international and European climate-change related institutions and agencies to build on a big picture of what are the main challenges that coastal cities face in relation to sea-level rise and climate-related hazards. Secondly, a bibliometric analysis was conducted using the Scopus and Web of Science databases to identify and synthetise relevant scientific literature. This analysis encompassed studies addressing climate change impacts and related hazards in the European coastal context, but also including the ten selected coastal cities. By combining these two approaches, a robust and inclusive knowledge base was established. The third approach relates to the liaison with the CCLLs in the context the SCORE project (Table 3.1), including a continuous exchange of ideas and knowledge through the utilization of questionnaires, meetings, and workshops. This interaction resulted in the identification of local information sources. Finally, in the cases where the information obtained from the previous sources was scarce, non-technical media were reviewed to fill possible gaps.

Table 3.1. Coastal City Living Labs partners and associated coastal area.

CCLL	**Country**	**Partners**	**Geographical coverage**
Sligo	Ireland	Atlantic Technological University	County Sligo
Dublin	Ireland	University College Dublin, and Dún Laoghaire-Rathdown County Council	Great Dublin
Vilanova i la Geltrú	Spain	Vilanova i la Geltrú City Council, Barcelona Provincial Council, and Environment and Management	Vilanova i la Geltrú municipality
Benidorm	Spain	University of Alicante	Benidorm municipality
Oarsoaldea	Spain	Oarsoaldea	Municipalities of Errenteria, Lezo, Pasaia and Oiartzun
Oeiras	Portugal	Câmara Municipal de Oeiras	Oeiras municipality
Massa	Italy	Municipality of Massa	Massa municipality

Piran	Slovenia	Science and Research Centre, Koper, Slovenia	Piran municipality
Gdańsk	Poland	University of Gdańsk	Gdańsk city
Samsun	Turkey	University of Samsun	Samsun province

Climate-change-related agencies and similar bodies, herein called “climate change agencies” for ease of reading, refers to organizations, institutions, and governmental or non-governmental entities that are actively involved in addressing climate change issues, conducting research, implementing policies, and providing expertise in the field. These climate change agencies provide information on climate change for policymakers and the general public, gathering data and producing assessments on a wide range of topics related to climate change (e.g., GHG emissions reduction, impacts on the environment and human-systems, climate change adaptation and mitigation or sustainable development). Moreover, they usually provide specific studies concerning climate change impact on coastal cities, due to their economic relevance for policymakers. Examples of such entities include the IPCC, national climate change adaptation agencies, environmental protection agencies, climate research institutions, Non-Governmental Organizations (NGOs), climate funds and financial institutions and meteorological and weather services (Table 3.2). Climate change agencies focusing on international to European and national-local scales were consulted through a desktop study, with the purpose of collecting the available information regarding climate change extreme impacts on coastal cities. Jointly, data from climate change agencies have been used to build an overall picture of the state of the art on the discussion topic. The baseline knowledge acquired from these sources has been utilized in the definition of the searching criteria for the systematic review of scientific literature.

Table 3.2. Examples of climate-change-related agencies and similar bodies operating at international and European levels.

Climate change agency category	**Description**	**Examples**
Intergovernmental Panel on Climate Change	An international body established by the United Nations Environment Programme and the World Meteorological Organization that assesses scientific research on climate change and its impacts.	IPCC reports
National climate change adaptation agencies	These agencies are established at the national level to oversee and coordinate adaptation efforts, formulate policies, and implement strategies to address the impacts of climate change within a specific country.	Europe: Germany: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety France: French Agency for Biodiversity United Kingdom: Committee on Climate Change
Environmental protection agencies	Government agencies responsible for monitoring and regulating environmental issues, including climate change mitigation and adaptation measures.	International: United Nations Environment Programme Europe: European Environment Agency
Climate research institutions	Academic and research organizations that specialize in studying climate change, conducting scientific research, and developing models to better understand its causes and effects.	International: National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration Europe: European Centre for Medium-Range Weather Forecasts, Met Office Hadley Centre, European Commission's Joint Research Centre
Non-governmental organizations	Various non-profit organizations dedicated to climate change advocacy, raising awareness, promoting sustainable practices, and implementing projects that contribute to climate change mitigation and adaptation.	International: Greenpeace, World Wildlife Fund, Friends of the Earth International, Center for Climate and Energy Solutions Europe: European Environmental Bureau, BirdLife International, Climate Action Network Europe

Climate funds and financial institutions	International funds and financial institutions specifically dedicated to supporting climate change mitigation and adaptation initiatives, such as the Green Climate Fund, World Bank Climate Investment Funds, and regional development banks.	International: Green Climate Fund, Global Environment Facility Europe: European Investment Bank, European Bank for Reconstruction and Development, EU's Green Deal Investment Plan
Meteorological and weather services	National and international agencies responsible for monitoring and forecasting weather and climate patterns, providing critical data and information for climate change analysis and decision-making.	International: World Meteorological Organization European: European Centre for Medium-Range Weather Forecasts, Copernicus, Meteo-France, UK Met Office

A systematic literature review was conducted in this study, focusing on scientific sources obtained from conference proceedings, scientific-technical reports and peer-reviewed scientific journal articles sourced from the reputable databases Scopus and Web of Science. The selection criteria for keywords used in the search tools were carefully considered. Firstly, the study sites were limited to cities situated along coastal zones. Secondly, extreme events or impacts are considered. Thirdly, climate change plays a significant role as the driving force behind these events or impacts. In addition, the search process adhered to practical considerations. The preference was given to keywords capable of capturing a wide range of climate change hazards, avoiding overly specific terms. For instance, "Coastal Erosion" was chosen over "Beach Erosion" or "Cliff Erosion" as it encompasses both of the latter two. Furthermore, concise and general keywords were favoured to generate broader results, allowing for subsequent filtering. For example, the term "Storm" was used instead of the more specific phrase "Coastal Storm Surge". Based on the aforementioned criteria, two sets of keywords were developed to facilitate the search process. Table 3.3 presents the keywords tailored to the global and European context, while Table 3.4 outlines the keywords specifically targeting the coastal cities under study. Each table

provides the preliminary results exported from Scopus and Web of Science for their respective series of keywords.

Table 3.3. Keywords and number of preliminary results targeting extreme impacts of climate change on coastal cities at international and European levels extracted from Scopus and Web of Science.

Keywords	**Scopus**	**Web of Science**
Climate Change Coastal Flooding	2,271	4,311
Climate Change Coastal Erosion	2,798	3,994
Climate Change Shoreline Retreat	283	394
Coastal Cities Sea-level Rise	859	910
Climate Change Coastal Cities Temperature Rise	77	99
Climate Change Coastal Cities Storm	320	376
Climate Change Extreme Impacts Coastal cities	160	224
Climate Change Coastal Cities Drought	86	88
Climate Change Coastal Cities Rainfall	148	225
Total	7,002	10,601

Table 3.4. Keywords and number of preliminary results targeting extreme impacts of climate change on coastal cities at the ten coastal cities studied extracted from Scopus and Web of Science, respectively.

Keywords	**Sligo**	**Dublin**	**Vilanova i la Geltrú**	**Benidorm**	**Oarsoaldea**
Climate Change	7; 10	71; 81	0; 1	7; 7	1; 0
Flooding	2; 2	18; 33	0; 0	0; 0	0; 0
Coastal Erosion	0; 0	1; 0	0; 0	0; 1	0; 0
Shoreline Retreat	0; 0	0; 0	0; 0	0; 0	0; 0
Sea-level Rise	0; 0	7; 4	0; 0	0; 0	4; 0
Temperature rise	1; 1	4; 18	0; 0	0; 3	0; 0
Storm	0; 0	35; 19	0; 0	12; 23	1; 0
Climate Change Extreme Impacts	0; 0	2; 2	0; 0	1; 0	0; 0
Drought	0; 0	8; 11	0; 0	3; 5	1; 2
Rainfall	3; 3	30; 33		3; 4	0; 2
Total	29	377	1	71	12

Keywords	**Oeiras**	**Massa**	**Piran**	**Gdańsk**	**Samsun**
Climate Change	2; 3	7; 4	6; 5	63; 86	14; 23
Flooding	0; 1	4; 0	4; 3	29; 57	6; 10
Coastal Erosion	0; 0	0; 0	0; 0	23; 20	6; 0
Shoreline Retreat	0; 0	0; 0	0; 0	1; 1	1; 0
Sea-level Rise	0; 0	0; 0	2; 1	22; 20	2; 4
Temperature rise	0; 0	1; 1	1; 0	13; 14	3; 13
Storm	1; 0	4; 1	2; 2	58; 42	1; 1
Climate Change Extreme Impacts	0; 0	0; 0	0; 0	3; 2	0; 0
Drought	1; 2	0; 0	0; 0	5; 3	12; 36
Rainfall	0; 2	8; 2	1; 1	16; 31	13; 17
Total	12	32	28	514	163

The above-mentioned results indicate the total number of scientific sources that were identified in the search process. Each source was required to contain all the specified keywords within either the title, abstract, or related keywords sections. The search was conducted without any limitations on publication dates, focusing solely on English-language documents and encompassing various types of publications, such as proceedings, books, and scientific articles. Pertinent metadata from the initially selected documents, including the scientific database, search keywords, document author(s), document title, year of publication, source title, volume, issue, number, page range, citation count, link, abstract, author keywords, and index keywords, were meticulously exported and saved in a dedicated database. Subsequently, a comprehensive review of the exported documents was performed by closely examining their abstracts. This process facilitated the identification of studies that fulfilled the eligibility criteria specified for the selected databases. Furthermore, a thorough screening process was carried out to ensure that the selected records were aligned with the defined research questions. Finally, records meeting the inclusion criteria were incorporated into the analysis conducted for the literature review,

enabling a comprehensive evaluation of the relevant studies within the scope of this investigation.

In order to foster a continuous exchange of ideas and knowledge, an ongoing and collaborative process was established through the utilization of questionnaires, meetings and workshops with the CCLL partners. These interactions served as platforms for engaging in meaningful discussions and sharing expertise. Through the structured questionnaires, valuable insights were gathered from each participant, facilitating a comprehensive understanding of the subject matter. Furthermore, the organized CCLL-individual meetings provided an opportunity for face-to-face interactions, allowing for in-depth conversations and the exploration of diverse perspectives. Additionally, the workshops held between 2021-2022 served as dynamic forums for collaborative problem-solving and the generation of innovative ideas. This iterative and interactive approach not only promoted a synergistic environment but also facilitated the acquisition and dissemination of knowledge among colleagues. The collaborative process permitted the collection of information from national and local climate-change-related agencies that otherwise may be missed (non-publicly available or difficult-to-access information or data from documents in other languages rather than English) and the identification of the most relevant climate-related hazards for each city. Table 3.5 provides insights on the topics discussed with the CCLL partners in the development of local expertise.

Table 3.5. Main topics of discussion with the Coastal City Living Lab partners and expected results.

Question	**Expectation**
What are the main sources (scientific-technical publications, local or national climate change / environment agencies/institutions, non-technical media or other) which provide information about climate change extreme impacts in your area?	Collection of local information that could be missed from the desk review and the systematic scientific literature review.

Is there any related past or ongoing project(s) on the area of the CCLL? If yes, could you please provide references and a brief summary of each of them?	Collection of local information regarding actions developed to face climate-related hazards.
Which of the selected natural or climate-related hazards (coastal flooding, storm surge, coastal erosion, land flooding, landslide, heat wave, drought or other) do you consider is the most dangerous for your CCLL and why?	Development of baseline understanding of what climate-related hazards primarily affect each CCLL.
Which of the selected impacts (tourism, cultural heritage, commercial buildings, residential buildings, energy network, transport network) do you consider is the most relevant for your CCLL and why?	Development of baseline understanding of what impacts driven by climate-related hazards primarily affect each CCLL.
What is the relationship between hazards and impacts in your associated coastal city? I.e.: how can flooding affect tourism?	Development of baseline understanding of the interrelationships between climate-related hazards and impacts for each CCLL.

In some instances, non-technical media sources such as newspapers or news portals have proven valuable in providing information regarding specific climate events or localized occurrences that may not have undergone technical or scientific assessment. Examples of such events include damages caused by flooding or landslides in certain cities, as well as photographic evidence capturing the magnitude of these events.

3.3. Results

The findings of the research for the ten coastal cities under study are presented hereinafter. These results encompass the synthesis of key scientific works, local knowledge provided by CCLL partners, and information obtained from national and local climate change agencies. As it will be observed, the significance of the information from each of the aforementioned sources varies for each city. Scientific results range from extensive to scarce, or even practically non-existent, depending on the case. The level of interaction with CCLLs also varies among cities, as it is a

complex process depending on multiple factors [194]. Lastly, the number and capacity of climate change agencies collected from the collaborative process involving the CCLLs also exhibit variability, generally being greater in larger cities such as Dublin or Samsun. Table 3.6 presents the climate change agencies closely related to the cities considered, including relevant documentation regarding climate change impacts.

Table 3.6. Climate-change-related agencies and similar bodies providing information on climate change impacts for the ten coastal cities studied.

Coastal city	**Climate change agencies**	**Documents**
Sligo	Office of Public Works Atlantic Seaboard North - Climate Action Regional Office Atlantic Technological University	Sand Dune Protection and Restoration Project Coastal Erosion & Flood Risk Management Study Sligo County Council's Climate Adaptation Strategy
Dublin	Office of Public Works Climate Action Regional Offices University College Dublin Dún Laoghaire-Rathdown County Council	Climate Change Action Plan 2019-2024 Flood Maps
Vilanova i la Geltrú	Environment Local Service and Local Energy Agency (both from the City Council) Bioacoustics Applications Laboratory (Polytechnic University of Catalonia) Neapolis Environment and Management	Climate Change Adaptation Plan of Vilanova i la Geltrú Sustainable Energy and Climate Action Plan of Vilanova I la Geltrú
Benidorm	Benidorm City Council University of Alicante	Climate Change Adaptation Plan of Benidorm
Oarsoaldea	Naturklima Ihobe Azti-Tecnalia	Klimatek Project
Oeiras	Association of Instituto Superior Técnico for Research and Development	Civil Protection Municipality plan

	Instituto of Geography and Spatial Planning - University of Lisbon Environment Portuguese Agency Portuguese Institute for Sea and Atmosphere, I. P. Câmara Municipal de Oeiras	Oeiras Climate Vulnerabilities Assessment for the Municipal Climate Adaptation Plan
Massa	Regional Functional Centre of Tuscany Environmental Monitoring and Modelling Laboratory for sustainable development (LAMMA) District Basin Authority of the Northern Apennines	Climate Change, a look at Tuscany Coastal Defence Works between Frigid River and Fosso Lavello Project
Piran	National Institute of Biology - Marine Biology Station Piran Environmental office of Municipality of Piran Science and Research Centre, Koper	I-STORMS Project SECAP - Supporting Energy and Climate Adaptation Policies Project ADRIADAPT - A Resilience Information Platform for Adriatic Cities and Towns Project
Gdańsk	Regional Water Management Board Gdańsk University of Gdańsk	Plan of Adaptation to Climate Change in the City of Gdańsk until 2030
Samsun	Samsun Metropolitan Municipality Samsun Kızılırmak Delta Conservation and Development Association Middle Black Sea Development Agency University of Samsun	Water Management Modelling of Kızılırmak Delta Project within the scope of Samsun's Adaptation Process to Climate Change Samsun Kızılırmak Delta Natural Site, Wetland and Bird Sanctuary 2019-2023 Management Plan Kızılırmak Delta Water Footprint Determination Report, 2018, Samsun Metropolitan Municipality Samsun Provincial Forest and Water Works Action Plan Samsun Provincial Agriculture and Rural Development Works Action Plan

The interaction with the CCLLs has provided valuable insights into the primary climate change-related hazards faced by each coastal city from their unique

perspective. In unison, the CCLL partners express notable concern regarding storm surges, coastal flooding, coastal erosion, land flooding, landslides, heatwaves and droughts. Additionally, the CCLLs are keen on understanding the potential impacts of these hazards on vital sectors such as tourism, cultural heritage, commercial and residential buildings, energy networks, transport systems and agriculture. The local knowledge contributed by the CCLL partners proved especially valuable for coastal cities where the systematic scientific literature review yielded limited results. In such cases, the CCLLs provided essential data and context to complement the research and enrich the understanding of the hazards affecting these regions.

No relevant journal publications have been identified for Sligo concerning climate change extreme impacts. Thus, the local expertise from the Sligo CCLL and the information from local climate change agencies were particularly relevant. According to these, the main climate-related hazards are winter storms, coastal and land flooding, and coastal erosion, as these hazards have caused the most significant impacts in recent years and have a high potential of causing substantial and irreparable damage. Particularly, the impact on municipal infrastructure and chronic, short-term transport disruption are especially relevant. The increases in the frequencies and magnitudes of severe rainfalls in Ireland (especially western Ireland) are confirmed by Leahy and Kiely (2011) [195]. Coastal flooding and erosion have a high potential of causing significant and irreparable damage. In addition, information regarding potential hazards and impacts is available in the Sligo County Council's Climate Adaptation Strategy, which contains technical and local information, as well as a list of actions that the Local Authority is committed to with regard to climate adaptation. Atlantic Technological University Sligo is also working with the Atlantic Seaboard North - Climate Action Regional Office, and their website contains useful information about climate, sustainability, energy, biodiversity, etc. Lastly, a survey of coastal issues in the Sligo Bay area is being carried out by the Office of Public Works [196] at the time of writing.

Similarly, coastal and land flooding and coastal erosion caused some of the most severe impacts recorded in recent years in Dublin. Coastal flooding may be expected to have a dramatic impact on Dublin over the coming years as there are limited defences in place and no significant public support to make the necessary improvements, such as higher flood walls [197]. For instance, in February 2002 the City of Dublin experienced severe flooding as a result of what was believed to be a combination of unusually high tides and meteorological surge [198]. Furthermore, historical analyses of exposure and vulnerability to flood hazards in Irish cities (Cork, Galway and Dublin) can be found in Jeffers (2014) [199], whereas the increasing trend in extreme rainfall has been confirmed by al Saji et al (2015) [200]. Among others, impacts on the municipal transport network are a critical issue, according to the CCLL partners. Besides, coastal flooding impacts the Dublin Area Rapid Transit (commuter rail system), as well as primary roadways and busy tourist areas in the city, disrupting the public and private transport in Dublin. In addition, the combined-drainage system can be blocked during floods. Additionally, there is relevant literature regarding droughts in Ireland. Wilby et al (2016) [201] analyse persistent meteorological droughts in Ireland, including in the city of Dublin. For instance, the summer of 2018 brought a significant meteorological drought [50]. Particular studies of maximum temperatures in County Dublin can be found as well in O'Sullivan et al. (2020) O'Sullivan et al. (2020), although heat-attributable deaths are very unusual in this area [203]. The Office of Public Works mentioned before, which coordinates flood management in Ireland, is another important source of information for Dublin, as it has developed flood plans and provides information about flood risk. Additionally, the implementation of the Climate Change Action Plan 2019-2024 is an ongoing shared vision of the four Dublin local authorities, which are working together to reduce GHG emissions, increase energy efficiency, and enhance the climate resilience of Dublin as a city region [204]. Likewise, the efforts of the local authorities are supported by the Climate Action Regional Offices.

The collaboration with Vilanova i la Geltrú CCLL has been of especial relevance as no-related scientific results were obtained from Scopus and WoS. Based on the local expertise, a combination of climate-related hazards, including storms, land flooding, strong winds, heatwaves, and forest fires, poses various risks to the local economy, particularly sectors reliant on tourism and the tertiary sector. Additionally, these hazards can lead to the loss of cultural heritage, damage to commercial buildings situated in coastal areas (such as restaurants, bars, hotels, and stores), harm to residential structures, and potential destruction of two wetlands along with their associated sandy and subaquatic habitats within the municipality. Furthermore, important civil infrastructures located along the coastal region, such as the port and road networks, are susceptible to damage. Lastly, the absence of an early warning system for extreme weather episodes exacerbates the danger posed to citizens, further emphasizing the need for improved mechanisms to alert and protect the local population. The main climate change agencies for Vilanova I la Geltrú are four: Environment and Management (ENT), the Environment Local Service and Local Energy Agency (both of them municipal), the Bioacoustic Applications Laboratory of the Polytechnic University of Catalonia, and Neapolis (a Technological centre connected to the municipality).

The erosion of the two main beaches of Benidorm (Levante and Poniente beaches) is the most critical issue for the city of Benidorm, due its huge tourism sector [205]. In this context, a review of daily soil erosion in Western Mediterranean areas between 1983 and 2004 can be found in Gonzalez-Hidalgo et al. (2007) [206]. The main conclusions reached are that the annual amount of soil eroded depends on a few daily extreme coastal erosion events, albeit soil erosion varies from site to site, and from year to year. In fact, each year (statistically), the three highest daily erosive events represent more than 50% of the annual soil eroded. Besides, the surface soil of Benidorm has the highest erodibility in Alicante province [207]. Furthermore, an increase in the frequency and intensity of droughts in the Mediterranean basin has been

observed since 1950, posing additional challenges to existing environmental problems [208]. Particularly in Alicante, a steady rise in minimum temperatures has been detected, while most of the precipitation is produced by just a few rainfall events with high variability in the interannual and interdecadal trends across the last decades [209]. In this context, insights of Benidorm's urban development under drought-prone conditions can be found at Cremades et al. (2021) [51]. Drought risk in the hotel sector has been drastically reduced with the creation of the supra-municipal water agency and the implementation of systems that use non-conventional water resources (treated wastewater and desalination) [210,211]. Broadly, adaptation strategies of the hydrosocial cycles in the Mediterranean region are also reviewed and analysed in Arahuetes Hidalgo et al. (2018) [212].

Scientific literature focusing in Oarsoaldea is scarce. Notwithstanding, based on the expertise provided by the partners from Oarsoaldea CCLL, it is recognized that the tourism sector faces significant challenges due to climate change impacts. These include shifts in climate patterns that may lead tourists to favour alternative destinations, as well as the adverse consequences of sea-level rise resulting in the erosion of beaches and tourist areas. Consequently, these phenomena not only cause physical damage but also generate economic losses, thereby negatively impacting businesses, employment opportunities, and residential areas. It has also been found that human impacts (e.g., artificialization and soil denudation, construction of channels for estuarine riverbeds and sediment accretion in river mouths due to the construction of coastal defence structures) overwhelm the effects of sea-level rise on Guipuzcoa coastal habitats (e.g., saltmarshes, vegetated dunes, shingle beaches, estuarine zones and piers), at least between 1954 and 2004 [213]. Furthermore, the Deba area (Guipuzcoa) is intensely affected by frequent shallow landslides triggered by rainfall [56] - with 1,180 landslides inventoried in a 60-years span. For instance, many Gipuzkoa municipalities are settled in old marshes, increasing the vulnerability of residential and tourist areas near the sea to flooding. Furthermore, the Deba area

(another coastal area in the vicinity) is intensely affected by frequent shallow landslides triggered by rainfall [56] - with 1,180 landslides inventoried in a 60-years span. Primarily based on the discussions with Oarsoaldea CCLL, but also on the two scientific works mentioned, the main climate change-related hazards identified in Oarsoaldea are storms, coastal and land flooding, and landslides. These hazards mainly impact on the tourism sector, residential uses and ecosystems, however cultural heritage, commercial buildings and energy and transport networks are also potentially affected.

Although Oeiras Municipality is connected to many climate-related hazards, flooding is seen as the most relevant one due to the historical occurrences [214], the expertise from the Association of Instituto Superior Técnico for Research and Development and the review of climate change assessments. The floods affect, inter alia, tourism and the daily lives of citizens, several assets (e.g., public facilities infrastructures), and society, impacting on health and public services [215]. Moreover, although droughts take longer to develop and be noticeable in comparison with floods, they affect the whole society in Oeiras as well; e.g., by introducing constraints in terms of water security. Both of these phenomena are expected to become more frequent and intense by climate-related changes in the years to come, each time with lower uncertainty [60-63]. Climate-induced changes of the rainfall pattern in Oeiras Municipality will have an impact on several economic sectors and ecosystem services. The impacts on the Portuguese wine industry around Oeiras are particularly relevant [219]. These predicted impacts, among others, will mainly come from alterations of the water availability throughout the hydrological year and sudden occurrences of extreme rainfall. The former can be translated into rainfall decrease, rainfall deficit, water scarcity, and drought; and the latter, into flood and flash floods. Additionally, as climate change models predict a drier climate in Portugal with longer summers and shorter rainy seasons accompanied by a significant increase in extreme rainfalls, droughts and, in particular, floods will become more frequent than in the last century

[60-63]. Various technical studies also assess climate change impacts, highlighting the series of documents involved in the Climate Change Adaptation Plan of Oeiras Municipality.

In Tuscany, as in other Italian regions, there is a trending increase of extreme precipitation episodes [65-68]. These have led to significant negative impacts on Massa in recent decades. From the point of view of the safety of people, and given the risk of producing lethal consequences, the most dangerous hazard is represented by the floods in lowland areas and landslides in the hilly area [223]. Extreme rainfall events have intensified in the last years in the Magra River basin, causing severe floods in December 2009, December 2010 and October 2011 [224]. This last flash flood was particularly extreme and caused important landslides [225,226]. Additionally, most hotels and second homes are located in flood-prone areas, meaning that if no solutions are put in place, these disasters can also have serious repercussions for tourism. From the point of view of economic consequences, the most dangerous hazard is represented by coastal erosion [227,228]. The reduction in the surface area of beaches by erosion is one of the main economic problems due to its impact on tourism. Over the years, the Region of Tuscany has financed a series of projects to secure the areas at greatest risk from flooding and landslides, some of which have been completed while others are still ongoing. Regarding coastal erosion, the Tuscany Region and the Municipality of Massa are carrying out several actions, including the development of plans of beach replenishment with reuse of the sands obtained by dredging port areas, coastal protection works, accommodation of waterways with remodelling and widening of the riverbeds, and maintenance of water courses and periodic cutting of vegetation on the riverbed. Lastly, the alert system operated by the Regional Functional Centre of Tuscany (RFCT) is the main source providing information about extreme impacts of climate change in the area of Massa (constant hydrological and hydraulic weather monitoring), although there are also a series of studies carried out by the Tuscany Region to analyse the impact of climate change. Together with the Environmental

Monitoring and Modelling Laboratory for Sustainable Development, which periodically publishes studies on this topic (e.g., *Climate Change, a look at Tuscany* [229]), which periodically publishes studies on this topic [229], the RFCT also contributes to the study of local climate change.

The northern area of the Adriatic Sea is prone to storms [230], including the city of Piran. The collaboration with local experts from the Science and Research Centre of Koper and the review of the reduced number of scientific publications indicate that coastal flooding is the main concern of this city. In fact, a review of coastal flooding events along the Slovenian coast with emphasis on their formation, extent and impacts can be found in Kovačič et al. (2016) [231]. The authors estimate the number of buildings affected and the number of inhabitants at risk due to flooding as a result of the projected 1 m of sea-level rise for Koper, a nearby harbour city. Aditionally, the authors deal with the discharge characteristics of rivers in the Slovene Istria. In a similar study [77], land exposure to flooding is determined for sea-level rises of 50 cm and 100 cm along the Slovenian coast. In the worst scenario, large urban areas would be submerged, including the old city centre of Piran. As main impacts, coastal flooding threatens important buildings and heritage sites. For instance, coastal flooding affected the Tartini Square (Piran) in November 2019. This event also damaged infrastructure, leading to road cut-offs and people isolation. Moreover, coastal flooding produces damage to life and property and water infrastructure, access to fresh water, and adverse effects on aquaculture facilities receiving the storm runoff.

The scientific literature concerning climate change impacts in Gdańsk is the most extensive between the study cities. Some of the main results indicate that there is a local warming tendency in the Gulf of Gdańsk [232,233], and the extreme changes in temperature (both heatwaves and spell colds) affect the human mortality in the city of Gdańsk [234]. Moreover, a variety of studies addressing sea-level rise in the Baltic Sea have been conducted within the last decades, showing that a major increase is expected in Gdańsk [77]. For instance, a 40 cm sea-level rise would considerably

increase the frequency of flooding [235]. Similarly, the amplitude of ESLs has increased during the last decades, with the highest peaks occurring in the autumn and winter months [236], and the storminess is expected to increase in the open, eastern part of the gulf, and to decrease in the sheltered, western part [237]. The increase in wave heights during extreme storms combined with anticipated higher storm surges will lead to a lower resilience of the coast to erosion and flooding [62]. Updated estimates of exposure of land, population and assets for storm surge and sea-level rise scenarios show that flood hazard concentrates in the Vistula (Gdańsk) and Odra estuaries [238]. The strongest impacts leaded by coastal flooding are expected on the service sector, mainly tourism, since all beach areas will be affected, as well as the water supply sector [239]. The coastal erosion events and the washing away of retention tanks due to heavy rain can lead to the introduction of large amounts of sedimentary deposits into the marine environment and the potential capacity to concentrate heavy metals [87-92]. In term of figures, threshold values of extreme sea and weather events on the Polish Baltic coast are determined in Tylkowski & Hojan (2018) [246], and probabilities of extreme rainfall events are analysed in Szpakowski et al. (2018) [247], showing that, since 2000, at least four rainfall events should be classified as 100-year events. For example, the severe flash floods occurred in Gdańsk in 2001 and 2016 produced important economic and social losses [95-98]. In this regard, a complete review of historical floods can be found in Marosz (2007) [251]. The main negative consequences due to climate change in Gdańsk are well stablished [252]. According to these authors, all beach areas will be strongly affected, with a negative impact on tourism in the region; additionally, industrial areas located near the coastline or the city canals may be affected. According to the authors, the impacts of sea-level rise will strongly affect beach areas, leading to negative consequences for regional tourism. Industrial areas near the coastline and city canals may also be affected by storms and river flooding, especially those areas with embankment walls below 1 meter. Groundwater areas relying on shallow quaternary aquifers along the shoreline could experience rising water tables due to brackish water intrusion. Lastly,

low-lying regions, such as the Vistula Delta Plain, are particularly vulnerable to river floods.

Lastly, with regards to Samsun, the literature review reveals a wealth of scientific studies, which have been discussed with the CCLL partners. The historical changes in the shoreline of the Kızılırmak Delta and adjacent areas have been extensively documented [101-104], leading to the development of several mathematical and physical models to analyse coastal and beach erosion [257,258]. Findings indicate the presence of diverse mechanisms and processes driven by factors such as river sediment loads, construction of a dam and coastal sediment retention, which contribute to the long-term dynamics of the coastline. Recent years have witnessed substantial erosional processes affecting the Kızılırmak Delta, leading to the shrinkage of certain parts by approximately 1 kilometre. However, based on the outcomes of a physical model, a system of shore protection structures was developed and implemented in the Bafra Plain, adjacent to the mouth of the Kızılırmak River, effectively mitigating erosion in that area. Complementarily, the development of a comprehensive digital record of all Black Sea beaches and the application of the Coastal Vulnerability Index and Coastal Sensitivity Index at national-scale encompass the identification of flood-prone areas resulting from sea-level rise and extreme sea conditions, the evaluation of associated potential socio-economic impacts and the assessment of shoreline changes and coastal erosion in response to sea-level rise [107-109]. Concerning flood hazard, the Mert River Basin, located in the Samsun district, is especially susceptible to flooding due to the overflow of the Mert River and seasonal rainfall, which eventually causes the failure of water-retaining constructions [22,261]. Collectively, coastal erosion emerges as a significant concern in the region, while coastal and land flooding also pose important hazards. The loss of ecosystems and agricultural land and the flooding of residential areas represent the most noteworthy impacts. Notably, the Kızılırmak Delta is designated as a Ramsar site and demands protection. Furthermore, as a crucial agricultural area, the delta makes a substantial contribution to the regional

and national economy. Additionally, sea-level rise in the Black Sea will disturb both the water quality and the ecosystem balance in the lagoons of the Kızılırmak Delta, which serve as habitats and protected areas for numerous rare species.

3.4. Discussion and conclusions

Based on a novel collaborative approach through the concept of CCLL and comprehensive literature review, this paper presents an overview of the current situation of the ten European coastal cities in relation to multiple climate-related hazards and contributes to the understanding of climate change impacts on European coastal cities by combining scientific literature with local expertise. Climate change agencies and non-technical media sources have served as useful resources for obtaining information from detailed local studies, first-hand accounts and visual documentation of climate-related incidents, contributing to a more comprehensive understanding of the localized impacts of climate-related phenomena. The knowledge obtained from this study extends beyond the ten cities investigated, as the variations observed among these cities are representative of a significant portion of European coastal cities. Consequently, the results can be extrapolated to a broader context. This generalization enables the application of findings to other coastal cities in Europe, enhancing the relevance and applicability of the research outcomes.

The generalised sea-level and temperature rise, in addition to the increasing frequency and intensity of storms and temperature extremes, exacerbates a variety of hazards: coastal flooding and erosion events, heavy rains and pluvial/river floods, heat waves and cold spells, and landslides, among others. Winter storms and intense coastal flooding and coastal erosion events driven by energetic Atlantic sea states, compounded land and coastal flood risk in large agricultural and industrial cities in the Baltic Sea and Black Sea and increasing droughts, heat waves and forest fires in Mediterranean areas are some of the examples covered in this work. Moreover, these

hazards may trigger a number of impacts: destruction of land which is permanently submerged or eroded; economic and social losses due to the impacts on infrastructure, buildings, facilities, services, industry and agriculture; and loss of coastal ecosystems produced when the environmental conditions are altered.

A distinguishing feature of this research lies in the incorporation of local expertise and perceptions through collaboration with city partners from the ten European coastal cities under study. The insights and references to local climate change agencies provided by the CCLL partners offer invaluable context-specific knowledge, shedding light on the nuanced challenges faced by each city. The collaboration ensures that the analysis accurately represents the local realities and allows for a more comprehensive understanding of the impacts of climate change. By integrating the perspectives of those on the front lines of climate change, this research goes beyond traditional analyses and provides a more nuanced and relevant assessment. For this reason, communication with the CCLLs has been crucial to understanding how climate change is affecting each coastal area and what are the most relevant impacts related to the extreme events.

The perception of the main climate-related hazards and impacts may vary between the CCLLs and peer-reviewed scientific literature. The viewpoint of CCLLs might be potentially biased, depending on the degree of specialization of local governmental agencies and research institutions related to these hazards and impacts, or due to resource constraints. Conversely, peer-reviewed scientific studies may inadvertently overlook certain hazards and impacts that could be relevant to a city, either due to lack of interest or limited funding for specific research areas. Furthermore, it is essential to acknowledge that the biases in local climate change agencies and scientific findings could vary, including confirmation bias and resource-based biases. These potential biases must be considered when interpreting the results. Relying solely on these outcomes to determine the key climate change-related hazards could lead to the unintentional neglect of significant hazards that are affected by these possible biases.

For instance, coastal erosion in a region with strong tourism ties might receive more attention in CCLL discussions due to its economic implications, while other equally crucial hazards like landslides or droughts might not receive the same focus. Similarly, scientific studies funded by certain industries may unintentionally downplay the impacts of hazards relevant to other sectors. As such, researchers and policymakers must approach the results with cautious scrutiny to ensure a comprehensive understanding of climate-related hazards and their potential impacts on different aspects of a city's infrastructure and socio-economic factors.

Results also show heterogeneity in the "geographical density" of publications, with most of the studies and regions concentrating on a few regions, which severely limits the availability of information on occurrences of extreme events in certain areas for the analysis. Indeed, while there are a few well-studied areas (primarily, Dublin, Samsun and Gdańsk), the scientific literature for the other cities is scarce, especially for Oarsoaldea, Vilanova i la Geltrú and Sligo. For this reason, the information and local knowledge provided by the CCLLs have been particularly valuable. Notwithstanding, some gaps remain, posing an opportunity to extend the knowledge on some cities during the development of the SCORE project. Furthermore, it is important to note that the study may not have adequately represented certain significant coastal areas in Europe. This could be the case for the northern continental regions of Europe, spanning from France to Russia, including the Scandinavian countries, for which Gdańsk in the Baltic Sea is the sole case study included. Additionally, some coastal cities located in island territories, particularly those outside the Mediterranean region, such as the Atlantic archipelagos of Madeira, Azores, and Canary Islands, may not have been sufficiently represented.

An understanding of the key climate change events and impacts concerning European coastal cities and adjacent areas was developed through the different study cases reviewed. By embracing this comprehensive approach, it is possible to develop more targeted and effective adaptation strategies to mitigate the impacts of climate change

on coastal cities, thereby fostering resilience in the face of an uncertain future. For instance, by synthesizing the available knowledge, this study offers a baseline assessment of the cities' vulnerabilities and exposure to climate change impacts. The presented findings serve as a vital foundation for further research and enable a more targeted exploration of specific hazards and adaptation strategies. However, there is a general lack of information on past extreme events and impacts in the scientific literature to support future data gathering and the development of hazard, exposure, vulnerability and risk maps. This contributes to an increasing interest of the scientific community in studying future climate-change-related trends using computational models and only a few past events to calibrate the models, instead of producing broader, more general reviews of past events.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 4.

State-of-the-Art in indices for multi-hazard climate risk assessment

This chapter corresponds to: Laino, E., Paranunzio, R., and Iglesias, G. **Scientometric review on multiple climate-related hazards indices**. Science of The Total Environment, 2024. **945**: p.174004.

ABSTRACT

As the spectre of climate change looms large, there is an increasing imperative to develop comprehensive risk assessment tools. The purpose of this work is to evaluate the evolution and current state of research on multi-hazard indices associated with climate-related hazards, highlighting their crucial role in effective risk assessment amidst the growing challenges of climate change. A notable gap in cross-regional comparative studies persists, presenting an opportunity for future research to enhance global understanding and foster universal resilience strategies. However, a significant surge in research output is apparent, following key global milestones related to climate change action. The research landscape is shown to be highly responsive to international policy developments, increasingly adopting interdisciplinary approaches that integrate physical, social, and technological dimensions. Findings reveal a robust emphasis on geospatial analysis and the development of various indices that transform abstract climate risks into actionable data, underscoring a trend towards localized, context-specific vulnerability assessments. Based on dataset systematically curated

under the PRISMA guidelines, the review explores how prevailing research themes are reflected in influential journals and author networks, mapping out a dynamic and expanding academic community. Moreover, this work provides critical insights into the underlying literature by conducting a thematic analysis on the typology of studies, the focus on coastal areas, the inclusion of climate change scenarios, the geographical coverage, and the types of climate-related hazards. The practical implications of this review are profound, providing policymakers and practitioners with meaningful insights to enhance climate change mitigation and adaptation efforts through the application of index-based methodologies. By charting a course for future scholarly endeavours, this article aims to strengthen the scientific foundations supporting resilient and adaptive strategies for regions worldwide facing the multifaceted impacts of climate change.

4.1. Introduction

The effects of climate change on urban environments have become increasingly evident and consequential on urban environments, both coastal and inland [146,262–265]. These urban areas, representing a confluence of high population density, economic activity, and infrastructural complexity, are at the front lines of experiencing and responding to climate-induced alterations [4,66–68]. The shift in climate patterns is not just a future prediction but a present reality, altering the daily lives of millions and reshaping the natural and built landscapes of cities [266–269]. This scenario underscores the critical need for a deeper understanding of the local impacts of climate change, beyond the broader global perspective [270–273]. Such insights are pivotal in devising effective, location-specific strategies for adaptation and resilience, tailored to the unique vulnerabilities and capacities of diverse urban settings [274–277].

The escalating impact of climate change presents formidable challenges in relation to climate-related hazards, which are increasingly at the forefront of global concern [13–20]. Evidence of this mounting alarm is the surge in international policy initiatives and scientific research dedicated to addressing these challenges [88,278,279]. This unprecedented upsurge highlights a global consensus on the urgent need for action to mitigate the multifaceted risks posed by climate-related hazards, including landslides, droughts, sea-level rise, intensified storm events, heat waves, coastal erosion and flooding, among others [21–25]. As such, understanding the scale and scope of these initiatives and the knowledge generated becomes critical in orchestrating effective responses to safeguard vulnerable areas [193,280].

The challenge posed by climate change is characterized by its complexity and the multiple climate-related hazards that it encompasses, each contributing to a complex landscape of risk (Rafael J Bergillos et al., 2020; Collins et al., 2013; Laino and Iglesias, 2023b; Singh et al., 2015). In this context, index-based methodologies emerge as a key tool for systematically evaluating the vulnerability and risk posed by these hazards [107,130]. By converting diverse climate-related hazards into quantifiable indices, these methods provide a structured framework to break down, understand, and confront these challenges [90,283,284]. Indices provide stakeholders with a synthesized view of data, helping to identify patterns and direct resources and efforts where they are most needed [285,286]. Embracing index-based methods is thus a critical step in creating cohesive responses to the widespread effects of climate change [112,287]. Moreover, the integration of emerging disciplines and technologies such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and remote sensing has the potential to revolutionize multi-hazard indices, enhancing their predictive capabilities and real-time monitoring effectiveness [110].

A wide array of approaches can be found in the literature addressing climate-related hazards, each offering unique methodologies and insights. These approaches include impact, hazard, vulnerability, and risk assessments, each serving a specific purpose in

the broader context of climate resilience. Impact assessments focus on quantifying the consequences of climate-related events on various sectors, such as agriculture, health, and infrastructure [275,276]. Hazard assessments, on the other hand, concentrate on identifying and characterizing the physical processes and events that pose potential threats [27]. Vulnerability assessments aim to determine the susceptibility of populations, ecosystems, and infrastructure to these hazards, often integrating socio-economic factors to provide a comprehensive understanding [95]. Risk assessments combine elements of hazard and vulnerability assessments to estimate the probability and potential severity of adverse outcomes [288]. Furthermore, studies on adaptation and resilience measures explore strategies to mitigate these risks and enhance the capacity of systems to recover from adverse events [289]. Additionally, there are reviews and databases that compile information on multiple past weather events, providing valuable historical context and facilitating the analysis of trends over time [104,290]. Conceptual frameworks propose definitions and methodologies for assessing these hazards, contributing to the development of standardized approaches and facilitating comparative studies across different regions and contexts [16].

Typically, various studies focus on specific groups of climate-related hazards, reflecting the diverse nature of climate impacts. Coastal hazards, such as storms, sea-level rise, coastal flooding, and coastal erosion, are extensively studied due to the high vulnerability of coastal areas and the significant economic and social implications of these events [291,292]. Temperature extremes, including cold spells and heatwaves, are another critical focus, as they have direct and often severe impacts on human health, agriculture, and energy demand [293,294]. Hydrological hazards, such as heavy precipitation, land flooding, and landslides, are also commonly analysed, given their potential to cause widespread damage and disrupt communities [53,55,56]. It is also possible, albeit infrequent, to find research that integrates a wide range of these hazards simultaneously, as it will be explored in this work. Such comprehensive studies provide a holistic view of the multifaceted nature of climate risks and the

interconnectedness of different hazard types [295,296]. By examining these integrated assessments, we can better understand the cumulative impacts of multiple hazards and develop more effective strategies for managing these risks.

The geographical coverage of these studies varies significantly, ranging from local to regional, national, and even supranational and global scales [92,297,298]. Local studies offer detailed insights into specific areas, identifying particular vulnerabilities and resilience capacities that are unique to those settings [299]. Regional and national studies provide broader overviews, identifying patterns and trends that can inform policy and management strategies at larger scales [300,301]. Supranational and global studies are crucial for understanding transboundary and global-scale climate impacts, fostering international cooperation and comprehensive mitigation strategies [90,302]. These broader studies often reveal the interconnectedness of climate risks across different regions and the need for coordinated efforts to address these challenges effectively.

Regarding temporal coverage, studies may focus on past events, providing valuable historical data that can help identify trends and inform future projections [101,290]. Baseline characterizations offer a snapshot of the current situation, serving as a reference point for measuring future changes and the effectiveness of adaptation measures [90,303]. Future scenario analyses, often employing well-known Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP), model potential outcomes under different climate and socio-economic conditions [304,305]. These scenarios are essential for anticipating future risks and planning effective adaptation and resilience measures [306]. By exploring a range of possible futures, these studies help policymakers and stakeholders understand the potential impacts of different decisions and actions, enabling them to develop robust strategies that can accommodate a variety of possible outcomes [36].

A variety of models and frameworks have been developed to assess multi-hazard risks, each with its unique approach and focus. Among these, CLIMADA by ETH Zurich stands out for its emphasis on quantifying and monetizing the direct impacts of natural disasters on socio-economic factors, integrating hazard, exposure, and vulnerability data [307]. Another notable framework is DIVA (Dynamic Interactive Vulnerability Assessment) from the Global Climate Forum, which assesses the biophysical and socio-economic consequences of sea-level rise and socio-economic development [308,309]. HAZUS, developed by the US Federal Emergency Management Agency, offers a comprehensive risk assessment software for earthquakes, floods and hurricanes, utilizing GIS technology to estimate impacts [310], while SLOSH (Sea, Lake, and Overland Surges from Hurricanes) is a critical tool for estimating storm surge and flooding impact from hurricanes [311]. Additionally, the Coastal Storm Modelling System (CoSMoS) provides valuable insights into coastal flooding due to sea-level rise and storms, integrating climate change scenarios with physical process models [312]. In the conservation domain, the ADAPT tool evaluates the impact of climate change on biodiversity, demonstrating the importance of ecological considerations in hazard assessments.

Previous scientometric studies have paved various paths in multi-hazard risk assessment research [27]. Owolabi and Sajjad (2023) employed state-of-the-art tools to provide a panoramic view of the MHRA field, covering different methodological tools to assess risk and revealing critical gaps in international collaboration and a predominant focus on landslide hazards. Curt (2021) took a textual analysis approach, categorizing the multi-risk literature into distinct thematic areas and calling for more comprehensive studies on the subject. Laino and Iglesias (2023c) combined bibliometric analysis with participatory processes involving European coastal cities to present an intricate picture of the impacts of climate change at the local level, introducing the innovative concept of CCLL [119,120]. Lima and Bonetti (2020) presented a historical and geographical perspective on social vulnerability in coastal

populations, highlighting an increase in studies related to climate change impacts and the need for a consensus in terminology. Our study builds upon these foundations but stands out by zeroing in on index-based methodologies, due to their crucial role in simplifying complex climate data into understandable formats that aid decision-makers in managing climate risks [98].

The relevance of this work lies in its comprehensive scope and systematic approach to synthesizing existing research on climate-related multi-hazard indices. As climate change exacerbates the frequency and intensity of various hazards, understanding the interconnected nature of these risks is paramount. Effective responses to climate change require coordinated efforts across borders, leveraging diverse expertise and resources. In this context, index-based methodologies provide a structured way to synthesize complex climate data, making it accessible and actionable for decision-makers. They enable the identification of critical patterns and trends necessary for developing targeted adaptation and mitigation strategies. Hence, this work addresses a crucial gap in the scientometric literature on climate-related multi-hazard indices.

This review will systematically evaluate diverse index-related approaches to studying climate-related hazards, the consideration of coastal areas and climate change scenarios, (Bergillos et al., 2020a; Bergillos et al., 2020; Gallina et al., 2020; Godwyn-Paulson et al., 2022; Mathew et al., 2020; Thakur and Mohanty, 2023) and a varied hazard, geographical, and temporal coverage [114,317–319]. Additionally, a meta-analysis of academic contributions will be conducted, examining influential authors, primary journals, and prevailing keywords through scientometric methods. This multi-layered approach will provide a comprehensive understanding of the existing literature, uncover trends, reveal research gaps, and identify the most impactful contributions, guiding future studies toward areas with significant potential for advancements. This review also traces the evolution of publication focus, highlighting a shift from physical hazards to policy, adaptation social and technological dimensions. By doing so, it underscores the dynamic nature of climate change research

and the increasing need for integrated, multidisciplinary approaches. Moreover, this work emphasizes the importance of international collaboration by proposing actionable pathways for enhancing global research partnerships.

Essentially, this review offers a thorough synthesis that is reflective of the field's past and anticipatory of its future, serving as a valuable resource for researchers, policymakers, and practitioners aiming to contribute to the field of climate risk assessment and management. Ultimately, this review is conceived to provide a robust understanding of the current state of index-based climate change research. In turn, it aims to contribute to advancing index-based approaches, informing better decision-making, fostering more resilient communities and ecosystems, enhancing our collective capacity to mitigate climate risks and adapt to changing conditions, and fortifying vulnerable areas against the detrimental effects of climate change.

4.2. Materials and methods

This work systematically reviews the publications on multiple climate-related hazards that incorporate indices. To ensure a systematic and transparent review process, this study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [320]. The PRISMA methodology enhances the clarity and rigor of the review by providing a structured approach to literature search, selection, and synthesis.

The primary data source for this review is Scopus, a renowned scholarly publication database widely recognized for its comprehensive coverage of academic research [142]. The search strategy was designed to ensure the inclusivity of relevant publications. Specific keywords were selected based on their relevance and common usage in the literature to capture a comprehensive range of studies focusing on indices related to multiple climate-related hazard. These keywords were systematically applied to the Title, Abstract, and Keywords fields without imposing any additional

search restrictions on 23rd October 2023. The search expression included variations such as "Climate multi-hazard index", "Climate multiple hazards index", "Climate-related hazard index", "Climate-induced hazard index", "Natural hazards index", "Natech hazards index", "Extreme climate events index", and "Multi-hazard assessment climate change". These terms broadly encompass the diverse terminology used by researchers in this field, ensuring a thorough inclusion of relevant studies. For example, "Natech hazards index" refers to indices that assess natural-technological hazards, while "Extreme climate events index" pertains to indices for extreme weather events. The complete query string applied was "TITLE-ABS-KEY (climate OR weather AND multi-hazard AND index) OR TITLE-ABS-KEY (climate OR weather AND multiple AND hazards AND index) OR TITLE-ABS-KEY (climate-related OR weather-related AND hazard AND index) OR TITLE-ABS-KEY (climate-induced OR weather-induced AND hazard AND index) OR TITLE-ABS-KEY (natural AND hazards AND index) TITLE-ABS-KEY (natech AND hazards AND index) OR TITLE-ABS-KEY (extreme AND climate OR weather AND events AND index) OR TITLE-ABS-KEY (multi-hazard AND quantification OR assessment OR methodology AND climate AND change)". This comprehensive keyword search returned a total of 292 publications, which formed the initial dataset for the scientometric analysis.

The collected publications were filtered through a three-phase process (Figure 4.1). Firstly, duplicate publications were identified and removed, along with studies lacking sufficient information. This initial phase resulted in the removal of 5 publications with insufficient information (5). Secondly, publications not in English (7) and those that did not focus on climate-related hazards (7) were eliminated. This phase involved a detailed examination of the title, abstract, and keywords to ascertain relevance. The third and final phase of filtering involved a thorough review of the full-text content of the remaining publications. Only those publications that unequivocally addressed the topic of "Studied on multiple climate-related hazards involving indices" were retained.

This rigorous assessment led to the exclusion of 180 publications. Following these three filtering phases, a final dataset of 93 publications was established, forming the foundation for the subsequent review.

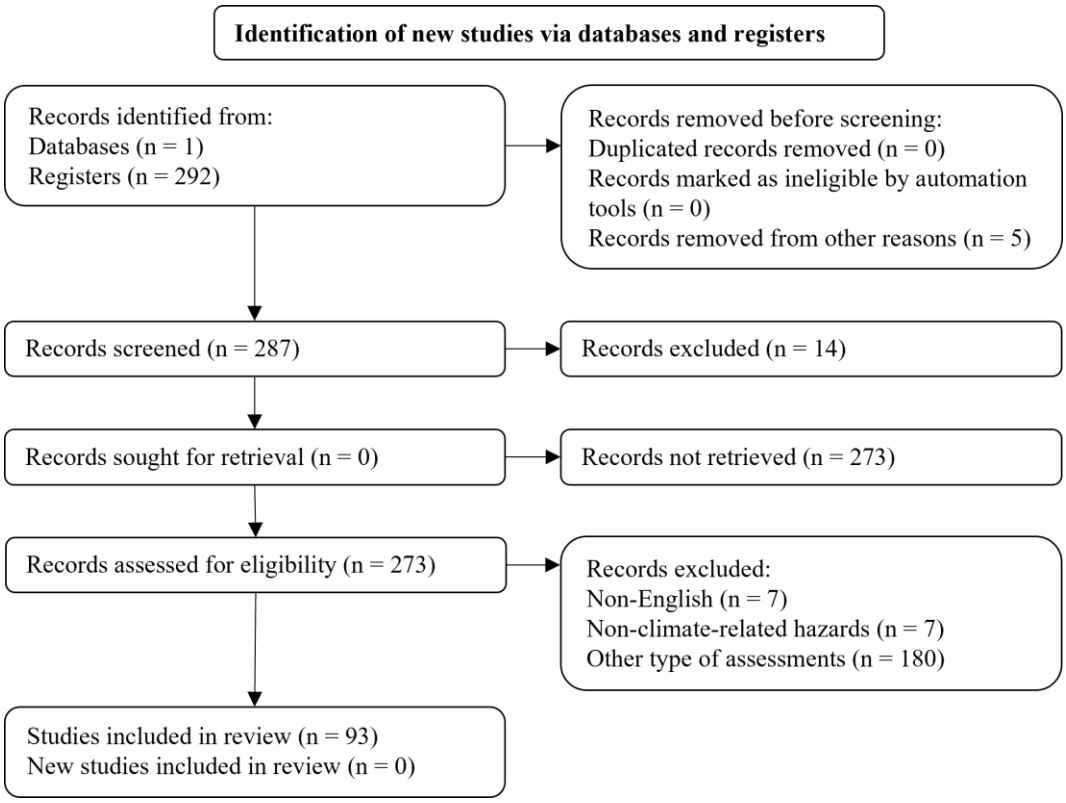


Figure 4.1. Screening process, in alignment with PRISMA 2020 methodology.

With this refined dataset, the review was conducted focusing on several key aspects. A thematic analysis was performed on the assessment methodologies, the focus on coastal areas, the inclusion of climate change scenarios, the geographical coverage, and the types of climate-related hazards covered by the publications. This was followed by a scientometric analysis to examine the historical evolution, geographical distribution, key authors and contributions, influential journals, citation patterns, and essential keywords within the research domain of climate-related multi-hazard indices. Ultimately, this work provides a comprehensive overview of the field, identifies significant trends, and discusses research gaps and strategic insights for policymakers and practitioners. A detailed workflow outlining the sequential steps from initial data collection to the final generation of insights is presented in Figure 4.2.

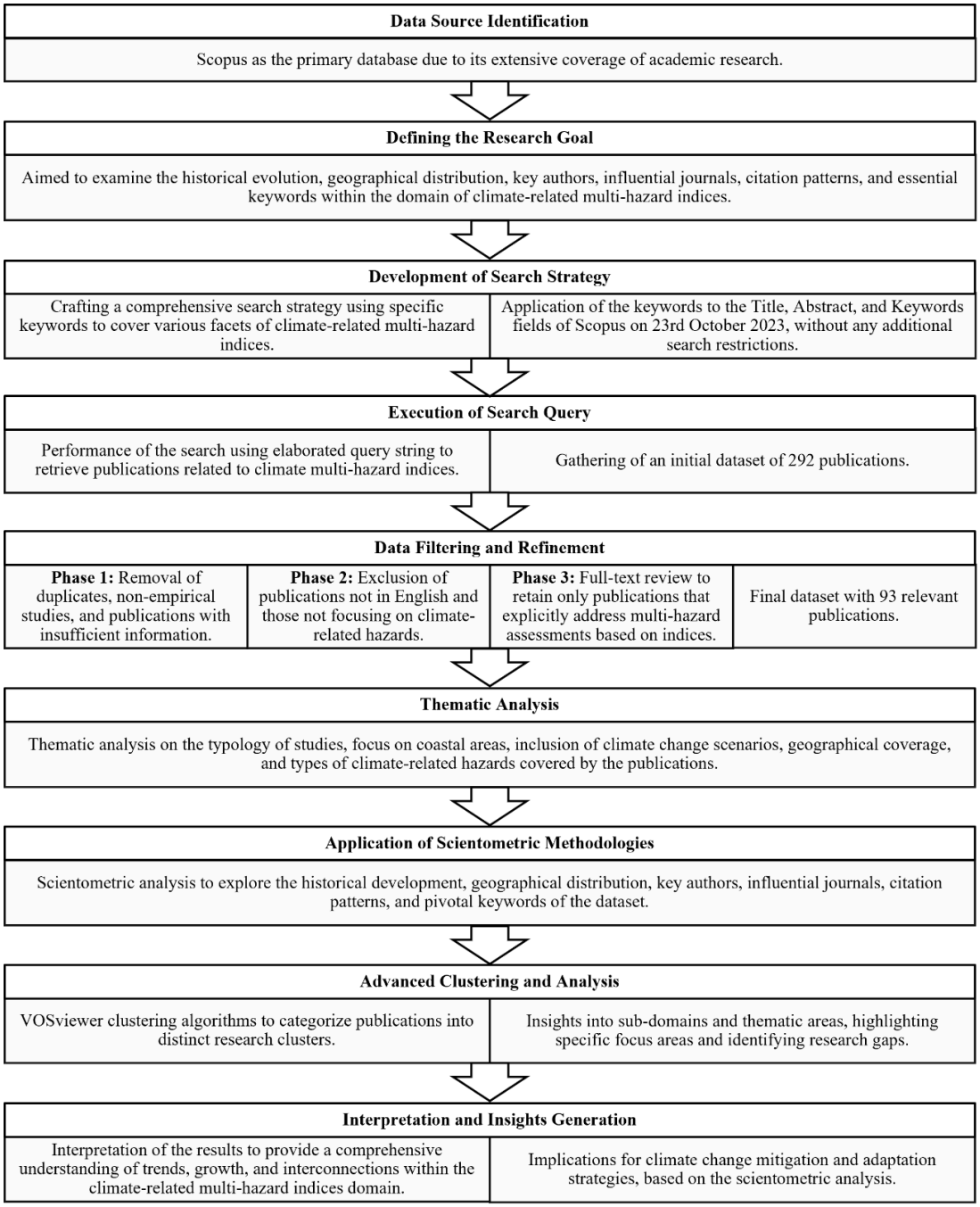


Figure 4.2. Flowchart of the methodological approach.

The thematic analysis classified the publications according to their main focus, including hazard assessment, vulnerability assessment, risk assessment, impact study, database, review, adaptation solutions, or conceptual work. The publications were discussed within these categories. Special attention was given to works aimed at evaluating coastal areas and those that integrated climate change scenarios. Publications were also classified based on their geographical coverage, ranging from

local, regional, national, to supranational levels. Additionally, the types of climate-related hazards assessed in the publications were catalogued. The analysis of storms encompassed cyclones, hurricanes, and tropical storms. While these could include other hazards such as strong winds, heavy precipitation, and flooding, these threats were considered separately depending on how each paper evaluated them. For example, some studies might assess heavy precipitation events without discussing storms. For clarity, coastal flooding analyses included its components, such as storm surge, tides, and waves. Other geohazards not directly attributable to climate, such as volcanoes, earthquakes, or tsunamis, as well as natural-technological (Natech) hazards, are outside the scope of this review.

Diverse software and visualization tools were employed in the scientometric review to effectively analyse the dataset and generate meaningful insights. Specifically, VOSviewer [143] was utilized to construct and analyse the complex co-authorship networks, citation networks, and co-occurrence networks of keywords. VOSviewer is an open-access tool that implements the VOS approach [144]. Co-authorship networks were employed to identify key authors and collaborations in the field. Citation networks enabled the identification of influential publications and tracing the impact of research over time. Lastly, the co-occurrence networks of keywords were utilised to reveal the central themes and emerging trends within the domain of climate-related multi-hazard indices. Furthermore, the advanced clustering algorithms of VOSviewer assisted in categorizing the publications into distinct research clusters, providing a clearer understanding of sub-domains and thematic areas within the broader field. This granularity served as a valuable tool to unveil the specific areas of focus and gaps in current research.

By systematically reviewing the literature, this study seeks to provide a comprehensive understanding of the field, identifying significant trends, growth, and interconnections, and highlighting research gaps. This approach ensures that the findings are robust and reliable, offering valuable insights for future research

directions and policy formulation in the context of climate-related multi-hazard indices.

4.3. Results

4.3.1 Trajectory of research

Figure 4.3 illustrates the progression in the volume of publications related to multi-hazard indices and climate-related hazards from 1999 to 2023. The timeline depicts a clear growth trend in research interest and output, reflecting the increasing academic and practical significance of this field.

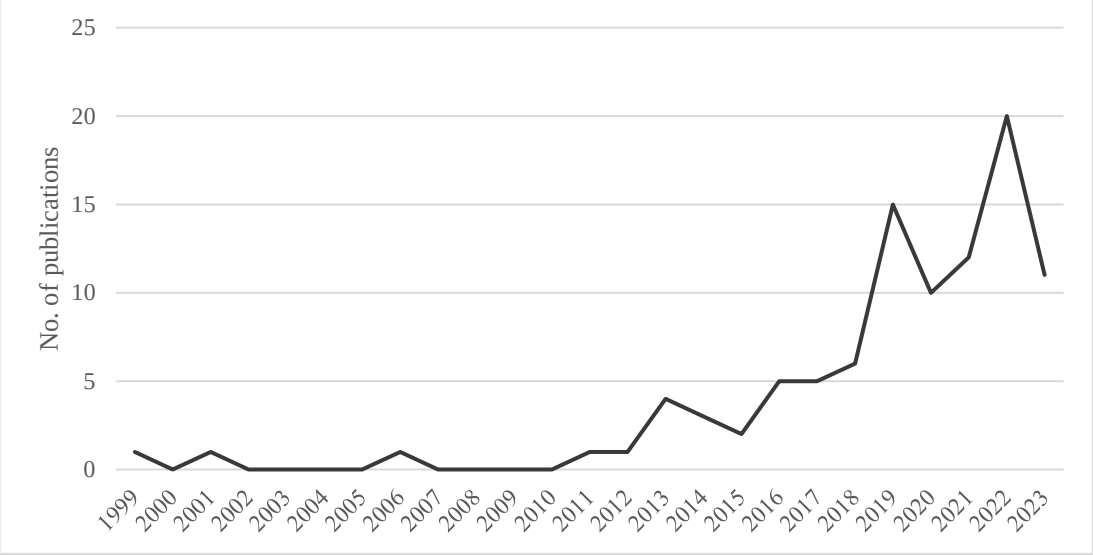


Figure 4.3. Number of publications regarding multi-hazard indices by year.

Initially, the field shows a nascent stage between 1999 and 2010, where the number of publications per year remains relatively low and consistent, suggesting a foundational period of research where key concepts and methodologies were being established.

The uptick in publication frequency beginning in 2011 suggests a growing interest that likely stems from an increased global recognition of climate change challenges. This

period preludes critical events in the climate change discourse, including the release of the IPCC's 5th Assessment Report and the adoption of the Paris Agreement in 2015. These significant milestones likely provided the impetus for the research community to intensify their efforts, which is reflected in the rise of scholarly articles during this time.

The surge after 2015 can thus be interpreted as a direct consequence of these global frameworks taking shape, reflecting a period where the academic community actively engaged with the evolving discourse on climate change and a global push for sustainable development goals. This engagement may be further supported by advances in data collection and analytical technologies, alongside an increase in climate-related research funding [11,129,321]. The momentum generated during this time appears to momentarily taper off during 2019-2020, a trend which may be attributable to the global disruption caused by the COVID-19 pandemic, suggesting a temporary shift in research priorities and capacities.

The subsequent recovery in 2021 and 2022 signifies the resilience of the field, with a potential increase in interdisciplinary research, policy-driven studies, and a focus on adaptation and mitigation strategies in response to escalating climate hazards [322].

The preliminary data for 2023 suggest a slight decrease from the previous year, which warrants further investigation to determine whether this is a temporary fluctuation or the start of a new trend. Overall, the trajectory of publications mirrors the dynamic nature of the field, with a clear upward trend indicative of its growing importance. This trend underscores the need for continued research and innovation to address the complex challenges posed by multi-hazard environments in the context of climate change.

4.3.2 Typology and focus of publications

The bar chart in Figure 4.4a reveals that only 10 out of the 93 records incorporate future scenarios using RCP or SSP. Additionally, 28 records focus on coastal areas. Among the studies dedicated to coastal zones, most concentrate on coastal hazards, traditionally employing the Coastal Vulnerability Index (CVI) [284,287,323]. An exception is the study by Zanetti et al. (2016), which integrates indicators of land flooding and landslides with the CVI to assess joint vulnerability in Santos, a coastal municipality in São Paulo state, Brazil.

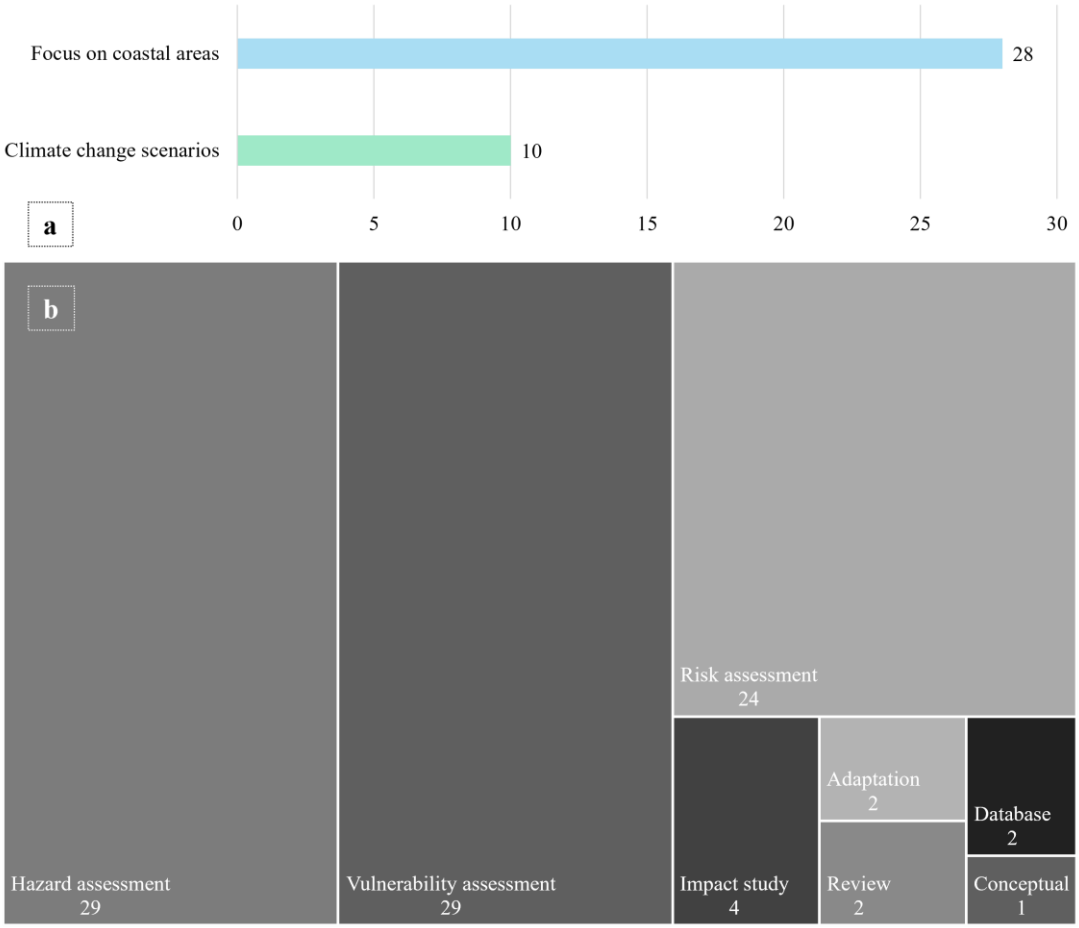


Figure 4.4. Number of studies according to the consideration of coastal areas or climate-change scenarios (a) and their typology (b).

Studies focusing on coastal areas that use the CVI typically do not evaluate future scenarios. The three studies that do incorporate future scenarios employ different

indices. For example, Antunes et al. (2019) uses the Extreme Flood Hazard Index to assess sea-level rise and coastal flooding for the years 2025, 2050, and 2100. Kapsomenakis et al. (2023) employs climate indices to evaluate hazards such as sea-level rise, heavy precipitation, droughts, extreme temperatures, and wildfires at UNESCO cultural and natural heritage sites in the Mediterranean. Mondal et al. (2022) assessed risks from storms, sea-level rise, coastal flooding, and land flooding in 15 villages in the Indian Sundarbans deltaic region using the DEMATEL methodology combined with the Livelihood Vulnerability Index and incorporating the RCP4.5 scenario.

The filtered dataset was classified into several categories based on their primary focus and contribution to the field of multi-hazard assessments (Figure 4.4b). The findings indicate a balanced distribution of studies across hazard, vulnerability, and risk assessments, with additional contributions in impact assessments, adaptation solutions, datasets and theoretical frameworks. Risk assessments were the focus of 24 publications in the dataset. These studies integrated hazard and vulnerability data to provide a comprehensive view of potential impacts. The proportion of risk studies is significantly lower compared to partial studies focusing on hazard (29) or vulnerability (29) assessments, considering these components together as part of risk studies. Multi-hazard assessments typically involved the identification and quantification of various climate-related hazards in different geographical regions and under varying climatic conditions [326–328]. The vulnerability assessments generally quantify the susceptibility of populations, infrastructures, and ecosystems to multiple climate-related hazards [329–331]. Impact assessments, which examine the direct and indirect effects of climate-related hazards on specific sectors or regions, comprised 4 publications [300,332–334].

In addition to these categories, 2 publications explored adaptation strategies and solutions to mitigate the impacts of climate-related hazards in historic areas and the Indian Sundarbans [335,336]. The dataset also included 2 review publications. Lima

and Bonetti (2020) applied scientometric techniques to the scientific production on social vulnerability of coastal populations, whereas Tappi and Santeramo (2022) reviewed the literature on index-based insurance with a focus on risk management policies in Italy. Furthermore, 2 databases were identified: one covering socioeconomic and climate risk scores through the Federal Emergency Management Agency National Risk Index, evictions, and housing indicators for Miami [337], and another encompassing various past extreme climate events (heat waves, cold waves, extreme temperatures, windstorms, and heavy precipitation events, including rainfall and snowfall) through the Weather Extremity Index [290]. Lastly, 1 publication focused on conceptual work, presenting a framework for the definition and assessment of Climatic Impact-Drivers. This conceptual study by Ruane et al. (2022) proposed a novel approach to understanding and evaluating the complex interactions between climatic factors and their impacts, offering a foundational framework for future research.

4.3.3 Geographical coverage and climate-related hazards

The geographical distribution of studies, illustrated in Figure 4.5a, indicates that regional studies constituted the largest portion, with 43 publications indicating a strong emphasis on localized assessments. National-level assessments also represented a significant part of the dataset, with 17 publications focusing on country-specific studies. Notable national-level studies cover countries such as the Czech Republic [290], Bangladesh [338,339], Italy [340], Mexico [341], the USA [300,342–344], Portugal [75], Colombia [334], China [345], and Brazil [53]. However, these studies cover a limited number of countries globally, with a significant number concentrated in the USA. Supranational studies, comprising 24 publications, underscore the importance of understanding climate-related hazards in a broader context. Notable examples include the comprehensive multi-hazard risk assessment proposal for deltaic regions worldwide by Hagenlocher et al. (2018), the multi-hazard assessment for

European regions incorporating climate-change scenarios by Lung et al. (2013), and the global mapping and ranking of mortality, affected populations, and GDP loss risks by Shi et al. (2016), covering a wide array of climate-related hazards such as storms, coastal and land flooding, droughts, landslides, heatwaves, cold spells, and wildfires. This subset also includes the review studies, one of the adaptation studies, and the conceptual work. Additionally, 9 publications focused on specific cities and localities, demonstrating detailed analyses of multi-hazard impacts at finer scales, e.g., city [294,298,337], industrial facility [299], or port [346].

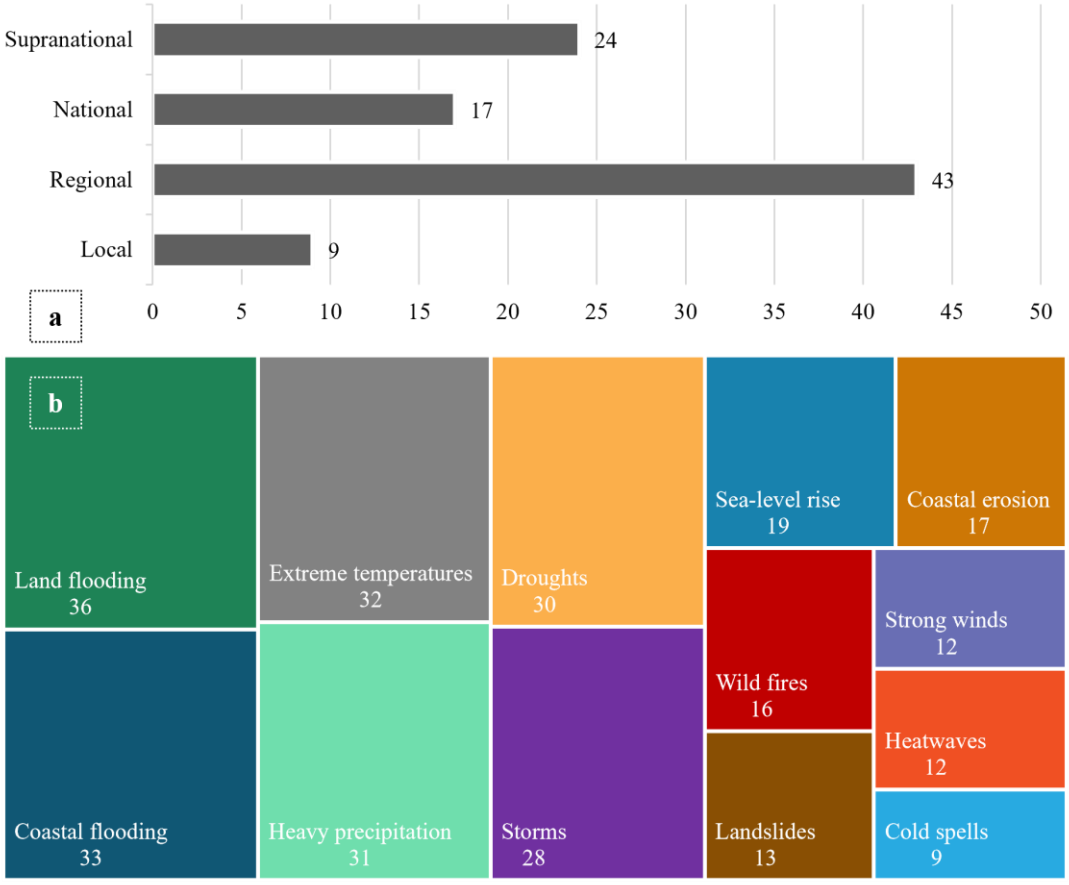


Figure 5. Number of studies according to their geographical coverage (a) and the climate-related hazards included (b).

The climate-related hazards covered in the 93 publications were classified into several categories, as shown in the treemap (Figure 4.5b). These categories include land flooding, extreme temperatures, coastal flooding, droughts, heavy precipitation,

storms, sea-level rise, coastal erosion, wildfires, strong winds, heatwaves, landslides, and cold spells. Land flooding was the most frequently studied hazard, appearing in 36 publications, reflecting the significant impact of flooding on various regions and the critical need for effective flood risk management strategies. Coastal flooding (33 publications), heavy precipitation (31 publications), and storms (28 publications) were also extensively studied, indicating a strong research focus on hydrological hazards [112,347,348]. In contrast, coastal erosion (17 publications) and landslides (13 publications) appeared less frequently, suggesting these areas might require additional research attention. Extreme temperatures (32 publications) and droughts (30 publications) were prominent focuses, highlighting widespread concerns over temperature extremes and aridity and their effects on human health, agriculture, and infrastructure [163,294,349]. It was noted that precipitation and temperature variables are often studied together [293,350,351]. Cold spells were the least frequently studied hazard, appearing in only 9 publications, indicating a relatively lower research emphasis on cold-related events compared to other climate hazards, possibly due to their lesser frequency or impact in certain regions. Heatwaves and strong winds also appeared less frequently, each addressed in 12 publications. However, it should be noted that heatwaves and cold spells are partially covered by assessments of extreme temperatures. This distribution of hazards highlights the diverse range of climate-related threats that researchers have focused on, emphasizing the comprehensive nature of multi-hazard assessments.

The scientometric analysis of the five most cited papers in this domain, summarised in Table 4.1, reveals both unique approaches and common themes that have emerged over time. This groundbreaking research and related methodologies have shaped the understanding of multi-hazard indices in the context of climate-related hazards [108,287,323,352,353].

Table 4.1. Top five cited articles.

Authors	Title	Year	Journal	Citations
I.S. Holand, P. Lujala and J.K. Rød	Social vulnerability assessment for Norway: A quantitative approach	2011	Norsk Geografisk Tidsskrift	149
A.Islam, D. Mitra, A. Dewan and S. H. Akhter	Coastal multi-hazard vulnerability assessment along the Ganges deltaic coast of Bangladesh-A geospatial approach	2016	Ocean and Coastal Management	142
N. Hoyos, J. Escobar, J.C. Restrepo, A.M. Arango and J.C. Ortiz	Impact of the 2010-2011 La Niña phenomenon in Colombia, South America: The human toll of an extreme weather event	2013	Applied Geography	120
T. Lung, C. Lavalle, R. Hiederer, A. Dosio and L.M. Bouwer	A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change	2013	Global Environmental Change	105
B. Sahoo and P. K. Bhaskaran	Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast	2018	Journal of Environmental Management	99

A number of common aspects and trends may be identified in these papers. A recurring theme is the development and application of various indices, such as the Socioeconomic Vulnerability Index [354], Coastal Risk Index [355], Built Environment Index [356], and Coastal Vulnerability Index [357]. These indices are critical for quantifying and visualizing the vulnerability and risks associated with climate-related hazards.

Many studies focus on a specific geographic region, underscoring the importance of localized research in understanding and mitigating the impacts of climate hazards [106]. This regional specificity allows for more accurate assessments and tailored

mitigation strategies. These studies often integrate data from diverse sources, including physical parameters, socio-economic data, and environmental factors [358]. This multidisciplinary approach enriches the analysis and provides a more holistic understanding of the hazards.

Another common thread in these studies is the acknowledgment and analysis of the impact of climate change on the increasing frequency and severity of hazards [359], which highlights the growing importance of climate change considerations in multi-hazard research [54,61]. Several papers not only assess current vulnerabilities but also project future scenarios [54,61,111]. This forward-looking approach is crucial for planning and preparing for upcoming challenges in hazard management [360].

Notwithstanding, the analysis of the existing literature provides relevant insights for future research. For instance, whereas regional studies are invaluable, there is a potential research gap in cross-regional comparative analyses, which could provide broader insights into global patterns and differences in vulnerability and resilience [361]. For instance, the integration of different fields of study, such as climatology, geography, social science, and urban planning, can further enhance our understanding and response to multi-hazard risks [113].

There is a need for further exploration of how these research findings can be translated into effective policy and practical solutions, especially in regions most vulnerable to climate-related hazards [362]. Multi-hazard indices can be integrated into urban planning frameworks, informing land use decisions, infrastructure development, and building codes. These indices may guide resource allocation, emergency preparedness, and response strategies, ensuring that adequate support mechanisms are in place before a disaster strikes. Moreover, raising public awareness and engaging communities in the development and implementation of these indices are crucial for their effectiveness and acceptance.

Leveraging advancements in remote sensing, GIS technologies, and big data analytics could provide new dimensions to multi-hazard index research [363]. The integration of AI, ML, IoT, and remote sensing technologies can enhance the precision, granularity, and predictive power of multi-hazard indices. AI and ML algorithms process vast datasets to identify trends and correlations, offering predictive insights into potential hazards. IoT devices enable real-time data collection, ensuring that indices are responsive to current conditions. Advanced remote sensing provides comprehensive data on geographical and environmental conditions, enriching the multi-hazard indices with high-resolution information.

4.3.4 Author connections and research topic evolution

The analysis utilized a filtered dataset comprising 93 publications from Scopus, revealing interesting insights into author collaborations and keyword trends. The most prolific author in our dataset has only two publications, indicating a nascent stage in this research domain. As depicted in Figure 4.6, the interrelationship among authors, each with at least one publication, is somewhat limited. This figure also shows the averaged publishing years for each author. These calculations are restricted between 2016-2024 for better comparability. As previously shown, the yearly number of publications reaches 5 from 2016 onwards. Altogether, results showcase an early development stage for the research topic, with authors predominantly working in small, isolated groups.

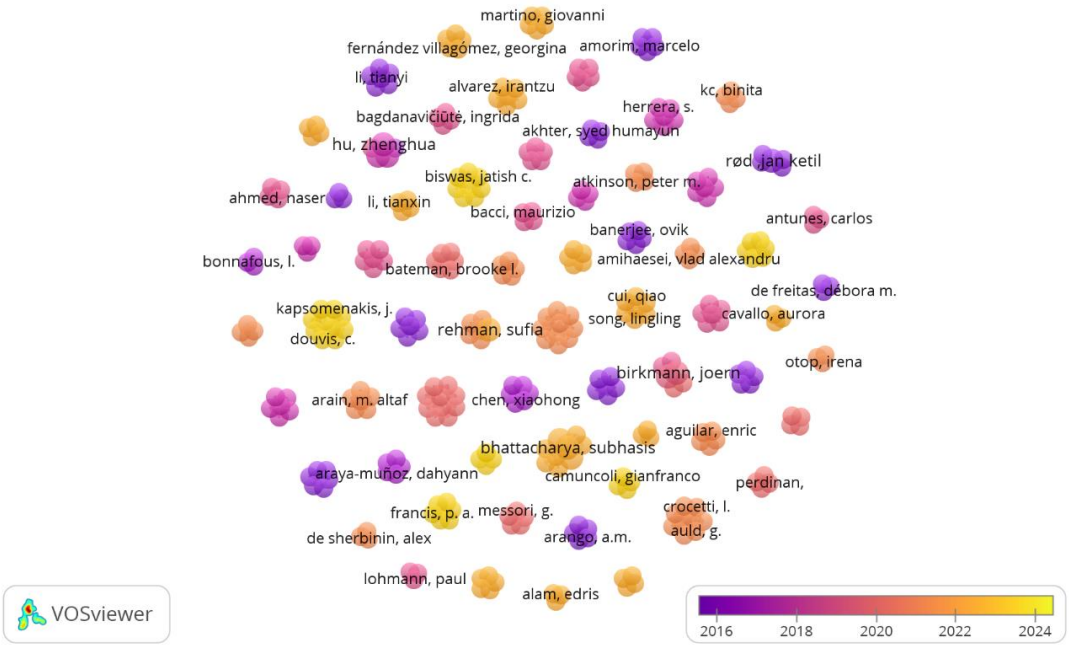


Figure 4.6. Temporal evolution and linkage between authors related to multi-hazard indices.

Interestingly, keyword analysis illustrates a more interconnected landscape. Dominated by 'climate change', the research field connects a diverse array of topics, as shown in Figure 4.7. After averaging the number of occurrences for each keyword between 2016 to 2022, a notable evolution in research focus may be observed:

- Early-Stage Keywords (2016-2018): Focused on hazard and physical system components, including “vulnerability”, “flood”, “forest fire”, “natural hazard”, “extreme events”, “coastal areas”, “multiple climate hazards”, “exposure”, “urban” and “rural”, among others.

- Intermediate Stage Keywords (2019-2020): Shift towards policy and adaptation, with terms such as “Paris Agreement”, “climate change policy”, “sea-level rise”, “climate change adaptation”, “disaster risk reduction” and “resilience” gaining prominence.

- Recent Stage Keywords (2021-2022): Emerging focus on social and technological aspects, with “machine learning”, “ecoregion”, “composite fragility index”, “socioeconomic factors", “emissions”, “gender composition", “threat perception”, “emergency preparedness”, “ecosystem services”, “green infrastructure” being key topics.

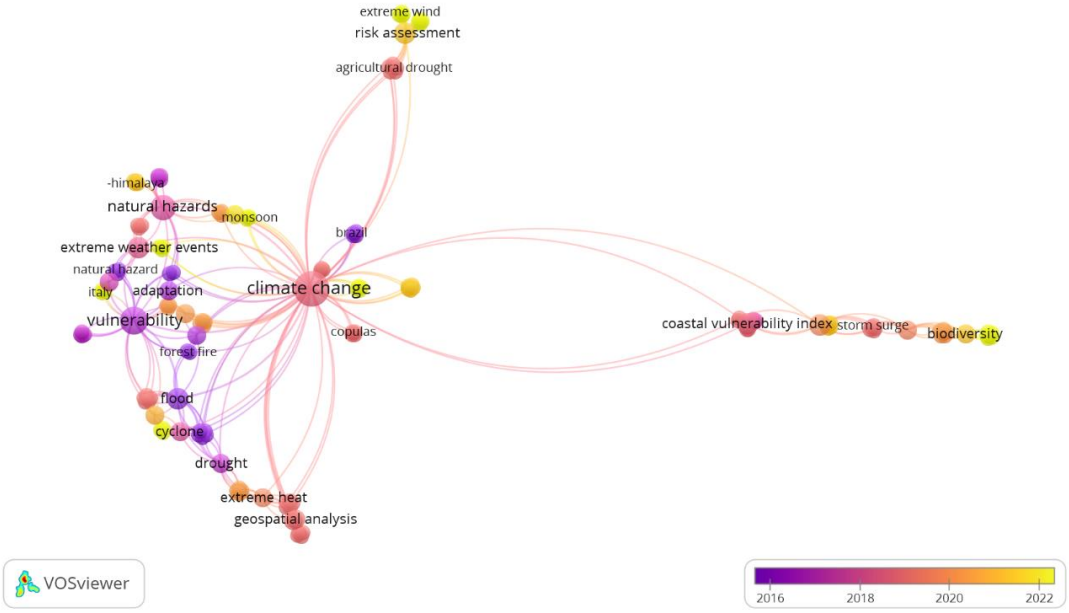


Figure 4.7. Temporal evolution and linkage between keywords related to multi-hazard indices.

This trend suggests a shift from studying the physical aspects of climate change to incorporating social dynamics and technological solutions, possibly reflecting the growing global concern about climate change impacts. In this regard, the integration of cutting-edge technologies in the development and application of multi-hazard indices represents a pivotal shift towards more dynamic, predictive, and responsive urban planning and disaster management strategies. The advent of AI, ML, IoT, and advanced remote sensing technologies has the potential to significantly enhance the precision, granularity, and predictive power of these indices.

ML algorithms can process vast datasets from diverse sources to identify patterns, trends, and correlations that might not be evident through traditional analysis [364]. For multi-hazard indices, this means the ability to predict the likelihood of specific hazards, their potential impact, and the vulnerability of different urban areas with a high degree of accuracy [365,366]. For instance, ML models can forecast the progression of coastal erosion, or the impact of an urban heat island based on historical data, current trends, and future projections, allowing city planners to allocate resources effectively and design proactive mitigation strategies.

IoT devices enable the real-time collection and transmission of data from various sources, including sensors placed in buildings, infrastructure, and natural environments [367]. These real-time data can be fed into multi-hazard indices, offering up-to-date information on risk factors such as air quality, water levels, ground stability, or structural integrity of buildings. The integration of IoT into dynamic indices which are responsive to current conditions can facilitate timely decision-making and resource allocation in response to emerging risks, as shown in early warning systems and digital twins [193].

Advances in remote sensing technologies, including satellite imagery and aerial drones, provide comprehensive, high-resolution data on geographical and environmental conditions [368]. These data are convenient for assessing risks associated with climate-related hazards over large areas and inaccessible terrains. By incorporating remote sensing data, multi-hazard indices can offer a more complete view of risk factors, spanning from topographical changes due to erosion or landslides to changes in vegetation patterns indicative of drought or fire risk [369].

4.3.5 Leading journals in climate-related multi-hazard indices research

Figure 4.8 presents a list of journals that have significantly contributed to the discourse on multi-hazard indices in the context of climate-related hazards, as evidenced by their citation counts. It showcases journals with more than one publication on the topic that have accumulated a significant number of citations, reflecting their impact and relevance in the field. The number in parentheses next to each citation count represents the number of publications from each journal, providing a quantitative measure of productivity and influence within the field. This analysis not only signifies the journals' scientific contributions but also guides researchers in identifying key platforms for literature in the domain of climate-related hazard indices.

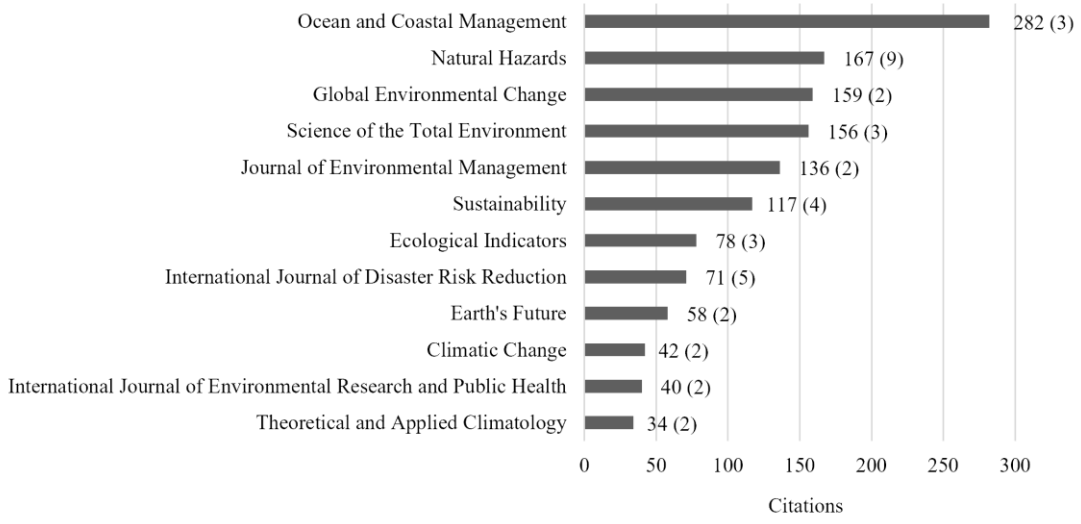


Figure 4.8. Citations and, in brackets, number of articles for the journals with more than two publications regarding multi-hazard indices.

Ocean and Coastal Management leads with the highest number of citations (282), indicating its prominent role in publishing influential research that addresses the intersection of marine systems and human activities, particularly with a focus on management strategies in the face of climate hazards. It may also indicate the relevance of coastal hazards within the study of climate-related risks [370].

Natural Hazards follows closely, which is consistent with its focus on the multidisciplinary nature of risks associated with natural phenomena. The journal's significant citation count (167) underscores the importance of integrative approaches to understanding and mitigating natural hazards.

Science of the Total Environment (156) stands out as well, reinforcing its reputation for covering a broad spectrum of environmental science research, including the study of multi-hazard risks and their implications on ecosystems and human health.

Other notable journals, such as *Global Environmental Change* (159), *Journal of Environmental Management* (136), and *Sustainability* (117), contribute a substantial body of work, reflecting a sustained interest in sustainable management practices and the broader implications of environmental change. Similarly, *Ecological Indicators* (78) and International *Journal of Disaster Risk Reduction* (71) also make notable contributions, highlighting the trend towards using indicators and risk reduction strategies in environmental research.

Somewhat less cited perhaps, yet significant, contributions originate from journals such as *Earth's Future* (58) and *Climatic Change* (42), *International Journal of Environmental Research and Public Health* (40) and *Theoretical and Applied Climatology* (34) which may focus on emerging themes – forward-looking research that integrates future scenarios, predictive modelling, and theoretical and applied aspects of climate science.

4.3.6 Author connections and research topic evolution

Results elucidate the spatial dynamics underpinning multi-hazard indices research, leveraging an integrative analysis that combines VOSviewer network insights with geographical mapping. The focal point of this exploration is the identification of key contributors and the examination of their collaborative and temporal research patterns, offering a panoramic view of the evolution of the field.

The distribution of research output and collaboration is not merely widespread but illustrates a strategic alignment among nations. Figure 4.9 delineates the core group of countries at the forefront of this domain, including but not limited to India, United Kingdom, United Stated of America, Germany, China, Bangladesh, Italy, Netherlands, Australia, France, Sweden and Norway. This visual representation underscores the connectivity and cooperative endeavours among 37 actively participating countries, emphasizing those with substantial contributions in terms of publications and citations.

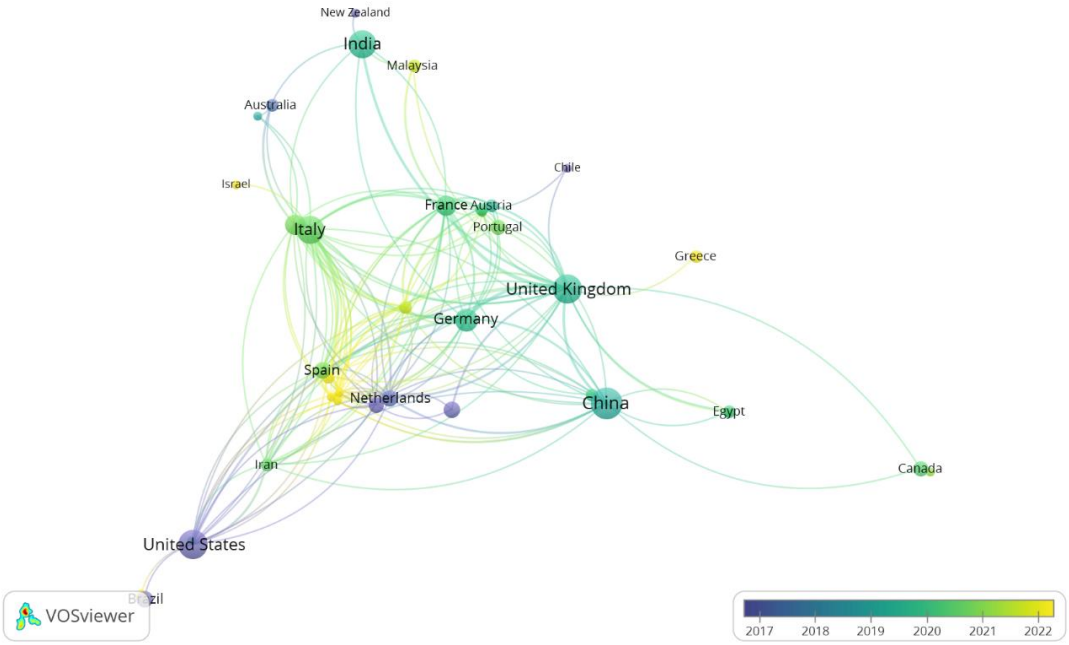


Figure 4.9. Network visualization of countries.

A noteworthy aspect of the analysis is the temporal progression of research contributions across different regions. For instance, the Netherlands, the USA, Brazil, and Australia are identified as the trailblazers, having initiated research efforts earlier than their counterparts. This temporal stratification reveals an evolving landscape where countries like China, the United Kingdom, Germany, and India have rapidly caught up, contributing significantly to the body of knowledge. Meanwhile, nations such as France, Italy, Spain, Portugal, and Iran represent a middle tier of contributors,

with Switzerland, Malaysia, Greece, Argentina, and the United Arab Emirates emerging as the newest entrants in the research scene. The collaboration pattern suggests a robust network of knowledge exchange that transcends geographical boundaries, hinting at the global prioritization of multi-hazard indices research. Moreover, the evolving leadership, with newer entrants making significant contributions, underscores the dynamic nature of the field and its expansion beyond traditional research powerhouses.

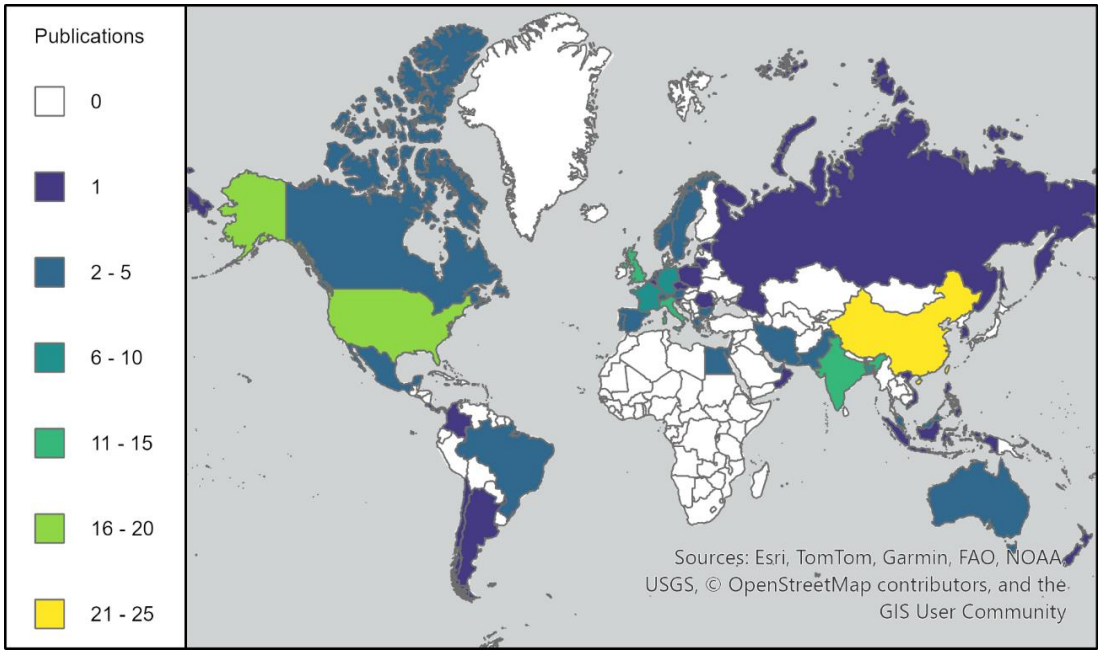


Figure 4.10. Geographical distribution of publications.

Further dissecting the geographical distribution of impact, as depicted in Figures 4.10 and 4.11, it is observed a differentiation between the volume of research output and the accumulation of citations. The data reveal that the top five citation-accumulating countries are India (533 citations), the United Kingdom (522), the United States (365), China (362), and Germany (354). Conversely, when focusing on the volume of documents produced, the leading countries slightly shift, with China (24 documents) at the forefront, followed by the United States (16), the United Kingdom (15), India (14), and Italy (13). Notably, India leads in citations, a testament to the influential nature of its research. In contrast, China dominates in the number of documents

produced, indicating a prolific research output. The discrepancy between citation impact and publication volume among leading countries may reflect differing research strategies and capacities or the focus areas of national research agendas. These insights not only enrich the understanding of the geographical distribution of multi-hazard indices research but also highlight the importance of fostering international collaborations and adapting research strategies to address global challenges effectively.

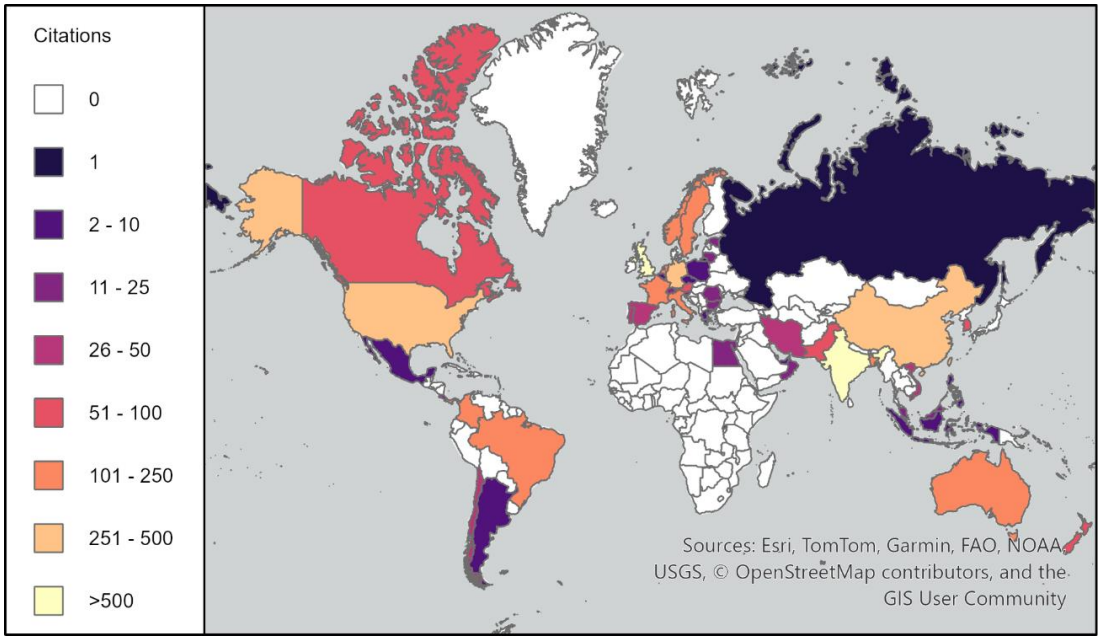


Figure 4.11. Geographical distribution of citations.

4.4. Discussion

The scientometric analysis of the publication landscape in multi-hazard indices in relation to climate-related hazards permits exploring the evolution of the field, closely echoing the intensifying global dialogue on climate change. The marked increase in scholarly output following key international climate milestones demonstrates the responsiveness of the research community to global policy shifts and emerging environmental concerns.

The prominence of geospatial analysis and index development across the most cited papers underlines the field's prioritization of tangible, actionable frameworks to approach the abstract complexities of climate risks. The progression from vulnerability assessment tools to more granular and localized indices underscores a change of paradigm towards context-specific methodologies that take into account the unique characteristics and needs of individual regions. Yet, the current scientometric landscape reveals a notable scarcity in cross-regional comparative studies – a gap that presents a fertile opportunity for future research. Bridging this divide may be expected to result in the development of a more cohesive global understanding of multi-hazard dynamics, fostering a platform for shared learning and cooperative mitigation efforts.

The collaborative networks and keyword trends shown after VOSviewer analysis reveals a blossoming academic community. The thematic evolution from physical aspects of hazards towards policy, adaptation, and the increasing interest in social and technological dimensions can indicate that the research production is maturing and diversifying. The emergence of keywords related to social dynamics and cutting-edge technology signals a field that is increasingly interdisciplinary and innovative, incorporating insights from a spectrum of scientific domains and societal concerns. The potential for expanding these networks is significant, with opportunities for more robust interdisciplinary partnerships and knowledge exchange poised to enrich the field further. Journals leading the research related to climate-related hazard indices serve as platforms for the dissemination of influential research, mirroring the urgency of coastal hazard adaption. These journals play a critical role not just in the academic field but also in guiding policy and practice.

The analysis of the spatial dynamics underlying multi-hazard indices research reveals a compelling narrative of global engagement and evolving leadership. The diverse geographical distribution of contributions, with significant outputs from countries like India, the United Kingdom, the United States, China, and Germany, underscores the universal recognition of the critical importance of multi-hazard assessment

frameworks. This widespread participation reflects a collective endeavour towards understanding and mitigating the risks posed by multiple simultaneous hazards, a crucial step for enhancing resilience at both national and global levels.

The temporal progression in research contributions highlights an expanding field where newer entrants are rapidly contributing to the discourse. This temporal trend signifies a shift towards more inclusive and diversified research ecosystems, encouraging fresh perspectives and novel methodologies in tackling complex multi-hazard challenges. The discrepancy between citation impact and publication volume among the leading countries offers another layer of insight. This variation suggests differing strategic focuses or research capacities, potentially indicative of varying national priorities or the influence of research infrastructure and funding mechanisms. It prompts a deeper inquiry into how research policies and resource allocation affect the development and dissemination of knowledge in the field of multi-hazard indices.

The integration of AI, ML, IoT, and remote sensing into multi-hazard indices represents a paradigm shift, offering dynamic, predictive, and responsive tools for urban planning and disaster management. However, challenges such as data privacy, the complexity of model interpretation, and the need for cross-disciplinary expertise must be addressed to fully leverage these technologies. Future research should explore the potential of emerging technologies in enhancing the capabilities of multi-hazard indices. Investigating how these technologies can be effectively integrated into existing frameworks to offer real-time, predictive insights into multi-hazard risks should be a priority.

The scientometric analysis underscores the necessity of translating research insights into actionable policy recommendations. Policymakers must leverage the insights from multi-hazard indices to inform strategic planning and resource allocation. The integration of these indices into policy frameworks can foster resilient urban environments capable of adapting to climate change impacts. Longitudinal studies that

track the effectiveness of multi-hazard indices over time can provide valuable data on their efficacy, adaptability, and impact on urban resilience.

While the scientometric analysis provides valuable insights, it is imperative to acknowledge its limitations. The review might be constrained by the scope of databases used, the selection criteria for publications, or the inherent biases in the literature. Future research should aim to include a broader range of databases, incorporate grey literature, and employ more inclusive criteria to capture a wide spectrum of research in this field. Future research should aim to include a broader range of databases, incorporate longitudinal studies, and explore the potential of emerging technologies in enhancing multi-hazard indices.

4.5. Conclusions

This scientometric review provides a holistic understanding of the research activity on multi-hazard indices in the realm of climate-related hazards, reflecting a growing academic and practical concern aligned with the escalating urgency of climate change impacts. The analysis has shown key trends in publication frequency, thematic focus, regional studies, and the emergence of innovative methodologies, all within the context of an expanding and evolving scholarly landscape.

Several key conclusions can be drawn from this review. The uptick in research publications correlates with major international climate reports and agreements, indicating that global policy developments significantly influence scholarly focus and productivity. The temporary decline observed in recent data suggests the need for ongoing monitoring to understand the long-term impacts of global events, such as the COVID-19 pandemic, on research trends.

The critical role of geospatial analysis and the development of various indices highlight the dedication of the field to translating complex climate hazards into

quantifiable, actionable data [371]. The diversity of indices reflects a robust effort to encapsulate the multifaceted nature of climate risks into tools for effective decision-making.

Although the focus on localized research has enhanced the precision of vulnerability assessments, there is a clear opportunity for comparative studies that can broaden our understanding across different regions [32]. Such comparative work is essential for identifying global patterns, sharing best practices, and developing universally applicable strategies.

The shift from physical components of hazards to policy, adaptation, and social and technological aspects reveals a field that is responsive and adaptive [372]. The integration of disciplines, including social sciences and technology, underscores the need for continued innovation and collaboration.

Furthermore, the analysis points towards several avenues for future research, including the development of cross-regional comparative studies, the exploration of interdisciplinary methodologies, and the incorporation of emerging technologies such as machine learning into climate hazard assessment [373].

These conclusions have significant implications for policy and practice. They urge policymakers and practitioners to leverage insights from index-based methodologies to inform strategic planning and resource allocation in climate hazard mitigation. There is a need for fostering stronger collaborative networks among researchers, policymakers, and practitioners to enhance the effectiveness of climate adaptation and resilience initiatives [374]. The review suggests a critical evaluation of current policies and practices in light of the most recent research findings, particularly those related to the integration of social and technological factors into climate hazard assessments.

This scientometric review reaffirms the dynamic and responsive nature of the multi-hazard index research field. As the climate crisis unfolds, it is incumbent upon the

academic community to continue advancing knowledge, tools, and collaborations that not only respond to emerging hazards but also pre-emptively shape resilient and sustainable futures for coastal cities worldwide. The foundation laid by past and current research efforts must now be leveraged to propel the field into new realms of inquiry and application, thereby fortifying societal responses to the multiple challenges posed by climate change.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 5.

Identifying key climate-related hazards through Coastal City Living Labs

This chapter corresponds to: Laino, E., and Iglesias, G. **High-level characterisation and mapping of key climate-change hazards in European coastal cities**. Natural Hazards, 2024. **120(4)**: p.3623-3659.

ABSTRACT

Sea-level and temperature rise due to climate change exacerbate existing climate-related hazards in coastal areas. In this work an approach based on Coastal City Living Labs is developed to carry out a high-level characterisation of key climate-related hazards for ten European coastal cities. The Coastal City Living Labs are conceived as physical and virtual spaces in which stakeholders meet for collaboration, co-creation and co-ideation to solve the challenges posed by climate-related hazards. The information on past extreme climate events and local knowledge thus obtained are combined to identify the main hazards for each city. Subsequently, these hazards are categorised based on the recommendations of the recent Sixth Assessment Report from the Intergovernmental Panel on Climate Change. The main climate-related hazards are found to be storms, coastal and land flooding, and coastal erosion. Importantly, significant differences are found between the specific cities as to the main

hazards of concern. Even within the same coastal city, relevant differences are found in respect of the main hazards, depending on the area considered. It follows that granularity in the characterisation of the hazards is fundamental in designing mitigation measures. To clarify the spatial extent of the different hazards in each coastal city, bespoke maps are produced through GIS software. In addition to the interest of the results for the specific cities investigated, this work provides a methodology to assess climate-related hazards in coastal areas using Coastal City Living Labs, which can be applied elsewhere.

5.1. Introduction

In many European countries the coastal zone is often not only densely populated but also the focus of much economic activity. Sea-level and temperature rise are poised to inundate wetlands and lowlands, erode shorelines, exacerbate coastal flooding during storms, impact water quality, and change the frequency, intensity and patterns of storms, heavy precipitation events, pluvial and river floods, heat waves, cold spells and droughts, among other impacts [6–8,44,375,376]. Overall, these changes would mostly affect tidal deltas, low-lying coastal plains, sandy beaches, barrier islands, coastal wetlands, and estuaries [29,377,378]. The impacts in Europe may vary from country to country, but they all affect large human and ecological values [28,379,380]. Many sectors and systems are likely to be affected, adversely or positively, depending on the climate scenario, region, or sector analysed [381–384].

In the last years, the European Commission has devoted particular attention, inter alia, to the concepts of integrated coastal zone management (ICZM), EBA and NBS to address the challenge of climate change in Europe [191,385,386]. These tools are critical to build the foundations for sustainable development and coastal management and to foster socio-economic development, biodiversity and ecosystem services [387–

392]. In the framework of the SCORE project (funded under the European Union's Horizon 2020 research and innovation programme), the impacts of sea-level rise and climate change will be mitigated by means of co-design and co-development with citizens and stakeholders, and by deploying, testing, and demonstrating innovative EBAs, smart technologies and hybrid NBSs on ten European coastal cities. For this purpose, extensive information on past extreme climate events is required.

Ten European coastal cities are considered in the SCORE project and in this article: Sligo (Ireland), Dublin (Ireland), Vilanova i la Geltrú (Spain), Benidorm (Spain), Oarsoaldea (Spain), Oeiras (Portugal), Massa (Italy), Piran (Slovenia), Gdańsk (Poland) and Samsun (Turkey). Each of them is represented in the project by a CCLL. Details on these areas and the corresponding CCLLs were given in Table 3.1.

This article presents the methodology used to identify and categorise the key climate-related hazards under baseline (current) climatic conditions for these coastal cities. This article is based on the literature review carried out previously [88] and on a participatory process involving the SCORE partners. In this context, the following indicative hazard categories have been considered: heavy precipitation, coastal flooding, coastal erosion, pluvial flooding, river flooding, landslides, droughts, heat waves, cold spells, storms, heavy snowfall, strong winds, forest fires, and other hazards. Finally, within these categories, the hazards have been identified and mapped using GIS software. As there is a range of information sources that provide data and information about extreme climate events on different levels, the collaboration between the SCORE partners has been crucial to collect the largest dataset possible.

5.2. Material and methods

The methodology is based on the novel concept of CCLL, which expands Living Labs to a wider vision for coastal cities and settlements. Hence, the CCLLs are conceived as physical and virtual coastal urban spaces, where citizens and public and private

agents collaborate to co-create and co-develop innovative measures to tackle local challenges related to sea-level rise, coastal erosion and extreme climate-related events.

The information on the extreme climate events which occurred in each city was collected not only considering pre-existing information, but also through engagement with the CCLLs, the SCORE partners, and local and regional stakeholders by means of workshops, questionnaires and meetings. The information was complemented with the results from the literature review on extreme impacts in European coastal cities developed in the SCORE project. Data were processed and a GIS model of the geographical coastal area was built for each city. In these models, the areas affected by past events were identified and mapped, and the past events assigned accordingly. The final step involved the formatting and reporting of the outputs, which are presented hereunder. Fig. 5.1 illustrates the methodology.

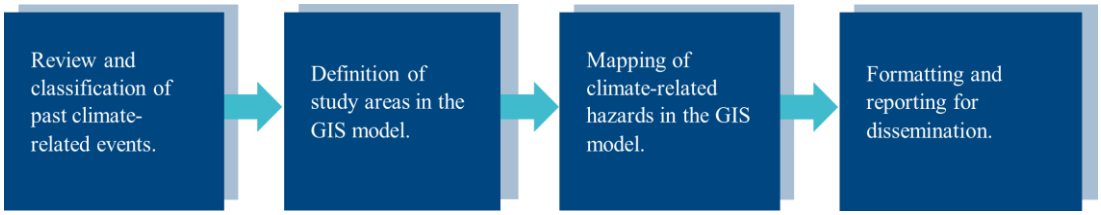


Figure 5.1. Workflow of the methodology to produce the maps illustrating the key climate-hazards in the coastal cities.

The climate-related events were classified under a wide variety of categories, mainly based on the Sixth Assessment Report from the IPCC (Chapter 12) [36]. The categories considered include heavy precipitation, coastal flooding, coastal erosion, pluvial flooding, river flooding, landslides, droughts, heat waves, cold spells, storms, heavy snowfall, electric storms, strong winds, forest fires, and other hazards, as shown in Fig. 5.2. The previous list is not exhaustive, and additional categories were included in the study when they were detected to be of concern to a particular coastal city. For the sake of mapping, the individualisation of each event was fundamental. In this sense, complementary data clearly defining the affected area, date, duration, category

of the event and a short description for each event were of great help in the production of the maps.

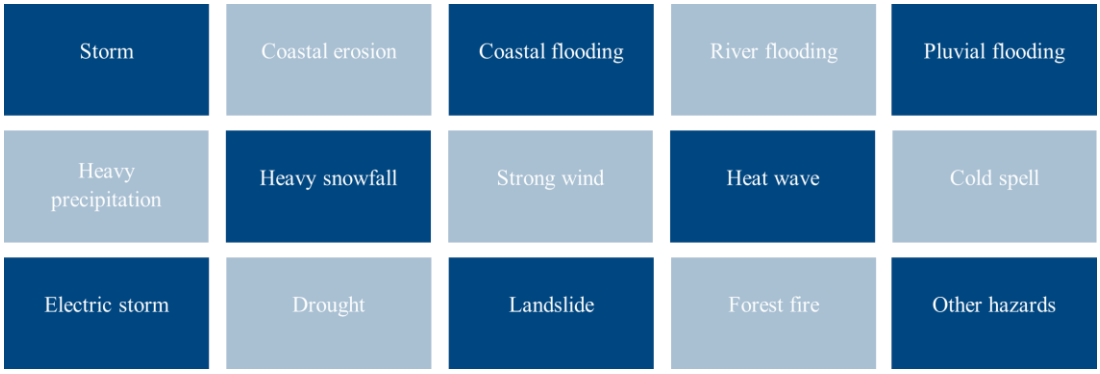


Figure 5.2. Overview of the climate-change-related events identified.

The level of detail of the results for each city depended on the information available. In most of the study cases, lists of past climate events were produced with the help of the participating CCLLs. In certain cases, in which this was not possible, the key hazards were identified through the analysis of other information sources, e.g., databases of notifications from the Civil Protection authorities, existing hazard and susceptibility maps, online web-viewers or scientific publications. The key climate-related hazards identified and the manner in which they were deduced, taking into consideration the different information sources available, are presented below.

5.3. Results

5.3.1. The collaborative approach

The methodology used allows connecting with the different authorities, administrations and institutions related to the study of the impacts of climate change in coastal cities, in the way in which they are part of it through the concept of CCLL, including even the participation of citizenship and private agents through the workshops and activities carried out during the SCORE Project. This interaction with local experts has eventually allowed to disaggregate the study of cities at lower levels

than usual. In particular, this disaggregation has been possible in the CCLLs of Benidorm, Oarsoaldea, Oeiras and Massa.

In the case of Benidorm (Spain), it has been observed through the collection of past extreme weather events how certain elements of the city are affected in a particular way on various occasions by certain hazards. This is the case of the beaches of Levante, Poniente and Finestrat, the Pere Maria Orts High School, the CV-70 road and the Terra Mitica theme park. It has been observed at an individual level how the different beaches are affected by episodes of erosion and flooding and the damage that these cause to them. It has also been observed how strong gusts of wind specifically affect the Terra Mitica theme park and the Pere Maria Orts High School. Ultimately, it has been identified how a landslide affected the CV-70 Highway. The availability of these data does not mean that the study of the rest of the elements of the city should be declined. Rather, it allows the identification of critical elements that are most frequently affected and that can be studied in more detail to draw lessons when taking measures during the development of future adaptation measures against climate change or design of actions within the city.

In the case of the Oarsoaldea region (Spain), it has been possible to identify the hazards related to climate change at the level of the municipalities of Errenteria, Oiartzun, Pasaia and Lezo. Even within these, it has been observed which are the areas where a higher incidence of extreme weather events occurs. Otherwise, it has also been observed how certain hazards affect the entire region or even have a greater scope. For example, river flooding especially affects the city of Errenteria and sometimes reach other areas. The pluvial floods, however, sometimes affect some municipalities and other times others. It has also been observed how storms especially affect the port area. The Gi-3440 road is frequently affected by landslides, as are certain other areas (port, lighthouse, coastal areas, urban areas).

In Oeiras, a municipality of Portugal with less than 50 km^2 of extension, the level of detail of the study has been sufficient to consider the parishes of Oeiras and S. Julião da Barra, Paço de Arcos and Caxias; Algés, Linda-a-Velha and Cruz Quebrada-Dafundo; Carnaxide and Queijas; Barcarena; and Porto Salvo both together and separately. Despite the small size of the area, it has been verified that the hazards related to the coast (coastal flooding, coastal erosion) have practically no incidence in the inland parishes, whereas they are relevant in the parishes along the coast. In fact, certain hazards affect the entire municipality (heat waves, cold waves and strong winds). The landslide hazard historically affects all parishes, with the exception of Porto Salvo, where events of this type have barely been recorded. Lastly, land floods affect the parishes of Oeiras and S. Julião da Barra, Paço de Arcos and Caxias in a localized manner; Algés, Linda-a-Velha and Cruz Quebrada-Dafundo; and Carnaxide e Queijas. These results serve as an initial orientation of what could be the scope of future adaptation measures.

Lastly, in the case of Massa (Italy), the interaction with local experts within the CCLL led to a zoning of the study area different from previous cases. Instead of using administrative boundaries, the affected areas were qualitatively divided into coastal zone, city centre, hilly area, and mountain area. These areas are qualitatively identifiable using aerial images. In this context, both coastal erosion and river flooding affect only the coastal area. The extent of coastal flooding exceeds the coastal area and reaches the city centre. Landslides generally occur in hilly and mountainous areas and are not relevant in the former areas. Finally, pluvial floods affect all areas. It is observed how a qualitative delimitation of the study area can be as useful as the use of administrative boundaries since these do not have to reflect the spatial distribution of hazards.

5.3.2. Identification and mapping of key climate-related hazards

Climate-related hazards are analysed and identified for the rest of cities (and also for Benidorm, Oarsoaldea, Oeiras and Massa) in the following lines, including bespoke maps representing these hazards. In this regard, a summary of the past climate-related events collected, categories, analysis period and supporting data for the ten coastal cities analysed is presented in Table 5.1 and a summary map illustrating the key climate-related hazards for each city is shown in Fig. 5.3. Complementarily, a breakdown of the number of events per category can be found in the Appendix (Table A.1 and Table A.2).

Table 5.1. Summary of the number of past climate-related events collected, categories, analysis period and complementary data for the ten coastal cities analysed.

Coastal zone	**Analysis period**	**No. of past events collected**	**Climate-related event categories[1]**	**Complementary data**
Sligo	1973-2021	49	CE; CS; HW; HS; HP; ST; DR; LF; CO; OT	-
Dublin	-	-	-	Past flooding events (online web-viewer).
Vilanova i la Geltrú	1988-2021	15	ST; SW; LF; FF	Briefs on extreme weather events (Meteorology Service of Catalonia). Tropical nights and hot days. Coastal evolution (Cartography and Geology Institute of Catalonia online tool).
Benidorm	1980-2020	37	LS; SW; PF; HP; CE; CF	-
Oarsoaldea	1900-2022	75	DR; ES; ST; HP; HW; CS; HS; LS; CF; PF; RF	-

Oeiras	1865-2021	51	LF; LS	Climate-related occurrences (landslides, coastal flooding and land flooding) (Civil Protection occurrences database). Hazard and susceptibility maps (Civil Protection Plan 2018).
Massa	1994-2021	31	RF; LS; PF; ST; HP	Hazard maps on coastal flooding, river flooding and landslides (District Basin Authority of the Northern Apennines).
Piran	2005-2021	16	LF	Hazard maps on flooding and landslides (Flood Cadastre Warning Map and Analysis of landslide occurrence in Slovenia and preparation of landslide probability map). Climate-related occurrences (coastal flooding, land flooding, strong winds, cold spells, droughts and landslides) (Civil Protection and Disaster Relief).
Gdańsk	1892-2017	23	LF	Changes in mean annual sea levels, storm surge values, and urban floods (1992-2016) (Plan of adaptation to climate change in the city of Gdańsk until 2030). Climate-related occurrences (floods) (Regional Water Management Board Gdańsk)."
Samsun	1963-2012	11	LF	Turkish Disaster Data Bank.

1: CE: coastal erosion, CS: cold spell, HW: heat wave, HS: heavy snowfall, HP: heavy precipitation, ST: storm, DR: drought, SW: strong wind, FF: forest fire, LF: land flooding, RF: river flooding, PF: pluvial flooding, CF: coastal flooding, ES: electric storm, LS: landslide, CO: compound event, OT: other.

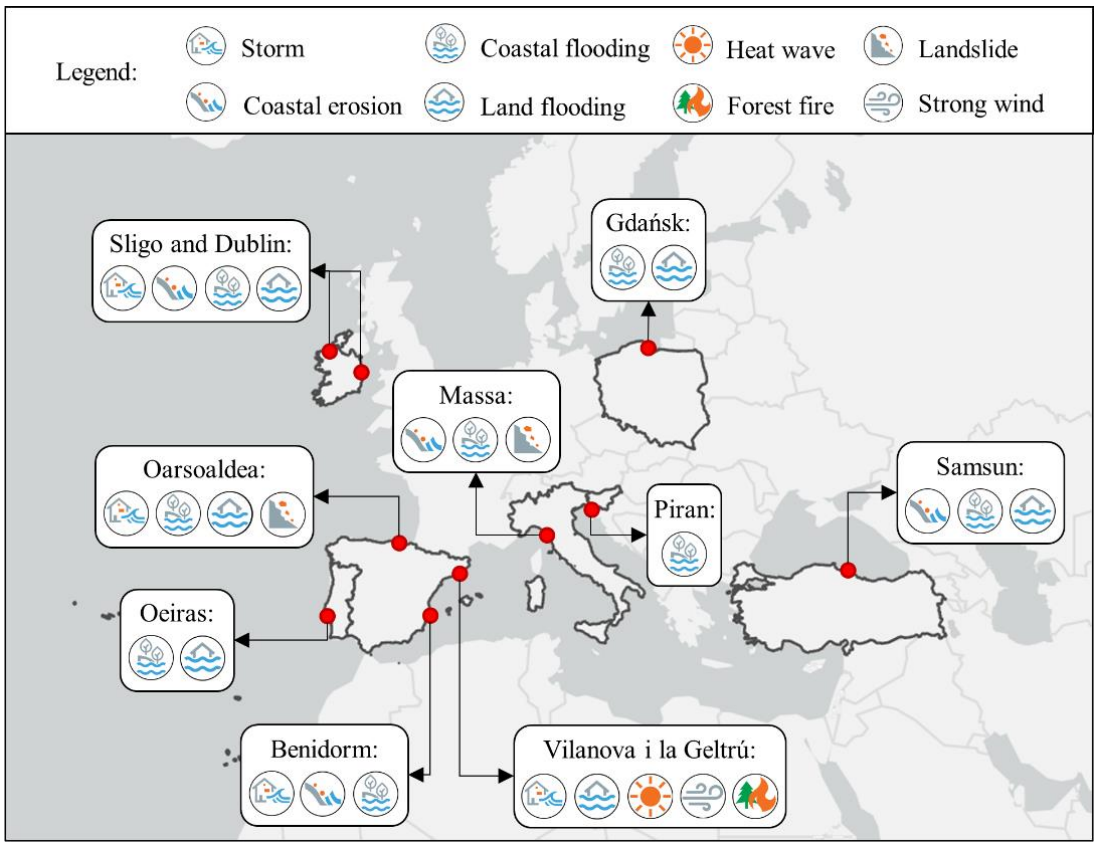


Figure 5.3. Schematic representation of the key climate-related hazards identified in the ten coastal cities studied.

In the Irish coastal areas of County Sligo and Great Dublin, the main natural or climatic-related hazards identified are storms, coastal and land flooding, and coastal erosion (Fig. 5.4). The increased frequency and intensity of winter storms is the main hazard identified [195]. In total, forty-nine (49) past climate-related events have been registered for Sligo, as summarised in Table A.3 in the Appendix. According to the information collected, storms are the most frequent extreme events, with fifteen (15) occurrences, followed by nine (9) flooding events. The less frequent extreme events are coastal erosion episodes, cold spells and heavy snowfalls, with two (2) occurrences each one, and heat waves, recorded only one (1) time. In addition, three (3) events have been categorised under the "Other" label, and six (6) events have been reported under the "Compound Event" category. Geographical data have been derived from the publication of Ordnance Survey Ireland on Ireland's Open Data Portal, which includes a dataset of the Irish Administrative Areas generated from the 2019 OSi National

Statutory Boundary dataset [393]. Storms, coastal and land flooding and coastal erosion are critical hazards in Dublin, too [195,198–200]. Regarding the past climate-related events, the National Flood Data Archive provides information on past flood event records. The past flood events information is currently accessible for events which occurred pre-Autumn 2014 in a web map [196]. This map provides information about the location of known flood events in Ireland and supporting information in the form of reports, photos and press articles.

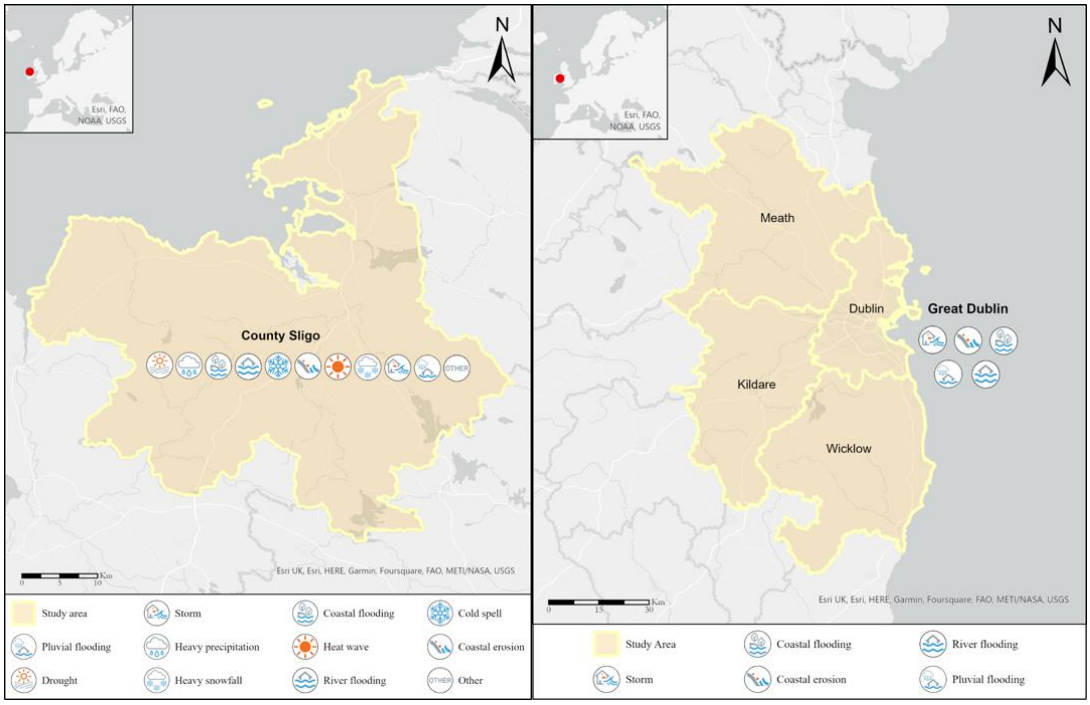


Figure 5.4. Schematic representation of the climate-related hazards identified in Sligo and Dublin, Ireland.

Storms, land flooding, heat waves, strong winds and forest fires have been identified as the main hazards affecting the area of Vilanova i la Geltrú (Fig. 5.6 left) [394–396]. Although most of the SLR studies in the Spanish Mediterranean coast are focused on the Catalonian coast (mainly the Maresme coast and the Delta del Ebro), there has not been found any work analysing Vilanova i la Geltrú [397]. The main data sources regarding past extreme climate events are the Meteorology Service of Catalonia, *Vilanova i la Geltrú Climate Change Adaptation Plan* and Cartography and Geology

Institute of Catalonia. The Meteorology Service of Catalonia holds a series of brief explanatory summaries of the main extreme weather events that have occurred in Catalonia over the last 300 years, especially since the mid-nineteenth century [398]. In addition, the document *Vilanova i la Geltrú Climate Change Adaptation Plan* holds information on extreme temperatures [399]. The number of tropical nights (in which the minimum temperature does not fall below 20.0°C) and days with maximum temperatures above 35.0°C in the period 1997-2013 is significant (Fig. 5.5). Tropical nights stand out especially in 2009 and 2012, with twenty-five (25) and eighteen (18) episodes respectively, followed by 2006 and 2010, with sixteen (16) and fourteen (14) episodes. Moreover, the days with temperatures above 35.0°C were highest in 2005 and 2009, with thirteen (13) and five (5) episodes. In 2017, the absolute maximum temperature reached 37.0°C in August. Furthermore, the Cartography and Geology Institute of Catalonia provides a web-viewer where the evolution of the Catalonian coastline since 2016 can be derived through ortho-imagery comparison [400]. In addition, two (2), three (3), six (6) and four (4) episodes of storms, strong winds, land flooding, and forest fires, respectively, have been registered (Table A.4 in Appendix). The geographical data were retrieved from the National Institute of Geography of Spain [401].

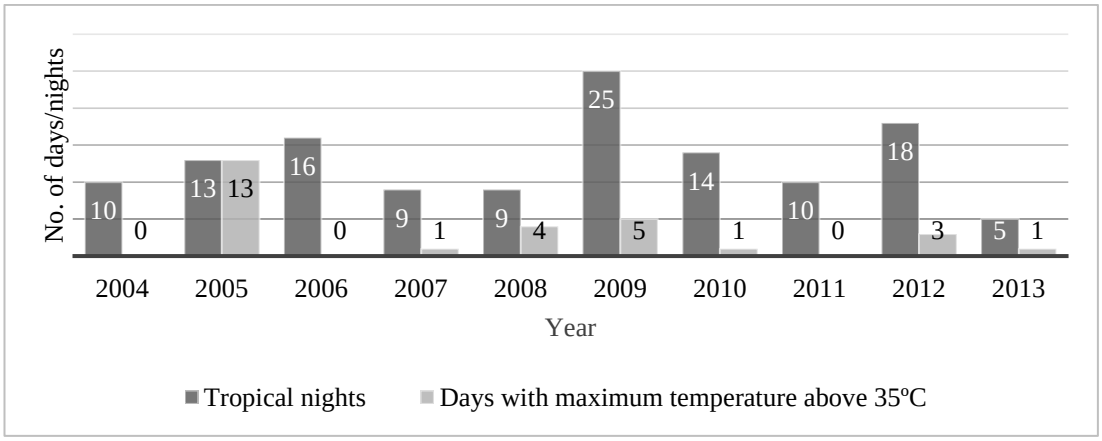


Figure 5.5. Evolution of the number of tropical nights and hot days at the Sant Pere de Ribes weather station (2004-2013). From: Vilanova i la Geltrú Climate Change Adaptation Plan.

The main concerns related to climate change in Benidorm are the increase in the frequency and intensity of torrential storms, coastal flooding and coastal erosion [205–207,209,402,403]. In summary, thirty-seven (37) past events have been recorded in Benidorm for the period 1950-2020, including episodes of coastal flooding, coastal erosion, pluvial flooding, strong winds, landslides and heavy precipitation (Fig. 5.6 right and Table A.5 in Appendix). Five (5) of them affected the whole area of Benidorm (heavy precipitation and pluvial flooding events). The remaining thirty-two (32) affected smaller areas, which have been defined in the GIS model. Levante Beach is the most affected area, with seventeen (17) occurrences of coastal flooding and coastal erosion. Poniente Beach has been affected ten (10) times by either coastal flooding or coastal erosion. The data indicate that Cala Finestrat has been flooded twice (2) by pluvial flooding. Two (2) relevant events of strong winds have been recorded at the Terra Mitica theme park and the Pere Maria Orts High School. And, finally, one (1) significant landslide occurred over the CV-70 road. Coastal flooding is the most recurrent event, with up to twenty-two (22) occurrences. The next categories in terms of number of occurrences are coastal erosion and pluvial flooding, with five (5) occurrences each one. Finally, the least recurrent events are strong winds (2), landslides and (1) heavy precipitation (2). The geographical data representing the study area (Benidorm municipality) has been derived from the Official Cartography of Valencian Community resources [404]. The shapefiles representing the three beaches (Levante, Poniente and Cala Finestrat) were provided by the Benidorm CCLL. The shapefiles representing the remaining areas (Terra Mitica theme park, Pere Maria Orts High School and CV-70 road) have been self-produced from satellite imagery.

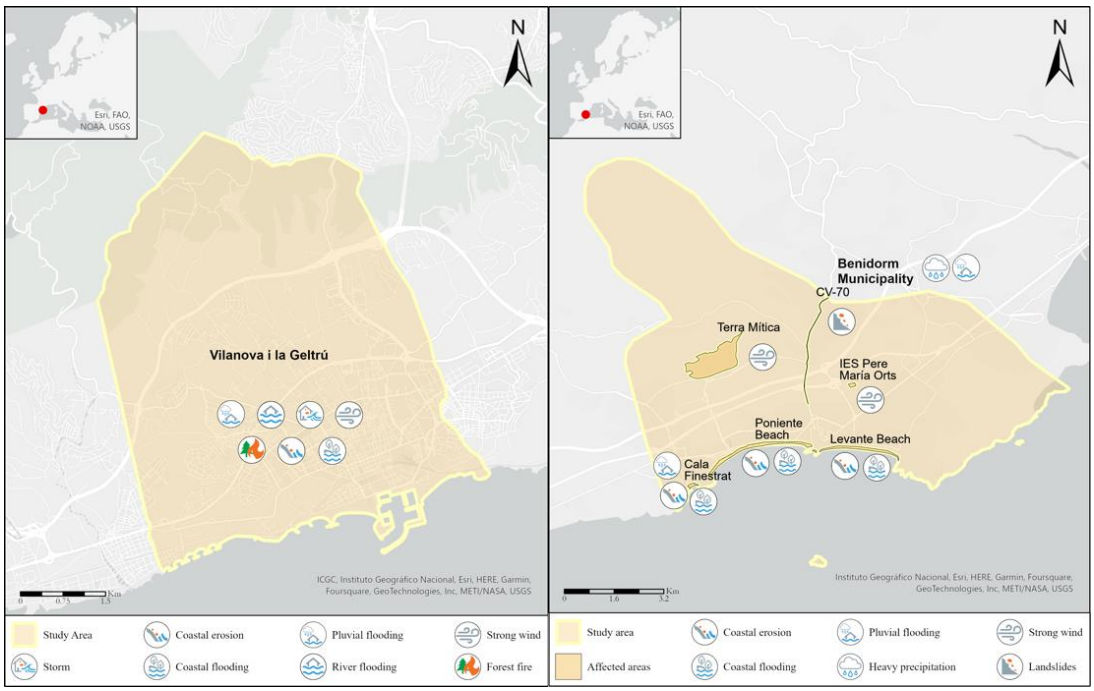


Figure 5.6. Schematic representation of the climate-related hazards identified in Vilanova i la Geltrú and Benidorm, Spain.

The main climate-related hazards identified in Oarsoaldea are storms, coastal and land flooding, and landslides [56,213,405]. The study area has been divided into the four municipalities which are part of Oarsoaldea, namely: Errenteria, Lezo, Oiartzun and Pasaia. In summary, seventy-five (75) past events have been collected in Oarsoaldea, including episodes of river flooding, pluvial flooding, coastal flooding, landslide, heavy snowfall, cold spell, heat wave, heavy precipitation, storm, electric storm, and drought (Fig. 5.7 left and Table A.6 in Appendix). Fifty (50) of them affected the whole area of Oarsoaldea, including heavy snowfall, cold spell, heat wave, heavy precipitation, storm, electric storm, and drought events. The remaining twenty-five (25), affected one or more of the municipalities included in Oarsoaldea, but not all the four. Each municipality has been analysed individually, so it has been counted how many times each municipality was affected by one of these last twenty-five (25) events. In this way, Errenteria has been affected eleven (11) times by either river or pluvial flooding; Oiartzun six (6) times by river or pluvial flooding again; Pasaia has been the most affected municipality registering eighteen (18) events including river flooding, pluvial flooding, coastal flooding and landslides; and Lezo has been the less affected municipality registering three (3) events of pluvial flooding or landslides. The

geographical data have been mainly collected from geoEuskadi website and consist of five 1:5000 scale shapefiles [406].

Coastal and land flooding are the most relevant climate-related hazard in Oeiras [23,214–216]. However, as explained hereinafter, other hazards are also important (Fig. 5.7 right). The main information sources on past climate events for Oeiras is the DISASTER database [407], from Institute of Geography and Spatial Planning – University of Lisbon (IGOT-UL). It contains information on landslides and floods (exclusively) that caused casualties; injuries; and missing, evacuated or homeless people; for the period 1865-2010. Other two complementary information sources are the Civil Protection's occurrences database [408], and the *Civil Protection Municipality Plan* [409], containing, respectively, a wide variety of natural and technological related hazards which occurred in Portugal since 2006, and susceptibility maps of the climate-related risks in Oeiras Municipality (e.g., extreme coastal floods, heat waves, cold spells, landslides, and river and pluvial floods). Based on the previous sources, the study area (Oeiras municipality) has been geographically divided at parochial level, including the parishes of Oeiras e S. Julião da Barra, Paço de Arcos e Caxias; Algés, Linda-a-Velha e Cruz Quebrada-Dafundo; Carnaxide e Queijas; Barcarena; and Porto Salvo. In total, forty-five (45) flooding events and six (6) landslides have been identified in the DISASTER Database in Oeiras during 1865-2020 (Table A.7 in Appendix). Most of the events are concentrated along the coastline, in the parishes of Oeiras e São Julião da Barra, Paço de Arcos, Caxias, Algés, Linda-a-Velha and Cruz Quebrada-Dafundo; whereas only one (1) event has been recorded in Porto Salvo. According to the three information sources described before, the main climate-related hazards affecting the study area are landslides, river flooding, pluvial flooding, coastal flooding, heat waves, cold spells and strong winds. The first three affect mainly the parishes of Carnaxide e Queijas; Oeiras e São Julião da Barra, Paço de Arcos e Caxias; and Algés, Linda-a-Velha e Cruz Quebrada-Dafundo, although landslides also affect Barcarena. Coastal flooding events are of concern for practically the entire Oeiras coastline. Finally, heat waves, cold spells and strong winds affect the whole municipality. The geographical data have been obtained and derived from the Portuguese Public Administration's open data portal (Public Administration of Portugal).

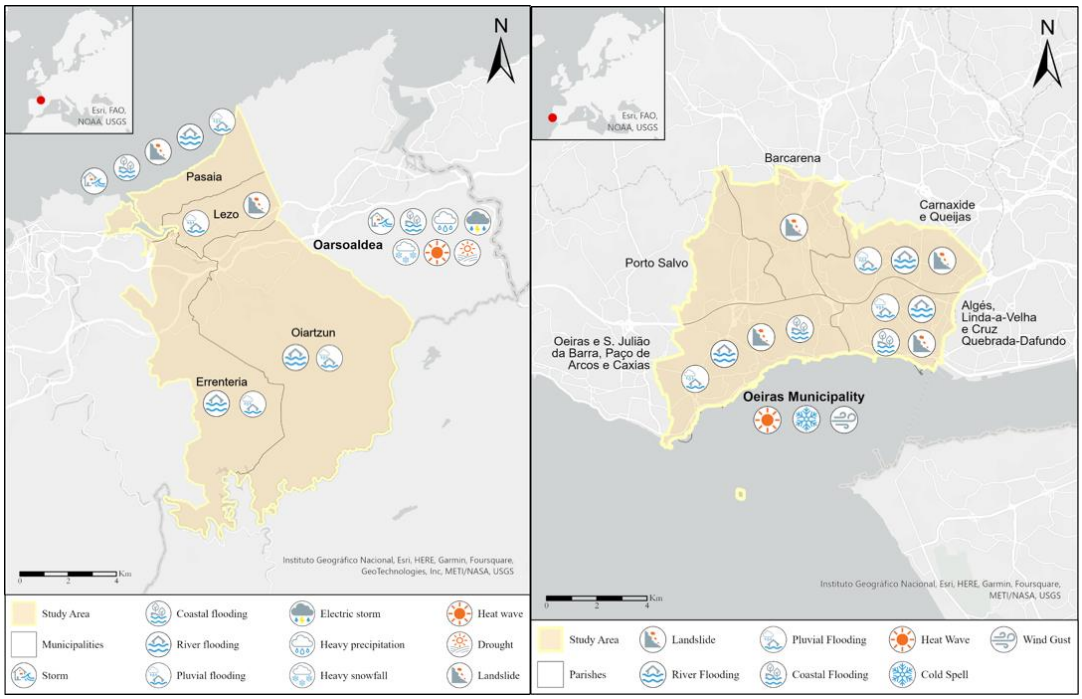


Figure 5.7. Schematic representation of the climate-related hazards identified in Oarsoaldea, Spain and Oeiras, Portugal.

As regard the coastal city of Massa, and following on the results from the literature review, the most dangerous climate-related hazards are represented by floods in lowland areas and landslides in the hilly area, from the point of view of the safety of people, and coastal erosion, from the point of view of economic consequences [220–223,227,228]. The main information source regarding extreme climate events is the alert system provided by the Regional Functional Centre of the Tuscany Region. Reports on past climate events since 2009 are available on its website [412]. The past events identified include the categories of heavy precipitation, coastal storm, coastal erosion, river flooding, pluvial flooding, landslides and strong winds (Fig. 5.8 left). The events mainly affect the areas of the city centre, the hilly and the mountain areas, and the coast. In total, thirty-one (31) events have been identified since 1994, as shown in Table A.8 in the Appendix. Most of them are landslides, with twelve (12) occurrences, followed by eight (8) coastal storm episodes. Seven (7) land flooding events, which five (5) have been catalogued as pluvial flooding and two (2) as river flooding, and four (4) heavy precipitation events complete the record. Furthermore, the District Basin Authority of the Northern Apennines have produced hazard maps on coastal flooding, river flooding and landslides, which are publicly available on a

web-viewer [413]. The geographical data representing the municipality of Massa was downloaded from the National Institute of Statistics of Italy [414].

The main concern for the Slovenian city of Piran is coastal flooding, whereas storms, land flooding, landslides, strong winds, droughts and cold spells are other relevant hazards (Fig. 5.8 right) [230,231,415]. The main source providing information is the platform managed by the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief. It contains a dataset of Civil Protection interventions related to climate events in Piran since 2005. The total amount of notifications recorded in the database is 1713, including coastal flooding, land flooding, strong winds, cold spells, droughts and landslides. The most frequent notifications are for coastal flooding, pluvial flooding, and strong winds, with 598, 362, and 616 occurrences, respectively, whereas other land flooding categories (river and groundwater), landslides, cold spells and droughts account for a reduced number of notifications in the city. Other complementary information sources are the series of integrated flood hazard maps, representing the floodplains for the 500-year, 100-year and 10-year return periods discharge value (Ministry of the Environment and Spatial Planning – Directorate of the Republic of Slovenia for Water). Similarly, the Flood Cadastre Warning Map of Slovenia, contains maps representing the areas of very rare floods, involving floods with a return period of 50 years or more; areas of frequent floods, which include floods with a return period of 2 to 5 years; and locations of individual flood events [419]. Besides, the document *Analysis of landslide occurrence in Slovenia and preparation of landslide probability* provides significant information on the landslide hazard in the city [420]. The probability scenarios included in the document show the negligible, very low, low, medium, high and very high probability areas of landslides. The areas where a landslide is more likely to occur are in the mountains, whereas the probability of landslides is lower in the plains. More details about the probability levels can be found in the reference document. There is a lack of scientific literature for the Slovenian coast, albeit multiple hazards have been assessed in adjacent Italian areas [313]. The shapefile representing Piran municipality was retrieved from the University of Texas at Austin portal [421].

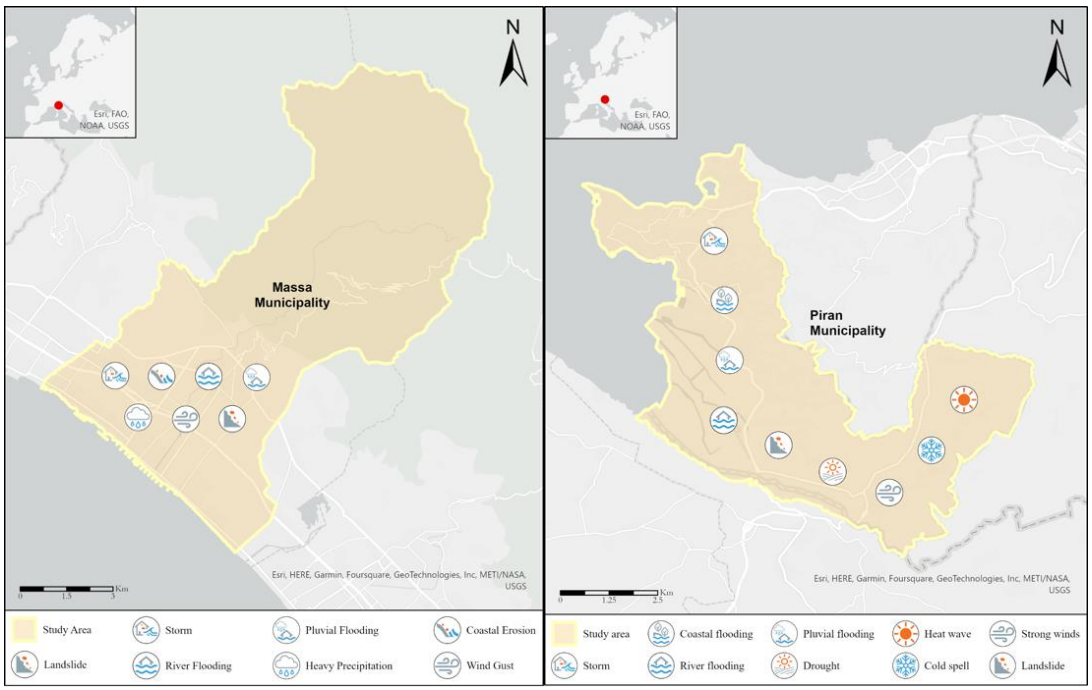


Figure 5.8. Schematic representation of the climate-related hazards identified in Massa, Italy and Piran, Slovenia.

The most serious threat in Gdańsk is the occurrence of sudden urban floods (flash floods), river floods and coastal flooding events (Fig. 5.9 left) [77,235,236,249,251]. Two are the main information sources on this regard in Gdańsk: the Regional Water Management Board Gdańsk and the document *Plan of adaptation to climate change in the city of Gdańsk until 2030* [422]. The Regional Water Management Board Gdańsk holds information on pluvial flooding notifications in Gdańsk for the years 2010-2017 and historical floods in the period 1829-1992. The document *Plan of adaptation to climate change in the city of Gdańsk until 2030* analyses, inter alia, the pluvial, river and coastal flooding events; the sea-level rise; and the storm surge in Gdańsk. According to this document, twenty-three (23) cases of urban floods were recorded around the city of Gdańsk in the period 1992-2016 (Table A.9 in Appendix). The distribution of the urban floods was characterised by an upward trend for the ordered time series. In Gdańsk Northern Port, slight increasing trends were noted in mean annual sea levels (circa 15 cm) in the period 1955-2015. Finally, for all the indicators of storm surge analysed (number of storm surges in a given year, number of hours above the Mean High-Water Level in a given year, and maximum level in a given year) in Gdańsk, a growing trend was visible for the ordered time series. The absolute maximum sea level occurred during a storm surge in 2004, corresponding to

an ordinate of 1.36 m above mean sea level and a maximum storm surge of 50 cm, according to the methodology described in the document. In fact, the Vistula mouth (and also the Odra River mouth) concentrates the coastal flooding hazard in Poland [238]. Additional important threats that affect Gdańsk are the occurrence of strong gusts of wind and torrential rains due to intense storms [237,246,247], and the increasing frequency of heat waves and hot days [232–234].

As a result from the *Literature Review Report* (SCORE project), it was found that coastal erosion is the most important concern for Samsun, whereas coastal and land floods are other important hazards for the city (Fig. 5.9 right) [22,261]. In this context, three scientific articles providing information regarding coastal erosion and shoreline change are outlined. Firstly, Ozturk et al. (2015), in *Spatiotemporal Analysis of Shoreline Changes of the Kizilirmak Delta*, determined the temporal shoreline changes of the Kızılırmak Delta (Samsun). Satellite imagery and three different methods were used to determine the shoreline changes. Secondly, a similar study was developed by [254] in *Shoreline change analysis of the Kizilirmak Lagoon Series*. The study determined the shoreline changes in the delta and the lagoons between 1962 and 2013 and discussed their relationship. Finally, the shoreline changes of the Kızılırmak Delta are also analysed in *The Black Sea coastline erosion: Index-based sensitivity assessment and management-related issues*. In this article, Tătui et al. (2019) computed a Coastal Sensitivity Index (CSI) around the Black Sea. The three articles show that the Kızılırmak Delta has been subject to intense coastal erosion historically. Regarding the climate events, eleven (11) historical flooding events have identified in the area for the period 1963-2012 (Table A.10 in Appendix). The greatest discharge value was produced in the Yilanli Stream in the fourth of July in 2012, reaching a peak discharge of 710 m^3/s. In addition, within the scope of the Turkish Disaster Data Bank (TDDB) project carried out by the Planning and Mitigation Department, the TDDB System has been launched for test broadcasting to include past climate-related events. Unfortunately, the web page was not working at the time of writing. The geographical data were derived from the Humanitarian Data Exchange portal [423].

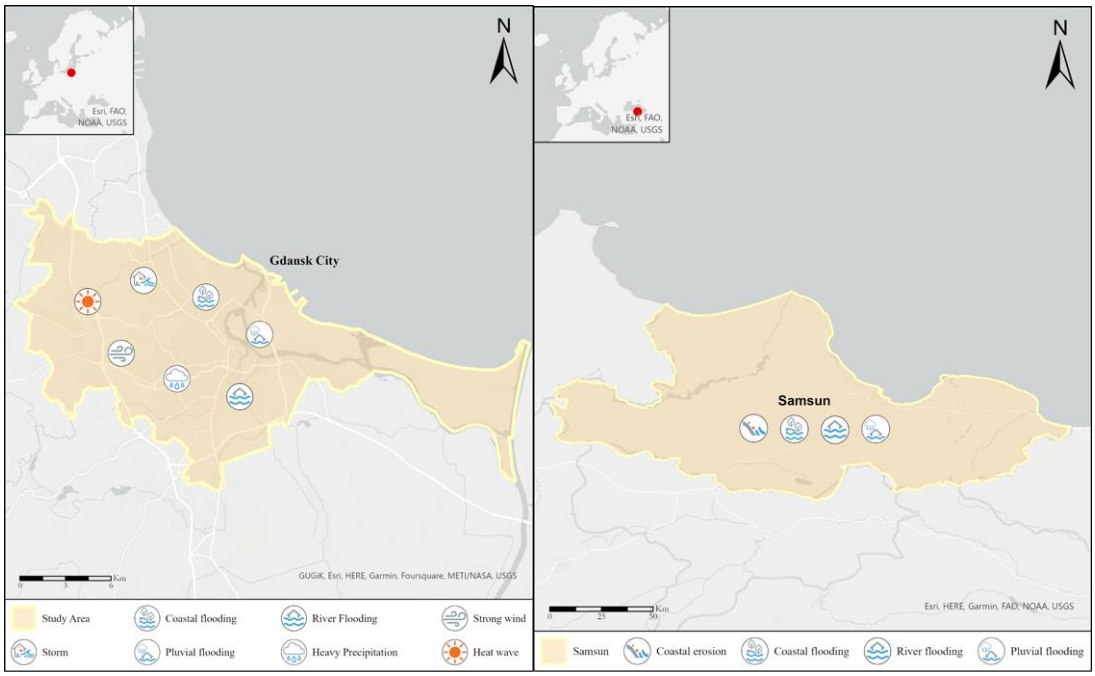


Figure 5.9. Schematic representation of the climate-related hazards identified in Gdansk, Poland and Samsun, Türkiye.

5.4. Discussion

This study has systematically addressed the critical need for a thorough understanding of the climatic hazards impacting European coastal cities. Our work, undertaken within the CCLLs, has established a foundational approach to hazard identification that reflects the unique climatic, ecological, and socio-economic contexts of ten distinct European coastal regions. By engaging local experts and stakeholders, this participatory methodology has yielded a nuanced perspective on the challenges posed by sea-level rise, coastal erosion, and extreme weather events, and has proven to be instrumental in enhancing data adequacy and specificity.

Through our collaborative efforts with the CCLLs, we have developed a comprehensive database of past extreme climate-related events and created detailed hazard maps. These tools have enabled us to delineate hazard zones and critical areas within the cities, thereby laying the groundwork for targeted adaptation measures. Our methodology's adaptability to different scales and its ability to incorporate zoning—ranging from administrative divisions to qualitative areas—underscores its potential utility for broader application beyond the European context.

The nuanced findings underscore the significance of localized approaches, as each city exhibits a distinct risk profile. For instance, the heightened vulnerability of Irish cities such as Sligo and Dublin is underscored by the intensification of winter storms, coastal and land flooding, and coastal erosion. These elements constitute major hazards that demand specific attention in the development of future resilience strategies.

Vilanova i la Geltrú faces a broad spectrum of hazards including storms, land flooding, heat waves, strong winds, and forest fires, necessitating a multifaceted adaptation approach. Benidorm's challenges are predominantly storms and the dual threats of coastal flooding and erosion. Oarsoaldea's situation is further complicated by landslides, while Oeiras not only contends with coastal and land flooding but also faces a suite of additional hazards such as droughts, heat waves, and cold spells.

Massa's primary concerns are coastal and land flooding coupled with erosion. In Piran, coastal flooding emerges as the central issue, paralleling the concern in Gdańsk. Finally, Samsun's most significant challenge is coastal erosion, although it too must prepare for the eventualities of both coastal and land flooding.

The key hazards identified pose significant risks to human life, infrastructure, and the environment. Particularly notable is the projected increase in frequency and intensity of some events, especially in northern and western Europe. The evidence suggests that existing coastal defences may be insufficient in the face of escalating coastal threats. Moreover, the varied hazard profiles across the cities studied reveal a complex landscape of risk that defies one-size-fits-all solutions.

5.5. Conclusions

Our investigation has provided pivotal insights into the varied and complex challenges posed by climate-related hazards across European coastal cities. While the shared European context might suggest uniformity, the reality is a tapestry of diverse climatic threats requiring equally diverse management and adaptation strategies.

The differences in the hazard profiles between the cities highlight the necessity for bespoke adaptation measures. For cities like Sligo and Dublin, addressing the intensification of winter storms and mitigating the effects of coastal and land flooding

are critical. In regions such as Vilanova i la Geltrú, a comprehensive plan must account for a wider range of hazards including heatwaves and forest fires.

The methodology developed and refined through collaboration with the CCLLs is flexible and robust, providing a scalable approach that is applicable not only across Europe but potentially in any coastal region worldwide. Nonetheless, it is merely the beginning of a comprehensive process that must include a thorough assessment of vulnerability and exposure to inform the development of targeted adaptation pathways.

As part of the SCORE project's integrated coastal zone management framework, this work has set a solid foundation for the development of advanced early warning systems, digital solutions, and smart policies tailored to the unique needs of each coastal city. The ultimate goal is to enhance the resilience of these urban areas, ensuring their long-term viability in the face of an ever-changing climate landscape.

Continued research and development of vulnerability and exposure indicators specific to European coastal cities will be essential. By doing so, we can better understand the risks, devise effective mitigation strategies, and share knowledge across networks of cities. The collective learning and actions taken as a result of this study are vital steps toward securing the future of coastal urban environments against the increasing threats of climate change.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 6.

Developing standardized indicators for comparative multi-hazard assessments

This chapter corresponds to: Laino, E., and Iglesias, G. **Multi-hazard assessment of climate-related hazards for European coastal cities**. Journal of Environmental Management, 2024. **357**: p.120787.

ABSTRACT

The assessment of risk posed by climate change in coastal cities encompasses multiple climate-related hazards. Sea-level rise, coastal flooding and coastal erosion are important hazards, but they are not the only ones. The varying availability and quality of data across cities hinders the ability to conduct holistic and standardized multi-hazard assessments. Indeed, there are far fewer studies on multiple hazards than on single hazards. Also, the comparability of existing methodologies becomes challenging, making it difficult to establish a cohesive understanding of the overall vulnerability and resilience of coastal cities. The use of indicators allows for a standardized and systematic evaluation of baseline hazards across different cities. The methodology developed in this work establishes a framework to assess a wide variety of climate-related hazards across diverse coastal cities, including sea-level rise, coastal

flooding, coastal erosion, heavy rainfall, land flooding, droughts, extreme temperatures, heatwaves, cold spells, strong winds and landslides. Indicators are produced and results are compared and mapped for ten European coastal cities. The indicators are meticulously designed to be applicable across different geographical contexts in Europe. In this manner, the proposed approach allows interventions to be prioritised based on the severity and urgency of the specific risks faced by each city.

6.1. Introduction

Coastal cities around the world are experiencing unprecedented growth and development, fuelled by urbanization and economic activities [69]. However, this expansion is unfolding in the shadow of an escalating threat – the increasing frequency and severity of climate-related hazards, a consequence of the rapidly changing climate [70,71,323,424]. As we journey further into the 21st century, the global population exposed to mean and ESL events is poised to grow significantly, leading to a surge in research endeavours aimed at comprehending the repercussions of climate change on coastal communities [9–12]. In Europe, this issue is of particular concern, as the continent's densely populated coastal areas serve as hubs for economic activities [88]. The looming threats of sea-level rise and temperature increase are poised to inundate wetlands, erode shorelines, exacerbate coastal flooding during storms, and usher in complex climatic changes [6–8]. These changes cast long shadows over tidal deltas, coastal plains, sandy beaches, and estuaries [29,377,378], affecting both human and ecological values.

In the case of coastal cities in Europe, coastal storms represent the primary climate-related hazard, leading to destructive ESLs, coastal flooding, and coastal erosion [28–30]. Projections indicate that ESLs will rise along European coastlines, with notable regional variations [7,74,76–78,181,182]. The North Sea region, the Baltic Sea, the

Atlantic coasts of the United Kingdom and Ireland are expected to experience the most substantial changes, while less severe changes are foreseen along the southwestern European coasts. Other climate-related hazards are anticipated to increase in frequency and intensity in the European continent, notably those related to heatwaves, droughts, and heavy precipitation events [79,80]. This increase could also lead to a surge in fatalities, primarily driven by an increase in heatwaves, especially in southern Europe. While progress has been made in addressing these climate change challenges, numerous European cities necessitate increased efforts to mitigate the most severe impacts [81,82].

The concept of MHA has acquired broad acceptance to refer to the consideration of the multiple hazards that have the potential to affect a particular area, since its first appearance in the United Nations' Agenda 21 for sustainable development (UNEP 1992), and the continuous use of this term in posterior United Nations' events (e.g., Johannesburg Plan (UN 2002) and the Hyogo Framework for Action (UN-ISDR 2005) [98]. In general, multi-hazard approaches consider the interrelationships between the most relevant hazards in the study area [425]. These interrelationships usually include the simultaneity or the interdependency between the occurrence and impact of various hazards [26,27]. The conception of the term multi-hazard in UNEP 1992 and its subsequent reinterpretations are also intimately related to the framework of vulnerability and risk assessment. Nowadays, numerous well-established approaches are accessible for most hazards when these are considered alone, but a significantly smaller number of methodologies deal with multiple hazards [27].

Gallina et al. (2016) have reviewed existing MHA concepts and tools applied by organisations and projects, showing that existing MHAs typically fail to take into account the effects of climate change and to provide a joint understanding of climate impacts, spatial visualization, comparison between, and communication to, end-users. Most of the popular MHAs are not developed to assess the relationship between

climate-related events and coastal cities [426–428]. Nevertheless, there are examples of proposals of MHA intended for coastal areas analysing climate-related events [291,313,314]. In general, these approaches apply variations of the CVI and other existing indices [354,356,429]. Other existing methodologies cover some climate-related hazard; however, these approaches do not focus on coastal cities [114,317,318]. It has been observed that the scope of the MHRAs developed for coastal cities is usually limited to coastal hazards (namely, storms, storm surges, coastal and pluvial flooding, and coastal erosion) and do not consider other climate-related hazards common to inland cities, such as heatwaves, cold spells, droughts, landslides and forest fires [297,304,430]. Also, the geographical coverage of these approaches may be limited [191]. An approach is lacking that permits a standardized and systematic MHA framework at European level, including all kind of climate-related hazards – not only those specific to coastal areas.

Altogether, the current state of multi-risk assessments, including MHA, reveals several critical deficiencies in the field [118]. First, there is a notable absence of adequate decision support tools, which hinders effective risk management strategies. Additionally, the integration of practices for multi-risk governance is lacking, with minimal collaboration among diverse risk-related communities. The communication of assessment results poses a significant obstacle to successful multi-risk management efforts. Furthermore, the consideration of diverse temporal hazard scenarios, particularly those associated with global changes, presents an additional challenge that necessitates comprehensive attention and improvement in the domain of multi-risk assessments [107].

In this context, indicator-based approaches represent a fundamental methodology for articulating the multifaceted nature of climate-related hazards [431,432]. These approaches employ a set of independent variables to characterize key aspects of such hazards, including storm characteristics, wave regimes, sea-level changes, precipitation patterns, and temperature fluctuations, among others [105,108,433].

Notably, these indicators can be occasionally aggregated to form a composite index, offering a summarized view of the overall hazard scenario [434]. This methodology not only facilitates a nuanced assessment of the various dimensions of hazard but also integrates these assessments within a coherent and standardized evaluation framework, thereby enhancing comparability and interpretability across different cases and hazard types [435].

Despite their widespread application and inherent strengths, it is important to acknowledge that the most popular indicator-based methodologies often exhibit limitations in their scope, typically concentrating on a select range of hazards or specific vulnerability parameters [436]. Common focal areas include coastal flooding, coastal erosion, physical vulnerability assessments, and the impacts on ecosystems [203,313,437]. This specialization, while beneficial for in-depth analysis of particular hazards, may overlook the interdependencies and cumulative effects of multiple hazards that concurrently affect coastal cities [362].

To address this gap, the methodology seeks to expand the traditional scope of indicator-based approaches by incorporating a comprehensive set of hazards relevant to coastal cities, thereby providing a more holistic view of the risk landscape. In doing so, it is recognized the necessity of adapting and refining existing methodologies to meet the specific requirements of the assessment. Drawing on the foundational work of researchers such as Klein and Nicholls (1999) and Nicholls et al. (2006) who have emphasized the importance of integrating diverse hazard indicators into coastal vulnerability assessments, the approach aims to bridge the existing methodological divide. By doing so, it is ensured that the MHA framework remains flexible and adaptable, capable of capturing the complex interplay of climate-related hazards that threaten European coastal cities.

Furthermore, the adoption of an indicator-based approach underscores the commitment for developing a methodology that is not only scientifically rigorous but

also practically applicable. By carefully selecting indicators that are relevant, measurable, and sensitive to the specific contexts of European coastal cities, policymakers and practitioners are provided with a valuable tool that allows the comparison of a wide variety of climate-related hazards in practically any coastal city in Europe. In connection with the aforementioned, the intention is also to develop a systematic and standardized methodology to discern in which cities it is more crucial to continue the study in more detail. For this reason, the indicator-based approach proposed allows for the results to be refined through incremental improvement in the accuracy of indicators. Ultimately, this approach is also designed to be flexible and not excessively complex, in order to facilitate its use in collaboration with coastal communities.

6.2. Materials and methods

6.2.1 *Case studies*

The selection of the study cities ensures a wide representation of the geographical and climatic diversity of Europe, enabling a comprehensive analysis of climate-related hazards across different coastal environments. These cities were selected in alignment with the objectives of the 'Smart control of the climate resilience in European coastal cities' (SCORE) project, covering ten diverse cities: Sligo and Dublin (Ireland); Vilanova i la Geltrú, Benidorm, and Oarsoaldea (Spain); Oeiras (Portugal); Massa (Italy); Piran (Slovenia); Gdansk (Poland); and Samsun (Türkiye).

This selection facilitates the study to span a broad spectrum of climate change challenges, from variations in risk exposure to differing urbanization levels, thereby providing a framework for evaluating not only different scenarios of hazard, but also of coastal vulnerability and resilience. The choice is further justified by the varying degrees of existing research on the impacts of climate change in these areas [101],

which allows the study to build upon and contribute to the existing body of knowledge with new insights into hazard assessment methodologies.

Moreover, the involvement of these cities in the SCORE project not only grants access to rich datasets and localized contexts but also positions the methodology for practical application. This integration promises to enhance the decision-making process for urban planning and climate adaptation measures, directly contributing to the advancement of climate resilience in European coastal cities. Through this approach, the research directly responds to the urgent need for actionable insights in the face of escalating climate threats, ensuring that the findings have both scientific and practical relevance.

In this vein, essential geographic information vital for the comprehensive analysis of the target coastal cities was obtained by means of robust data acquisition techniques. The acquisition of city coordinates was accomplished through OpenStreetMap data, facilitated by the geopy library – a renowned geolocation tool. The Local Administrative Units (LAU) dataset sourced from Eurostat, a reputable repository of European statistical data, was employed to further refine the geographical characterization of the coastal cities. For the specific case of Turkey, geographical data aligned with the Nomenclature of Territorial Units for Statistics (NUTS) 2021 classification from Eurostat was employed. In this context, the territorial boundary of the province of Samsun, delineated at the NUTS 3 level, was utilized to represent the coastal area of the city of Samsun.

These meticulously obtained city coordinates and boundaries served as the foundational geographic references that underpinned the subsequent analyses (Table 6.1). The approach seamlessly integrated a bespoke Python script with Geographic Information System (GIS) data, enabling the automated retrieval of latitude and longitude coordinates. This methodological synergy assured precision and consistency

in the geographical data, setting the stage for the calculation of various indicators elaborated upon in subsequent sections of the paper.

Table 6.1. Geographic characterisation of coastal cities.

Coastal city	**Coordinates (Latitude, Longitude)**	**Geographical extents (LAU or NUTS names)**
Sligo	(54.192986, -8.730543)	Sligo-Drumcliff; Sligo-Strandhill
Dublin	(53.349380, -6.260559)	Artane-Whitehall; Ballyfermot-Drimnagh; Ballymun-Finglas; Cabra-Glasnevin; Clontarf; Donaghmede; Kimmage-Rathmines; North Inner City; Pembroke; South East Inner City; South West Inner City
Vilanova i la Geltrú	(41.224199, 1.725633)	Vilanova i la Geltrú
Benidorm	(38.540626, -0.129093)	Benidorm
Oarsoaldea	(43.312527, -1.898613)	Pasaia; Lezo; Errenteria; Oiartzun
Oeiras	(38.712497, -9.271300)	Porto Salvo; Barcarena; União das freguesias de Carnaxide e Queijas; União das freguesias de Oeiras e São Julião da Barra, Paço de Arcos e Caxias; União das freguesias de Algés, Linda-a-Velha e Cruz Quebrada-Dafundo
Massa	(44.035932, 10.139552)	Massa
Piran	(45.528492, 13.568449)	Piran/Pirano
Gdańsk	(54.348291, 18.654023)	Gdańsk
Samsun	(41.230356, 35.968334)	Samsun (NUTS3)

6.2.2 *Selection of indicators*

The selection of indicators, summarised in Table 6.2, was based on a synthesis of authoritative sources and recent research findings tailored to the European context. First, the Sixth Assessment Report by the IPCC served as a foundational reference

[36], offering a comprehensive classification of climate-related events, which underpins the understanding of potential hazards affecting coastal environments.

Second, further refinement of the indicator selection was informed by the European Topic Centre on Climate Change Impacts, Vulnerability, and Adaptation, which evaluates and prioritizes climate-related hazard indices for Europe based on their significance, adaptation relevance, data availability, and data robustness [128]. This prioritization aims to produce indicators that can be applied homogeneously and systematically in the European coastal context.

Finally, the approach aligns with and builds upon recent studies that employ hazard indicators. Lung et al. (2013) and Hincks et al. (2023) analyse a range of hazards including coastal, temperature extremes, precipitation, flooding, drought and landslide for regional risk assessments in Europe. The collaborative research conducted by Laino and Iglesias (2023c), which combines a review of existing literature with insights from local stakeholders in the study cities, provides critical insights into the local perceptions of climate-related hazards. This alignment with established research ensures that the methodology is not only grounded in the latest scientific understanding but also addresses the specific challenges and local concerns faced by coastal cities in adapting to climate change.

Table 6.2. Summary of indicators, including units and spatial and temporal resolution and coverage.

Indicator (units)	**Spatial resolution and coverage**	**Temporal resolution and coverage**	**Data source**
MSL rate (mm/year)	1-degree grid; global	Decade; 2020 relative to a 1995-2014 baseline	NASA Sea-Level Projection Tool [322,438,439]
Storm surge level (m)	0.1-degree grid; Europe	Value corresponding to the 50th percentile of the 50-year return period from 2001-2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century [440–442]
Significant wave height (m)	0.1-degree grid; Europe	Average value between the 90th and 100th percentiles from 2001-2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century Wave [440–442]

Peak wave period (s)	0.1-degree grid; Europe	Average value between the 90th and 100th percentiles from 2001-2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century Wave [440–442]
Annual highest high tide (m)	0.1-degree grid; Europe	Value corresponding to the 50th percentile of the 50-year return period from 2001-2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century Wave [440–442]
Coastal flooding extents (%)	100-metre; most Europe	Values corresponding to the 50-year return period and 36-hour duration storm	ECFAS Pan-EU Flood Catalogue [443,444]
LECZ area (%)	3-arc-seconds; global	Single values reflecting conditions pre-2017	MERIT DEM [445]
Coastline length undergoing erosion (%)	200 m; Europe	Single values reflecting conditions up to the early 2000s	Eurosion [446]
Land flooding area (%)	100 m; Europe and its surrounding areas	Values for the 100-year return period based on daily river flows between 1990-2016	River flood hazard maps for Europe and the Mediterranean Basin region [447]
Heavy rainfall frequency (day/year)	0.25-degree; Europe	Day; 1981-2019	Extreme precipitation risk indicators for Europe and European cities from 1950 to 2019 [441,448]
Drought frequency (month/year)	1-degree; global	Month; 1981-2020	Global Drought Observatory [449]
Extreme high temperature threshold (°C)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory [450]
Extreme low temperature threshold (°C)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory [450]
Heatwave frequency (day/year)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory [450]

Cold spell frequency (day/year)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory [450]
Strong winds frequency (event/year)	1 km; 20W-35E, 35N-70N regular latitude-longitude grid	Hour; 1981-2020	Winter windstorm indicators for Europe from 1979 to 2021 derived from reanalysis [441,451]
Landslide-prone area (%)	200 m; Europe	Single values reflecting conditions pre-2018	ELSUS v2 [452]

6.2.3 *Sea-level rise*

Sea-level rise is the sustained increase in the average height of the ocean's surface over a specified period, primarily driven by the thermal expansion of seawater and the melting of polar ice caps and glaciers. In the context of coastal cities hazard assessments, sea-level rise is a critical parameter to consider, as it poses a substantial and escalating risk to these urban areas [453]. It may lead to coastal flooding, erosion, and intensified storm surge impacts, significantly amplifying the vulnerability of these regions to natural disasters and necessitating robust adaptation and mitigation strategies to safeguard both human populations and critical infrastructure [21].

Sea-level change rates have been estimated using the NASA Sea-Level Projection Tool [322,438,439]. Values are measured for the year 2020 under the SSP2-4.5 scenario (relative to a 1995-2014 baseline), including global and regional contributions from changes in steric conditions, Greenland and Antarctic ice sheets, glaciers, ocean dynamics, gravitational-rotational-deformational effects of the Earth, land-water storage and glacial isostatic adjustment and other drivers of vertical land motion.

6.2.4 *Storm surge, wave regime and tidal range*

The addition of storm surge, waves and tides to regional sea-level rise results in ESL [129]. Indicators for these parameters have been measured from the downscaled meteorological forcing from the ERA5 climate reanalysis for the period 2001-2017 through the application *Indicators of water level change for European coasts in the 21st Century Wave* [440–442]. Results for each indicator are averaged from the stations located within a circle centred in the coastal city of radii 0.5° (circa 55.6 km) for Sligo, Dublin, Gdańsk and Samsun and 0.2° (circa 22.2 km) for the rest of cities using a regular latitude-longitude grid with a spatial resolution 0.1°.

The significant wave height (H_s) and peak wave period (T_p) are key descriptors for characterizing wave conditions in marine and coastal environments. Hs quantifies the average height of the highest one-third of waves in a given wave dataset. T_p is a measure of the time interval between successive wave crests passing a fixed point. It represents the dominant or most frequent time period between individual wave crests in a wave train. Values corresponding to the average between 90th and 100th percentiles for H_s and T_p were selected as these offer a compromise between conservatism and practicality. They account for wave conditions that are higher than most observed conditions but do not go to the extreme levels of the 99th and 100th percentiles.

The Surge Level (SL) and Annual Highest High Water (AHHW) complete the selection of indicators for the high-level characterisation of ESLs. Storm surge (and consequently SL) is a temporary and abnormal rise in sea level, typically associated with storm conditions. It results from a combination of factors, including strong winds, atmospheric pressure changes, and the geomorphology of the coastline. AHHW includes the contribution from the statistical annual highest hide tide, mean sea level and sea-level rise, but does not account for storm surge caused by atmospheric forcing. The 50-year return period and 50th percentile have been utilised as they address the potential for rare but significant surge events and are typically considered for critical

infrastructure and long-term urban planning. The 50th percentile represents a neutral approach corresponding to the median surge level within the 50-year return period.

6.2.5 *Coastal flooding extents and low-elevation coastal zone*

The examination of areas vulnerable to coastal flooding is integral to delineating the scope of flood risk. Such analysis is foundational for identifying prevailing flood risk patterns and temporal trends, which are essential for conducting thorough risk assessments and formulating strategic planning and mitigation efforts. To this end, two indicators were developed based on most recent coastal flooding maps and the concept of Low-Elevation Coastal Zones.

The European Coastal Flood Awareness System (ECFAS) Pan-EU Flood Catalogue was employed as a primary data source to quantify the extent of areas susceptible to coastal flooding within the study cities [443,444]. This comprehensive repository offers detailed mappings of coastal flood projections across Europe. These projections are based on 15 scenarios that simulate synthetic storms of varying intensities and durations. The scenarios are constructed around Total Water Levels (TWLs) for return periods extending from 2 to 50 years, coupled with storm durations spanning 12, 24, and 36 hours, and are rendered at a spatial resolution of 100 meters, ensuring detailed and accurate delineation of flood extents.

For the purpose of this study, the most conservative scenario—representing a 50-year return period and a 36-hour storm duration—was selected. This decision was aimed to capture the full spectrum of potential flood impacts, thereby facilitating a comprehensive assessment of urban areas at heightened risk and also to enhance the reliability of the findings in supporting the development of adaptive strategies and policy interventions.

The Low Elevation Coastal Zone (LECZ) is commonly utilized as an indicator to assess the vulnerability of coastal areas to a range of climate-related hazards in the

context of coastal cities [309]. It is defined as a contiguous geographical area situated in close proximity to the coastline, with an elevation less than 10 m above Mean Sea Level (MSL). LECZs hold particular significance in hazard assessment due to their typical characteristics of high population density and economic development, as well as their close proximity to the sea, rendering them susceptible to various coastal hazards.

For the purpose of this study, LECZ areas were systematically determined for each coastal city under investigation. This determination was facilitated by employing the Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM), a global digital elevation model characterized by a high level of accuracy [445,454]. The MERIT DEM boasts a spatial resolution of 3 arc-seconds, equivalent to approximately 90 m at the Equator, and ±2 m of vertical resolution. The MERIT DEM is constructed by amalgamating data from various existing spaceborne DEMs, including the NASA SRTM3 DEM v2.1, JAXA AW3D-30m DEM v1, and Viewfinder Panoramas' DEM. Furthermore, it is complemented by other pertinent datasets in order to minimize multiple error components.

To further assess coastal vulnerability, the LECZ areas were delineated using the MERIT DEM data and subsequently compared to the overall coastal city area. This assessment provided a valuable metric for expressing the extent of coastal exposure, effectively quantifying the vulnerability of these urban coastal regions to climate-related hazards.

6.2.6 *Coastline length under erosion*

Coastal erosion refers to the net removal of material from one coastal location to another, influenced by various natural factors including storm surge, changes in wave energy, sediment supply, and sea-level rise. The inevitability of coastal erosion often

culminates in shoreline retreat, be it gradual due to sea-level rise or episodic due to ESLs or coastal flooding [29,39].

Coastline erosion trends (erosion, aggradation, stability) have been analysed for each coastal city, with the exception of Samsun, using data from Eurosion database [455]. The European coastal database Eurosion contains information regarding shoreline evolution over the 1990s with a scale of 1:100,000. In particular, coastline segments are classified according to the observed erosional trend. These segments are classified in four categories: erosion, aggradation, stable or undetermined. Categories of erosion, aggradation and stable directly refer to the erosional trend for each coastline segment, and undetermined applies when no data are available. The total coastline lengths under erosion were computed and expressed as a percentage of the total coastline length for each study city.

6.2.7 *Heavy precipitation and land flooding*

Land flooding, defined as the inundation of terrestrial areas by water resulting from various factors, including heavy rainfall, storm surges, rising sea levels, and river flooding, holds a paramount role in the hazard assessment of coastal cities, significantly augmenting their risk profiles [22]. This can lead to severe consequences, such as property damage, infrastructure disruption, and threats to ecosystems and human lives, making it a critical factor in the evaluation and mitigation of hazards in coastal urban environments [456].

Heavy rainfall events refer to periods of intense and excessive precipitation, characterized by a significant and often rapid accumulation of rainfall within a specific geographic area or time frame, exceeding the average or expected rainfall amounts for that region or period [457,458]. In this study, heavy rainfall events have been characterized by calculating the frequency of daily rainfall exceeding 20 mm, due to their consistency for cross-city comparisons, relevance in areas with limited soil

infiltration, utility in assessing infrastructure resilience, effectiveness in risk communication, and swift risk identification. The underlying rainfall data used to calculate these values are derived from the ERA5 reanalysis, encompassing a spatial resolution of 0.25° x 0.25° for the period 1979-2019, as per Mercogliano et al. (2021).

The flood extents represent the areas susceptible to flooding and have been extracted for the coastal cities using data sourced from the "River flood hazard maps for Europe and the Mediterranean Basin region" from the Joint Research Centre dataset [447]. Specifically, the flood extents correspond to events with a 100-year return period and spatial resolution of 100 m, thus providing a robust perspective on the potential severity of flooding in these regions and detailed and precise mapping of flood-prone areas. Flood-prone areas are expressed as a percentage of the total coastal city area for subsequently comparison.

6.2.8 *Droughts*

Droughts can be defined as extreme events related to climate, marked by enduring and significantly dry weather patterns that upset the balance of hydrological processes, causing widespread impacts [47,48,459]. Such conditions are often associated with reduced precipitation, soil moisture, and water storage levels, which contribute to the categorization of drought into three types, namely meteorological, agricultural, and hydrological drought, respectively.

The Standard Precipitation Index with a 3-month aggregation window (SPI-3) is a widely recognized and accepted indicator for meteorological drought assessment [460]. In this study, drought events were evaluated using this indicator, specifically, the number of drought months within the period spanning from 1981 to 2020 for each city. To derive this indicator, the geographic coordinates of the cities mentioned earlier are employed. The quantification of drought months was accomplished through the utilization of the SPI-3 data from EDO, with a spatial resolution of 1 degree and

calculated over the reference period of 1991-2020 [49,449]. Drought months are considered those with SPI-3 falls below -1.

6.2.9 *Temperature extremes, heatwaves and cold spells*

Extreme temperatures, which hold significant relevance for sectors such as agriculture, forestry, fire management, public health, and infrastructure planning, were systematically quantified [461,462]. To this end, relative thresholds were established based on daily temperature data. These thresholds were carefully designed to capture the unique characteristics and variations of the local climate, thus providing a more refined and context-specific evaluation of extreme temperatures, as opposed to the use of absolute temperature values [21]. Furthermore, this approach facilitated the precise identification and differentiation of various extreme temperature events, including heatwaves and cold spells.

Temperature extremes, heatwaves and cold spells occurrences have been calculated based in the dataset comprising daily interpolated maximum and minimum temperature observations from EDO for the period 1981-2020 [450]. The temperature data is derived from an extensive network of approximately 4000 weather stations distributed across Europe and its adjacent regions. Interpolation of these temperature data was performed utilizing an inverse distance algorithm, with a search radius of 200 km and on a grid with a spatial resolution of 0.25 decimal degrees. A maximum of 20 nearby weather stations were considered for interpolation at any given location and a correction for elevation was applied by incorporating a temperature adjustment factor of 0.65 degrees Celsius per 100 m of elevation change.

The definitions of heatwaves and cold spells, which are often subject to variability [463], were carefully chosen to align with widely accepted standards. For climatological heatwaves, the criteria set forth by the European Environment Agency [128]. A heatwave is defined thereby as a period of at least three consecutive days

when the daily maximum temperature exceeds the 99th percentile of daily maximum temperature values from May to September in a given location over the reference climate period. Similarly, climatological cold spells have been defined as periods of at least three consecutive days when the daily minimum temperature is below the 1st percentile of daily minimum temperatures from November to March [464]. In this context, the reference period for defining extreme temperature thresholds was established as 1981-2000.

6.2.10 *Strong winds*

Strong winds are defined as high-velocity air movements significantly exceeding typical or average wind speeds for a given region. In Europe, many of the most powerful windstorms originate in the North Atlantic Ocean during the winter session [61]. These storms are often referred to as North Atlantic storms or extratropical cyclones and can bring heavy rain and strong winds to western and northern Europe.

To assess the exposure of coastal cities to the forces of these winter storms, storm footprints were employed as a fundamental element. These footprints represent the spatial extent of each storm's impact. Specifically, for each storm track associated with windstorms occurring between October and March, the maximum 3 s 10 m wind gusts over a 72-hour period were analysed for each coastal city. These data are sourced from ERA5 reanalysis and are based on hourly assessments, with a spatial resolution of 1.0 kilometre [451]. To assess the potential hazard posed by these windstorms, a threshold was set at wind speeds exceeding 20 m/s, corresponding approximately to Beaufort Scale categories ranging from "gale" to "strong gale".

6.2.11 *Landslides*

Landslides can be defined as the abrupt downward movement of earth material, often triggered by various factors such as heavy rainfall, seismic activity, or human activities [57]. In this study, landslide exposure was assessed using data derived from the

European Landslide Susceptibility v2 (ELSUS v2) dataset [452,465]. ELSUS v2 offers a comprehensive representation of landslide susceptibility across the European continent, characterized by a spatial resolution of 200 m. This dataset is the result of a heuristic-statistical modelling approach that integrates key landslide conditioning factors, encompassing slope angle, shallow sub-surface lithology, and land cover characteristics, in addition to geospatial information regarding over 149,000 actual landslide occurrences.

The resulting ELSUS v2 landslide susceptibility map classifies susceptibility levels into a categorical scale encompassing the following classifications: 'no data,' 'very low,' 'low,' 'moderate,' 'high,' and 'very high,' represented numerically within a range of 0 to 5. To evaluate the exposure of coastal cities to landslide susceptibility, an analysis focused on pixels corresponding to susceptibility levels of 4 and 5 was conducted for each coastal city domain. By aggregating these pixels, the corresponding area was computed and expressed as a percentage of the total land area occupied by each coastal city.

6.3. Results

Sea-level rise amplifies the adverse impacts of coastal flooding and erosion, progressively submerging land as MSL continues to rise. A critical aspect of our analysis is the assessment of MSL rate variations for each coastal city. Our findings reveal a spectrum of MSL rates across these cities, ranging from 2.4 mm/year in Sligo to 5.4 mm/year in Vilanova i la Geltrú and Gdańsk. Intermediate MSL rates, falling between 3.4 mm/year and 3.8 mm/year, are observed in Benidorm, Massa, Piran, and Samsun. Dublin, Oarsoaldea, and Oeiras exhibit higher MSL rates, spanning from 4.0 mm/year to 4.5 mm/year (Figure 6.1).

Considering the implications of these diverse MSL rates, it becomes evident that some coastal cities face a more rapid sea-level rise than others. This discrepancy underscores the need for tailored adaptation strategies and proactive measures in regions experiencing accelerated MSL increases. Moreover, understanding the underlying factors contributing to these disparities is crucial for informed decision-making and sustainable coastal management.

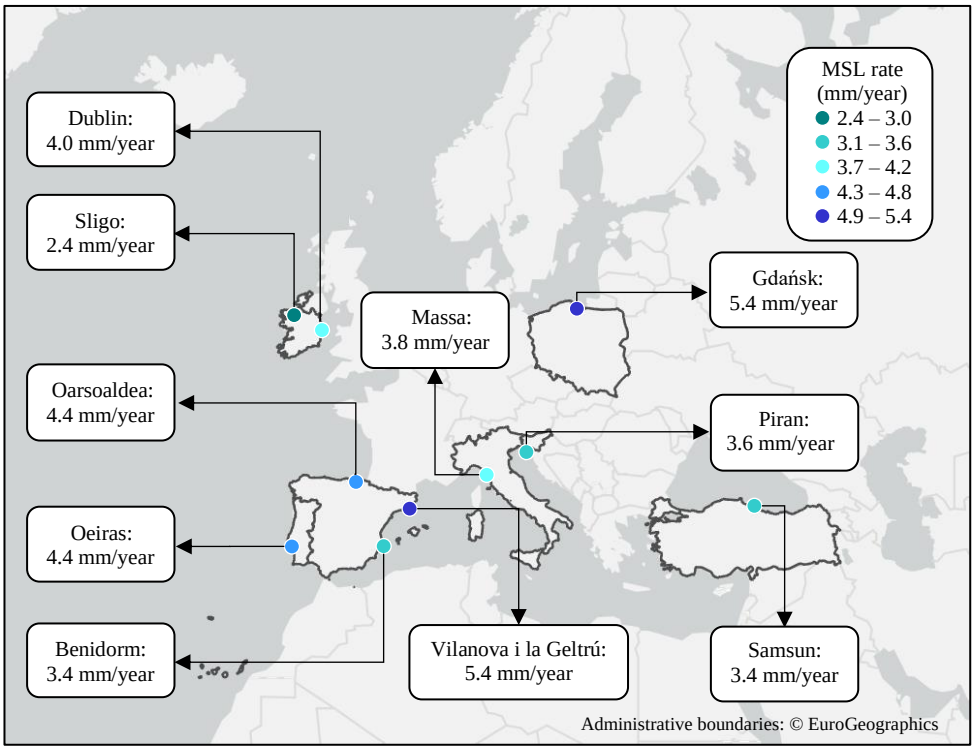


Figure 6.1. Sea-level change rates in 2020 under the SSP2-4.5 scenario (relative to a 1995-2014 baseline). Data source: NASA Sea-Level Projection Tool [322,438,439].

A comprehensive assessment that accounts for extreme high-tide, surge, and wave levels provides valuable insights into the potential for extreme sea level events in coastal cities. Figure 6.2 presents an overview of the combined values of these crucial parameters. Notably, wave action emerges as the predominant contributor to the overall ESL across all coastal cities. The indicators show that Sligo, Oarsoaldea, and Oeiras are poised to experience the most substantial ESLs, reaching heights of 10.23 m, 8.07 m, and 7.61 m, respectively. Coastal cities situated along enclosed or semi-enclosed seas, such as the Mediterranean, Baltic, and Black Seas, generally exhibit

lower ESL values, hovering around 3 m, with Samsun recording the lowest at 2.22 m. Tidal influence remains notably minimal in these cities, typically measuring less than 0.20 m, except for Piran, where it reaches 0.76 m. Surge levels exhibit variability among cities, with peak values observed in Sligo and Gdańsk at 1.12 m and 1.15 m, respectively.

These findings underscore the critical role of wave dynamics in shaping extreme sea levels in coastal cities, highlighting the significance of wave-related preparedness measures in these regions. Additionally, the notable differences in extreme sea levels among coastal cities, especially in relation to surge levels, raise questions about the local factors contributing to such variations. Further research into the specific geographic, geological, and environmental factors influencing surge levels in these regions could provide valuable insights for coastal planning and resilience efforts.

The quantification of coastal flooding extents and LECZ areas, as percentages of total city areas, provides a critical lens through which the vulnerability of European coastal cities to sea-level rise and potential inundation can be assessed. Figure 6.2 juxtaposes these two pivotal indicators to identify areas most at risk of coastal flooding. The findings reveal a nuanced landscape of hazard across the studied cities. Specifically, the analysis based on the ECFAS dataset indicates that, with the exception of Oarsoaldea, coastal flooding extents are generally smaller than the corresponding LECZ areas. This discrepancy underscores the varied nature of threat landscapes, with Oarsoaldea presenting a unique case where the risk of coastal flooding aligns closely with its LECZ designation. In terms of relative coastal flooding exposure, Piran stands out, with 17.4% of its area falling within flood-prone zones, the highest among the cities studied, followed by Gdańsk with a notable 6.1% exposure.

Furthermore, Gdańsk emerges as the city with the highest LECZ proportion, with a staggering 46.8% of its total area falling within this zone. This finding underscores the acute vulnerability of Gdańsk to rising sea levels, demanding immediate attention to

mitigate potential impacts on infrastructure, urban planning, and the livelihoods of its residents. Piran follows closely, with a substantial 29.1% of its city area classified as LECZ. This places Piran in a high-risk category for coastal inundation, emphasizing the need for proactive measures to safeguard against sea-level rise-induced threats. Massa, with 18.6% of its area in the LECZ, also demonstrates a notable susceptibility to coastal hazards. The results suggest that Massa faces a considerable challenge in terms of preserving its coastal assets and managing potential flooding events. In contrast, cities such as Benidorm (3.0%), Oeiras (2.3%), and Oarsoaldea (1.1%) exhibit relatively lower LECZ proportions, indicating a comparatively reduced exposure to sea-level rise within their city boundaries. Dublin (15.6%), Samsun (9.6%), Sligo (8.3%) and Vilanova i la Geltrú (5.5%) fall within the medium range, indicating a need for comprehensive coastal management strategies to address potential impacts in these regions.

The indicators encompassing areas exposed to coastal flooding, defined as percentages of city territory, highlight the diverse range of coastal vulnerability levels across the studied cities. They underscore the critical importance of tailored adaptation and resilience strategies to safeguard these coastal regions and their communities from the escalating challenges posed by sea-level rise and coastal inundation.

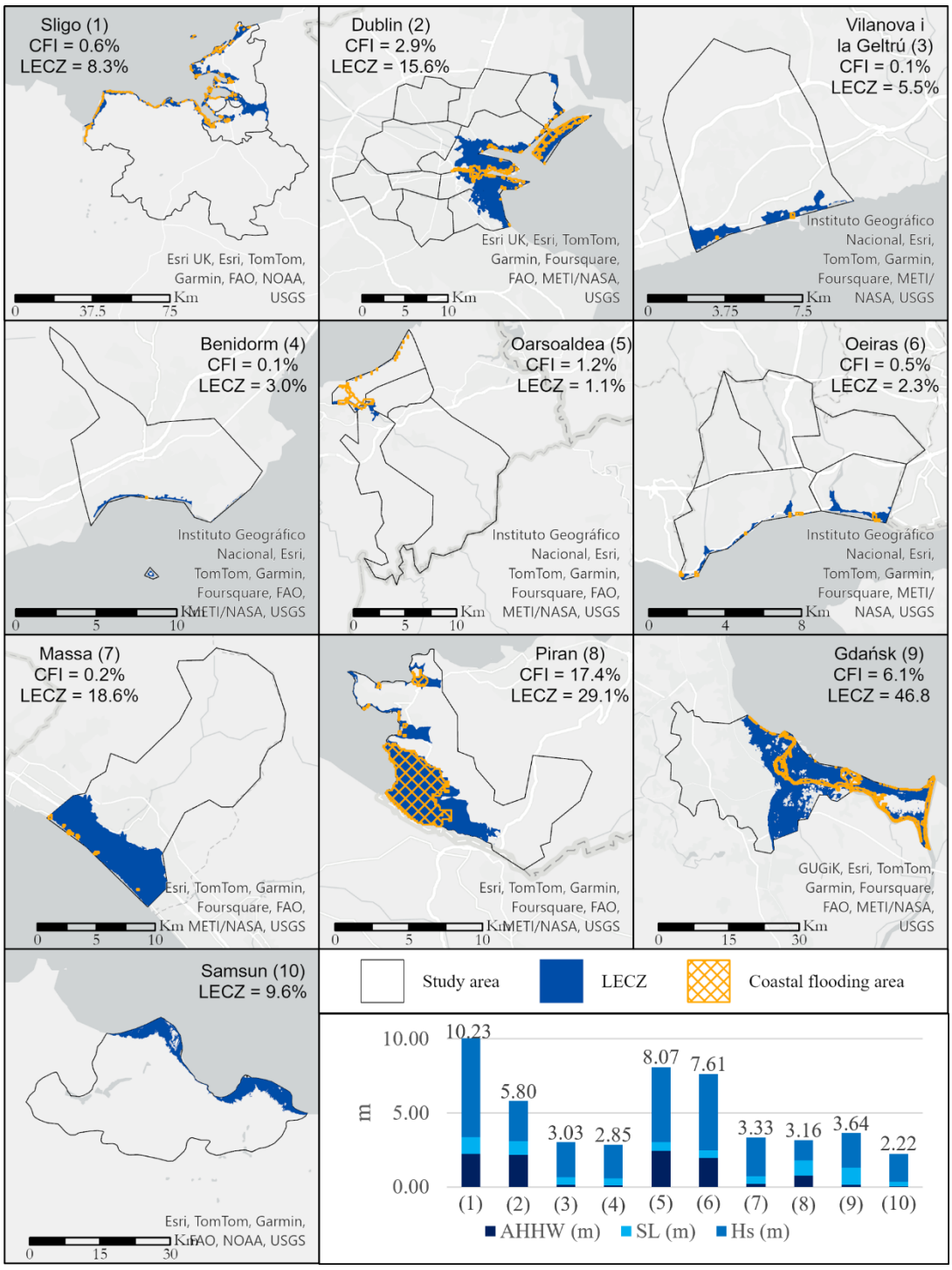


Figure 6.2. Coastal flooding extents (CFI) based on the data from the ECFRAS Pan-EU Flood Catalogue for the synthetic storm scenario of 50-year return period and 36-hour duration, LECZ extents and percentage expressing LECZ area over total city areas and averaged values of significant wave height (median of averaged 90th and 100th percentiles), surge (median of 50-year return period) and annual highest high

water (median) levels between 2001-2017 for the coastal cities. Data source: Yamazaki et al. (2017) and ERA5 reanalysis [440–442].

The evaluation of coastal erosion, expressed as a percentage of the total city coastline, offers invaluable insights into the susceptibility of coastal cities to this widespread natural phenomenon (Figure 6.3). It is worth noting that cities with artificial seafronts, where the impact of coastal erosion on these segments may be minimal, tend to exhibit lower susceptibility values. Additionally, it is important to acknowledge that some results may be outdated due to data being from 2004 or earlier, given the ongoing development of adaptation and mitigation efforts.

Massa presents a stark scenario, with its entire coastline affected by erosion, which translates into an alarming 100.0% susceptibility. This underscores the urgency of the extensive mitigation and adaptation actions undertaken in the region in recent years [88]. Piran (26.8%), Vilanova i la Geltrú (26.1%), Gdańsk (21.3%) and Sligo (19.6%) also have significant sections of coastline undergoing erosion. While not as severe as Massa, these cities nonetheless face significant challenges in managing and mitigating erosion impacts. Conversely, Dublin, Benidorm, and Oarsoaldea report 0.0% susceptibility, reflecting the presence of artificial seafronts or cliffs in these areas. However, it is essential to recognize that contemporary observations reveal ongoing coastal erosion affecting the Levante and Poniente beaches in Benidorm [88,205]. Unfortunately, data for Samsun remained unavailable for this analysis. Nevertheless, other studies advocate for comprehensive data collection efforts to comprehensively assess and address this significant hazard in the coastal city [253].

In summary, the assessment of coastline under erosion as a percentage of the total city coastline provides a crucial metric for understanding and comparing the vulnerability of coastal cities to this environmental challenge. These findings provide a solid foundation for targeted studies and the formulation of policy measures aimed at bolstering the resilience of these cities in the face of persistent coastal erosion.

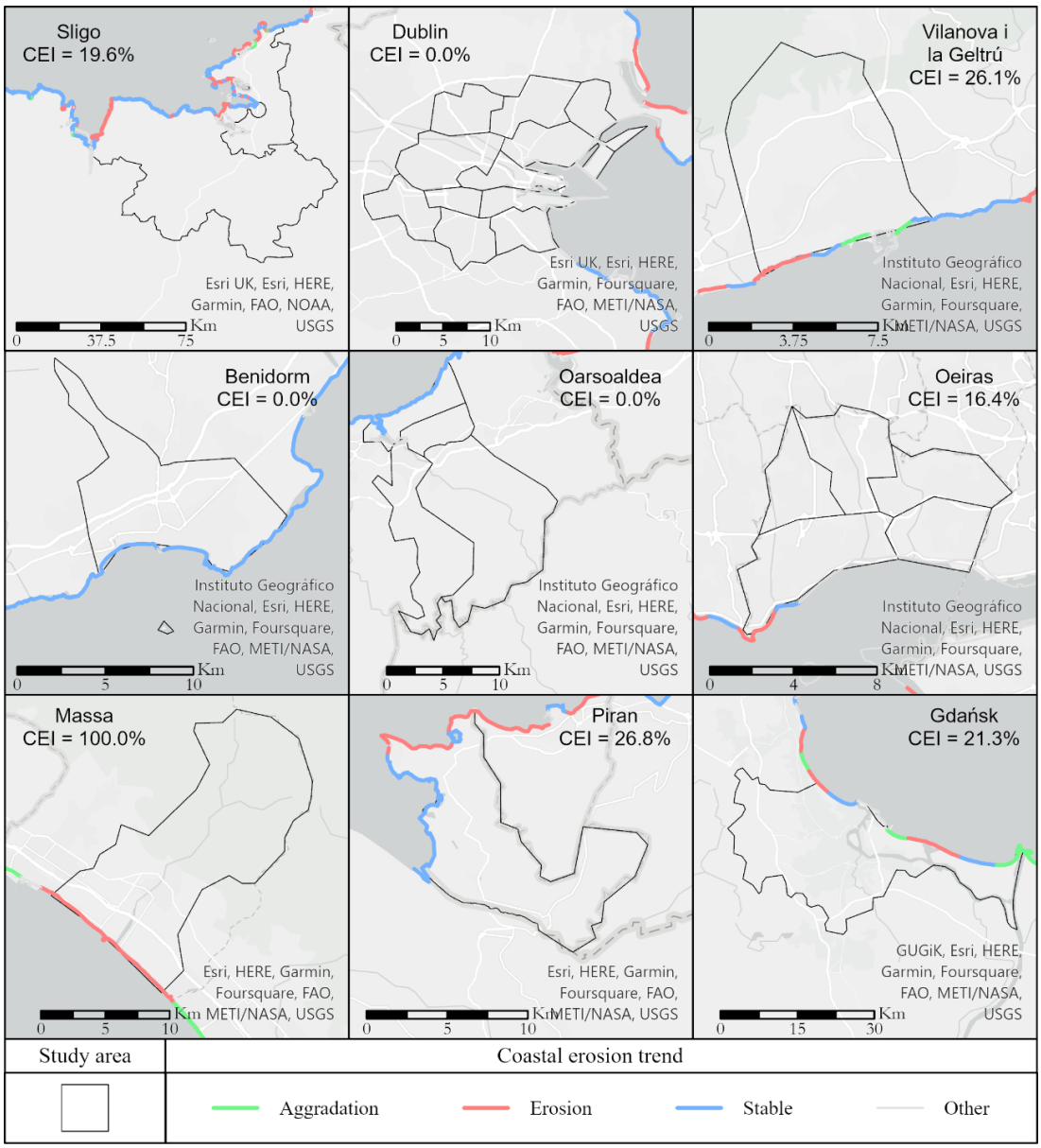


Figure 6.3. Coastline evolution trends and percentage of coastline undergoing erosion over the total coastline length (CEI) for the coastal cities of Sligo, Dublin, Vilanova i la Geltrú, Benidorm, Oarsoaldea, Oeiras, Massa, Piran and Gdańsk. Data source: Eurosion (2004).

The analysis of the extent of floods and water depths corresponding to river flooding events with a 100-year return period offers a critical perspective on the vulnerability of coastal cities to this specific hazard. As illustrated in Figure 6.4, these data enable a comparative assessment of flood exposure across the study cities. It is important to note that the reference dataset does not encompass flooding events in areas with

narrow (river width < 100 m) watercourses or ravines, which may pose distinct flood risks. For such cases, we will delve into heavy rainfall events later in this study, providing additional insights into flood susceptibility.

In cities covered by the data from Dottori et al. (2021), flood extents and water depths have been combined (namely, LFI) to assess river flooding hazard. The LFI values are most pronounced in Gdańsk, Samsun, and Dublin, measuring at 55.72 cm, 20.75 cm, and 6.22 cm, respectively. This metric facilitates a direct comparison of river flood hazards among these cities. It is worth emphasizing that while the LFI cannot be accurately calculated for cities with small watercourses, our analysis highlights the historical prominence of river flooding hazards in Dublin, Gdańsk, and Samsun compared to the other cities under examination [88]. This underscores the continued relevance of the LFI as a valuable indicator for assessing and addressing river flood hazards.

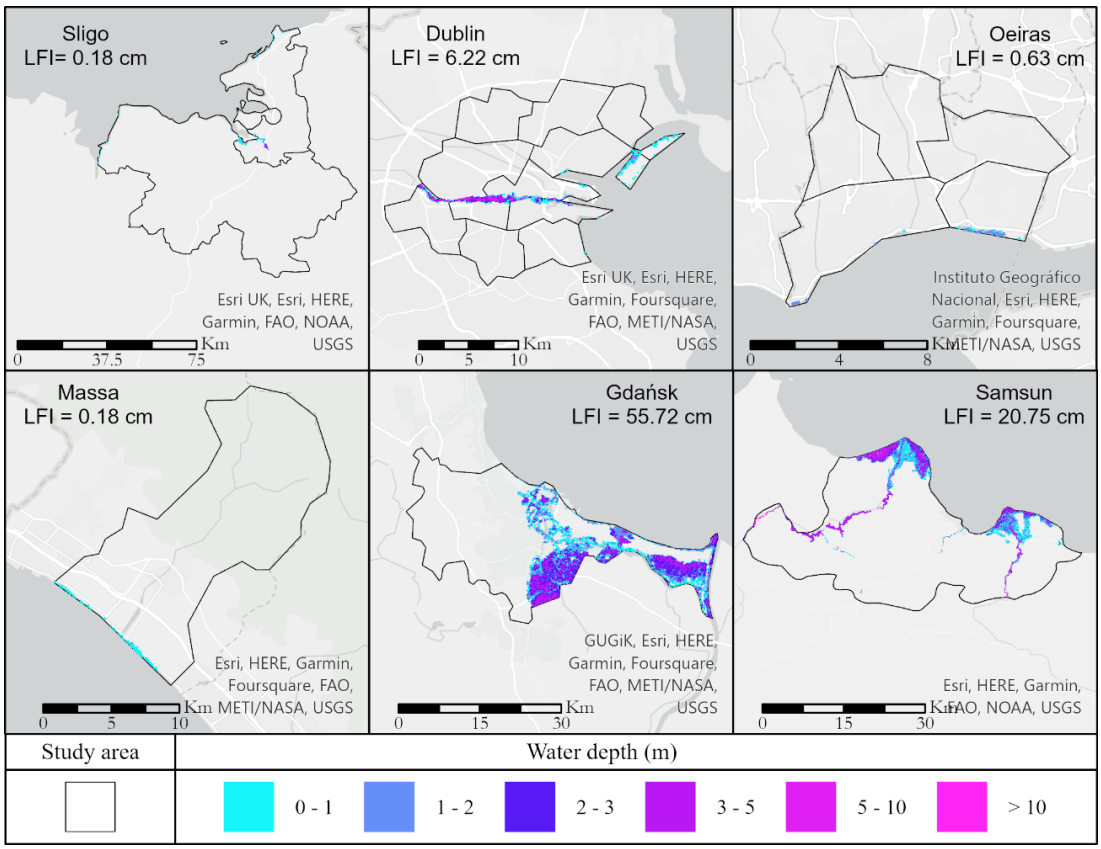
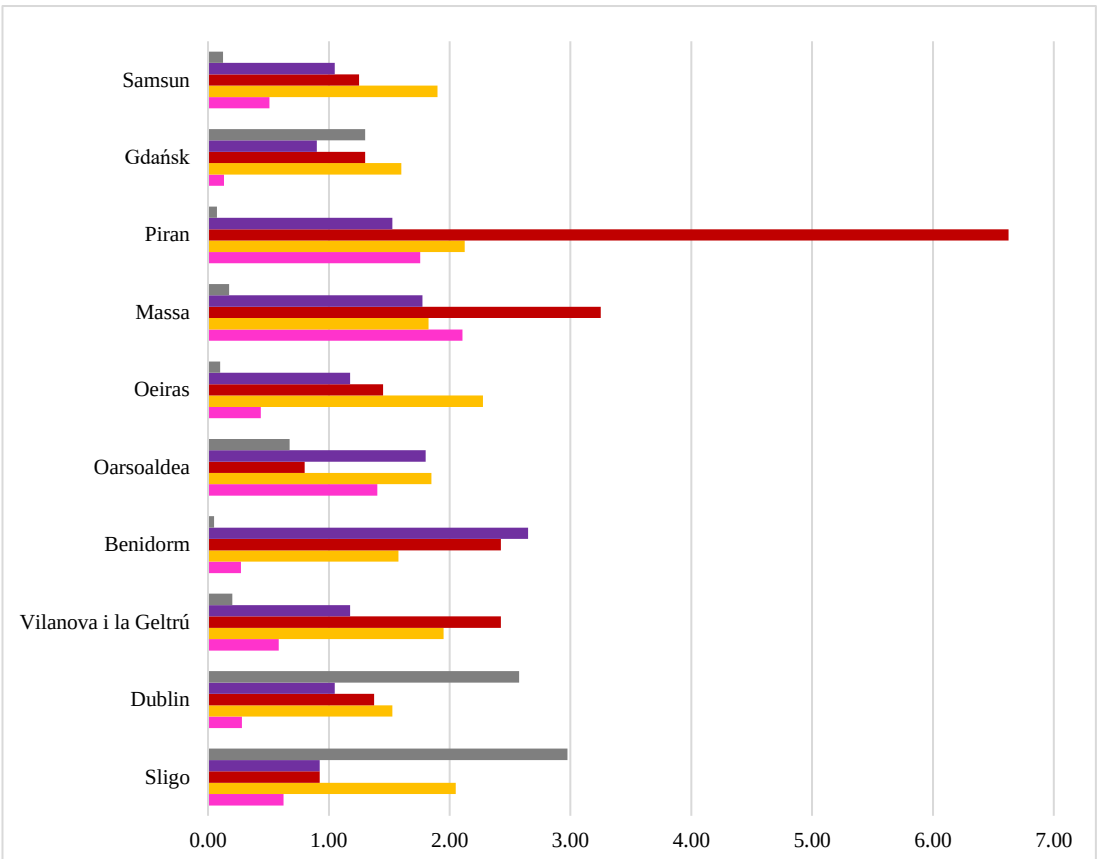


Figure 6.4. Water depths and height (cm) corresponding to the elevation of the flood volume relative to the total area of each coastal city (LFI) for river flooding events of 100-year return period. Cities where flood extents are null are not represented. Data source: Dottori et al. (2021).

The analysis of days with daily precipitation exceeding 20 mm between 1981-2019 offers valuable insights into the susceptibility of coastal cities to heavy rainfall events (yearly averaged and scaled by a factor of 10^{-1} in Figure 6.5 for visual comparison). This parameter displays noteworthy variations among the coastal cities under study. Massa, Piran, and Oarsoaldea stand out with the highest occurrences, tallying 821, 685, and 546 instances, respectively. In contrast, Gdańsk, Benidorm, and Dublin record the lowest occurrences, with 52, 106, and 109 instances, respectively. Meanwhile, Sligo, Vilanova i la Geltrú, Oeiras, and Samsun accumulate around 200 days of such heavy rainfall events, with 244, 228, 170, and 198 occurrences, respectively. Significant trend changes are not apparent across the coastal cities

between 1981-2000 and 2001-2019. However, there is a subtle increase in the number of heavy rainfall events observed in Dublin and Benidorm during this period.

These findings underscore the diversity in heavy rainfall exposure among coastal cities, with some cities consistently experiencing a higher frequency of such events. While overall trends remain relatively stable, the slight uptick in heavy rainfall events in Dublin and Benidorm suggests the need for continued monitoring and adaptation strategies to address potential increases in extreme precipitation in these regions. However, it is worth noting that while this study provides valuable insights into the frequency of heavy rainfall events in coastal cities, changes in rainfall intensity have not been examined specifically. Future research should delve deeper into the intensity of precipitation events, as this aspect can provide a more comprehensive understanding of the evolving precipitation patterns and their potential impacts on these coastal regions [54].



	Sligo	Dublin	Vilanova i la Geltrú	Benidorm	Oarsoaldea	Oeiras	Massa	Piran	Gdańsk	Samsun
SWI	2.98	2.58	0.20	0.05	0.68	0.10	0.18	0.08	1.30	0.13
CDI	0.93	1.05	1.18	2.65	1.80	1.18	1.78	1.53	0.90	1.05
HDI	0.93	1.38	2.43	2.43	0.80	1.45	3.25	6.63	1.30	1.25
DMI	2.05	1.53	1.95	1.58	1.85	2.28	1.83	2.13	1.60	1.90
HPI/10	0.63	0.28	0.58	0.27	1.40	0.44	2.11	1.76	0.13	0.51

Figure 6.5. Yearly-averages of number of days with daily precipitation exceeding 20 mm (HPI) (1981-2019), number of months with SPI-03 below -1 (DMI) (1981-2020), heatwave days (HDI) (1981-2020), cold spell days (CDI) (1981-2000) and number of windstorms events with maximum 3 s and 10 m height wind gust velocities exceeding 20 m/s (SWI) (1981-2020). Data source: Mercogliano et al. (2021), European Commission and Joint Research Centre (JRC) (2021), Lavaysse et al. (2018) and Copernicus Climate Change Service, Climate Data Store (2022).

The examination of the number of months with SPI-03 below -1 (1981-2020) as depicted in Figure 6.5 serves as a valuable indicator of the likelihood of drought episodes in coastal cities. Oeiras stands out with the highest cumulative count of such months, registering at 91 [23,218]. Notably, these drought events have become more

prevalent in the past two decades, increasing from 38 months (1981-2000) to 53 months (2001-2020). Sligo and Piran also exhibit substantial counts, with 82 and 85 months respectively falling under these defined drought conditions during the period of 1981-2020. Similar to Oeiras, Sligo and Piran have witnessed an escalation in drought events, with 33 months to 49 months and 32 months to 53 months respectively, when comparing the time spans of 1981-2000 and 2001-2020.

Conversely, coastal cities such as Dublin (61), Benidorm (63), and Gdańsk (64) record lower total counts of drought months for the same period. In some of these cities, namely Benidorm (42 against 21), Gdańsk (38 against 26), and Samsun (41 against 35), there is even a declining trend in drought months, suggesting a relative mitigation of drought risk in recent years. Additionally, several coastal cities, including Vilanova i la Geltrú (78), Oarsoaldea (74), Massa (73), and Samsun (76), exhibit intermediate total counts of drought months. Notably, Massa demonstrates a significant increase in drought months between 1981-2000 and 2001-2020, rising from 29 to 44 months.

These findings emphasize the need for proactive drought management strategies in cities with increasing drought trends, while also highlighting the decrease of drought-risk in others. Tailored approaches to drought resilience should take into account the specific challenges faced by each coastal city, as demonstrated by the variations in drought occurrence and trends across the studied regions.

The calculation of extreme temperature values based on daily minimum and maximum temperature data yields a wealth of critical information. Beyond facilitating the assessment of heatwaves and cold spells, which will be discussed in detail later, these indicators offer invaluable insights with wide-ranging applications, encompassing climate resilience planning, public health, infrastructure development, energy management, agricultural practices, tourism, climate mitigation strategies, and emergency preparedness, among others.

Table 6.3 illustrates the 99th percentile for daily maximum temperatures and the 1st percentile for daily minimum temperatures between 1981-2000 across the coastal cities in our study. Notably, Oeiras stands out as the coastal city with the highest recorded maximum temperature, reaching a scorching 38.2°C. It is closely followed by Oarsoaldea, Vilanova i la Geltrú, and Benidorm, all located in the Iberian Peninsula, with maximum temperatures of 35.2°C, 34.4°C and 34.4°C, respectively. Conversely, Gdańsk emerges as the coastal city with the most frigid recorded minimum temperature, plummeting to -16.3°C. This stark contrast is followed by Massa (-6.4°C), Samsun (-5.9°C), and Sligo (-5.7°C), emphasizing the considerable variation in minimum temperature extremes among the studied coastal cities. Notably, Dublin and Sligo, both situated in Ireland, exhibit the lowest recorded high temperatures among the coastal cities, with values of 24.5°C and 24.3°C, respectively. Regarding the maximum recorded low temperatures, the Iberian Peninsula cities once again lead the pack, with Oeiras and Vilanova i la Geltrú registering 2.8°C, Benidorm recording -1.8°C, and Oarsoaldea reporting -3.2°C.

Table 6.3. Percentiles 99th for daily maximum temperatures and 1st for daily minimum temperatures between 1981-2000 for the coastal cities. Data source: [450].

Coastal city	**Low extreme temperature threshold (°C)**	**High extreme temperature threshold (°C)**
Sligo	-5.7	24.3
Dublin	-4.5	24.5
Vilanova i la Geltrú	2.8	34.4
Benidorm	-1.8	34.4
Oarsoaldea	-3.2	35.2
Oeiras	2.8	38.2
Massa	-6.4	30.6
Piran	-4.1	32.9
Gdańsk	-16.3	29.8
Samsun	-5.9	33.9

These temperature extremes underscore the vast climatic diversity across the coastal cities under study, with some experiencing sweltering high temperatures while others endure extreme cold. The comprehensive nature of this temperature analysis not only aids in understanding local climate patterns but also highlights the multifaceted implications for various sectors and industries operating in these regions.

The analysis of heatwaves and cold spells in this study focuses on instances when daily maximum temperatures, in the case of heatwaves, and daily minimum temperatures, in the case of cold spells, surpass predefined thresholds based on percentiles. Periods lasting three or more days with these conditions occurring between 1981-2020 were evaluated for the coastal cities, with the yearly-averaged cumulative duration of these events presented in Figure 6.5.

In the context of heatwaves, Piran emerges as a standout, with a total duration of 265 days of heatwave conditions recorded over the four decades under scrutiny. Massa follows in second place with 130 days, while Benidorm and Oarsoaldea rank third, each experiencing 97 days of heatwave conditions. Conversely, Gdańsk, Samsun, Sligo, and Oarsoaldea report the lowest duration of heatwave events, with 52, 50, 37, and 32 days, respectively. When examining cold spells, the variation in duration between the first and second places is less pronounced. Benidorm leads with 106 cumulative days of cold spells, followed closely by Oarsoaldea with 72 days. Massa ranks third with 71 days, while Piran records 61 days. Gdańsk, Sligo, Dublin, and Samsun occupy the lower positions in terms of cold spell duration, with 36, 37, 42, and 42 days, respectively. Interestingly, it is evident that the frequency of heatwaves and cold spells doesn't necessarily correlate directly with the extremity of temperature values in general. For example, Gdańsk, known for having the coldest recorded minimum low temperature, reports a relatively lower frequency of cold spells. Moreover, coastal cities such as Sligo, Dublin, Oeiras, Gdańsk, and Samsun experience lower frequencies of both heatwaves and cold spells. In contrast, Benidorm, Massa, and Piran exhibit relatively higher frequencies of these events.

These findings emphasize that the occurrence and duration of heatwaves and cold spells are influenced by a complex interplay of local climate factors, and they do not necessarily align with the extremity of temperature values alone. These phenomena not only impact the local environment but also have significant implications for the residents and various sectors operating within these cities. For instance, cities with higher occurrences of heatwaves may need to prioritize public health measures, such as heat action plans, to protect vulnerable populations during extended periods of extreme heat. Conversely, regions experiencing frequent cold spells may require infrastructure and energy management strategies to ensure resilience in the face of cold-related disruptions. Furthermore, it is essential to recognize that these variations in temperature extremes can influence urban planning, tourism trends, and even agricultural practices. By understanding the intricacies of heatwaves and cold spells within the context of specific coastal cities, policymakers and stakeholders can make more informed decisions to enhance climate adaptation and improve the overall quality of life for their communities.

Remarkably, Sligo and Dublin, both located in Ireland, emerge as the most exposed to these intense wind events, with a cumulative count of 119 and 103 strong wind occurrences, respectively (Figure 6.5). These figures underscore the vulnerability of these regions to the fierce winter storms that sweep across the Atlantic Ocean. Such exposure can pose significant challenges, including infrastructure damage, power outages, and coastal erosion, necessitating robust resilience planning and preparedness measures. Conversely, Gdańsk and Oarsoaldea record comparatively lower counts of 52 and 27 strong wind events, indicating a relatively reduced exposure to extreme wind conditions during the winter season. While these cities are not immune to the impacts of winter storms, their lower exposure levels may mitigate some of the associated risks. The remaining coastal cities in our study report occurrences of less than 10, underscoring their comparatively lower susceptibility to such potent wind

gusts. This variance in exposure highlights the diverse range of challenges faced by coastal communities in Europe.

Sligo and Dublin, positioned along the Atlantic coast, consistently experience a higher frequency of these events, potentially reflecting the influence of Atlantic winter storms. This correlation invites further investigation into the specific meteorological patterns that shape the exposure of coastal cities to extreme winter winds, offering valuable insights for climate resilience and risk mitigation strategies.

The calculation of susceptibility levels 4 (high) and 5 (very high) for each coastal city, except for Samsun due to data limitations, provides valuable insights into the potential landslide hazards faced by these regions. When expressed as a fraction of the total city area (Figure 6.6), this indicator reveals a wide spectrum of susceptibility levels, ranging from 0.0% in Gdańsk to a significant 66.8% in Massa. Remarkably, Massa stands out with the highest susceptibility level, covering almost two-thirds of its city area (66.8%), emphasizing the heightened landslide risk in this region. Oarsoaldea (41.0%) and Piran (38.0%) also record substantial values, underscoring the importance of landslide mitigation efforts in these areas. In contrast, Oeiras (23.0%), Benidorm (17.8%), and Sligo (18.1%) exhibit medium levels of susceptibility, indicating a moderate but notable vulnerability to landslide hazards. These cities would benefit from targeted measures to enhance their resilience against potential landslide events. Conversely, Vilanova i la Geltrú (3.2%), Dublin (0.2%), and Gdańsk (0.0%) report the lowest susceptibility values, suggesting a relatively lower risk of landslides in these coastal cities.

The varying degrees of landslide susceptibility among coastal cities underscore the need for region-specific strategies to address this hazard effectively. Cities with high susceptibility, such as Massa, may require extensive measures to mitigate landslide risks and protect vulnerable areas. Meanwhile, cities with medium susceptibility levels, like Oeiras, Benidorm, and Sligo, should prioritize adaptive measures that

balance the potential risks and resources available. Lastly, cities with low susceptibility levels, including Vilanova i la Geltrú, Dublin, and Gdańsk, may still benefit from proactive planning and monitoring to ensure long-term resilience.

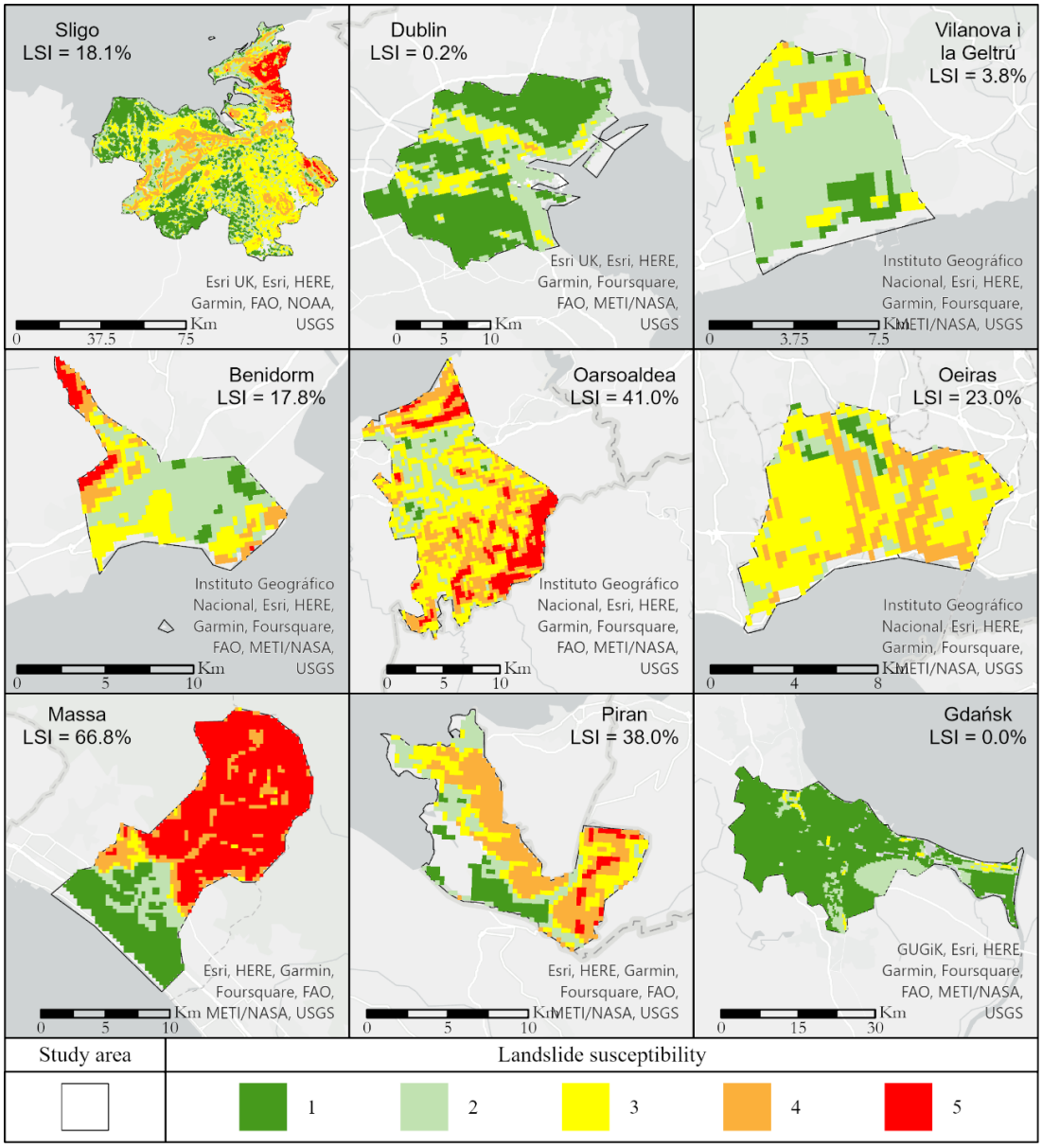


Figure 6.6. Landslide susceptibility indicator (LSI) measured as the percentage of the area corresponding to the landslide susceptibility levels 4 (high) and 5 (very high) over the total area for the coastal cities of Sligo, Dublin, Vilanova i la Geltrú, Benidorm, Oarsoaldea, Oeiras, Massa, Piran and Gdańsk. Data source: Günther et al. (2014) and Wilde et al. (2018).

6.4. Discussion

The integrated approach developed in this work provides valuable insights into the multifaceted challenges faced by coastal cities in relation to climate-related hazards, ensuring that adaptation and resilience strategies are not developed in isolation but are informed by a comprehensive understanding of the local context [119]. The high-level characterisation of coastal hazards integrates a combination of indicators, including sea-level rise rates, extreme sea levels, coastal erosion susceptibility, coastal flooding extents, and LECZ areas. These results underscore the extent to which coastal cities are exposed to sea-level rise and the potential for inundation and coastal erosion. The comparison of the results between the coastal cities emphasizes the acute exposure of some cities to these hazards, highlighting the urgent need for proactive measures. Piran and Gdansk present the worst scenarios regarding areas exposed to coastal hazards, whereas the cities situated along the Atlantic Ocean face higher water levels, which is coherent with existing studies [238,370,415,466]. However, it is essential to emphasize that even in cities with lower exposure, the potential impact of sea-level rise should not be underestimated, warranting continuous monitoring and adaptive planning [467].

Nonetheless, the selection of optimal return periods and percentiles for the previous indicators is a pivotal consideration for further analyses [468]. Generally, shorter return periods, such as 2, 5, or 10 years, serve to evaluate the city's susceptibility to more frequent yet less severe surge events, making them instrumental in assessing vulnerabilities in infrastructure and property for common coastal flooding occurrences. Conversely, longer return periods, such as 25, 50, or 100 years, are employed to address less frequent but more intense surge events, playing a pivotal role in the design and fortification of critical infrastructure against rare, high-impact events. The selection of the most suitable return period should be underpinned by an intricate evaluation of factors including risk tolerance, financial constraints, and the

criticality of assets and human populations exposed to the ESLs [469]. For instance, a comprehensive risk assessment necessitates the consideration of multiple return periods to encapsulate the spectrum of plausible ESL scenarios.

This work recognises the role of indicators that may appear non-correlated or less directly relevant to coastal hazards yet significantly influence policy-making processes. The developed indicators include broader climate-related hazards not exclusive to coastal contexts, namely heavy rainfall, land flooding, droughts, extreme temperatures, heatwaves, cold spells, landslides, and strong winds. As these hazards also affect urban resilience, infrastructure vulnerability, and community preparedness, the approach enables well-rounded policy responses, by covering a diverse spectrum of climate-related hazards inherent in urban coastal environments [120].

In cities covered by the data, flood extents and water depths have been combined to assess river flooding hazard. While it is important to note that this reference dataset does not encompass flooding events in areas with narrow watercourses or ravines [101], i.e., Benidorm [470], the findings are still illuminating. These values facilitate a direct comparison of river flood hazards among these cities, highlighting the historical prominence of river flooding hazards in Dublin, Gdańsk, and Samsun [251,261,370]. This underscores the continued relevance of this indicator for assessing and addressing river flood hazards.

The analysis of days with daily precipitation exceeding 20 mm between 1981-2019 offers valuable insights into the susceptibility of coastal cities to heavy rainfall events. Some cities, such as Massa, Piran, and Oarsoaldea, experience a higher frequency of these events, while others like Gdańsk, Benidorm, and Dublin record lower occurrences [56,223,224]. While overall trends remain relatively stable, the slight uptick in heavy rainfall events in Dublin and Benidorm suggests the need for continued monitoring and adaptation strategies to address potential increases in extreme precipitation in these regions [211]. It is important to note that these findings

emphasize the diversity in heavy rainfall exposure among coastal cities. Researchers may also want to examine factors like the intensity, duration, and spatial extent of heavy rainfall events to gain a more comprehensive understanding [217,471].

In our approach, the SPI-3 values enabled us to discern periods of below-average precipitation, subsequently identifying and tallying the months characterized by meteorological drought conditions for each city [472]. Coastal cities like Oeiras, Sligo, and Piran exhibit substantial counts of months falling under these defined drought conditions [23,358]. While some cities experience an increase in drought events, others, like Benidorm, Gdańsk, and Samsun, report lower counts and even a decline in drought months. These findings emphasize the need for proactive drought management strategies in cities with increasing drought trends, while also highlighting the decrease of drought risk in others. While the SPI-3 with a threshold of -1 is a widely accepted criterion, it is important to note that the choice of threshold can influence the identification of drought events. The appropriateness of this indicator may vary depending on the specific research objectives and the regional climatic characteristics of the study area [303]. Therefore, its usage in this study was contingent upon its applicability to the context of the investigation and the availability of relevant data. Additionally, the spatial resolution of 1 degree in the SPI-3 data may smooth out local variations in drought conditions. These limitations should be considered when interpreting the results.

The measurement of extreme temperatures using relative thresholds from daily minimum and maximum temperature values permits the assessment and comparison of changes in unusually warm or cold days at different locations, independently of the baseline climate. These thresholds take into account the local climate and variations, making them a valuable tool for assessing climate-related risks and vulnerabilities. Results highlight the climatic diversity across the coastal cities (from the highest maximum temperature of 38.2°C in Oeiras to the coldest minimum temperature of -16.3°C in Gdańsk) [13]. Similarly, the analysis of heatwaves and cold spells in this

study focuses on instances when daily maximum and minimum temperatures surpass these relative thresholds. Some cities, like Piran and Massa, experience a high duration of heatwave conditions, while others, such as Gdańsk and Sligo, record lower occurrences. Results show that the frequency and duration of heatwaves and cold spells are influenced by complex local climate factors, and they do not necessarily correlate directly with the extremity of temperature values alone.

In assessing landslide hazards among diverse coastal cities, the application of susceptibility levels 4 (high) and 5 (very high) as a relative fraction of total city area serves as a practical and informative tool for comparison. By quantifying the proportion of city area with higher susceptibility, we can readily identify regions most exposed, such as Massa and Oarsoaldea [56,223,226]. Other cities exhibit varying degrees of landslide susceptibility, emphasizing the need for region-specific strategies to address this hazard effectively. This comparative approach aids in prioritizing resources, targeting mitigation efforts, and guiding policy decisions tailored to the specific landslide risk profiles of each coastal city.

The determination of the frequency and spatial distribution of wind events exceeding the defined threshold in close proximity to the selected coastal cities facilitated a high-level evaluation of their exposure to strong winds during the winter season. Sligo and Dublin, situated along the Atlantic coast, experience a notably higher frequency of strong wind events, potentially reflecting the influence of Atlantic winter storms. This correlation invites further investigation into the specific meteorological patterns that shape the exposure of coastal cities to extreme winter winds, offering valuable insights for climate resilience and risk mitigation strategies.

The importance of differentiating between densely built and non-built coastal zones is recognized, as urban density significantly influences the vulnerability and potential impacts of coastal hazards. The selection of cities within this study was designed to encompass a broad spectrum of urban settings, ranging from densely populated

metropolitan areas to less developed coastal regions. This strategy ensures the applicability of the findings across diverse urban contexts, offering insights into the general exposure to coastal hazards. However, it is acknowledged that the methodology primarily focuses on the delineation and analysis of physical climate-related hazards. While urban density and land use patterns are crucial for a comprehensive understanding of vulnerability and exposure to these hazards, such indicators were not the central focus of this research. The emphasis was placed on establishing a baseline understanding of hazard prevalence and intensity, crucial for initiating the broader process of risk assessment. Future research is suggested to expand on the findings by incorporating detailed assessments of vulnerability and exposure. These should include considerations of urban density, infrastructure resilience, population dynamics, and socio-economic factors to provide a holistic risk profile for coastal cities. By concentrating on hazard identification and characterization, this study contributes to the foundational knowledge required for more detailed analyses of vulnerability and exposure. It lays the groundwork for subsequent research to integrate urban density considerations, among other factors, thereby enhancing strategies for risk reduction and resilience improvement in coastal urban environments.

6.5. Conclusions

The indicator-based approach devised in this work enables multiple climate-related hazards to be compared in ten European coastal cities in a systematic, standardized manner. The comparison and contrast of the findings from different types of coastal cities allows for the identification of commonalities and differences, recognition of patterns, and development of a more comprehensive understanding of climate-related hazards on regional or national scales. Leveraging the influence of climate-related hazards enables policymakers, urban planners, and communities to make well-

informed decisions regarding urban planning, land-use management, infrastructure development, adaptation strategies and disaster risk reduction [473].

The methodology presented herein is founded on a series of hypotheses tailored to the unique challenges that coastal cities face in relation to climate-related hazards. First, the coastal cities are collectively and systematically examined, enabling decision-making bodies to discern varying climate-related hazards and prioritize budget allocation based on the degree of exposure. By applying this methodology, decision-makers can efficiently identify the specific needs of each coastal city and allocate resources more effectively to mitigate potential hazards. This hypothesis implies that the methodology encompasses various coastal cities concurrently. Conversely, the methodology is not devised to evaluate the coastal cities in isolation; rather, its purpose is to compare climate-related hazards among them. Consequently, this approach is not aimed at detailed local studies.

Second, the methodology concentrates on the coastal cities themselves. Numerous indicator-based approaches have been developed to appraise extensive coastal regions, rather than specifically focusing on coastal cities. The methodology described in this work is explicitly devised for assessing coastal cities and their associated coastal areas. This methodology permits the incorporation of specific aspects unique to the coastal cities, which might otherwise be disregarded. These aspects include the different characteristics of the cities (size, morphology, population, urbanization, ecosystems, etc.), current state of the related literature, involvement of local expertise, identification of key climate-related hazards and consideration of local coastal adaptation planning, among others.

Third, the methodology is suitable for evaluating multiple climate-related hazards. This suitability arises from the fact that the coastal cities encompass diverse climatic regions, resulting in variations in climate-related hazards among them. Consequently, the proposed set of indicators captures essential aspects related to hazard exposure for

each selected coastal city and climate-related hazard. These indicators are meticulously designed to be applicable elsewhere, allowing for standardized comparisons across different geographical contexts.

Fourth, the availability of data is very heterogeneous between the coastal cities. In certain instances, global datasets have been utilized to construct these indicators. However, it should be noted that the spatial resolution and uncertainty of the global datasets may be insufficient for the study areas with limited geographical coverage, such as Vilanova i la Geltrú, Benidorm, and Massa.

Fifth, the methodology allows for refinement. In this process, a set of indicators is employed to evaluate the different coastal cities collectively. In future stages, the weights assigned to these indicators may be adjusted by each coastal city according to their individual criteria, or even new indicators may be introduced. Furthermore, if higher-resolution datasets become available, the indicators can be assessed with increased precision. Consequently, the methodology can be continuously improved, while the level of detail can be increased.

Finally, it is crucial to recognize that the evaluation is characterized by a high-level approach based on indicators. Conducting a thorough evaluation of each city would necessitate an exhaustive study incorporating localized data, climate models, and assessments by local authorities [474]. The information provided herein serves as a general basis for comparison. Notwithstanding, the application of the proposed methodology can serve as a basis for further quantitative assessments.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 7.

The novel methodology for multi-hazard risk assessment

This chapter corresponds to: Laino, E. and Iglesias, G. **Beyond coastal hazards: A comprehensive methodology for the assessment of climate-related hazards in European coastal cities**. Ocean & Coastal Management, 2024. **257**: p.107343.

ABSTRACT

As climate change intensifies, European coastal cities face escalating risks from multiple climate-related hazards. Addressing these challenges requires capturing the multifaceted nature of climate risks adequately. This paper presents a novel multi-hazard risk assessment methodology for European coastal cities, which integrates indicators of hazard, exposure, sensitivity, and adaptive capacity. It advances beyond existing models by incorporating a wide array of climate-related hazards and significant indicators. Applied to six diverse coastal cities across different climatic zones and urbanization levels, the methodology proves robust and versatile, offering a comprehensive approach to understanding climate risks. The findings reveal that Varna has the lowest hazard score compared to other cities. Cork and Viana do Castelo are significantly affected by coastal hazards, while La Spezia exhibits very low coastal hazard scores but high land hazard scores. The exposure component ranges between medium and low values, with a maximum in Klaipeda and a minimum in Viana do Castelo. In terms of vulnerability, Viana do Castelo and Bergen stand out, while Cork

exhibits the lowest score. Finally, risk presents a balanced landscape, where cities with the highest scores in hazard and exposure also exhibit the lowest levels of vulnerability and vice versa. The discussion on policy implications advocates for participatory resilience-building, leveraging new technologies and non-traditional indicators to enhance urban adaptive capacity. The granularity and specificity inherent to the proposed methodology offer a tool to compare and identify high-risk cities systematically, allowing for a more informed and targeted approach to resilience building and strategic allocation of often limited resources.

7.1. Introduction

In the face of escalating climate change impacts [1–5], MHRAs have become essential to understanding and mitigating the diverse threats posed by climate-related hazards [32,43,475,476]. These assessments typically employ index-based approaches, recognized for their robustness in calculating risk as a function of hazard, exposure, and vulnerability, in line with recommendations from the IPCC [477]. A variety of models and frameworks have been developed to address these challenges, each offering distinct methodologies and insights [97,107,478].

Globally recognized models, such as CLIMADA by ETH Zurich and the DIVA model from the Global Climate Forum, constitute benchmarks in this field. CLIMADA integrates hazard, exposure, and vulnerability data to quantify and monetize natural disaster impacts [307], while DIVA focuses on the socio-economic and biophysical consequences of sea-level rise and socio-economic development [308,309]. Additionally, DELTARES models provide invaluable insights into coastal dynamics and flood risk management through detailed physical simulations – methodologies highly relevant to the European coastal context.

Specifically tailored to European coastal cities, EUROSION offers detailed analyses of coastal erosion processes, providing essential guidelines for coastal zone management in Europe. Costs from diverse hazards are assessed in the ConHaz project. The focus on urban climate change adaptation and mitigation of the RAMSES Project, including cost-benefit analysis tools, is particularly relevant for city planners. Moreover, initiatives like the BRANCH Project and the OPERR framework address biodiversity impacts and ecological forecasting, including riverine discharges – essential aspects of coastal management in Europe. The European Climate Adaptation Platform (Climate-ADAPT) and the ESMERALDA Project further enrich this landscape by offering resources for climate adaptation planning and ecosystem services assessment, which are crucial for holistic urban and environmental planning in coastal areas.

Amidst these advancements, the SCORE project emerges as a pivotal initiative, aiming to co-create climate change adaptation and resilience strategies in coastal cities [101,119]. This endeavour is achieved through collaborative participation between public institutions, research centres, decision-making, and operational bodies, all centred around the novel concept of the CCLL. This approach to tackling the challenges posed by climate change, especially in terms of sea-level rise and climate-related hazards, necessitates effective communication and decision-support tools [479]. Such tools are crucial for fostering collaboration among stakeholders, enabling informed decision-making and the development of innovative solutions tailored to the unique dynamics of coastal urban environments [480–482].

In this context, academic research offers noteworthy examples of approaches addressing multiple climate-related hazards in Europe. Lung et al. (2013) combined indicators of climatic and non-climatic change to assess regional-level impacts in Europe. Their indicator-based framework integrates climate models with socio-economic data to quantify changes in heat-related, river flooding and forest fire hazards. Crespi et al. (2020) offer a comprehensive analysis of climate-related hazard

indices in Europe, selecting 32 indices using a wide array of data from the C3S CDS, including E-OBS (daily gridded observation dataset over Europe), ERA5 (fifth generation ECMWF atmospheric reanalysis of the global climate), ERA5-Land (enhanced resolution ERA5 for land variables), UERRA (regional reanalysis of near-surface variables for Europe), CMIP5 (fifth phase of the Coupled Model Inter-comparison Project), CORDEX (regional climate model data for Europe), and other key index datasets described in the report. The methodical approach in compiling and analysing these indices provides a solid foundation for future research on climate-related hazards in Europe. Hincks et al. (2023) develop a new typology of climate risk at NUTS3 level under the call of IPCC for sub-national climate change risk awareness. They use K-means clustering to analyse 49 variables, creating a detailed classification that highlights the varying climate change risks across Europe.

In the international context, Binita et al. (2021) developed a climate risk index for the United States at the county level for some climate-related hazards. They combined high-resolution downscaled climate projections and indicators of exposure and vulnerability to estimate future climate risks for planning and implementing targeted adaptation strategies at the local level. Tiepolo et al. (2019) emphasize the importance of combining local and scientific knowledge in assessing multi-hazard risks in Mauritania. Their approach integrates community input with scientific data to assess risks and propose appropriate risk treatment actions. Araya-Muñoz et al. (2017) and Pourghasemi et al. (2019) further contribute to the methodological diversity in this field, highlighting the benefits of innovative and data-driven approaches. The former uses spatial fuzzy logic modelling to assess multiple hazards in Chile, while the latter develops a multi-hazard probability map for Iran using a novel ensemble model.

The increasing impacts of climate change necessitate comprehensive MHRAs to understand and mitigate the diverse threats posed by climate-related hazards. While numerous studies have focused on climate-related indices in Europe, a significant gap remains in the development of cross-regional methodologies that address the full

spectrum of climate-related hazards, particularly in coastal cities [27,97,99]. These cities, which are central to societal and economic well-being, face compounded risks where land and coastal hazards converge, further exacerbated by climate change [22,205,217,483]. Current models and frameworks provide valuable insights but do not fully address the unique dynamics of coastal urban environments. Additionally, there is a notable lack of cross-regional comparative studies, which limits the ability to benchmark and implement targeted interventions across different coastal cities [99]. Effective risk assessment and management in these coastal regions are critical yet challenging.

In this context, this study sets out with several research objectives. It aims to provide a set of critical climate-related indicators necessary for a comprehensive multi-hazard risk assessment in European coastal cities, covering a wide variety of climate-related hazards. The methodology involves leveraging a rich array of indicators for hazard, exposure, and vulnerability in a systematic and standardized approach that builds on current risk assessment practices and facilitates more effective climate adaptation strategies. Furthermore, it is designed to allow for comparative baseline analysis across European coastal cities, providing a unique opportunity for benchmarking and collaborative resilience-building efforts [484,485]. To demonstrate its applicability and effectiveness in varied regional contexts, the proposed methodology is tested in six diverse European coastal cities, contributing reliable insights across different urban environments. The ultimate goal is to form the foundation for a decision-support tool designed for policymakers and urban planners, enabling them to prioritize coastal management actions based on the severity and urgency of the specific risks faced by each city.

7.2. Materials and methods

7.2.1 *Risk framework*

In this study, the conception of risk follows the risk assessment framework developed by the IPCC [89]. At the core of this framework is the concept that risk is a function of hazard, exposure, and vulnerability. Hazards refer to climate-related physical events or trends, such as extreme weather events or long-term shifts in climate patterns. Exposure denotes the presence of populations, ecosystems, or assets in places that could be adversely affected by these hazards. Vulnerability involves the sensitivity and adaptive capacity of these systems, highlighting their propensity to suffer harm. This paradigm is applied here by developing a series of indicators that capture the different elements of risk, allowing for a detailed and systematic evaluation of diverse climate-related threats. By systematically integrating these elements, the framework provides a structured approach to risk assessment, enabling policymakers and stakeholders to prioritize actions that enhance resilience and reduce vulnerability to climate change. Figure 7.1 illustrates the relationship between the indicators developed in this study and their corresponding risk parameters, which is detailed hereinafter.

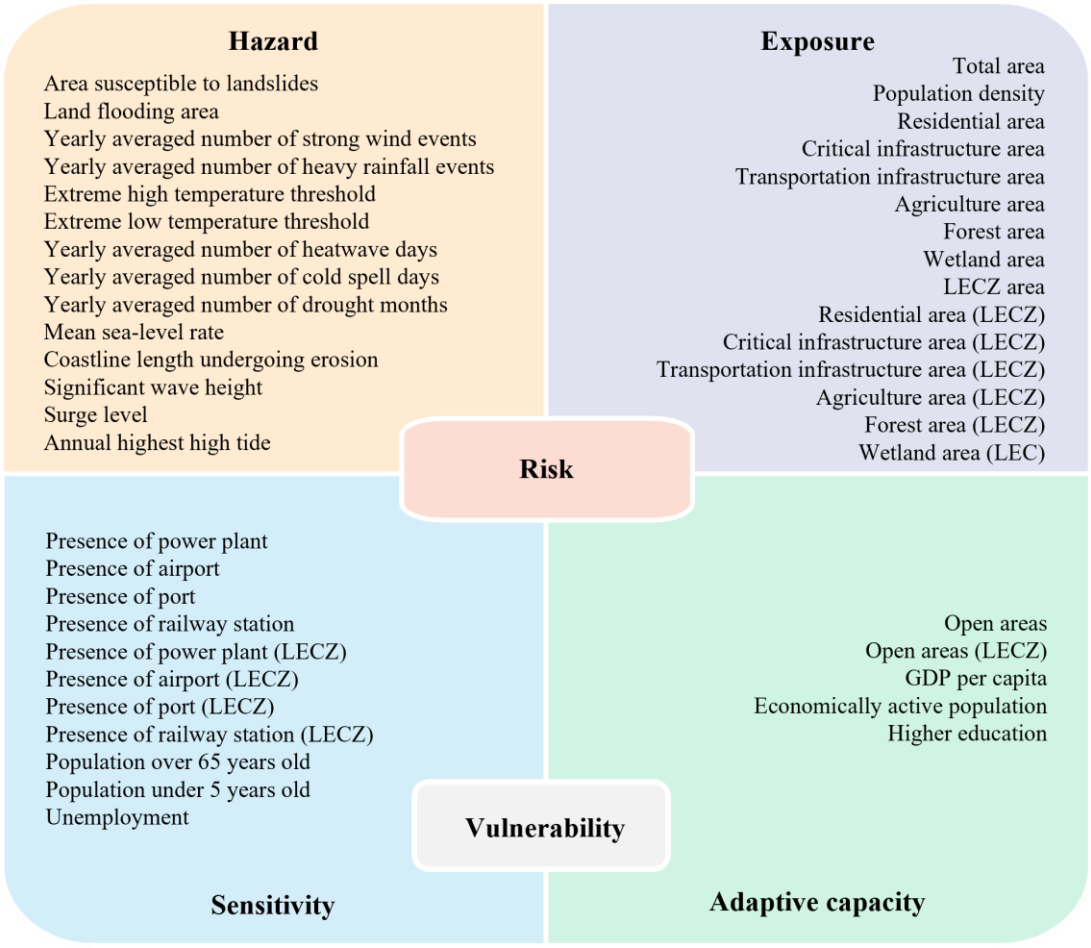


Figure 7.1. Relationship between developed indicators and corresponding risk parameters.

7.2.2 *Selection of indicators*

The indicators for developing the MHRA were devised by means of a methodological framework designed to ensure robustness, relevance, and operational practicality. This framework was built on the pillars of comprehensive literature review, local engagement, and stringent evaluation criteria addressing both conceptual and technical aspects. Each step in the selection process was informed by the overarching goal to effectively measure and interpret climate-related hazards, taking into account the inherent complexities and specificities in the context of coastal cities across Europe.

A thorough review of academic literature, policy documents, and grey literature was conducted to gather a broad spectrum of perspectives on the risk elements including

hazard, exposure, sensitivity, and adaptive capacity [88,191]. Data sources were evaluated for their credibility, relevance, and compatibility with the objectives of the study. This involved an assessment of data repositories at both European and international levels to ensure comprehensive coverage.

Engagement with local expertise through the SCORE project was integral to the process, ensuring that the selection of indicators resonated with the practical needs and insights of those actively involved in climate risk management [101,120]. Workshops and meetings provided platforms for discourse, allowing for the refinement of the role of the new methodology, methodological development, and the contextualization of future outputs.

Conceptual relevance was a primary criterion, ensuring that each selected indicator aligned effectively with the identified risk themes: hazard, exposure, sensitivity, and adaptive capacity. Technical robustness was assessed based on several parameters including data availability at the required spatial unit (e.g., city-scale), clarity and comparability of definitions, transparency in data collection methods, continuity in methodologies, relevance, and the presence of appropriate time series data.

The definition of thresholds, whether fixed or percentile-based, was carefully considered, acknowledging the advantages and drawbacks of each approach. The temporal and spatial resolution of data was aligned with the characteristic scales of the climate-related hazards under study, ensuring that the indices could effectively capture and represent localized and short-term hazard events.

The complexity involved in computing each indicator was evaluated, with a preference for indices that, while comprehensive, remained interpretable and feasible in terms of data requirements. The robustness of each index was critically assessed, taking into account uncertainties in threshold choices, model data, and the practical implications of spatial resolution mismatches.

The operationalization of indices was tailored to specific applications and end-user requirements. This involved thoughtful considerations regarding the choice of reference periods, climate scenarios, and visualization elements. The selection process was dynamic, allowing for adjustments and refinements to ensure that the indices remained relevant and practical for policymaking, planning, and climate risk mitigation efforts.

7.2.3 *Study cases*

Six diverse coastal cities were selected representatives of different climate zones, seas, existing academic results, degree of urbanization and Gross Domestic Products (GDP). The geographic characterization of selected coastal cities was conducted using a combination of datasets. The extents of urban areas were delineated utilizing the Urban Atlas 2012 dataset, which provides detailed land use and land cover data across European cities. This dataset was employed to define the city extents, aligning them with the respective administrative boundaries. For the cities of Bergen, Klaipeda, La Spezia, and Viana do Castelo, the city extents were matched with their municipality-level boundaries. In the cases of Cork (reflecting the pre-2019 administrative structure) and Varna, the extents were aligned with the boundaries defined at the city council level.

The LECZ – land located below 10 meters and contiguous to the sea – was delineated using the high-resolution MERIT DEM [445,454], identifying areas most exposed to coastal hazards. Specific coordinate points were sourced from OpenStreetMap (OSM), a comprehensive open-source mapping platform, for later calculations. The retrieval of these coordinates was facilitated by the geopy library, a Python-based toolset designed for geocoding, which enabled efficient extraction and manipulation of geospatial data from OSM. This integration of datasets provided a robust framework for the comprehensive geographic characterization of the selected coastal cities, as depicted in Figure 7.2.

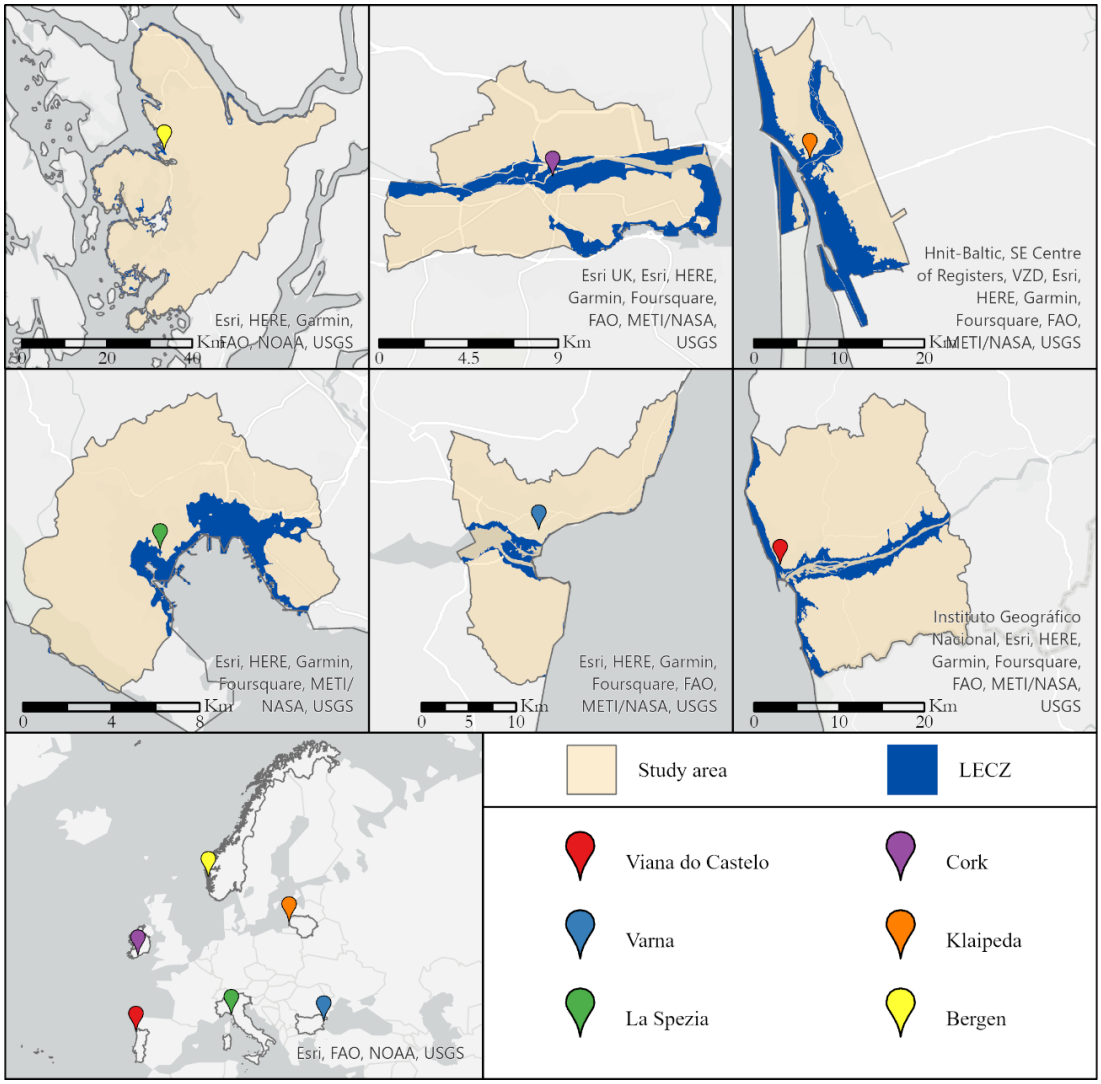


Figure 7.2. Study areas, including city boundary and low-elevation coastal zone. Data source: OpenStreetMap, Copernicus Land Monitoring Service (2012) and Yamazaki et al. (2017).

7.2.4 *Climate-related hazards indicators*

The methodology is characterised for evaluating a comprehensive suite of climate-related hazards. These hazards, which are already outlined in Table 6.2, encompass sea-level rise, coastal and land flooding, coastal erosion, heavy rainfall, droughts, extreme temperatures, heatwaves, cold spells, strong winds, and landslides. The indicators are the result of integrating insights from leading sources and contemporary studies, specifically designed for the European setting [90]. Initially, the Sixth

Assessment Report by the IPCC was utilized as a key document [36], presenting a detailed categorization of climate-related phenomena, which lays the groundwork for recognizing potential threats to coastal areas.

Subsequently, the process of refining the indicators was guided by insights from the European Topic Centre on Climate Change Impacts, Vulnerability, and Adaptation. This body assesses and ranks climate hazard indices for Europe, considering their importance, relevance to adaptation, availability of data, and the reliability of that data [42]. The goal is to develop indicators that are uniformly and systematically applicable to the European coastal context.

The methodology is also informed by and contributes to recent research that utilizes hazard indicators. Studies by Lung et al. (2013) and Hincks et al. (2023) examine various hazards such as coastal threats, extreme temperatures, precipitation events, floods, droughts, and landslides for regional risk evaluations in Europe. The recent study by Laino and Iglesias (2023c), which merges a review of the existing literature with feedback from stakeholders in the target cities, offers essential perspectives on local views of climate-related risks. This methodology ensures that the approach is anchored in the most recent scientific findings while also catering to the unique challenges and concerns of coastal cities in climate change adaptation.

Sea-level rise rates for 2020 were estimated using the NASA Sea-Level Projection Tool against a 1995-2014 baseline within the SSP2-4.5 scenario [322,438,439]. Extreme sea-level events, crucial for coastal flooding analysis [10,487–489], were characterized by the significant wave height (Hs), the storm surge level and the annual highest high astronomical tide, based on their probability distributions derived from the ERA5 reanalysis dataset [440–442]. The proportion of coastline experiencing erosion was determined with data from the Eurosion project, considering the total coastline length [446]. For pluvial flooding, annual average precipitation events exceeding a 20 mm threshold were averaged from the dataset “Extreme precipitation

risk indicators for Europe and European cities from 1950 to 2019" [448]. River flooding was estimated by quantifying the extents associated with the centennial return period, informed by dataset "River flood hazard maps for Europe and the Mediterranean Basin region" [447]. Meteorological drought hazard was evaluated using the SPI-3 index [49], identifying monthly values below -1 throughout the 1991-2020 period [460]. The assessment of extreme temperatures involved percentile-based thresholds (99th for high and 1st for low) from daily temperature records during key seasonal windows for the baseline period 1981-2000 [42]. Heatwaves and cold spells were quantified by the annual average of days from the periods of at least three consecutive days when the daily maximum or minimum temperature exceeded the previous extreme temperature thresholds [42]. Storm impact was studied through the annual frequency of strong wind gusts (defined as the maximum 3 s 10 m wind gusts over a 72-hour period) exceeding 20 m/s, reflecting the North Atlantic storm influence, based on data from the ERA5 reanalysis from C3S CDS [441,451]. Landslide susceptibility was estimated based on the ELSUS v2 dataset, focusing on areas classified as 'high' or 'very high' in susceptibility. These areas were computed and expressed as a percentage of the total city area. While these indicators provide robust measures for various climate-related hazards, it is important to note that they do not fully capture the entirety of each hazard. The complexity and multifaceted nature of climate-related risks mean that some aspects may not be fully represented by the selected indicators.

7.2.5 *Land cover and land use indicators*

Land use and land cover (LULC) indicators are widely recognized for providing fundamental insights into the physical, environmental, and socioeconomic aspects of coastal cities, which are essential for a comprehensive risk assessment [490–492]. LULC distribution has been thoroughly investigated utilizing the Urban Atlas 2012 dataset [486], due to its comprehensive coverage of European cities, regular updates,

and a level of precision deemed appropriate for this study. Urban Atlas classifies cities in 17 urban classes with a Minimum Mapping Unit (MMU) of 0.25 ha and 10 Rural Classes with a MMU of 1 ha in 2012, with high thematic accuracy.

For tailoring this dataset to the risk assessment framework, we reclassified the default categories in Urban Atlas. This reclassification involved accounting for areas covered by residential uses, critical infrastructure, agriculture, open spaces, natural vegetation, wetlands, water bodies and other miscellaneous uses. These area calculations were executed for both the entire study region and the LECZs to generate standardized indicators allowing for cross-city comparisons. The computed areas are expressed as percentages of the total city area or the LECZ, respectively. The indicators are compiled in Table 7.1, detailing their respective contributions to risk.

Table 7.1. Indicators relating to land cover and land uses measured over total city area and Low-Elevation Coastal Zone.

Indicator	**Units**	**Coverage**	**Parameter of risk**	**UA coding**
Residential area	%	Areas with predominant residential use	Exposure	11100, 11210, 11220, 11230, 11240 and 11300
Open areas	%	Green urban areas, sports and leisure facilities and open spaces with little or no vegetation	Vulnerability (adaptive capacity)	14100, 14200, 33000
Transportation infrastructure	%	Areas associated to road, railway, port and airport infrastructure	Exposure	12210, 12220, 12230, 12300 and 12400
Other critical infrastructure	%	Healthcare facilities, water and wastewater treatment plants, communication infrastructure, power plants, emergency services, military facilities, educational institutions, cultural heritage sites, industrial and commercial areas and	Exposure	12100

		other public, and private services not related to the transport system		
Agricultural area	%	Areas with predominant agricultural use	Exposure	21000, 22000, 23000 and 24000
Natural vegetation area	%	Forest and herbaceous vegetation associations	Exposure	31000 and 32000
Wetland area	%	Inland and coastal wetlands.	Exposure	40000
Water bodies	%	Sea, lakes, fishponds, rivers and canals.	Exposure	50000
Other areas	%	Mineral extraction, dumping sites and construction sites and land without current use.	Not scored	13100, 13300 and 13400

7.2.6 *Presence of critical infrastructure elements*

In the realm of disaster risk assessment, the spatial distribution of critical infrastructure within hazard-prone areas is a paramount factor for determining urban sensitivity [432]. Examples of common elements which are essential for the functioning of a city include, but are not limited to, hospitals, educational centres, water treatment facilities, public buildings, cultural heritage sites, and emergency services. A high concentration of such infrastructure signifies heightened sensitivity since any damage or disruption can lead to significant detriments to societal functions [28]. In developing a methodology tailored to coastal cities, it is a reasonable assumption that these locales encompass the majority, if not all, of these critical infrastructure elements.

Nevertheless, it is crucial to identify that certain critical infrastructure components, such as power generation plants, ports, airports, and railway stations, may not be as uniformly present across coastal cities. The occurrence and operational capacity of these elements vary considerably and can profoundly influence the risk profile of cities [493–495]. The presence of these less ubiquitous yet highly significant infrastructural

components have been evaluated for each city under study, both for the total city area and the LECZ, providing a set of indicators for sensitivity within the risk analysis framework. Data on the location and spread of such infrastructure has been retrieved from OSM. The indicators consist of a series of binary variables that indicate the presence or absence of a power plant, airport, port, and railway station within the total city area and the LECZ. These indicators are integral to understanding the potential impact of disasters on critical urban systems and the cascading effects on the broader socio-economic landscape.

7.2.7 *Socioeconomic indicators*

Socioeconomic indicators are fundamental in the context of risk assessment, particularly within coastal urban environments, where the interplay of human and environmental factors is most pronounced [496]. These indicators provide critical insights into the demographic composition, economic stability, and social infrastructure of communities, factors that collectively define the vulnerability and adaptive capacity of urban populations to climate-related hazards. Population density, age distribution, workforce engagement, and educational attainment are among the key variables that influence the resilience of communities, shaping their ability to prepare for, respond to, and recover from adverse climatic events. Inclusion of these indicators in risk assessment frameworks allows for a nuanced analysis that goes beyond environmental parameters, offering a holistic view of risk that encompasses the socio-economic intricacies of affected populations. This approach ensures that risk mitigation strategies are not only technically sound but also socially inclusive, aligning closely with the real-world complexities and needs of the communities at the forefront of climate change impacts.

In this study, Eurostat, a principal statistical office of the European Union, was selected as the primary data source for analysing demographic and economic indicators of coastal cities (Table 7.2). By employing the most recent Eurostat data,

this study benefits from the methodological rigor, extensive geographic coverage, and standardized data collection methods, ensuring that the socioeconomic indicators are robust, comparable, and reflective of the current state. These indicators, when analysed collectively, provide a comprehensive picture of the socioeconomic dynamics that influence the resilience and vulnerability of coastal cities to climate-related hazards. The integration of these indicators into the MHRA, contextualizing them within the framework of exposure, sensitivity, and adaptive capacity, is aimed at identifying patterns, assessing needs, and informing targeted, context-specific strategies for enhancing urban resilience.

Table 7.2. Indicators of socioeconomic activity assessed over the total city area.

Indicator name	**Short description**	**Parameter of risk**	**Variables from Eurostat employed**
Population density	Total city population for a specific year over city area, expressed as inhabitants per squared kilometre.	Exposure	DE1001V: Population on the 1st of January, total
Population under 5 years old	Population under 5 years old for a specific year, expressed as a percentage of the total population for the same year.	Vulnerability (sensitivity)	DE1040V: Population on the 1st of January, 0-4 years, total;
Population over 65 years old	Population over 65 years old for a specific year, expressed as a percentage of the total population for the same year.	Vulnerability (sensitivity)	DE1028V Population on the 1st of January, 65-74 years, total. DE1055V: Population on the 1st of January, 75 years and over, total
Economically active population	Persons that are either employed or unemployed and not part of the economically inactive population for a specific year, which covers all residents over 15 who are not economically active, expressed as a percentage of the total population for the same year.	Vulnerability (adaptive capacity)	EC1001V: Economically active population, total

Unemployment	Total population under unemployment, expressed as a percentage over total population.	Vulnerability (sensitivity)	EC1010V: Persons unemployed, total
Higher education	Population with high educational background for a specific year, expressed as a percentage of the total population for the same year.	Vulnerability (adaptive capacity)	TE2031V: Persons aged 25-64 with ISCED level 5, 6, 7 or 8 (from 2014 onwards) as the highest level of education
GDP per capita	GDP per capita at market prices, measured at NUTS3 level	Vulnerability (adaptive capacity)	-

7.2.8 *Risk calculation*

The methodology for scoring the indicators hinges on the analysis of a diverse array of cases, which are deemed adequate for establishing benchmarks against which the indicators can be evaluated. These benchmarks derive from the extremities of observed values for each indicator, specifically the minimum and maximum recorded values. To facilitate a baseline methodology for the scoring and aggregation of these indicators, a normalized scoring system is employed, wherein each indicator value for the cities under consideration is assigned a score within the interval $[0, 1]$, corresponding to its relative position between the observed extremities, with the exception of critical elements indicators, which were ascribed binary scores of 0 or 1. This normalization process employs the linear scale transformation of min-max method to map the raw indicator values to their respective scores [497].

Denoting $I_{i,j}$ the raw value of the i-th indicator for the j-th city, with $i = 1, 2, \dots, N$ and $j = 1, 2, \dots, M$, where N is the total number of indicators and M is the total number

of cities analysed, the normalization of these values into scores, $S_{i,j}$, is accomplished as per

$$S_{i,j} = \frac{(S_{i,max} - S_{i,min})(I_{i,j} - I_{i,min})}{I_{i,max} - I_{i,min}} + S_{i,min}\,, \qquad (1)$$

where $I_{i,min}$ and $I_{i,max}$ represent the minimum and maximum values recorded for the i-th indicator across all cities, and $S_{i,min}$ and $S_{i,max}$ are equal to 0 and 1, respectively.

Indicators were systematically classified under the paradigms of hazard, exposure, or vulnerability. A holistic score per category was derived, facilitating an aggregate risk assessment, wherein equal weights were applied, in alignment with recent related studies [112,302,314,323,355],. To compute the composite score for each category C_k in the j-th city, the scores of the indicators within each category are aggregated,

$$A_{C_k,j} = \frac{\sum_{i \in C_k} S_{i,j}}{N_{C_k}}, \qquad (2)$$

where N_{C_k} denotes the number of indicators within risk category C_k, namely hazard, exposure and vulnerability. The indicators which have reverse effect on vulnerability, i.e., indicators of adaptive capacity, were subtracted from 1 for consistency.

The components of hazard, exposure and vulnerability were integrated into a final European Multi-hazard Index (EMI) score of risk through multiplicative aggregation. For this calculation, the risk components were equally weighted according to

$$EMI_j = \prod_k A_{C_k,j}, \qquad (3)$$

where EMI_j denotes the risk for the j-th city and k ranges between the number of components of risk, thus $k = 1, 2, 3$. The complete list of indicators and their corresponding notation is provided in Table 7.3. The results encompass maps and graphs elucidating both individual and aggregated indicators scores. To improve the interpretability of the risk assessment results, the cubic root transformation was

applied to the calculated risk values. This transformation helps normalize the data and stabilize variance, making the results more intuitive, especially for extreme values. The cubic root of risk allows for a more balanced representation of low and high-risk areas, facilitating easier comparison and prioritization of risk management actions. The transformed risk values were used in all subsequent analyses and visualizations to ensure consistency and clarity in the interpretation of the findings.

It is noteworthy that despite the representativeness of the values for setting thresholds in Europe, the sample size precludes extensive correlation analyses among variables. This limitation guided the methodological decision to eschew variance-based weighting techniques such as sphericity tests, Kaiser-Meyer-Olkin measure, and principal component analysis [177].

Table 7.3. Summary of indicators, including their units, corresponding parameter of risk and label.

Label	**Indicator**	**Units**	**Parameter of risk**
H1	Area susceptible to landslides	% of total area	Hazard
H2	Land flooding area	% of total area	Hazard
H3	Yearly averaged number of strong wind events	$Year^{-1}$	Hazard
H4	Yearly averaged number of heavy rainfall events	$Year^{-1}$	Hazard
H5	Extreme high temperature threshold	°C	Hazard
H6	Extreme low temperature threshold	°C	Hazard
H7	Yearly averaged number of heatwave days	day/year	Hazard
H8	Yearly averaged number of cold spell days	day/year	Hazard
H9	Yearly averaged number of drought months	month/year	Hazard
H10	Mean sea-level rate	mm/year	Hazard
H11	Coastline length undergoing erosion	% of total coastline length	Hazard

H12	Significant wave height	m	Hazard
H13	Surge level	m	Hazard
H14	Annual highest high tide	m	Hazard
E1	Area	km^2	Exposure
E2	Population density	inhabitants/km^2	Exposure
E3	Residential area	% of total area	Exposure
V1	Open areas	% of total area	Vulnerability (adaptive capacity)
E4	Critical infrastructure area	% of total area	Exposure
E5	Transportation infrastructure area	% of total area	Exposure
E6	Agriculture area	% of total area	Exposure
E7	Forest area	% of total area	Exposure
E8	Wetland area	% of total area	Exposure
V2	Presence of power plant	Yes/No	Vulnerability (sensitivity)
V3	Presence of airport	Yes/No	Vulnerability (sensitivity)
V4	Presence of port	Yes/No	Vulnerability (sensitivity)
V5	Presence of railway	Yes/No	Vulnerability (sensitivity)
E9	LECZ area	% of total area	Exposure
E10	Residential area (LECZ)	% of LECZ area	Exposure
V6	Open areas (LECZ)	% of LECZ area	Vulnerability (adaptive capacity)
E11	Critical infrastructure area (LECZ)	% of LECZ area	Exposure
E12	Transportation infrastructure area (LECZ)	% of LECZ area	Exposure
E13	Agriculture area (LECZ)	% of LECZ area	Exposure
E14	Forest area (LECZ)	% of LECZ area	Exposure
E15	Wetland area (LEC)	% of LECZ area	Exposure
V7	Presence of power plant (LECZ)	Yes/No	Vulnerability (sensitivity)
V8	Presence of airport (LECZ)	Yes/No	Vulnerability (sensitivity)
V9	Presence of port (LECZ)	Yes/No	Vulnerability (sensitivity)
V10	Presence of railway station (LECZ)	Yes/No	Vulnerability (sensitivity)
V11	Population over 65 years old	% of total population	Vulnerability (sensitivity)
V12	Population under 5 years old	% of total population	Vulnerability (sensitivity)
V13	Unemployment	% of total population	Vulnerability (sensitivity)
V14	GDP per capita	% of total population	Vulnerability (adaptive capacity)
V15	Economically active population	% of total population	Vulnerability (adaptive capacity)

V16	Higher education	% of total population	Vulnerability (adaptive capacity)

7.3. Results

The main objective of this study is to integrate the diverse indicators of risk in a systematic and standardized approach, enabling a comprehensive understanding of the risks faced by each city and allowing comparisons with other European coastal cities. The hazard indicators consolidate abundant information from diverse climate-related hazards. In this vein, graphical representations are crucial for visualizing and interpreting the spatial and temporal distributions of these hazards. Figure 7.3 is an example for Klaipeda, designed to provide insights into the calculation process of the hazard indicators before their normalization, employing GIS and calculation software. The map on the left of the figure highlights the LECZ and coastal erosion trends, where the areas experiencing significant erosion are marked in red. The LECZ area, calculated from MERIT DEM and expressed as a percentage of the total city area for comparison, results in 42.2%, the highest value among the study cases. This significant percentage indicates that nearly half of the area of Klaipeda area is susceptible to sea-level rise and related coastal hazards. Similarly, the length of coastline undergoing erosion, measured from Eurosion data and expressed as a percentage of the total coastline length, yields a relatively low value of 12.7%. This lower percentage suggests that while coastal erosion is present, it affects a smaller portion of the coastline compared to other hazards. The middle map illustrates the extents corresponding to the 100-year river flooding event, as per Dottori et al. (2021), marked in pink, indicating flood-prone areas due to their proximity to the Danė River and low-lying topography. These flood-prone areas are critical for urban planning and infrastructure development, as they highlight zones that may be affected by compound flooding hazard. The map on the right shows the distribution of landslide susceptibility in Klaipeda according to Wilde et al. (2018), categorized as very low, low, medium, high, and very high. The indicator accounts only for areas with high and very high

susceptibility levels. In Klaipeda, these levels are not reached, indicating a low landslide hazard. However, the presence of any susceptible areas, even at lower levels, warrants continuous monitoring, especially in zones with significant human activity or infrastructure.

The bar charts below the maps show the yearly distribution of heatwaves, cold spells, heavy rainfall events, and droughts. The extreme temperature thresholds provided, -19.0°C and 29.0°C, were employed to calculate the heatwave and cold spell events, defined as periods of at least three days exceeding these thresholds [450]. Klaipeda experiences approximately 2.0 days of heatwaves per year, while cold spells occur approximately 0.8 days per year. These frequencies summarize the total number of days per year for these events and are crucial for public health planning and energy management, particularly during extreme temperature events. The indicators for heavy rainfall and droughts summarize the yearly average of precipitation events exceeding 20 mm/day and meteorological drought months where SPI-3 is below -1, respectively. Klaipeda experiences about 1.8 days of heavy rainfall per year, whereas droughts occur approximately 2.1 months per year. These rainfall and drought indicators are essential for water resource management and agricultural planning, providing insights into the frequency and severity of these events. The indicators measure the yearly average for these hazards, though the graphs also aid in understanding the temporal evolution and potential trends. For example, an uptrend in heatwaves and a downtrend in droughts can be noted, providing critical insights into the changing climate dynamics in Klaipeda. Understanding these trends is vital for developing adaptive strategies to mitigate the impacts of climate change, ensuring the resilience and sustainability of the city.

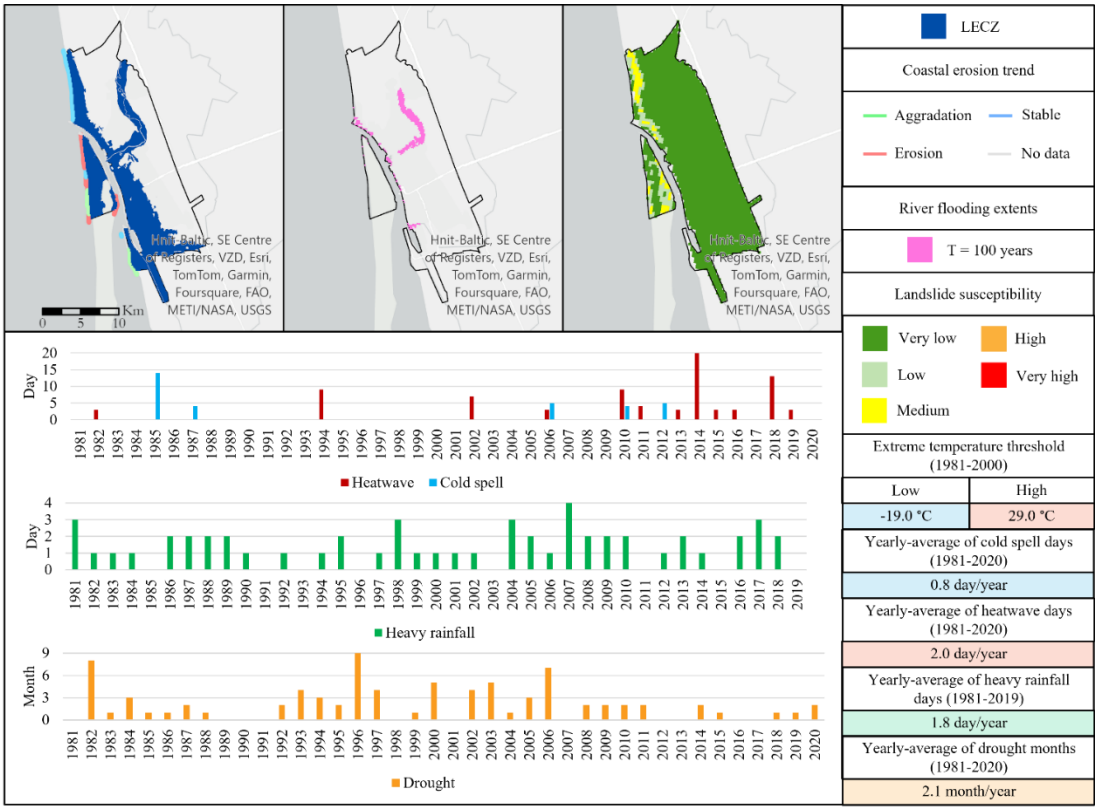


Figure 7.3. Graphical visualization of some indicators of hazard for Klaipeda, including Low-Elevation Coastal Zone area, coastal erosion trend, river flooding area, landslide susceptibility, extreme temperature thresholds, and heatwave, cold spell, heavy rainfall and drought frequencies. Data source: Dottori et al. (2021), European Commission and Joint Research Centre (JRC) (2021), Lavaysse et al. (2018), Lenôtre et al. (2004), Mercogliano et al. (2021), Wilde et al. (2018) and Yamazaki et al. (2017).

The comparative assessment of these indicators reveals distinct patterns that reflect the unique climatic and geographical context of each city. Another example before the normalization of the indicators is illustrated in Figure 7.4, covering extreme sea levels and sea-level rise. The data reveal a clear demarcation between cities subjected to the influence of the Atlantic Ocean and those sheltered within the Mediterranean basin. The bar chart on the left illustrates the annual highest high tide, surge level, and significant wave height for the six cities. These indicators provide an estimation of the extreme sea-levels that the cities can potentially suffer from, based on data from ERA5 reanalysis [440–442]. The map on the right of the figure shows the baseline MSLR

rates for these cities, based on data from NASA for the year 2020 under the RCP4.5 scenario [322,438], with colour coding representing different rates of rise ranging between 3.0 mm/year and 5.1 mm/year. The data highlight the varying impacts of sea-level rise and extreme sea levels on the coastal cities. Atlantic cities, particularly Cork and Viana do Castelo, are subject to higher extreme sea levels compared to Mediterranean cities, likely due to more significant wave heights and storm surges. Viana do Castelo displays the highest combined water level, with an annual highest high tide of 1.3 meters, a surge level of 1.4 meters, and a significant wave height of 6.0 meters, resulting in a total extreme water level of approximately 8.7 meters. The MSLR rates also vary, with Klaipeda experiencing the highest rate of sea-level rise, suggesting a need for tailored coastal management and mitigation strategies to address these specific challenges.

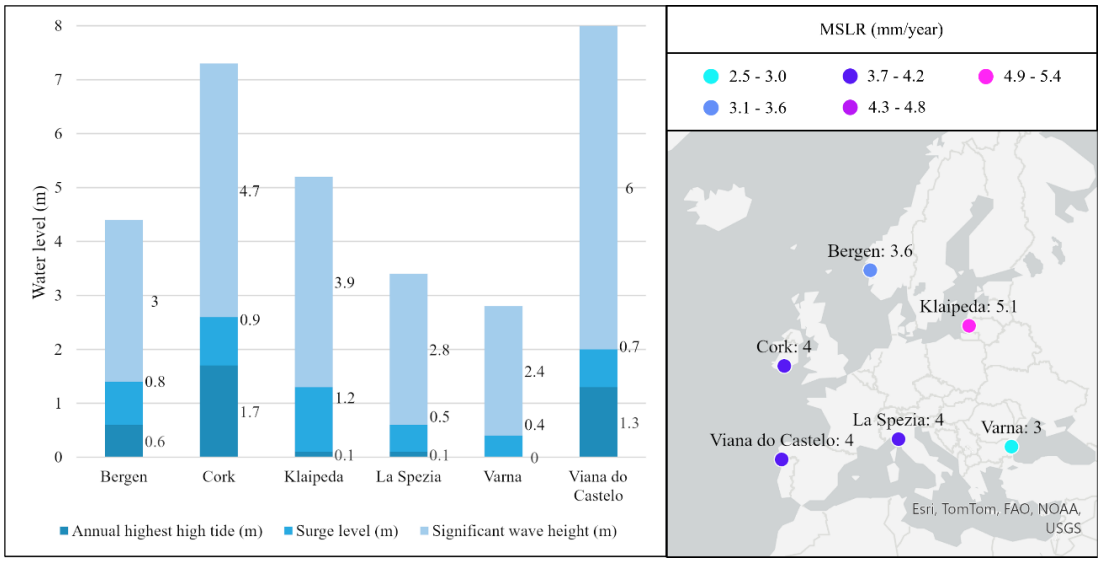


Figure 7.4. Indicators regarding sea-level rise and extreme sea-levels. Data source: Caires and Yan (2020), Hersbach et al. (2020), Kopp et al. (2023) and Yan et al. (2020).

The complete set of hazard indicators encompass a spectrum of climate-related phenomena, including extreme weather events and long-term climatic shifts. The heatmap visualization in Figure 7.5 synthesizes these observations after min-max normalization, based on the data from Table 7.4, which summarizes the values

obtained for the indicators, offering a comparative view of hazard intensities across the cities. The indicators demonstrate the capacity to discern subtle differences between these urban areas. La Spezia emerges as a focal point for hazard intensity, with near-maximal scores in indicators associated with landslides, extreme temperatures, heatwaves, cold spells, and droughts – a reflection of the vulnerability inherent to the trend towards desertification of the Mediterranean region. In contrast, coastal and riverine flooding hazards, along with strong winds, are comparatively subdued here, likely due to the mitigating effects of the Mediterranean climate. Indicators of sea-level rise and heavy precipitation also display moderate values, suggesting a nuanced hazard landscape. The oceanic climate of Cork is reflected in mild extremes in temperature but heightened indicators for heavy rainfall and strong winds – conditions that are echoed in Viana do Castelo, albeit with a slightly warmer, less volatile climate. These cities exemplify the propensity of Atlantic climate for dynamic weather patterns, characterized by significant precipitation and strong wind events. La Spezia and Varna, with their minimal scores, epitomize the sheltering effects of the Mediterranean Sea and the relative calm of the Black Sea, respectively.

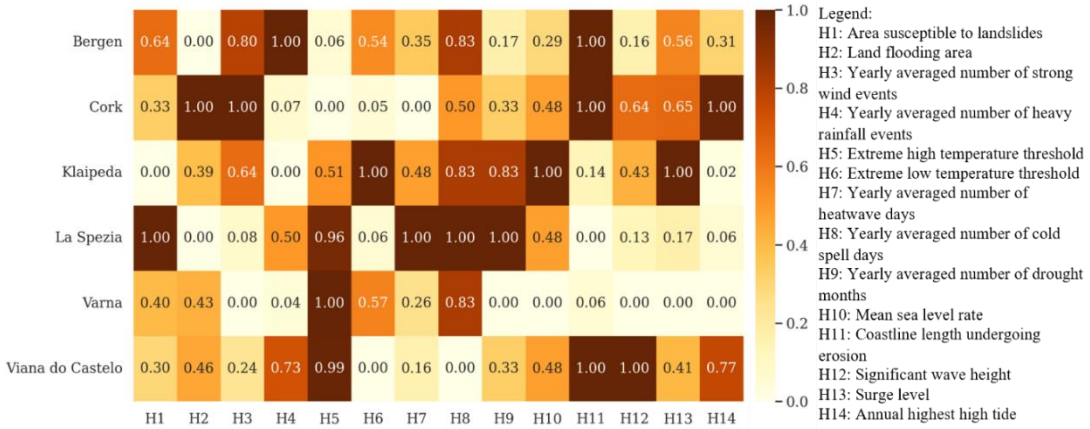


Figure 7.5. Heatmap representation of the indicators of hazard after min-max normalization to a range of 0-1.

The contrasting hazard profiles of cities influenced by the Atlantic Ocean versus those within the Mediterranean basin have significant implications for urban planning and

emergency management. In Atlantic-facing cities like Cork and Viana do Castelo, the focus might be on strengthening coastal defences against storms and enhancing flood-prevention measures. In contrast, Mediterranean cities may prioritize coping with extreme heat and ensuring water security. This understanding may guide city planners in allocating resources and developing tailored risk mitigation strategies. Cities with challenging topographies, notably La Spezia and Bergen, exhibit heightened landslide hazards. The position of La Spezia amongst hills and the topography of Bergen, characterized by mountains and fjords, contribute to their pronounced susceptibility to landslides. Conversely, flatter urban landscapes, particularly evident in Cork, show a predisposition towards river flooding, which highlights the interplay between topography and hazard potential. For cities like Cork, the historical development along riverbanks may contribute to its higher river flooding scores.

Table 7.4. Results of the indicator-based assessment.

Indicator	**Bergen**	**Cork**	**Klaipeda**	**La Spezia**	**Varna**	**Viana do Castelo**
Landslide-prone area (%)	41.6	21.4	0.0	64.6	26.1	19.7
Land flooding area (%)	0	10.3	4.0	0	4.4	4.7
Strong winds frequency (event/year)	2.0	2.5	1.6	0.2	0.0	0.6
Heavy rainfall frequency (day/year)	46.9	4.8	1.8	24.5	3.8	34.6
Extreme high temperature threshold (°C)	25.0	24.5	29.0	33.0	33.4	33.3
Extreme low temperature threshold (°C)	-11.0	-2.5	-19.0	-2.8	-11.6	-1.7
Heatwave frequency (day/year)	1.6	0.5	2.0	3.6	1.3	1.0
Cold spell frequency (day/year)	0.8	0.6	0.8	0.9	0.8	0.3
Drought frequency (month/year)	1.7	1.8	2.1	2.2	1.6	1.8

Mean sea-level rate (mm/year)	3.6	4	5.1	4	3	4
Coastline length undergoing erosion (%)	50	50	12.7	0	5.2	88.2
Significant wave height (m)	3	4.7	3.9	2.8	2.4	6
Surge level (m)	0.8	0.9	1.2	0.5	0.4	0.7
Annual highest high tide (m)	0.6	1.7	0.1	0.1	0	1.3
Area (km^2)	464.7	39.6	88.2	51.5	154.0	319.0
Population density (inhabitant/km^2)	622.7 (2022)	2996.6 (2011)	1725.1 (2022)	1791.3 (2022)	2160.3 (2022)	269.6 (2022)
Residential area (%)	16.0	45.2	17.2	17.4	25.0	11.1
Open areas (%)	6.3	11.6	4.8	2.6	5.0	1.2
Critical infrastructure area (%)	2.5	16.5	13.1	8.0	7.5	1.5
Transportation infrastructure area (%)	3.3	11.7	9.7	8.7	7.7	3.0
Agriculture area (%)	3.9	7.1	22.6	6.3	14.1	25.2
Forest area (%)	63.3	1.6	29.6	55.1	34.2	53.2
Wetland area (%)	4.2	3.6	0.8	0.2	5.1	2.9
Presence of power plant (0 or 1)	1.0	0.0	1.0	0.0	0.0	1.0
Presence of airport (0 or 1)	1.0	0.0	0.0	0.0	1.0	0.0
Presence of port (0 or 1)	1.0	1.0	1.0	1.0	1.0	1.0
Presence of railway station (0 or 1)	1.0	1.0	1.0	1.0	1.0	1.0
LECZ area (%)	2.3	19	42.2	12.3	5.3	9.9
Residential area (LECZ) (%)	36.5	15.5	15.5	12.9	3.1	4.9
Open areas (LECZ) (%)	3.6	16.5	5.4	10	5.7	4.7
Critical infrastructure area (LECZ) (%)	6.8	17.7	13.1	35.5	12.6	1.6
Transportation infrastructure area (LECZ) (%)	8.8	20.8	15.1	34.7	18.2	4.1
Agriculture area (LECZ) (%)	3.8	6.7	11.9	0.7	5.1	39.7

Forest area (LECZ) (%)	25.4	3.1	34.9	0.7	4.3	20.5
Wetland area (LECZ) (%)	14.7	15.6	1.8	3.8	47.6	18
Presence of power plant (LECZ) (0 or 1)	0	0	0	0	0	1
Presence of airport (LECZ) (0 or 1)	1	0	0	0	0	0
Presence of port (LECZ) (0 or 1)	1	1	1	1	1	1
Presence of railway station (LECZ) (0 or 1)	1	1	0	1	1	0
Population over 65 years old (%)	14.5 (2013)	15 (2011)	19.5 (2018)	26.7 (2018)	17.5 (2018)	22.4 (2019)
Population under 5 years old (%)	6.4 (2011)	5.1 (2011)	5.2 (2022)	3.6 (2022)	4.8 (2022)	3.7 (2022)
Unemployment (%)	0.9 (2011)	8.9 (2011)	3.3 (2022)	4.8 (2020)	3 (2021)	2.8 (2021)
GDP per capita	50,300	144,000	16,600	29,800	8,000	15,700
Economically active population (%)	25.8 (2021)	45.2 (2011)	54.8 (2022)	44.6 (2020)	46.8 (2021)	45.8 (2021)
Higher education (%)	14.4 (2022)	16.3 (2011)	27.5 (2022)	11.4 (2021)	25.9 (2022)	13.7 (2022)

The exposure of the coastal cities to the previous climate-related hazards is evaluated by examining land use and population density metrics in the total area in both the total area of study and the LECZ. These indicators are compared in the heatmap shown in Figure 7.6. Regarding the total coverage, Bergen covers the largest area among the cities studied (465 km^2), suggesting a broad interface with natural environments that may influence exposure patterns. Viana do Castelo also spans a considerable area (319 km^2), indicative of its reach along the coastline. In contrast, La Spezia and Cork are more compact (51.5 km^2 and 39.6 km^2, respectively), which emphasises the diversity in city sizes and the potential concentration of risks in smaller urban spaces.

Klaipeda exhibits an extensive LECZ, covering almost one-half of the total area, which explains its vulnerability to sea-level rise and coastal flooding. Cork, La Spezia, and Viana do Castelo also have notable LECZ areas, albeit less extensive than Klaipeda. Bergen and Varna have the smallest LECZ proportions (2.3% and 5.3%, respectively), suggesting a lower direct exposure to sea-level influences. Historically, the development of Klaipeda has been closely tied to its port, with economic activities concentrated along the coast. The extensive LECZ implies a heightened susceptibility to sea-level rise and coastal storms, which could disrupt these critical economic activities. A deeper exploration into the urban planning and coastal defences could reveal strategies for mitigating this exposure, such as the implementation of green infrastructure or revised zoning laws designed to reduce the concentration of critical assets and populations in vulnerable areas.

High population density is a critical component of exposure, as may be seen in Cork, which could lead to amplified impacts from climate hazards. Varna, La Spezia, and Klaipeda have similar population densities, while Bergen and Viana do Castelo have lower densities, possibly providing more space for dispersion of risks. In Cork, the high population density within a constrained urban area intensifies the potential impact of climate-related events. This density, when overlaid with the LECZ, reveals a compounded vulnerability. Areas of high population density that coincide with high-risk zones may face challenges in emergency response and evacuation efficiency. It is essential that urban planning strategies be developed to incorporate these factors into risk assessments, ensuring that evacuation routes, emergency shelters, and infrastructure are designed to handle the demands of a dense population facing a heightened risk of flooding and other coastal hazards.

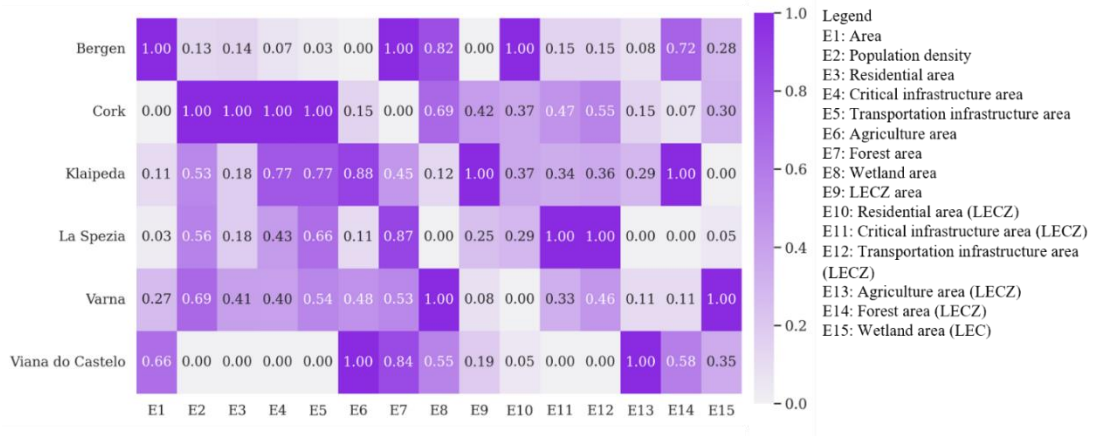


Figure 7.6. Heatmap representation of the indicators of exposure after min-max normalization to a range of 0-1.

The level of urbanization within these cities varies widely. Cork is the most urbanized, with extensive residential and infrastructure development. Bergen and Viana do Castelo show a lower level of urbanization, which is evident in the distribution of land uses (Figure 7.7). The size and spread of residential areas influence not just the density of the population but also the capacity of the city to respond to emergencies. More urbanized areas may face greater challenges in mobilizing resources and managing evacuations, especially if the infrastructure is not designed with resilience in mind. The analysis of urbanization should therefore be coupled with an assessment of emergency preparedness, including the adequacy of evacuation routes and the accessibility of safe zones.

When analysing the total area, Cork has a notably larger residential area compared to Bergen, reflecting its urban density. The distribution of residential, infrastructure, and transportation areas varies with the degree of urbanization. Forest and agricultural lands tend to be more prevalent in less urbanized cities. Wetland distribution does not directly correlate with urbanization levels – it may show high values in both urbanized and less urbanized settings. Focusing on the LECZ, the trend shifts. The residential area of Bergen is relatively large within the LECZ – a somewhat counterintuitive finding considering the overall urban profile of the city. Cork shows moderate values,

whereas La Spezia has significant critical infrastructure and transport areas within its LECZ. The wetland areas see a substantial increase within the LECZ, which could have implications for biodiversity and ecosystem services in these zones.

Notwithstanding, the role of wetlands, particularly within the LECZ, is multifaceted. In Varna, the increase in wetland areas within the LECZ (from 5.1% to 47.6%) could be seen as a potential asset, providing natural buffers that mitigate exposure to storm surges and flooding. The conservation and restoration of wetlands should be integral to climate adaptation strategies, leveraging these ecosystems to provide natural defences that complement engineered solutions. This balance between the natural and built environments can be crucial for building a resilient urban landscape.

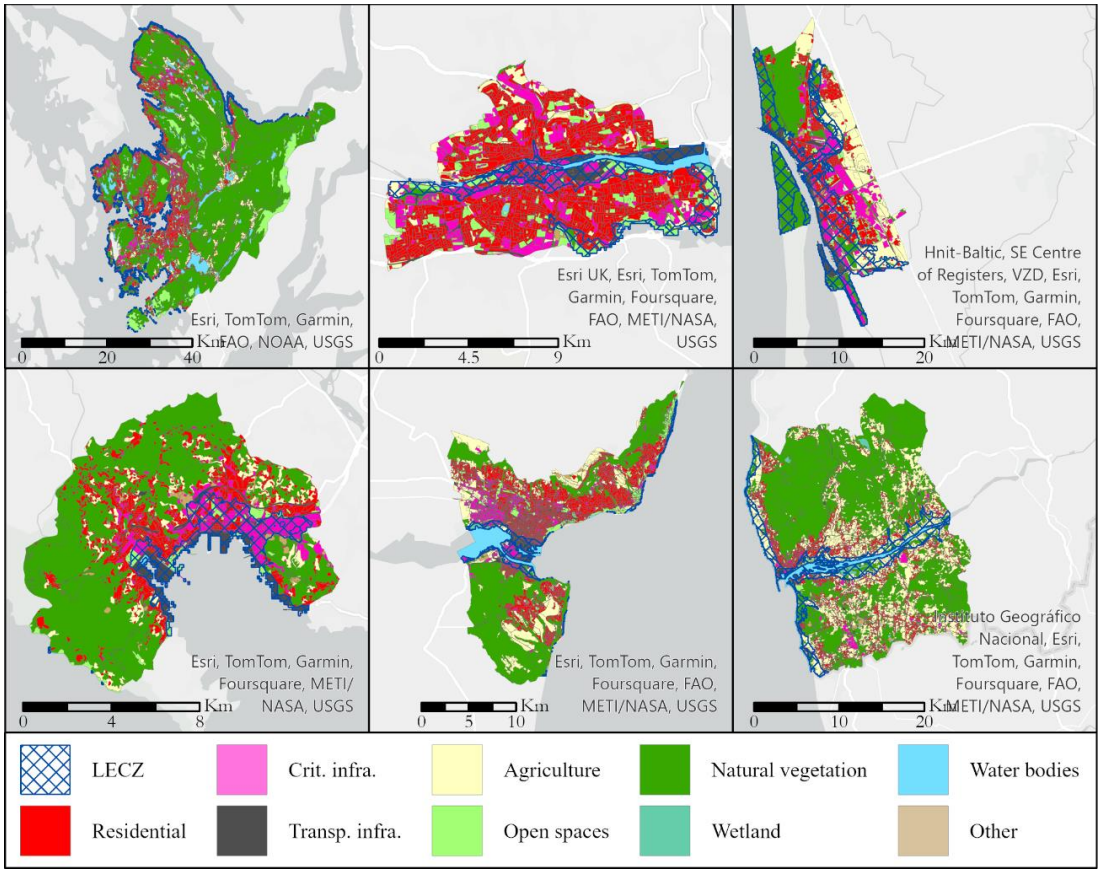


Figure 7.7. Map of land uses based on the reclassification of Urban Atlas categories and low-elevation coastal zones.

It is important to note that the use of administrative boundaries to define the study areas can influence the exposure indicators and, therefore, risk. To address this, alternative methods could be employed, such as delineating study areas based on physical geography, such as watersheds or topographical features, or using population density maps to identify areas of high human concentration. These approaches would provide different perspectives on the spatial dynamics of hazard exposure and vulnerability. Additionally, incorporating participatory GIS methods could engage local communities in identifying and validating high-risk zones, leading to a more nuanced and grounded understanding of exposure.

LULC patterns extend beyond exposure to encapsulate sensitivity, crucial for understanding the nuanced responses of coastal cities to climate-related hazards. For example, urban areas, characterized by their impervious surfaces, directly influence water runoff and drainage dynamics, intensifying flood risks. As previously discussed, Cork exhibits higher urbanization rates when considering the total study area, yet within their respective LECZs, both Cork and Bergen share a similar percentage of urbanized land (52.1% and 54.0%, respectively, when residential, critical infrastructure, and transportation are accounted for). This parity indicates a substantial presence of sensitive and impervious areas within the LECZ of Bergen, raising its vulnerability to coastal hazards. A similar trend is observed in La Spezia, indicating an increased sensitivity within these regions.

Urbanized regions also contribute to the Urban Heat Island (UHI) effect, where temperatures in built-up areas exceed those of surrounding rural regions. This phenomenon can amplify the effects of heatwaves, with repercussions for public health and energy demand. La Spezia, with its significant urban areas and high heat hazard and drought indicators, must prioritize addressing these risks. Planning should incorporate green spaces and reflective materials in urban design to mitigate the UHI effect. Furthermore, LULC is intricately linked to socioeconomic dynamics. Land uses such as forests and wetlands may display less sensitivity to flooding but are more

vulnerable to temperature and precipitation hazards. Conversely, agricultural lands may be sensitive to a wider array of dangers. This intricate relationship is reflected in the indicators for Viana do Castelo.

The spatial distribution of infrastructure and essential services critically shapes the vulnerability profile of cities (Figure 7.8). Ensuring that infrastructure such as hospitals, power plants, and water treatment facilities is not only robust but also strategically sited is paramount. Data from OpenStreetMap reveal commonalities across the cities, with ports being a universal feature within the LECZ. Notably, Klaipeda and Viana do Castelo lack railway stations within their LECZs. Only Bergen and Viana do Castelo have airports within the study area, with the airport of Bergen also falling within the LECZ. Power plants are present only on the periphery of Bergen, Klaipeda, and Viana do Castelo, with the facility of Viana do Castelo located within the LECZ, potentially increasing its sensitivity to coastal hazards.

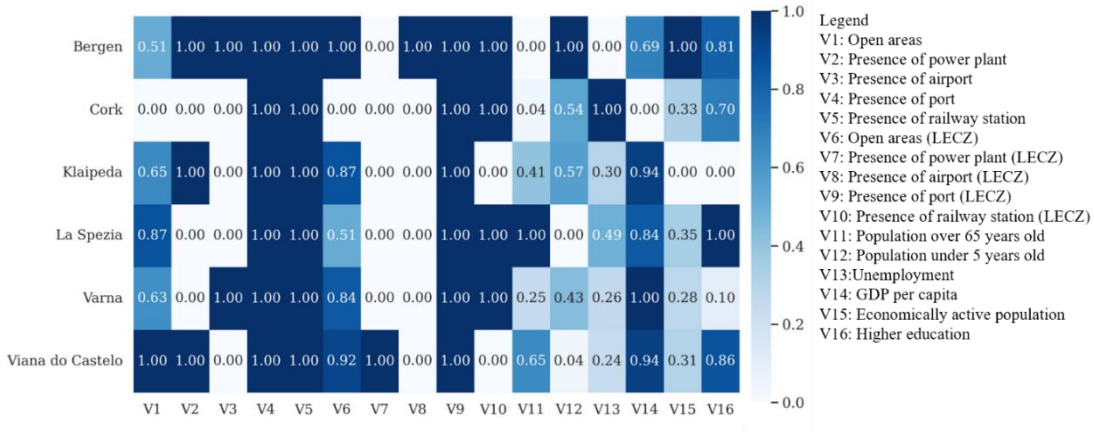


Figure 7.8. Heatmap representation of the indicators of vulnerability after min-max normalization to a range of 0-1.

Demographic profiles, especially the proportion of vulnerable age groups (under 5 and over 65), are indicative of sensitivity. These groups typically require additional resources during climate events due to their specific needs and lower resilience. Figure 7.9 illustrates the evolution of these indicators, including the rates of unemployment and economically active population, based on data from Eurostat. Most recent data

show that La Spezia has the oldest population (26.7%), followed by Viana do Castelo (22.4%) and Klaipeda (19.5%), while Bergen and Cork are at the lower end (14.5% and 15.0%, respectively). The youngest populations are found in Bergen (6.4%), Cork, and Klaipeda (5.1% and 5.2%), contrasting with La Spezia (3.6%) and Viana do Castelo (3.7%), characterized by aging demographics.

Unemployment rates serve as an indirect indicator of the economic resilience to climate-related shocks. For Bergen, the unemployment rate was last recorded at 0.9% in 2011. In contrast, Cork had an unemployment rate at the time of 8.9%. Notably, the unemployment rate in Bergen, although based on older data, is the lowest among the cities studied, occasionally matched only by Varna during brief periods. The most recent rates of unemployment available for the other cities are 3.3% for Klaipeda (2022), 4.8% for La Spezia (2020), 3.0% for Varna (2021), and 2.8% for Viana do Castelo (2021). While historical data for some cities show lower unemployment rates, the 2020-2022 figures provide a more contemporaneous assessment for these urban areas. It is important to note that data for Viana do Castelo are quite limited, with only two records available (2011 and 2021).

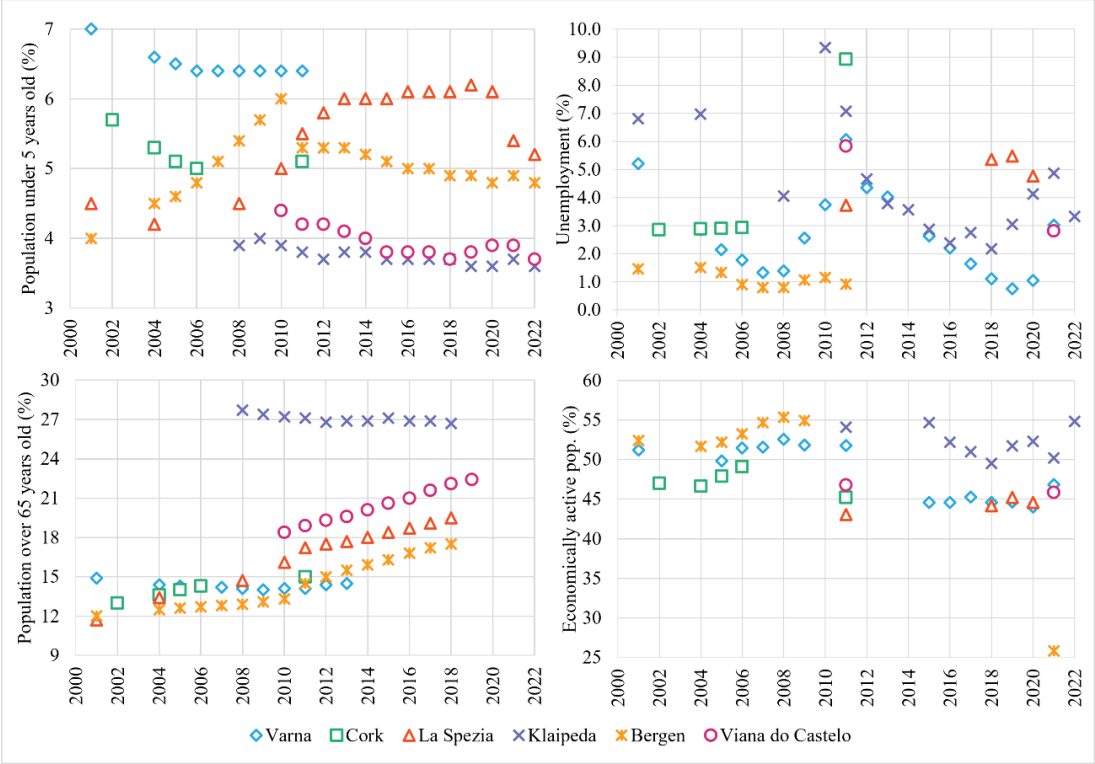


Figure 7.9. Evolution of indicators on population. Data source: Eurostat.

The proportion of economically active population is indicative of economic vibrancy and resilience. This demographic is central in maintaining workforce stability and can indicate how a city might cope with climate-induced economic fluctuations. The data calls for careful interpretation, particularly in light of recent disruptions such as the COVID-19 pandemic. Notably, Bergen reported an economically active population of 25.8% in 2021, with an unemployment rate last recorded in 2011. This points to the potential for outdated data to skew the risk assessment. Conversely, Cork's 2011 figure of 45.2% for the economically active population may no longer reflect current conditions. Recent figures for other cities present a more current assessment, with Klaipeda ranking highest at 54.8% in 2022, La Spezia at 44.6% in 2020, Varna at 46.8% in 2021, and Viana do Castelo at 45.8% in 2021.

GDP per capita serves as a proxy for the availability of resources crucial for climate adaptation and mitigation. A higher GDP per capita suggests a greater potential for investment in resilience-building initiatives. The stark contrast between Cork, with the

highest GDP per capita at €144,000, and the rest of the cities, with Bergen at €50,300 and Varna at the lower end with €8,000, underscores the disparity in resource availability for tackling climate challenges.

Higher education correlates with increased awareness and the implementation of innovative strategies to address climate-related issues. The variability in the level of educational attainment (measured as the percentage of the population over 25 with higher education degrees) between the cities studied is notable, ranging from 27.5% in Klaipeda and 25.9% in Varna to a lower 11.4% in La Spezia and 13.7% in Viana do Castelo. This diversity highlights the importance of education in cultivating adaptive capacity and points to potential areas for investment in human capital.

These results exemplify that risk is not static; it fluctuates significantly over time. The indicators underscore the necessity for a dynamic analysis, calling for continuous monitoring and updating of data to inform adaptive strategies. Only through such rigorous, dynamic evaluation can coastal cities effectively bolster their resilience.

The adaptive capacity has been assessed as a multifaceted concept that hinges on various indicators, including land use patterns, socioeconomic dynamics, and educational attainment. Open spaces play a critical role in enhancing the adaptive capacity, for they serve as natural retention areas during flood events, mitigate the urban heat island effect, and can act as firebreaks. Moreover, they improve the overall quality of life, signifying a resilient urban environment. A robust transportation network is equally essential, particularly when mobilizing resources and individuals in response to extreme climate events. Cork stands out in this respect, showcasing a significant proportion of such land uses within both its total study area and the LECZ – particularly regarding open spaces. The LECZ of La Spezia has an extensive transport network, whereas Cork, Klaipeda, and Varna also present noteworthy figures.

The aggregate scores of the indicators are visually represented in Figure 7.10 in a scale between 0-100. The risk component of hazard exhibits similar scores, between 46 and 50%, for all cities except Varna, which has a score of 25.7 points. However, interpreting this risk score requires nuance when considering individual cities. In Cork and Viana do Castelo, coastal hazards contribute significantly, while land hazards score low. Klaipeda and Bergen show medium scores for both types of hazards. Conversely, La Spezia has very low coastal hazard scores and high land hazard scores, while Varna scores low for both. This analysis highlights the importance of examining individual indicator scores to accurately understand the final risk components.

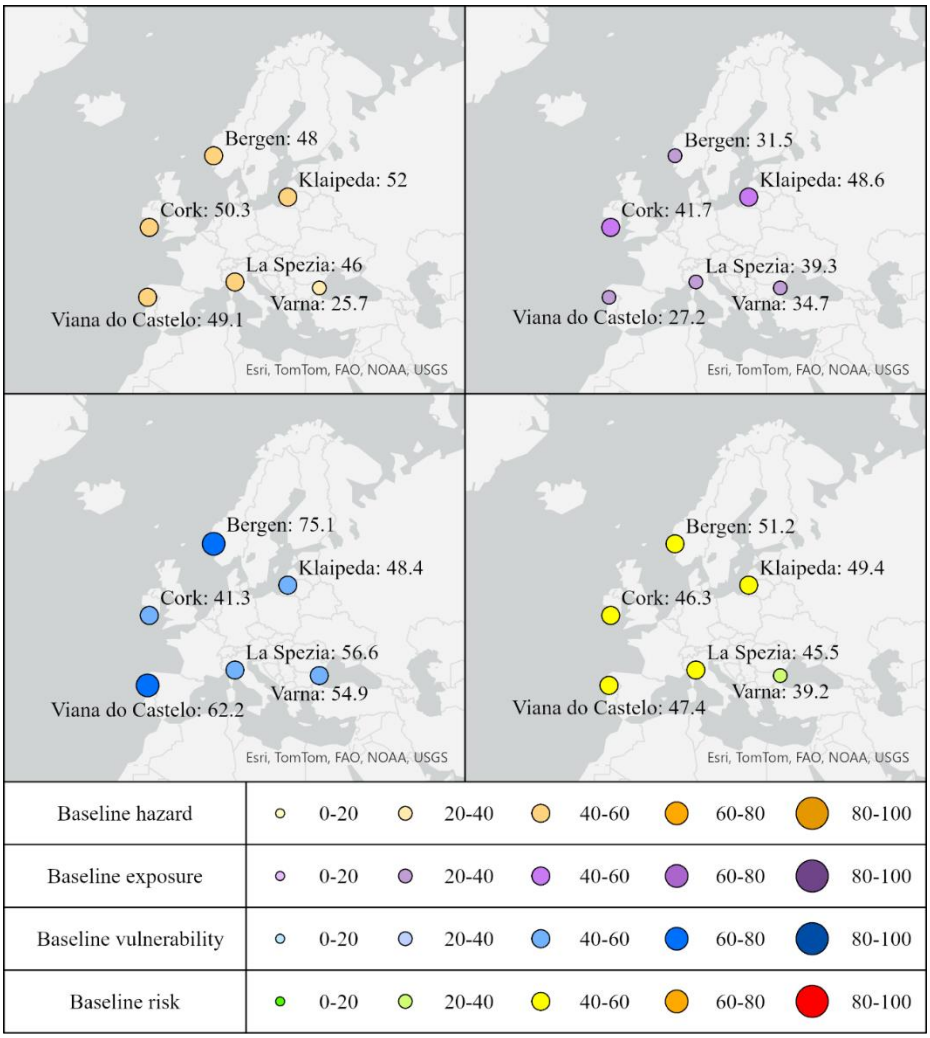


Figure 7.10. Results of the indicator-based assessment after the aggregation of the indicators into the risk categories of hazard, exposure, sensitivity and adaptive capacity.

The exposure component displays medium and low values, ranging from a maximum of 48.6 points in Klaipeda to a minimum of 27.2 points in Viana do Castelo. While detailed analysis of individual indicators reveals significant differences between cities, such as population density and urbanization levels, the aggregate score masks these variations. The situation is different with regard to vulnerability, where significant variation is found between cities. Viana do Castelo and Bergen stand out for their high scores (62.2 and 75.1 points, respectively) based on the measured indicators. In contrast, Cork exhibits the lowest score (41.3 points). The remaining cities display medium scores, approximately between 45 to 55 points. The substantial annual fluctuations observed in socioeconomic indicators necessitate cautious interpretation of the vulnerability score – it is far from static and depends heavily on the timing of the assessment. Importantly, the vulnerability parameter of adaptive capacity relies on the fewest indicators, which amplifies the relative importance of each individual indicator for the final score.

The observed risk landscape presents a balanced picture, with no city standing out remarkably compared to the others. Interestingly, the cities with the highest scores in hazard and exposure (Cork and Klaipeda) also exhibit the lowest levels of vulnerability. Conversely, Viana do Castelo and Bergen, with lower scores in the initial components, have high vulnerabilities.

7.4. Discussion

The advancement in risk assessment methodologies for European coastal cities highlighted by this research signifies a notable shift toward methodologies that are not only more inclusive and nuanced but also dynamic in nature. This shift is paramount in the context of climate change, where the static and compartmentalized approaches of the past are increasingly insufficient to address the complex, interwoven challenges that cities face today. By integrating a broad spectrum of indicators covering hazard,

exposure, sensitivity, and adaptive capacity, the methodology introduced herein offers a comprehensive lens through which to view and assess the multifaceted nature of climate risks. Such an approach is invaluable in an era where the impacts of climate change are both far-reaching and deeply interconnected, affecting not just the physical but also the socio-economic fabric of urban areas.

The methodology distinctly advances beyond the scopes of established models like CLIMADA and DIVA, which, while pioneering in their respective foci on natural disaster impacts and sea-level rise, offer a somewhat limited view of climate risk. By broadening the analytical lens to include a wider array of hazards and, crucially, their socio-economic repercussions, the present study addresses a critical gap in the existing literature. It acknowledges that the threats posed by climate change are not isolated incidents but are systemic, with far-reaching implications that necessitate a holistic assessment approach [498]. This is especially pertinent in urban areas, where the density of population and infrastructure magnifies the potential impact of climate hazards will improve the accuracy of risk assessments [390,391,499][112,113]

The comparison of the results with existing studies yields valuable insights. The geographical configuration of Liguria makes it particularly prone to flash floods, storms, forest fires, and landslides [500–502]. This is consistent with our findings, where the hazard indicators for La Spezia prominently feature landslides, extreme temperatures, and droughts. Although the indicator for land flooding is negligible, the heavy rainfall indicator is relatively high, especially for a Mediterranean city. This demonstrates the necessity of careful interpretation of indicators, as they may not always provide a clear picture.

In Cork, various studies emphasize the significance of coastal hazards and land flooding, which align well with the indicators [195,503]. The potential compounding of these hazards is a crucial consideration [64]. The articles on adaptation and resilience provide guidelines that could be beneficial for other cities that have not

advanced as much in these areas [199,504]. This highlights the advantage of comparing cities and sharing results and experiences.

Although the indicators are not very high for Bergen, the study by Venvik et al. (2019) indicates that subsidence is a serious problem in certain areas of the city centre. It also points out that increased precipitation, sea-level rise, and storm surges due to climate change will lead to higher flooding events. The possible combinations of hazards and risks are numerous, and detailed studies are essential to understand the local conditions of each city.

The indicators related to coastal hazards are high in Klaipeda compared to the other cities in this study. However, the application of a coastal risk index along the Baltic Sea shores of Lithuania reveals that the coastal risks in Klaipeda are relatively lower compared to other areas along this coastal strip [355]. This underscores the need for further case studies to broaden our understanding.

In Varna, the hazard indicators highlight extreme temperature hazards more than in other cities, while coastal hazards are relatively low. Nonetheless, the existing literature focuses on coastal hazards, and no studies on extreme temperatures were found [506,507]. This may indicate an underestimation of extreme temperature hazards or an overestimation of coastal hazards in this city. It also underscores the tendency to prioritize coastal hazards in coastal cities over other types of hazards. A more detailed study on the potential impact of extreme temperature hazards and coastal hazards could be illuminating to further explore this disparity.

Southern Europe is generally warmer compared to the rest of Europe. However, Viana do Castelo, located in the northern Iberian Peninsula and exposed to the Atlantic, has an oceanic climate. The indicator results show that the high temperature threshold is significant in this city, along with numerous indicators related to coastal and land flooding, aligning with previous studies [75,216–218,508]. The drought indicator is low, which aligns with the findings of Santos et al. (2010) indicating that droughts in

northwest Portugal are less severe than in the south. The results for Viana do Castelo also prompt reflection on the size of the study area. The study area was defined based on administrative boundaries, which includes large portions of non-urbanized territory, significantly influencing land cover and socioeconomic variables.

The adaptability of this methodology is one of its core strengths, resonating with the latest recommendations from the Intergovernmental Panel on Climate Change for dynamic and comprehensive climate risk frameworks [89]. The ability to incorporate evolving data sets and adapt to the progressing nature of climate science underscores the potential of the methodology for future enhancements and longevity. For example, datasets such as Urban Atlas (2018) and Coastal Zones (2012 and 2018) from Copernicus were not validated for external use at the moment of writing. Such flexibility ensures that, as the understanding of climate science advances and as new data become available, the methodology can be updated and refined to remain at the forefront of climate resilience planning.

From a theoretical standpoint, this research embodies a shift towards conceptualizing urban resilience within the contexts of adaptability and systemic vulnerability. It aligns with the perspective advocated by Cutter et al. (2003), among others, that resilience transcends mere physical robustness to encompass the adaptive capabilities of urban systems. This approach is crucial for recognizing cities as complex socio-ecological systems, where resilience is contingent upon a multifaceted strategy that includes not just infrastructural but also social, economic, and environmental considerations [431]. Such a strategy acknowledges the interconnectedness of urban systems and the importance of addressing resilience at multiple scales and dimensions [433]. However, while this study provides a comprehensive set of indicators, it acknowledges that the indicators of adaptive capacity are fewer than those for other risk parameters. This discrepancy highlights a limitation of the study, underscoring the challenges in developing adaptive capacity indicators for such assessments.

Notwithstanding, the findings of this study underscore the critical importance of socio-economic factors and community engagement in building adaptive capacity [270,352]. In this context, the LULC indicators primarily serve as proxies for exposure to the climate-related hazards. However, the character of these indicators can vary. For example, the presence of green spaces such as parks and urban forests has been recognized for their role in mitigating the impacts of urban flooding by facilitating water infiltration and providing water retention areas, thereby reducing surface runoff and potential flood damage [509–511]. In addition to their hydrological benefits, these green areas offer shade and reduce the urban heat island effect, enhancing urban resilience to heatwaves [21,132]. Furthermore, strategic placement of urban green spaces can create natural firebreaks that help contain wildfires and protect urban infrastructure [461]. Transportation infrastructure can also be considered as an element of sensitivity, as any disruption can have cascading effects on the productivity and economic stability of cities [152]. On the other hand, well-designed transportation networks are integral to emergency response and evacuation processes, enhancing the resilience of cities to disasters [437]. For instance, the comprehensive allocation of land to open spaces and transport infrastructures underscores a proactive stance in urban planning in Cork [509]. However, the dynamic nature of urban development, especially in the aftermath of global disruptions such as the COVID-19 pandemic, necessitates the use of the most current data to accurately gauge these indicators [512]. The pandemic has underscored the volatility of urban systems and the critical need for timely data to inform adaptive strategies. Historical data alone may not capture the socio-economic shifts or infrastructural developments that impact resilience capacity in real time.

The literature on adaptive capacity emphasizes the importance of economic activity and workforce stability as resilience metrics [66]. The data presented suggest that cities like Klaipeda and Varna have vibrant economic profiles, potentially translating into greater adaptive capacities. Yet, the aforementioned limitation of data currency

remains pertinent, signalling the need for ongoing data collection and interpretation. While GDP per capita is a traditional marker of resource availability for climate adaptation, it offers a narrow lens on the overall adaptive capacity of a city. The adaptive capacity is also significantly influenced by its public health infrastructure, which dictates the ability to respond to, and recover from, health-related climate impacts. Social equity and community engagement levels are additional dimensions that determine how inclusive and comprehensive adaptive measures are [513]. These factors warrant incorporation into the adaptive capacity assessment, for the purpose of providing a more holistic understanding of urban resilience. The educational attainment of the population of a city is a pivotal determinant of its adaptive capacity, equipping residents with the knowledge and skills to implement and support resilience strategies. The variability of the results reflects differential capacities for innovation and adaptation, in line with previous findings [510] to the effect that education fosters socio-ecological resilience by enhancing the ability of communities to engage with, and adapt to, changing climatic conditions.

This emphasis is also in line with the broader resilience discourse, which highlights the significance of social capital, governance, and institutional flexibility [273]. These elements are indispensable in equipping cities to navigate and recover from the shocks and stresses related to climate change. The integration of socio-economic indicators into the risk assessment framework not only enriches the analysis but also ensures that the resultant strategies for enhancing resilience are grounded in the realities of urban life [67]. It acknowledges that the strength of the response of a city to climate challenges is deeply influenced by the engagement and empowerment of its communities, alongside the robustness of its governance and institutional structures [15].

The policy implications of this research are both significant and timely. The granularity and specificity inherent to the proposed methodology offer a blueprint for urban planners and decision-makers to identify high-risk areas, allowing for a more

informed and targeted approach to resilience building. This specificity is particularly crucial in the context of climate adaptation, where the strategic allocation of often limited resources can markedly influence the efficacy of mitigation efforts [514,515]. By prioritizing adaptation measures based on a detailed understanding of risk, cities can optimize their resilience strategies, ensuring that investments are directed where they are most needed and can have the greatest impact.

The emphasis on cross-sectoral collaboration and stakeholder engagement as highlighted by this research underscores a critical shift in the paradigm of climate adaptation planning. The integration of diverse perspectives, from local communities to various sectors of governance and industry, is fundamental to the development of robust resilience strategies [453,516]. This collaborative approach not only enriches the planning process with a multitude of insights and expertise but also ensures that resilience measures are deeply rooted in the local context and are responsive to the specific needs and vulnerabilities of communities [287]. It highlights the importance of moving beyond top-down approaches to embrace more participatory, inclusive methods of resilience planning, where stakeholders are actively involved in shaping the strategies that affect their lives and environments.

The integration of emerging technologies and innovative methodologies into the framework presents a frontier for enhancing climate risk assessment and adaptation planning [517]. The advent of geospatial analytics, artificial intelligence, and citizen science opens up new possibilities for both refining the precision of risk assessments and fostering community engagement in resilience efforts [110,123,365]. For example, machine learning algorithms applied to vast datasets of climate information could significantly improve the predictability of hazard events, enabling cities to anticipate and prepare for potential impacts with greater accuracy [364,366,392]. Similarly, participatory GIS and citizen science initiatives can empower local communities, giving them a voice and stake in identifying vulnerabilities and co-

creating solutions, thereby democratizing the process of resilience building [119,367,518].

The exploration of non-traditional indicators, such as digital connectivity, green roofs, psychological resilience, and cultural assets, introduces an innovative dimension to understanding and enhancing urban adaptive capacity [130,178,519,520]. These factors, often marginalized in conventional risk assessments, have the potential to unlock new avenues for building resilience [373]. Recognizing the role of digital infrastructure in facilitating communication and access to information during crises, the importance of mental health and community cohesion in recovery processes, and the value of cultural heritage in fostering a sense of identity and belonging, can all contribute to more resilient urban environments [9,521]. These dimensions add depth to the understanding of what makes cities resilient, pointing to the need for adaptive strategies that are not only physically robust but also socially and culturally resilient.

This work analyses risk under current climatic conditions. However, considering future scenarios is crucial in climate risk assessment and coastal management [3,31,522]. Most hazard indicators are based on climate data that can be updated with climate projections, such as sea-level rise, temperature, precipitation, and oceanic variables. Projecting other indicators, specifically coastal erosion, river flooding areas, and landslide susceptibility, poses a greater challenge, although not insurmountable. Data from Urban Atlas, OSM and Eurostat were used for the assessment, although there are various studies on the urban and demographic evolution of coastal cities throughout this century [69,305,523]. The methodology developed has the potential to be transferable to projecting future risk, which is a crucial step considering the exacerbation of climate-related hazards under climate change.

Recent studies show how climate projections might affect the findings of this study until 2100 [7,79,80,524]. According to the latest climate models, global temperatures are projected to rise significantly, likely resulting in more frequent and severe

heatwaves in Europe. This increase in temperature could exacerbate heatwave indicator scores for cities already experiencing high temperatures, such as Mediterranean cities, while also impacting cold spell frequencies. Similarly, the desertification of southern Europe poses challenges regarding drought and water availability. Future flooding patterns are also expected to change, with projections indicating increased intensity and frequency of both river and coastal floods. This is particularly relevant for cities like Bergen and Viana do Castelo, which already exhibit high vulnerability to such events. The projected sea-level rise, estimated to reach up to 1 meter or more by 2100, will further compound these risks, leading to more extensive coastal erosion.

These changes underline the necessity for proactive urban planning and the integration of adaptive measures to mitigate these impacts. The implications for sustainable coastal management are profound. Integrating climate projections into urban planning is crucial for developing resilient infrastructure and reducing vulnerability [362,525,526]. Future recommendations based on these projections include continuous monitoring and updating of climate data and risk assessments. In this sense, the framework applied in this study can be further adapted to other coastal cities by considering local data and conditions. Encouraging collaboration between cities to share best practices and resilience strategies will enhance overall urban resilience. This adaptability is key for accurately assessing and addressing climate risks in diverse geographical contexts. By tailoring the framework to local realities, cities can develop more effective risk management and adaptation strategies. Adaptive strategies, such as the implementation of green infrastructure, enhanced drainage systems, and robust coastal defences, are vital for managing the anticipated changes. Additionally, increased investment in resilient infrastructure and community engagement in climate adaptation and coastal management initiatives is essential for preparing cities to face future climate challenges.

7.5. Conclusions

By integrating a broad array of indicators covering hazard, exposure, sensitivity, and adaptive capacity, the study provides a novel methodology to assess a wide variety of climate-related risks in European coastal cities. This approach is crucial for addressing the systemic and interconnected impacts of climate change on coastal urban areas, emphasizing the importance of dynamic and comprehensive assessment frameworks. Indeed, the applicability and effectiveness of the proposed methodology are further underscored by its implementation across six diverse European coastal cities: Bergen, Cork, Klaipeda, La Spezia, Varna, and Viana do Castelo. This selection encompasses cities with different climate zones, levels of urbanization, economic profiles, and susceptibility to various climate-related hazards. The findings are consistent with a broad range of existing research, yet our study introduces a novel aspect by enabling comparisons between cities. This approach highlights certain hazards that may not have been extensively studied in some areas but could be significant, underscoring the importance of cross-regional analyses to uncover overlooked risks.

By examining these cities, the research not only validates the comprehensive and dynamic nature of the methodology, but also highlights the importance of contextual factors in climate risk assessment and coastal management. For instance, the distinct climatic influences of the Atlantic Ocean versus the Mediterranean Sea on the selected cities underscore the necessity for location-specific adaptation strategies. Similarly, the study of socioeconomic indicators, such as population density and GDP per capita, across these varied urban contexts reveals how economic and demographic factors significantly influence the adaptive capacity of cities.

The findings highlight the critical role of socio-economic factors, urban planning, and infrastructural resilience in determining the vulnerability and adaptive capacity of coastal cities to climate-related hazards. Urban green spaces, efficient transportation networks, and the spatial distribution of critical infrastructure are identified as key

elements that influence the resilience to climate impacts of cities. These factors underscore the necessity of incorporating socio-economic dynamics and community engagement into resilience-building efforts.

The study acknowledges the dynamic nature of climate risk and the importance of continuously updating data and strategies to reflect current conditions. The variability in socio-economic indicators, such as unemployment rates and educational attainment, points to the need for a real-time understanding of urban resilience. This calls for adaptive planning that can respond to evolving climate science and urban development trends.

The granular risk assessment provided by the methodology offers valuable insights for urban planners and policymakers, enabling the identification of high-risk areas and the optimization of coastal management and adaptation strategies. The emphasis on cross-sectoral collaboration and the integration of diverse stakeholder perspectives highlight the shift towards more participatory and inclusive approaches to climate adaptation planning.

The exploration of emerging technologies, such as geospatial analytics and artificial intelligence, presents opportunities for refining risk assessments and enhancing community engagement in resilience efforts. Additionally, considering non-traditional indicators, such as digital connectivity and cultural assets, could provide new dimensions to understanding and enhancing urban adaptive capacity.

In conclusion, the research underscores the complexity of assessing and addressing climate risks in European coastal cities. It advocates for a multi-dimensional approach that incorporates physical, socio-economic, and infrastructural factors into resilience planning. The dynamic nature of climate change necessitates continuous adaptation and innovation in methodologies and strategies. Engaging a wide range of stakeholders and leveraging emerging technologies are crucial steps towards building

resilient urban environments that can withstand the challenges posed by climate change.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 8.

Case study application of the multi-hazard risk assessment methodology

This chapter corresponds to: Laino, E., Toledo, I., Aragonés, L. and Iglesias, G. **A novel multi-hazard risk assessment framework for coastal cities under climate change**. Science of The Total Environment, 2024. **954**: p.176638.

ABSTRACT

Coastal cities, as centres of human habitation, economic activity and biodiversity, are confronting the ever-escalating challenges posed by climate change. In this work, a novel Multi-Hazard Risk Assessment framework is presented with a focus on the Coastal City Living Lab concept. The methodology provides a comprehensive assessment of climate-related hazards, including sea-level rise, coastal flooding, coastal erosion, land flooding, heavy precipitation, extreme temperatures, heatwaves, cold spells, landslides and strong winds. Its application is illustrated through a case study: the Coastal City Living Lab of Benidorm, Spain. The methodology incorporates remote sensing data from various satellite sources, such as ERA5, Urban Atlas and MERIT DEM, to evaluate multiple hazards through a systematic and standardized indicator-based approach, offering a holistic risk profile that allows for comparison with other European coastal cities. The integration of remote sensing data enhances the accuracy and resolution of hazard indicators, providing detailed insights into the spatiotemporal dynamics of climate risks. The incorporation of local expertise through

the Coastal City Living Lab concept enriches data collection and ensures context-specific adequacy. The integration of local studies and historical extreme climate events enhances the validity and context of the risk indicators. The findings align with regional trends and reveal specific vulnerabilities, particularly related to heatwaves, heavy rainfall, and coastal flooding. Despite its strengths, the MHRA methodology faces limitations, including its high-level scope and the complexity of integrating multiple hazards. Continuous updates and adaptive management strategies are essential to maintain the accuracy and relevance of risk assessments. The broader implications of the methodology for global coastal cities highlight its potential as a model for developing targeted adaptation strategies.

8.1. Introduction

The imperative to understand and mitigate the impacts of climate change on coastal urban environments has intensified in recent years (Lane et al., 2013; Vousdoukas et al., 2018a; Vousdoukas et al., 2018). This urgency arises from a more profound understanding of the complexities posed by climate change and its increasingly severe implications [28,29,41]. Coastal cities, as centres of human habitation, economic activity, and biodiversity, are particularly vulnerable to these changes [69,149]. Recent studies highlight the accelerating pace and increasing severity of climate change impacts on coastal cities (Laino and Iglesias, 2023a; Nicholls, 2004; Vousdoukas et al., 2018b; Vousdoukas et al., 2017). The rise in the frequency and intensity of storms exacerbates coastal flooding and erosion [10,31,35,93]. According to the Sixth Assessment Report by the IPCC, global sea-levels have risen by approximately 20 cm since the start of the 20th century, with projections suggesting an additional rise of 30 to 60 cm by 2100 under moderate emission scenarios [36,322,524,529]. These changes

pose significant risks to coastal urban environments, necessitating urgent and comprehensive mitigation strategies [1,3,11,134,434].

The evolution of climate risk assessment has been marked by a transition from focusing solely on physical environmental factors to incorporating soc[99,284,297,373]. The growing investment in climate change research reflects the increasing recognition of its importance [191,389,392]. Adaptation strategies have similarly evolved, showing significant variation across different geographic and socio-economic contexts [283,496,530].

The integration of remote sensing technologies, such as satellite imagery and DEMs, in climate risk assessments has proven to be highly beneficial, particularly for monitoring and managing environmental changes in urban and coastal areas [531–534]. These technologies enable precise and comprehensive data collection on factors such as land use, topography, and climate variables. Remote sensing products, including datasets like ERA5, Urban Atlas, and MERIT DEM, provide high-resolution and accurate information crucial for assessing a wide range of climate-related hazards. Techniques such as satellite radar, optical imagery, and LiDAR (Light Detection and Ranging) are integral to generating datasets like Urban Atlas and MERIT DEM, which are essential for accurate topographic and land use analysis in climate risk assessments. For instance, detailed high-resolution imagery is essential for analysing urban heat islands, forest cover, agricultural areas, wetlands, and water bodies [21,535–538]. This level of detail allows for precise monitoring of changes in land use and the identification of vulnerable areas that require targeted intervention [539–541]. In coastal cities, such data is indispensable for tracking coastal waters and managing the impacts of urbanization on the natural environment [370,520,542,543].

The application of multi-satellite data to assess climate-related hazards is another critical advancement [544–548]. Remote sensing has enabled the monitoring of storms, droughts, wildfires, hydrological hazards, sea-level rise, wave dynamics, wind

patterns, and landslides, among others, with unprecedented accuracy [43,549–552]. For example, satellite observations can track the progression of storms and predict their potential impacts, while hydrological models informed by remote sensing data can forecast flooding events [64,365,499,553,554]. These capabilities are particularly valuable for coastal cities, where the intersection of multiple hazards requires comprehensive and integrated management strategies [368,536,555,556]. In this vein, satellite data products, such as those derived from ERA5, offer detailed and high-resolution information that is crucial for understanding and mitigating the impacts of climate change [441,557–559]. These datasets facilitate the evaluation of sea-level rise, coastal flooding, and other extreme weather events with enhanced spatial and temporal resolution. Recent studies utilizing remote sensing data have highlighted the effectiveness of these technologies in tracking climate-induced changes and supporting urban resilience planning [120,441,445,559].

Index-based methodologies represent a fundamental approach within MHRA, allowing for the articulation of the multifaceted nature of climate-related hazards [90,106,431]. These methodologies employ a set of independent variables to characterize key aspects of such hazards, including storm characteristics, wave regimes, sea-level changes, and temperature fluctuations [111,113,276,283]. Composite indices, which aggregate these variables, offer a summarized view of the overall hazard scenario, facilitating a nuanced assessment that is both coherent and standardized [94,95,105,432,437]. This approach enhances the comparability and interpretability of hazard assessments across different cases and hazard types. Despite their strengths, many existing indicator-based methodologies often exhibit limitations, such as focusing on a select range of hazards or specific vulnerability parameters [97,99]. This specialization can overlook the interdependencies and cumulative effects of multiple hazards that concurrently affect coastal cities [27,98]. To address these gaps, modern MHRA methodologies seek to expand the traditional scope by incorporating a comprehensive set of hazards relevant to coastal cities, thus providing

a more holistic view of the risk landscape [90,108,109,358]. This includes adapting and refining existing methodologies to meet the specific requirements of coastal urban environments [130,560].

Innovative approaches within MHRA also emphasize the integration of local and scientific knowledge [112,113]Overall, the advancement of MHRA methodologies reflects a growing recognition of the need for comprehensive, integrative approaches to climate risk assessment and management [288,291,561]. By leveraging diverse data sources, incorporating innovative modelling techniques, and fostering stakeholder collaboration, these methodologies aim to enhance the resilience of coastal cities to the increasing challenges posed by climate change [114,118,317]. In this study, we employ a MHRA methodology to evaluate the climate-related risks facing Benidorm, a coastal city in Spain. By integrating remote sensing data with socio-economic indicators and historical climate records, we aim to provide a comprehensive assessment of the climate-related hazards, exposure and vulnerabilities of the city. The use of digital technologies such as GIS, Python, and high-resolution DEMs enables us to offer detailed insights into the impacts of climate change on the coastal and urban environments of Benidorm. This approach will not only enhance our understanding of local risks but also contribute to the broader discourse on urban resilience and climate adaptation.

There has been a rise of innovative concepts in climate resilience, such as MHRA, EBA, NBS, digital twins, citizen science, and CCLL [116,123,191,192,562]. Specifically, the CCLL concept represents an expansion of the Living Labs model, offering a comprehensive framework for addressing the unique challenges faced by coastal cities, including sea-level rise, coastal erosion, and extreme climate events [119]. This approach fosters collaborative innovation among various stakeholders in both physical and virtual settings. In response to these challenges, Benidorm has established a CCLL through the SCORE project [101,563].

Benidorm, located on the Mediterranean coast of Spain, presents a compelling case study for examining climate-related hazards due to its unique combination of geographic and socio-economic factors [211,564]. The city is characterized by a densely populated urban area, a thriving tourism industry, and significant coastal infrastructure, all of which are vulnerable to climate impacts such as sea-level rise, storm surges, and extreme weather events [565,566]. Additionally, the proactive stance of Benidorm on climate adaptation, exemplified by the establishment of the CCLL through its participation in the EU-funded SCORE project, makes it an ideal candidate for this study [101]. In this context, remote sensing devices play a pivotal role in providing real-time data and long-term environmental monitoring. These labs are designed to foster innovation and collaboration among various stakeholders, including scientists, policymakers, and local communities. By leveraging remote sensing technologies, CCLLs can enhance their ability to monitor environmental changes, assess risks, and develop adaptive strategies that are informed by accurate and up-to-date information. The efforts of the city of Benidorm to implement and test innovative resilience strategies will provide valuable insights for other coastal cities facing similar challenges [563].

Besides, despite the wealth of research on individual climate-related hazards in coastal cities, there is a notable gap in studies that integrate these hazards within a comprehensive assessment framework [27,82,99,135]. Existing literature often focuses on singular aspects, such as the hydrodynamic modelling of storm surges or the socio-economic impacts of coastal erosion [72,292,567]. However, the interconnected nature of climate hazards necessitates a holistic approach to accurately assess risks and inform adaptation strategies [26,107]. This research aims to bridge this gap by employing a novel MHRA methodology that synthesizes various hazard data into a unified risk profile for Benidorm. The MHRA methodology employed in this study represents an advanced approach to climate risk assessment, integrating multiple data sources and analytical techniques to provide a comprehensive

understanding of hazards. This methodology involves the systematic collection and analysis of climatic, geographic, and socio-economic data, combined with advanced modelling tools such as GIS and hydrodynamic simulations. By evaluating the combined effects of multiple hazards, MHRA offers a nuanced perspective on risk that is essential for developing effective adaptation strategies. This approach is particularly valuable in the context of coastal cities, where overlapping risks from sea-level rise, extreme weather, and human activities converge.

While there is a substantial body of research addressing individual climate-related hazards in Benidorm, such as increased storm intensity, flooding, and erosion [205–207,209,402,403], there is a noticeable gap in studies that integrate these various hazards within a comprehensive framework. This paper aims to fill this gap. It builds on the existing foundation of scientific and legislative understanding, alongside a record of historical climatic events. Utilizing an innovative MHRA methodology that includes a collaborative partnership with the city of Benidorm, this study seeks to dissect the multifaceted impact of climate change on the city. This paper also aims to validate the MHRA methodology employed by comparing the results of its application in Benidorm with existing studies. Additionally, it seeks to contribute standardized and systematic results on Benidorm within a European context. In this manner, this study not only assesses the multifaceted impact of climate change on Benidorm but also provides a robust framework that can be applied to other coastal cities, enhancing the overall resilience of urban environments against climate-related hazards. The ultimate objective is for this methodology to become a powerful decision-making tool, enabling Public Administrations to propose advanced and holistic solutions to enhance the resilience of Benidorm against the mounting challenges posed by climate change.

8.2. Materials and methods

Benidorm, located on the Mediterranean coast of Spain, is the focal point of this study (Figure 8.1). The city is known for its high-density urban planning and high-rise buildings, developed in the 1960s during the rise of mass tourism, which remains its main economic activity [568]. The success of Benidorm is partly due to its two beaches, Poniente and Levante, characterized by fine sediment and averaging over 2 km in length and 50 m in width [205]). These beaches are part of a closed coastal system forming a promontory cove, with abundant Posidonia oceanica seagrass meadows on sandy and rocky seabed [569]. The area is in a microtidal zone where storm surges are more significant than astronomical tides [563]. Ravines in the city flow into these beaches, and extensive urbanization has altered the hydrological and hydraulic behaviour of the basins, increasing risks [563].

Benidorm is particularly susceptible to climate impacts such as sea-level rise, storm surges, and extreme weather events. These phenomena can significantly damage coastal infrastructure, including street furniture and the seafront. These natural hazards and their consequences have been recorded over time [570]. Its proactive approach to climate adaptation, demonstrated by its participation in the SCORE project and the establishment of a CCLL, makes Benidorm an ideal setting to apply and validate the MHRA methodology developed in Laino and Iglesias (2024b).

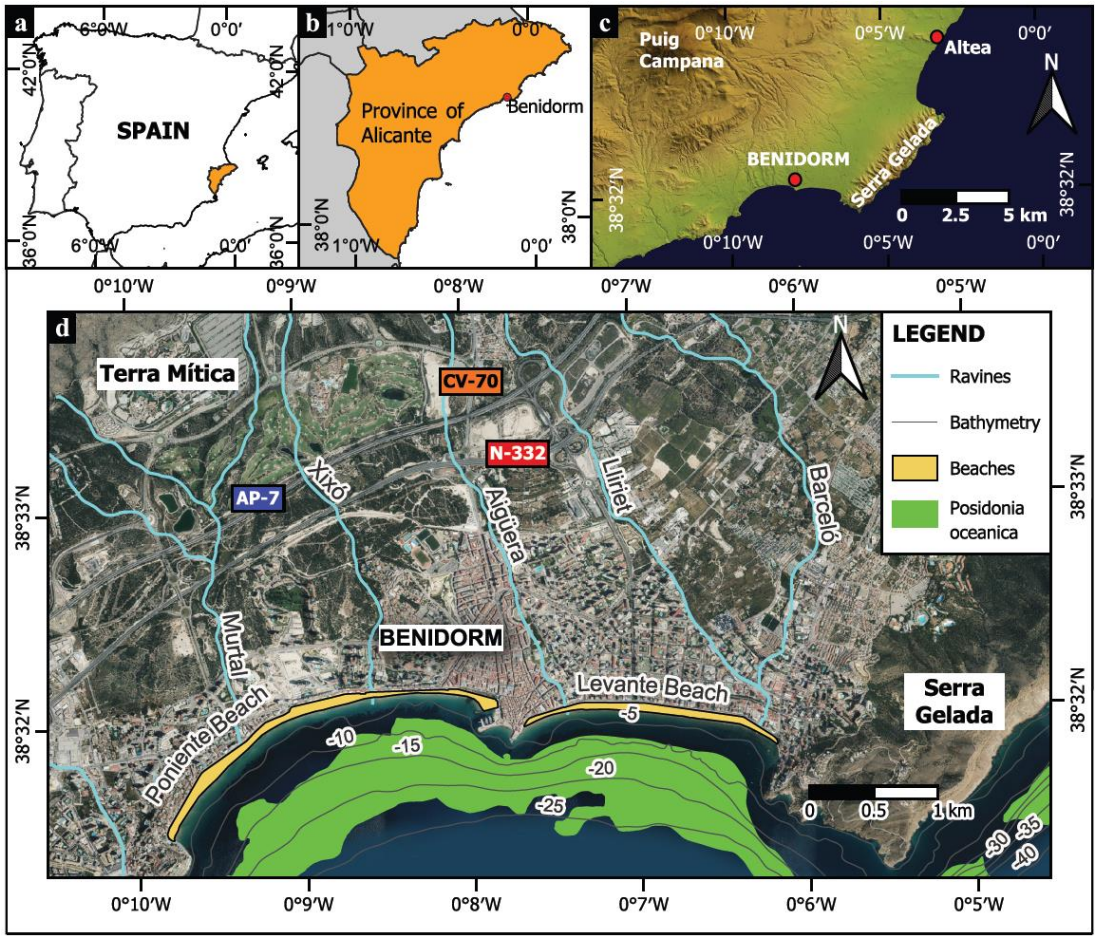


Figure 8.1. (a) Study area located in Spain, (b) location in the province of Alicante, (c) detail of the study area, and (d) locations of Poniente Beach, Levante Beach, and the ravines within Benidorm

The MHRA methodology represents an advanced, systematic approach to assessing climate-related hazards. For this assessment, the spatial extents of Benidorm were derived from the Urban Atlas dataset [486], which provides high-resolution satellite imagery for detailed LULC analysis. The Urban Atlas dataset utilizes Very High Resolution (VHR) satellite imagery, which offers high-resolution optical images suitable for urban planning and environmental monitoring. Besides, a representative point for the city was identified using OSM data and the geopy library in Python. These coordinates were used to calculate various hazard indicators.

Comprehensive data on climatic, geographic, and socio-economic factors were initially collected, including historical climate data, GIS data, and socio-economic

indicators relevant to Benidorm and comparable to other European coastal cities. These indicators were categorized under the risk parameters of hazard, exposure, and vulnerability, where vulnerability encompasses sensitivity and adaptive capacity [36].

The remote sensing data were utilized to derive various hazard indicators, such as mean sea-level rise (MSLR), storm surge, significant wave height (Hs), AHHT, coastal flooding extents, coastal erosion, river flooding extents, heavy precipitation events, droughts, extreme high and low temperatures, heatwaves, cold spells, strong winds, and landslides. The ERA5 products from C3S CDS provide high-resolution climate reanalysis data, offering hourly estimates of a large number of atmospheric, land, and oceanic climate variables at a spatial resolution of circa 31 km. Details on these indicators, including their spatiotemporal resolution, coverage, and source references, are already provided in Table 6.2, with further information available in Laino and Iglesias (2024a).

The indicators of exposure and vulnerability encompass various measures, including the LECZ, LULC, population and socio-economic factors, and the presence of critical infrastructure elements (Table 8.1). The LECZ, defined as land contiguous to the sea and below 10 meters in elevation, is highly susceptible to sea-level rise, storm surges, and coastal flooding [571]. The LECZ was calculated using GIS software and the MERIT DEM dataset, expressed as a percentage of the total city area [445,454]. The MERIT DEM dataset is generated using satellite radar data from missions such as the Shuttle Radar Topography Mission (SRTM) and the Advanced Land Observing Satellite (ALOS).

The LULC categories from Urban Atlas were reclassified into residential areas, critical infrastructure, transportation infrastructure, agricultural areas, open spaces, natural vegetation, wetlands, water bodies, and other miscellaneous uses as per Laino and Iglesias (2024b). These area calculations were performed for both the entire study area and the LECZ, expressed as percentages to create standardized indicators for cross-

city comparisons. The socio-economic indicators, derived from Eurostat data, include population density, percentages of the population under 5 and over 65 years old, GDP per capita, rates of economically active population and unemployment, and levels of high educational attainment. The presence and distribution of power plants, airports, ports, and railway stations within Benidorm were mapped and analysed using open-source geospatial data from OpenStreetMap via Overpass Turbo.

Table 8.1. Summary of exposure and vulnerability indicators, including their units and corresponding parameter of risk.

Indicator	**Units**	**Parameter of risk**
Area	km^2	Exposure
Population density	inhabitants/km^2	Exposure
Residential area	% of total area	Exposure
Open areas	% of total area	Vulnerability (adaptive capacity)
Critical infrastructure area	% of total area	Exposure
Transportation infrastructure area	% of total area	Exposure
Agriculture area	% of total area	Exposure
Forest area	% of total area	Exposure
Wetland area	% of total area	Exposure
Presence of power plant	Yes/No	Vulnerability (sensitivity)
Presence of airport	Yes/No	Vulnerability (sensitivity)
Presence of port	Yes/No	Vulnerability (sensitivity)
Presence of railway	Yes/No	Vulnerability (sensitivity)
LECZ area	% of total area	Exposure
Residential area (LECZ)	% of LECZ area	Exposure
Open areas (LECZ)	% of LECZ area	Vulnerability (adaptive capacity)
Critical infrastructure area (LECZ)	% of LECZ area	Exposure
Transportation infrastructure area (LECZ)	% of LECZ area	Exposure
Agriculture area (LECZ)	% of LECZ area	Exposure
Forest area (LECZ)	% of LECZ area	Exposure
Wetland area (LEC)	% of LECZ area	Exposure
Presence of power plant (LECZ)	Yes/No	Vulnerability (sensitivity)
Presence of airport (LECZ)	Yes/No	Vulnerability (sensitivity)
Presence of port (LECZ)	Yes/No	Vulnerability (sensitivity)

Presence of railway station (LECZ)	Yes/No	Vulnerability (sensitivity)
Population over 65 years old	% of total population	Vulnerability (sensitivity)
Population under 5 years old	% of total population	Vulnerability (sensitivity)
Unemployment	% of total population	Vulnerability (sensitivity)
GDP per capita	% of total population	Vulnerability (adaptive capacity)
Economically active population	% of total population	Vulnerability (adaptive capacity)
Higher education	% of total population	Vulnerability (adaptive capacity)

Risk was calculated following the approach established in Laino and Iglesias (2024b), aligning with the IPCC paradigm of risk as a function of hazard, exposure, and vulnerability. The indicators were normalized between $[0, 1]$ using a linear scale transformation of the min-max method [497]. The extremities of the interpolated interval are determined by the maximum and minimum observed values for each indicator across a series of benchmarking cities: Bergen (Norway), Cork (Ireland), Klaipeda (Lithuania), La Spezia (Italy), Varna (Bulgaria), and Viana do Castelo (Portugal). These cities represent diverse climatic, socioeconomic conditions, and varied urban settings within Europe. For the indicators measuring the presence of critical infrastructure elements, scores of 0 or 1 were assigned to indicate absence or presence, respectively.

The normalization of the indicators into scores, S_i, was accomplished as per:

$$S_i = \frac{(S_{i,max} - S_{i,min})(I_i - I_{i,min})}{I_{i,max} - I_{i,min}} + S_{i,min}\,, \qquad (4)$$

where I_i represents the raw value of the i-th indicator for Benidorm, with $i = 1, 2, \dots, N$, (where N is the total number of indicators), $I_{i,min}$ and $I_{i,max}$ are the minimum and maximum values recorded for the i-th indicator across the benchmarking cities, and $S_{i,min}$ and $S_{i,max}$ are equal to 0 and 1, respectively.

The indicators were categorized under the parameters of hazard, exposure, and vulnerability to calculate a partial score for each parameter,

$$A_{C_k} = \frac{\sum_{i \in C_k} S_i}{N_{C_k}}, \quad (5)$$

wherein indicators for each category are equally weighted and aggregated, a common practice [112,302,314,323,355]. N_{C_k} denotes the number of indicators within the risk category C_k (hazard, exposure and vulnerability), and thus $k = 1, 2, 3$. The indicators of adaptive capacity were subtracted from 1, as they have a reverse effect on vulnerability.

The partial scores were integrated into the EMI score of risk through multiplicative aggregation:

$$EMI = \prod_k A_{C_k}, \quad (6)$$

where EMI denotes the risk for Benidorm.

This methodology enables contextualizing the results for Benidorm with data from other European coastal cities. By benchmarking the indicators for Benidorm against those from these cities, the study highlights unique vulnerabilities and strengths, providing a more comprehensive understanding of the risk profile of Benidorm within a broader European context.

The findings from the MHRA methodology were further refined and validated through local knowledge obtained via the Benidorm CCLL. The collaborative process involved reviewing and synthesizing the relevant local documents and legislative frameworks to ensure the results aligned with existing policies and regulations, especially with the Climate Change Adaptation Plan (CCAP) of Benidorm. This step was crucial for integrating the MHRA methodology within the local context and ensuring its practical applicability. A comprehensive record of historical extreme

weather events in Benidorm was also compiled. These historical data provided valuable context and served to further validate the risk indicators calculated through the MHRA methodology. By comparing past events with the indicators, the study could assess the accuracy and relevance of the methodology.

Furthermore, existing scientific publications related to climate change impacts in Benidorm were reviewed. This included examining previous research findings and methodologies to incorporate the latest scientific knowledge and ensure that the study built upon a solid foundation of existing work. Intangible knowledge generated through interactions with local experts and stakeholders also played a significant role. Insights gained from CCLL workshops and activities were instrumental in refining the assessment process, allowing for a more granular disaggregation of the study at lower levels than typically possible, and providing a detailed and context-specific understanding of the risks.

The application of this comprehensive and collaborative framework aimed to validate the MHRA methodology proposed by Laino and Iglesias (2024b). By comparing the results of its application in Benidorm with those from other European cities, the study sought to demonstrate the robustness and utility of the methodology. Additionally, the standardized and systematic results contribute valuable insights into the specific climate-related risks for Benidorm, enhancing the overall resilience of the city against such hazards.

8.3. Results

8.3.1. Normalisation of indicators and scores of risk

The risk index EMI and its partial scores for Benidorm are compared with other European coastal cities in Figure 8.2. A cubic root transformation was applied to the calculated risk values to enhance interpretability. The findings indicate a low risk

profile for Benidorm, with all risk parameters ranging between 20-30 points. This contrasts with higher values observed in the other cities, particularly in vulnerability scores, where Bergen scores 75.1 points compared to 28.5 points for Benidorm. Due to the nascent stage of the MHRA methodology, these results should be interpreted cautiously. A key aim of this study is to validate these results, which are discussed subsequently.

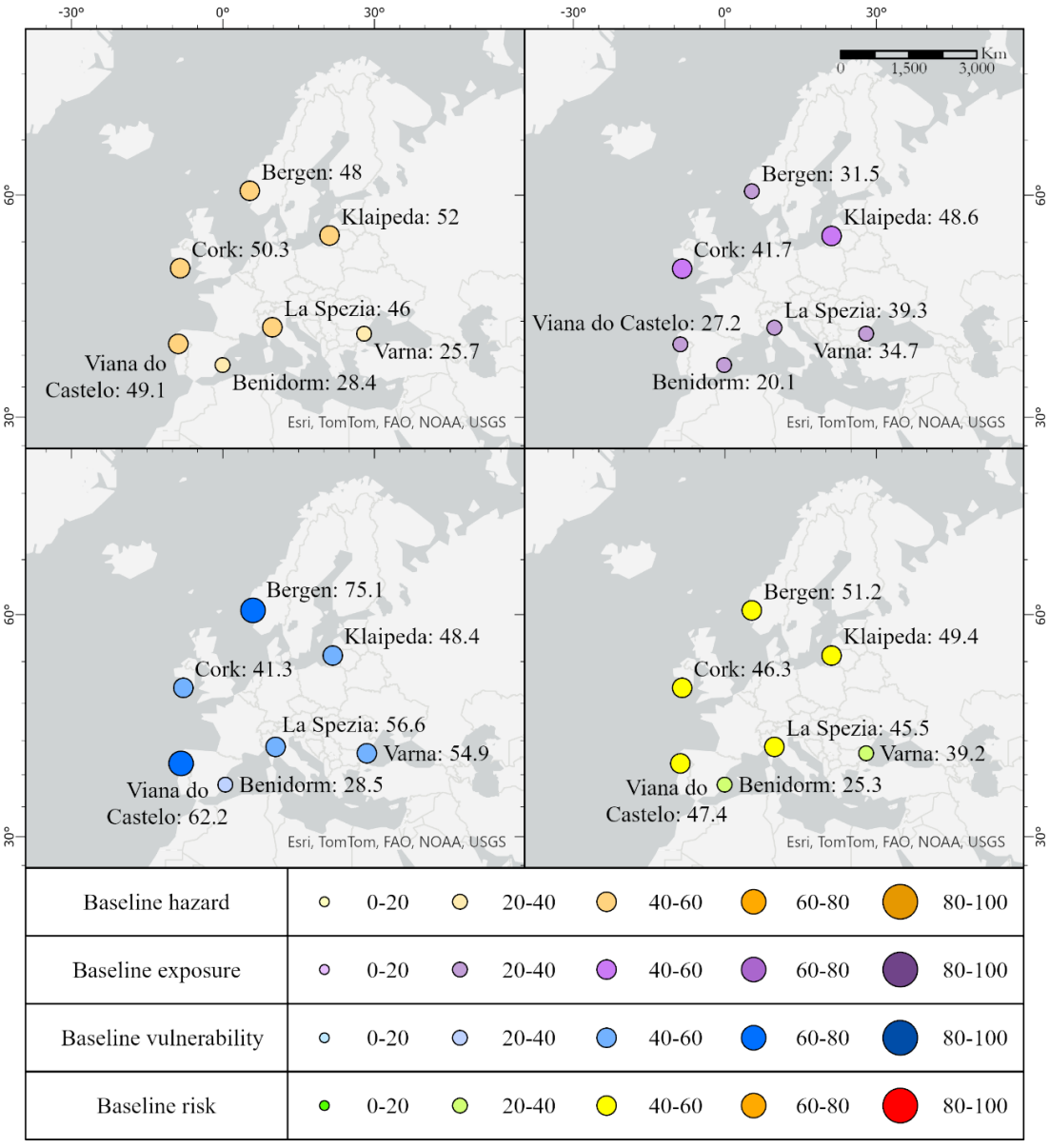


Figure 8.2. Scores of hazard, exposure, vulnerability and risk for diverse European coastal cities, including Benidorm, Spain

The scores are based on the indicators presented in Table 8.2, which includes the minimum and maximum thresholds derived from the assessment of other European coastal cities, providing a comparative context for the results for Benidorm. These cities were selected to represent diverse climatic and socioeconomic conditions across Europe, ensuring a comprehensive benchmarking process. Based on these thresholds, results have been normalized on a scale from 0 to 1. The risk profile of Benidorm is characterized by relatively high values in indicators such as extreme high temperature thresholds, natural vegetation areas, unemployment, and economically active population.

These normalized results are thematically grouped in Figure 8.3 and will be critically discussed hereinafter. Among the coastal hazard indicators, the MSLR rate is particularly notable, while other hazards register low values within the European context. This is logical given the Mediterranean location of Benidorm, which generally experiences less severe coastal hazards compared to the Atlantic or North Sea regions. Regarding land hazards, indicators for heatwaves and extreme high temperatures are elevated, consistent with the position of Benidorm in southern Europe, which is prone to such extreme weather conditions.

Table 8.2. Results of the indicator-based assessment for Benidorm, Spain, including thresholding and scoring after min-max normalization to a range of 0-1.

Indicator	**Value**	**Lower threshold**	**Upper threshold**	**Score (0-1)**
Mean sea-level rate (mm/year)	3.4	0	6	0.57
Coastline length undergoing erosion (%)	0	0	90	0
Significant wave height (m)	2.3	1	8	0.19
Surge level (m)	0.5	0.3	2	0.12
Annual highest high tide (m)	0.1	0.1	3	0
Landslide-prone area (%)	17.8	0	66.7	0.27
Land flooding area (%)	0	0	10	0
Strong winds frequency (event/year)	0.1	0	2.5	0.04
Heavy rainfall frequency (day/year)	2.7	0	50	0.05

Extreme high temperature threshold (°C)	34.4	24	38.2	0.73
Extreme low temperature threshold (°C)	-1.8	3	-20	0.21
Heatwave frequency (day/year)	2.4	0	3.6	0.67
Cold spell frequency (day/year)	0.5	0.3	2.5	0.09
Drought frequency (month/year)	1.6	1.5	2.3	0.13
Area (km^2)	38.6	25	650	0.02
LECZ area (%)	3	2.5	50	0.01
Population density (inhabitant/km^2)	4,062.8	250	4,000	1
Residential area (%)	16.1	10	40	0.2
Open areas (%)	9.4	0	15	0.63
Critical infrastructure area (%)	9.3	2	30	0.26
Transportation infrastructure area (%)	6	3	15	0.25
Agriculture area (%)	10.4	10	15	0.08
Natural vegetation area (%)	45.8	0	50	0.92
Wetland area (%)	0	0	10	0
Presence of power plant (0 or 1)	0	0	1	0
Presence of airport (0 or 1)	0	0	1	0
Presence of port (0 or 1)	0	0	1	0
Presence of railway station (0 or 1)	1	0	1	1
Residential area (LECZ) (%)	20.5	10	40	0.35
Open areas (LECZ) (%)	40.9	0	15	1
Critical infrastructure area (LECZ) (%)	7.4	2	30	0.19
Transportation infrastructure area (LECZ) (%)	3.9	3	15	0.08
Agriculture area (LECZ) (%)	4.8	10	15	0
Forest area (LECZ) (%)	7.3	0	30	0.24
Wetland area (LECZ) (%)	0	0	30	0
Presence of power plant (LECZ) (0 or 1)	0	0	1	0
Presence of airport (LECZ) (0 or 1)	0	0	1	0
Presence of port (LECZ) (0 or 1)	0	0	1	0
Presence of railway station (LECZ) (0 or 1)	0	0	1	0
Population over 65 years old (%) (2022)	19.4	14.5	26.5	0.41
Population under 5 years old (%) (2022)	3.5	2.6	6.4	0.24
Unemployment (%) (2020)	8.91	0.9	12	0.72
GDP per capita (2021)	19,700	8,000	150,000	0.08
Economically active population (%) (2020)	48.7	25.8	55	0.72
Higher education (%) (2020)	14.6	5	30	0.38

8.3.2. Land Use and Land Cover

In terms of land use, Benidorm exhibits high indicators for natural vegetation areas. Despite the extensive urbanization and dense population, significant green spaces exist within its municipal boundaries, such as the Serra Gelada Natural Park and the areas surrounding Puig Campana. The area of open spaces is significantly greater than the established thresholds, primarily due to the small size of the LECZ, which is predominantly occupied by beaches. Consequently, residential land use is not as predominant as in other cities, such as Cork, Ireland. Similarly, the percentage of land allocated to critical infrastructure and transportation is relatively low. Unlike Viana do Castelo, Portugal, Benidorm does not allocate substantial land to agriculture, nor does it have extensive wetlands like Varna, Bulgaria, or Piran, Slovenia. In terms of critical infrastructure, Benidorm lacks major regional or national ports, airports, or power stations. The city does have a regional railway, but it does not extend into the LECZ, limiting its impact on the coastal area.

The presence of significant green spaces within Benidorm is noteworthy, given the dense urbanization of the city. These green spaces, including natural parks and open areas, contribute to the overall resilience of the city by providing ecological benefits and recreational opportunities. The Serra Gelada Natural Park, in particular, is a critical asset for biodiversity conservation and serves as a natural barrier against coastal erosion and other environmental hazards. The urban planning of Benidorm has managed to balance development with the preservation of natural areas, which is reflected in its land use indicators. The limited presence of critical infrastructure in the LECZ reduces the potential impact of coastal hazards on essential services and facilities. However, this also highlights a potential vulnerability in terms of connectivity and accessibility, as the transport infrastructure of the city is not as extensive as in other European coastal cities.

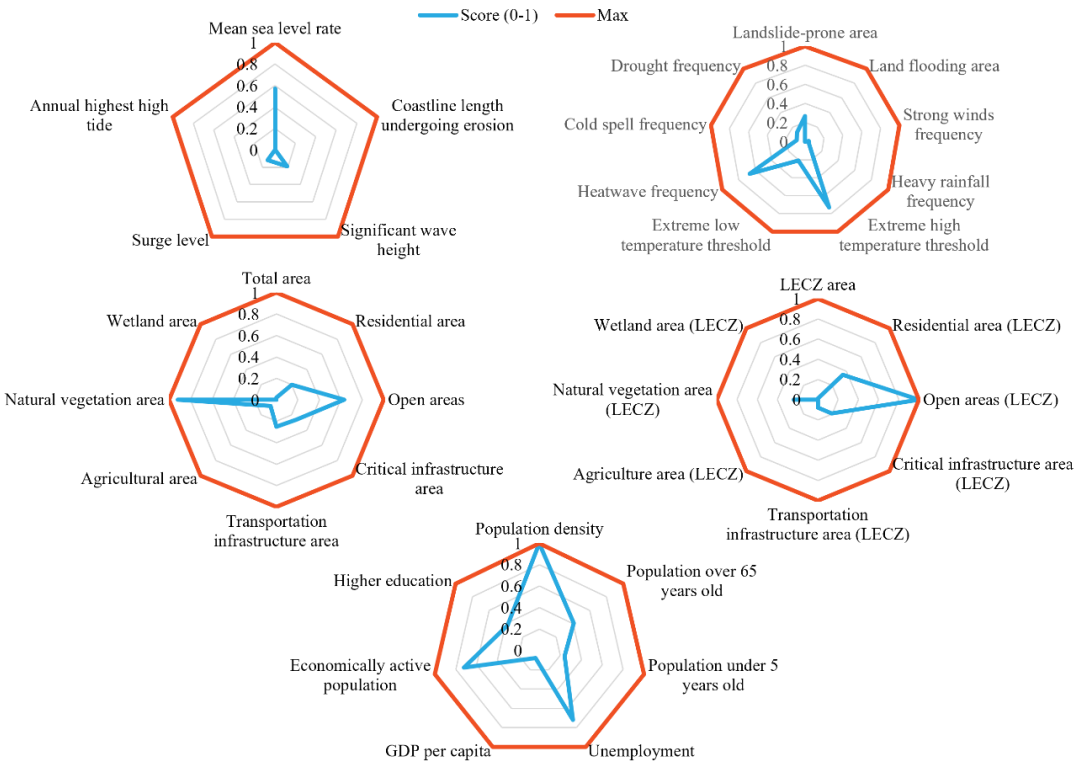


Figure 8.3. Normalisation of risk indicators based on thresholds from the assessment of diverse European coastal cities for Benidorm, Spain, as per Laino and Iglesias (2024b).

8.3.3. Coastal hazards

The results concerning coastal flooding and the LECZ indicate that coastal hazards primarily impact the beaches and do not extend far inland in Benidorm (Figure 8.4). This contrasts with other European coastal cities, where these hazards tend to have a more extensive impact (Laino and Iglesias, 2024a, 2024b). In Benidorm, the coastal flooding areas identified in the ECFAS Pan-EU Flood Catalogue cover only 0.1% of the total municipal area, located at the eastern end of Poniente Beach. The LECZ, representing 3% of the total area, encompasses small coves under Serra Gelada and the Levante and Poniente beaches, extending into the highly urbanized promenade area. While the Eurosion dataset does not indicate significant coastal erosion in Benidorm, recent evidence suggests otherwise [205]. Additionally, the seabed in this

region, mostly composed of unconsolidated very fine-grained sediments such as sand, is part of a protected natural area, which increases its sensitivity.

In comparison, the results for other coastal cities in the study—Bergen, Cork, Klaipeda, La Spezia, Varna, and Viana do Castelo—reveal greater variability in both LECZ and coastal erosion values. Specifically, the LECZ values for these cities are 14.7%, 15.6%, 1.8%, 3.8%, 47.6%, and 8.0%, respectively. The coastal flooding zones account for 0.2%, 0.0%, 2.4%, 0.6%, 5.2%, and 3.7% of the total area for each city, respectively. In terms of coastal erosion, the percentages of coastline affected are 0.0%, 0.0%, 12.7%, 0.0%, 5.2%, and 88.3%, respectively [100]. These results highlight significant differences in LECZ and coastal erosion values across cities, with Benidorm showing comparatively lower values for both indicators. Coastal flooding areas also generally exhibit low percentages, with Benidorm standing out again for its minimal impact. The LULC distribution for these six cities has been detailed in previous research (Laino and Iglesias, 2024b), while this study focuses on describing the LULC of Benidorm.

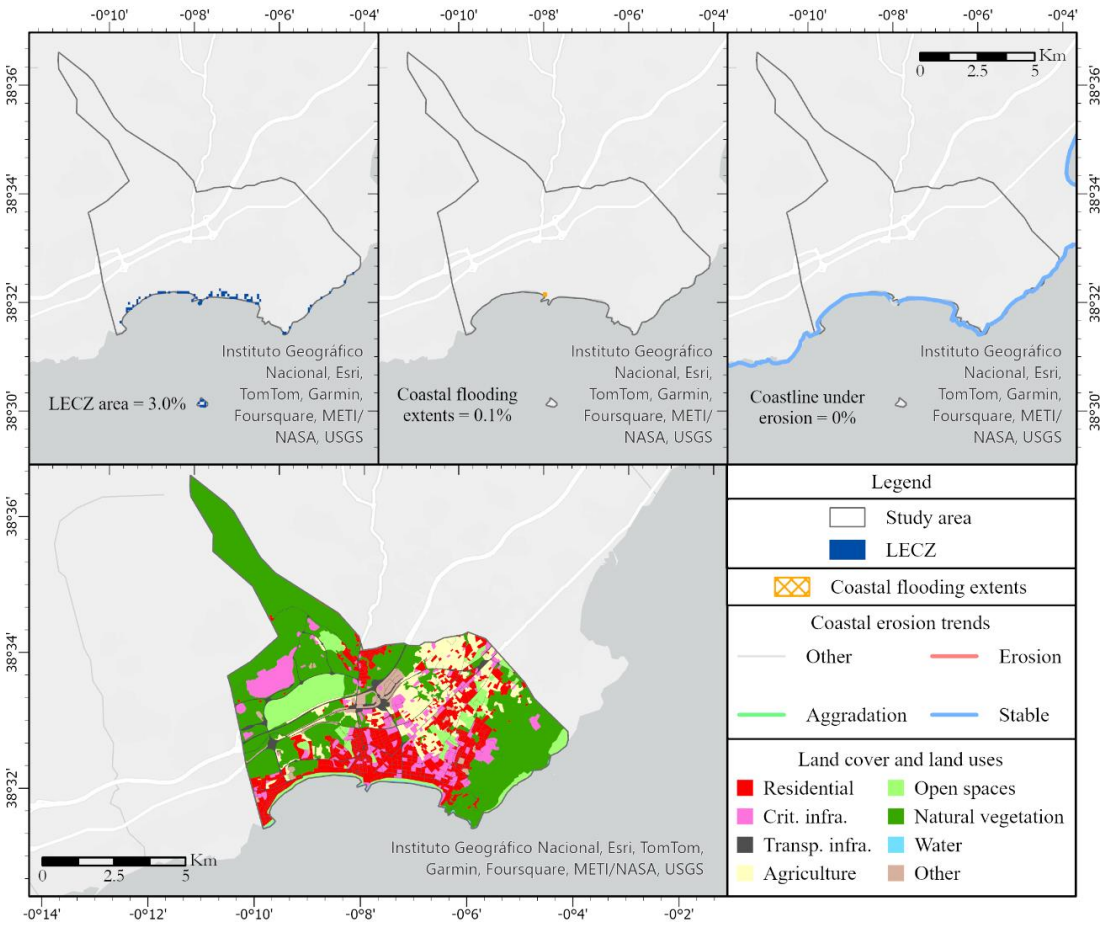


Figure 8.4. Low-elevation coastal zone, coastal flooding extents, coastal erosion trends and land use of Benidorm, Spain.

Since 1980, episodes of coastal erosion have been frequent, typically affecting the beaches and the promenade, as shown in Table 8.3. The significant importance of the beaches as a tourist destination elevates the vulnerability of Benidorm to these hazards. The economic dependence of the city on tourism means that even minor erosion events can have substantial economic impacts. Additionally, the local government has implemented various mitigation measures, such as beach nourishment and coastal defences, to protect these vital areas. However, these measures have varying degrees of success and longevity, requiring continuous monitoring and adaptation.

Table 8.3. Past coastal flooding and coastal erosion events in Benidorm, as provided by Benidorm CCLL.

Date	Short description
27/12/1980	The sky-cable platform disappears; two Red Cross boats are rescued in Rincón de Loix; the wind knocks down two ice cream kiosks; the waves flood a locutorio del Rincón; the waves flood the road between Torrechó and Pachá; the beach is flooded and covered with dirt; the furniture disappears; the waves rip out the sewage pipes.
02/01/1982	Poniente Beach is filled with dead remains of Posidonia oceanica.
04/10/1984	Evicted bathers at the risk of being swept away by the huge waves that break out in 15 minutes in Poniente Beach.
21/02/1985	Important loss of sand in the Torrechó; undermining the foundations of City Hall.
14/11/1985	Floods in Avda. de la Marina Española; damage to beach furniture; a freighter takes refuge in the bay.
27/09/1986	Beach flooding: the rupture of a pipe causes discharges of sewage into the sea.
03/11/1987	Flooding of the beach and damage to the foundations of a Telefónica booth.
17/10/1988	Misalignment of the buoys in the bathing area of Levante Beach. Undermining of foundations of the promenade in Fontanelles (Poniente Beach); damage to the promenade railing and beach furniture; undermining of the foundations of the promenade in La Cala; a British sailboat runs aground in Fontanelles and suffers damage.
04/09/1989	The beach furniture is removed so that the waves do not wash it away; damage to the retaining wall of Avda. de Alcoy and storm drain in Levante Beach. Damage to street furniture in La Cala (Poniente Beach); the waves exceed the beach and cause damage to the road; significant loss of sand in Fontanelles (1 km of beach disappears); flooding of Avda. de la Marina Española; large deposit of sand accumulated by the sea next to the promenade of La Cala.
20/02/1992	New profile of the beach, 1 km of «llosar» and a pipe in the cable-ski area are exposed (Levante Beach). Important loss of sand in the Cala (Poniente Beach); pile of sand near the port.
06/01/1994	Significant loss of sand (sections from 30 to 8-10 m wide); the "llosar" is exposed; damage to street furniture.
22/09/1994	Damage to the leisure platform.
11/11/1996	Beach flooding of Levante and Poniente beaches; significant loss of sand in the Torrechó; damage to beach furniture, which is thrown onto the promenade like projectiles.
08/04/1997	The waves come up to the boardwalk; beach furniture removed; significant loss of sand in the Torrechó.
30/09/1997	Moderate damage to the boardwalk; sand losses, the pipes are left in the air.

06/11/1997	A large portion of Levante beach is flooded, damage to accesses and beach facilities. The waves reach the wall of the Paseo de Colón in Poniente Beach; an area is flooded; beach furniture removed.
10/11/2001	Damage to disabled access.
30/10/2003	Important loss of sands; damage to furniture on the promenade.
27/03/2004	Accumulation of tons of dead remains of Posidonia.
03/12/2004	Losses for the tourism sector; visitors shorten their stay during the bridge of the Constitution.
19/01/2020	The sea-level rises half a meter, strong waves in the Torrejó area and the waves break directly against the promenade. Cleaning services have had to remove debris from walkways and beach furniture.

Water level indicators in Benidorm are not particularly high (Figure 8.5), which is typical for the Mediterranean. However, as indicated in the CCAP, these values are sufficient to cause flooding episodes. The AHHT has a median value of 0.109 m. The significant wave height for the median between the 90th and 100th percentiles range from 1.9 to 3.0 m, with a median of 2.365 m. The surge contribution is approximately 0.46-0.48 m, with a median of 0.47 m. This aligns with the coastal flooding event on January 19th, 2020, when the sea level rose by half a meter. In a worst-case scenario, where these three contributions coincide, extreme sea-level values between 2.5 and 3.6 m could occur, primarily driven by wave height.

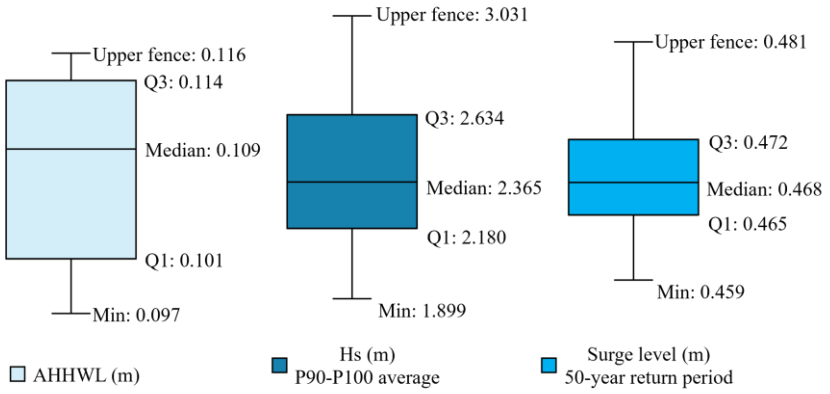


Figure 8.5. Indicators of extreme water levels, including annual highest high-water level (AHHWL), significant wave height (Hs) and surge level for Benidorm, Spain.

8.3.4. Temperature-related hazards

Heatwave and cold spell events are defined as those exceeding the temperature threshold for three consecutive days or more – the 99th percentile of the daily maximum temperature series between 1981-2000 for heatwaves (34.4 °C), and the 1st percentile of the daily minimum temperature series between 1981-2000 for cold spells (-1.8°C). Figure 8.6 shows the variation in heatwave and cold spell events between 1981-2020, indicating the total days of each event per year. The heatwave data do not reveal clear trends, except that heatwaves were frequent between 1984-1994 and from 2015 to the present. Conversely, no cold spell has occurred since 1988, suggesting a shift towards a warmer climate. The compilation of past extreme climate events does not include heatwaves or cold spells. However, the Benidorm CCAP examines the maximum and minimum average temperatures for the quinquennia from 2000-2020, based on data from the Altea meteorological station, part of the IVIA Network of the Generalitat Valenciana, located 10 km from the study area and with records from 1999 to the present. The conclusions indicate a significant increase in minimum temperatures during the warm months, associated with the warming of the Mediterranean Sea. No significant changes are observed for the other months, with stable or slightly increasing maximum temperatures during the summer and slightly increasing maximum temperatures during the winter months.

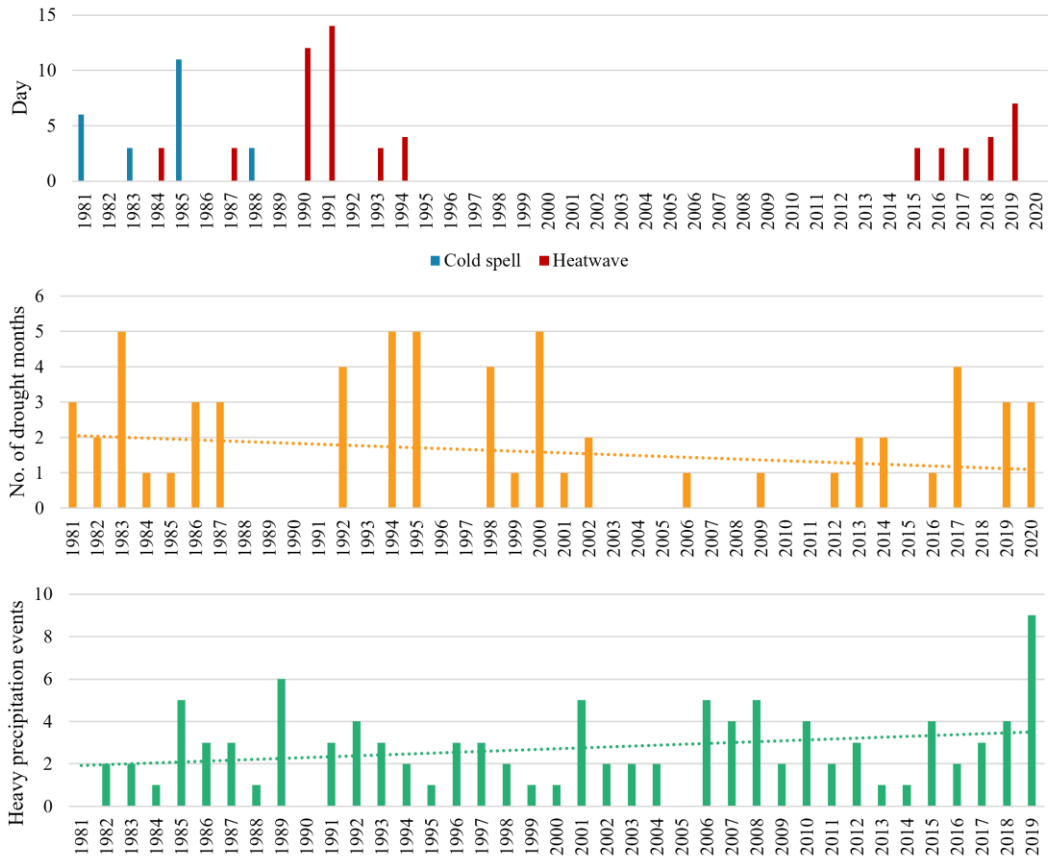


Figure 8.6. Yearly evolution of cold spell and heatwave days, drought months and heavy precipitation events for Benidorm, Spain.

8.3.5. Droughts and heavy precipitation events

The number of drought months shows a decreasing trend between 1981-2020, while the number of extreme precipitation events has an increasing trend between 1981-2019. In 2019, there was a historic high of nine extreme precipitation events, surpassing the previous high of six in 1989. These results can suggest that the climate in Benidorm has become wetter, with fewer droughts and more extreme rainfall events. However, these data do not rule out the possibility that the precipitation pattern has become more extreme, with the annual precipitation volume potentially remaining the same but concentrated in fewer events.

Records of heavy precipitation or pluvial flooding events begin with an event on November 3rd, 2006, where 89 l/m² of precipitation fell in less than 12 hours. Since

then, data include five pluvial flooding events and another heavy precipitation event, all described in Table 8.4. The extreme nature of these events is reflected in figures such as 74 mm/day on November 1st, 2015, or 177 mm over four days in April 2019. These events cause significant damage to buildings, infrastructure, beaches, and urban furniture, traffic disruptions, and even loss of life.

The adaptation plan also highlights the importance of ongoing monitoring and community engagement in mitigating the impacts of these climatic events. Local authorities have implemented measures such as improved drainage systems, early warning systems, and public awareness campaigns to enhance preparedness and response. These initiatives are crucial in reducing the vulnerability of the population and infrastructure to extreme weather events.

Table 8.4. Heavy precipitation events leading to flooding in Benidorm, as collected by Benidorm CCLL.

Date	**Short description**
03/11/2006	89 litres/m2 of precipitation fell in less than 12 hours.
13/10/2007	Two small hotels were evicted as a result of flooding.
21/10/2011	Two British tourists killed and five injured in a flood in Cala Finestrat. The water swept people and vehicles.
01/11/2015	The town has collected a total of 74 litres per square meter in the La Cala area. The rain damages an access staircase from the Plaza de la Senyoría to the Mal Pas beach and causes traffic cuts on Toledo Street at its intersection with Bernat de Sarriá and on El Murtal avenue.
18/12/2016	A deceased by a flood in the street that ends in Cala de Finestrat. Heavy rains also forced the evacuation of some 89 caravans from a campsite in the Rincón de Loix area.
17/01/2017	Various municipal buildings and facilities, public lighting, trees, El Tossal de La Cala, pumping stations, beaches and the Rincón de Loix health centre were affected.
19/04/2019	Benidorm collects 177 litres per square meter in four days. The rains have caused several potholes in the road, the occasional closure of traffic on some streets due to accumulation of water, the fall of some trees, and damage to one of the perimeter fences of the 'Antonio López' football fields.

8.3.6. Land flooding

The indicator for river flooding areas [447] shows no significant results for Benidorm. However, land flooding in Benidorm is characterized by the sudden overflow of several ravines that traverse the municipality from north to south during intense torrential rain events [470]. Therefore, land flooding is largely driven by these heavy precipitation events, which lead to flooding at the outlets of the ravines. For this reason, a map based on the findings from the regional flood study PATRICOVA, which provides a more detailed analysis of land flooding hazards, has been included (Figure 8.7). This map shows the envelope of different land flooding-prone areas, including the extent of the 100-year return period flood event with a water depth of 0.8 m, the 500-year return period flood event with the same depth, and runoff areas. The land flooding hazard is concentrated in the downstream sections of the Lliret-Derramador and Barcelo ravines, which are densely populated. Critical elements within this area include hotels, campsites, traffic infrastructure, green areas, residential and commercial buildings, and the Levante Beach and its associated services. Additionally, there is the potential for compound flooding in this area due to the interaction of land and coastal flooding.

These results indicate that the land flooding indicators developed in Laino and Iglesias (2024) are not capable of showing the affected areas by land flooding under the climatic conditions of Benidorm. However, the heavy precipitation events indicator can provide some insight. It has been observed that these events are frequent in Benidorm and show an increasing trend. In Mediterranean coastal cities like Benidorm, without permanent watercourses, it is essential to consider the possibility of flooding due to ravine overflows during torrential rain events. The occurrence of such events can be indicated by analysing extreme precipitation events. In response to these hazards, Benidorm has implemented several flood mitigation measures, including improved drainage systems, flood barriers, and early warning systems. The city also conducts regular maintenance of ravines and stormwater infrastructure to

ensure they function effectively during heavy rainfall events. Community engagement and education programs have been launched to raise awareness about flood risks and preparedness strategies among residents and businesses.

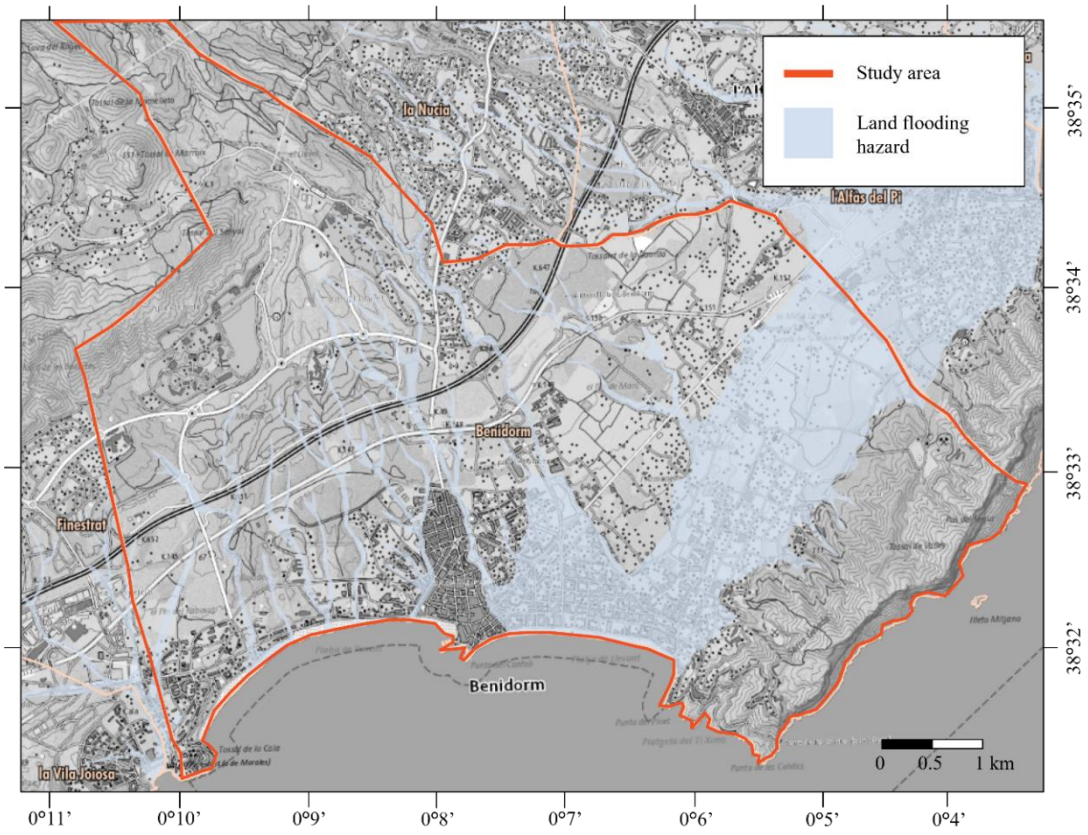


Figure 8.7. Areas exposed to land flooding in Benidorm, Spain, according to PATRICOVA. Source: Flood Hazard Envelope. Sectoral territorial action plan on flood risk prevention in the Valencian Community – PATRICOVA 2015 CC BY 4.0 © Institut Cartogràfic Valencià, Generalitat and Grey basemap 2019 CC BY 4.0 © Institut Cartogràfic Valencià, Generalitat

8.3.7. Landslides

The assessment of landslide hazard using the ELSUS v2 dataset shows varying susceptibility values (Figure 8.8). The highest values are concentrated in the northwestern extremes of the municipality. Serra Gelada also records high susceptibility values. The periphery of the beaches registers medium values, particularly Poniente Beach. The central areas of the municipality show low to very

low values. The list of past events includes only one landslide that occurred on November 12th, 2012, leading to the temporary closure of the regional road CV-70. The CCAP does not analyse this hazard in great detail, though it occasionally references landslides. For instance, it mentions that landslides can affect certain sectors, such as industry and construction, due to the increase in extreme phenomena resulting from climate change. In particular, the exacerbation of erosive processes on cliffs may generate more frequent landslides during large storms along the coastal sector of Benidorm and Serra Gelada. In light of these findings, the local government has initiated slope stabilization projects and monitoring systems in high-risk areas to prevent future landslides. These projects involve reinforcing cliff faces, installing drainage systems to reduce water infiltration, and continuous monitoring to detect early signs of ground movement.

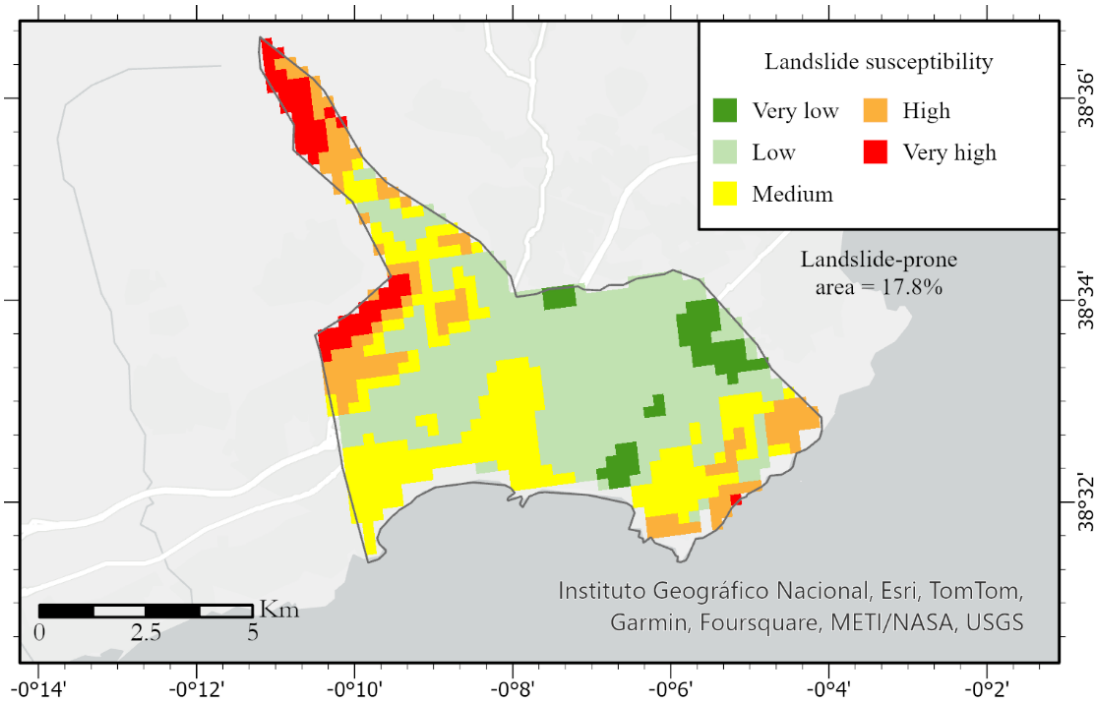


Figure 8.8. Landslide susceptibility in Benidorm, Spain. Source: ELSUS v2

8.3.8. Strong winds

The measurements of extreme wind events associated with winter storms, defined as those with 3-second, 10-meter gusts exceeding 20 m/s, indicate 0 to 4 events over 40

years within the municipality. This value is very low compared to other coastal cities facing the Atlantic Ocean [90]. The list of past climatic events reflects two such episodes. One occurred on December 13th, 2009, with gusts up to 90 km/h (25 m/s), causing damage in the popular theme park Terra Mitica, especially to roofs, street furniture, shaded areas, landscaping, signage, and office buildings. The second event occurred on January 19th, 2013, with recorded gale winds (around 20 m/s), where strong gusts ripped open the walls and roof of the barracks. The CCAP explains that maximum average wind speeds usually occur in winter months and are typically associated with the general westward circulation, usually from the NW component. This finding supports the validity of the wind indicator for Benidorm. To mitigate wind-related damage, Benidorm has enforced stricter building codes to enhance structural resilience against high winds. The city also promotes the use of windbreaks and other landscape features to reduce wind speed and protect vulnerable areas.

8.3.9. Socioeconomic indicators

The evolution of various socioeconomic indicators, based on data from Eurostat, is illustrated in Figure 8.9. The proportion of the population under five years old shows a downward trend, while the population over 65 years old is increasing. This demographic shift results in an inverted population pyramid, which is typically more vulnerable to the impacts of climate change due to the higher dependency ratio and increased health risks associated with an aging population.

Benidorm stands out for its high population density, economically active population, and unemployment rates. However, data on the economically active population are scarce and have not been updated since 2018, making it challenging to understand the current state of this variable, especially considering the potential impact of COVID-19 on labour markets [572]. The unemployment rate has shown a decreasing trend over the past decade, which may indicate an increase in the resilience of the population. Similarly, the proportion of the population with higher education has

grown to around 20%. Despite these improvements, the overall percentage of the population with higher education remains lower compared to cities like Klaipeda, Lithuania, and Varna, Bulgaria.

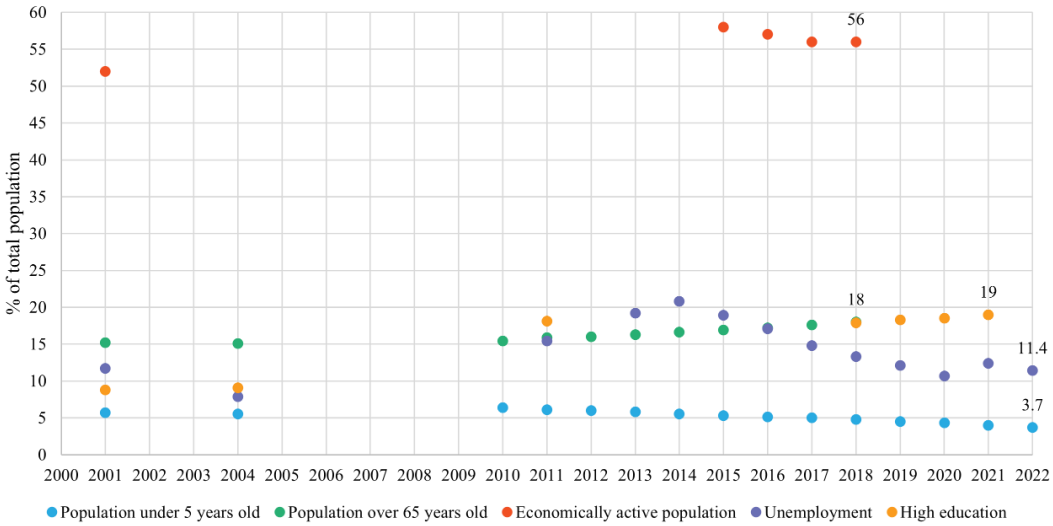


Figure 8.9. Evolution of indicators on the population of Benidorm, Spain. Source: Eurostat.

In terms of economic indicators, the GDP per capita in Benidorm is lower than in other economies, such as Ireland (circa €50,000 per capita) and Finland (circa €35,000 per capita). This economic disparity highlights potential challenges in funding and implementing comprehensive climate adaptation measures. Additionally, the proportion of the population under five years old is low compared to cities like Bergen, Norway, further emphasizing the aging demographic trend.

Contrasting with cities like La Spezia, Italy, or Viana do Castelo, Portugal, the population of Benidorm is not significantly aged. However, the growing elderly population necessitates targeted adaptation strategies to protect this vulnerable group from climate-related health risks and ensure adequate healthcare and social services. These strategies could include the development of age-friendly infrastructure, accessible healthcare services, and community support programs to enhance the resilience of the elderly population.

Moreover, the economic impact of tourism on the economy of Benidorm cannot be overlooked. The dependency of the city on tourism revenues means that climate change effects, such as extreme weather events or shifts in tourist patterns, could have significant economic repercussions. Diversifying the local economy and investing in sustainable tourism practices are essential to mitigate these risks.

8.4. Discussion

8.4.1 Relevance of the assessment

This study extends and demonstrates the utility of the MHRA methodology developed by Laino and Iglesias (2024b) in providing a comprehensive assessment of climate-related risks in Benidorm. By evaluating multiple hazards through a systematic and standardized indicator-based approach, the methodology offers a holistic risk profile that traditional single-hazard assessments lack. This approach facilitates the comparison of results with different coastal cities across Europe, serving as a valuable tool for policymakers and decision-makers at various levels. The application of remote sensing data, such as ERA5, Urban Atlas, and MERIT DEM, enhances the accuracy and resolution of hazard assessments in Benidorm [369,573–575]. These datasets provided comprehensive and high-resolution information on land use, topography, and climate variables, which are crucial for assessing a wide range of climate-related hazards. The integration of results with local studies, including a database of past climate events, further enhances the assessment by providing historical context and validation for the risk indicators. This comprehensive view is crucial for understanding the full spectrum of climate-related risks and developing effective adaptation strategies [576].

The choice to focus on a single city in this study was a deliberate step in validating the new methodology. Although the datasets employed cover a broader geographical range across Europe, it was deemed essential to first test the methodology in a well-

documented city where existing results provide opportunities for direct comparison. This approach ensures that the method is reliable and accurate before expanding its application. While this study lays a solid foundation for understanding multi-hazard risks in coastal cities, it is acknowledged that expanding the analysis to include a larger and more diverse set of cities could enhance the statistical robustness of the results. The framework is inherently scalable and adaptable, and its application to other coastal cities across Europe is feasible, provided sufficient data is available. The study can be extended to incorporate more coastal cities in future works, aiming to provide a broader and more comprehensive understanding of coastal risk under climate change. This expansion can improve the reliability of statistical analysis and enable more generalized conclusions about coastal vulnerability across various regions.

The participatory approach through the CCLL concept is particularly noteworthy. Engaging local stakeholders enriches the data and insights while also building community resilience and ensuring that adaptation measures are culturally and socially appropriate. This model of inclusive, science-based planning can be replicated in diverse urban contexts, enhancing global resilience to climate change. Further development of the CCLL concept can enhance the effectiveness of the methodology, including exploring new ways to engage stakeholders and integrating advanced technologies such as real-time monitoring and data analytics into the risk assessment process [577].

8.4.2 Comparison with previous studies

The assessment of the various indicators calculated in this study generally aligns with previous research, confirming known vulnerabilities and revealing new insights through its integrative approach. The indicators related to coastal flooding and extreme sea levels show results similar to existing studies. For instance, the distribution of wave height and wave direction for the most unfavourable storm, as noted in Toledo et al. (2024), shows values around 2.5 m on the Levante and Poniente beaches for

wave heights with a 0.137% probability of being exceeded. This is comparable to the significant wave height values corresponding to the median between the 90th and 100th percentiles calculated in this study using ERA5 reanalysis data. Furthermore, the surge levels proposed are consistent with values reported in past climate events from Laino and Iglesias (2023c) (approximately half a meter) and Toledo et al. (2024) (0.63 m). The results regarding the extent of coastal flooding, based on the calculation of the LECZ and coastal flooding extents from ECFAS data, are also coherent with the flood studies of Toledo et al. (2024), which indicate that coastal flooding primarily affects the promenade and barely advances inland. However, the results from our study are not capable of distinguishing the differences in the impact of coastal flooding between the different beaches.

Other studies, such as those by Gonzalez-Hidalgo et al. (2007) and Imeson et al. (1998), have highlighted specific hazards like heatwaves, heavy precipitation, and pluvial flooding. However, the holistic assessment approach carried out in this study, which combines multiple hazards into a unified risk profile, provides a more interconnected understanding of how these risks compound and interact. For instance, the identified increase in heatwave frequency aligns with broader regional trends noted in IPCC reports and localized studies like those of Camarasa-Belmonte et al. (2020). This study also contextualizes these trends within the framework of socio-economic vulnerabilities and land use patterns. Additionally, other climate-related hazards not commonly studied in the scientific literature for Benidorm, such as cold spells, landslides, and strong winds, have been evaluated here, offering a more comprehensive understanding of the vulnerability of the city to climate change.

The study by Fernández Montes and Sánchez Rodrigo (2014) on climate variability in the southeast Iberian Peninsula provides valuable context for understanding temperature and precipitation trends in Benidorm. The pattern of torrential rainfall described in their work aligns with the results presented in this study. In Benidorm, river flooding areas identified by Dottori et al. (2021) are negligible, making heavy

rainfall indicators particularly important in evaluating land flooding. The significant increases in daily maximum and minimum temperatures, especially in highly urbanized areas like Alicante-Murcia, reflect broader regional trends driven by urbanization and land-use changes. These findings are consistent with the observed increase in heatwave frequency and intensity in Benidorm. Additionally, the slight recovery in precipitation since the 1980s, primarily during winter months, suggests a complex interaction between climate variability and local environmental changes. This recovery could mitigate drought conditions to some extent but also indicates a trend towards more extreme precipitation events, as shown in this study, which can lead to increased flooding and soil erosion. These findings call for comprehensive adaptation plans that integrate sustainable urban planning, improved water resource management, and enhanced monitoring systems to mitigate the impacts of climate change.

8.4.3 Implications of the findings

Demographic and socio-economic factors highlight both the strengths and vulnerabilities of the population of Benidorm in the context of climate resilience. The increasing proportion of higher-educated individuals and the decreasing unemployment rate are positive signs of socio-economic resilience. However, the challenges posed by an aging population and lower GDP per capita must be addressed through comprehensive and inclusive adaptation planning. Integrating socio-economic factors more deeply into the risk assessment process can provide a fuller picture of vulnerabilities [291,315]. Understanding how climate risks intersect with issues such as poverty, inequality, and health disparities is crucial for developing comprehensive and equitable adaptation strategies.

The implications of these findings are critical for regulatory bodies and urban planners in Benidorm. The highlighted risks necessitate the revision and strengthening of existing coastal management policies. The inclusion of comprehensive climate risk

assessments in urban planning and the establishment of stricter building codes in vulnerable areas are essential steps [578]. The Benidorm CCAP already outlines measures to address some of these risks, but the data from this study can provide more detailed and targeted insights to enhance these strategies. Collaboration with regional and national bodies can ensure that adaptive measures are harmonized and effectively implemented. Detailed studies are vital for a better understanding of risk, as exemplified by the flood patterns in Benidorm mentioned earlier [468].

The findings from this study align with those from similar coastal cities, reinforcing the need for an integrative approach to climate risk assessment [470,565]. Studies on erosion dynamics in Guardamar and San Juan Beaches emphasize the critical role of sedimentological factors and the impact of human interventions [579,580]. Comparing these results with those from Benidorm highlights that while localized solutions are essential, broader regional strategies must also be developed to address common vulnerabilities and enhance overall resilience. Cities with similar vulnerabilities, such as Alicante, Valencia, and other Mediterranean coastal cities, can adopt this methodology to enhance their resilience planning.

The localized findings for Benidorm also have broader implications for other coastal cities globally. As cities worldwide face increasing risks from climate change, the integrative approach demonstrated here can serve as a model. By standardizing methodologies and leveraging local knowledge, cities can better understand their unique vulnerabilities and develop targeted adaptation strategies. The methodology described here is valid for virtually any European city due to the wide geographical coverage of the datasets within Europe. Extending this methodology to other coastal cities can provide comparative data that can help refine and validate the approach. Cross-city comparisons can enable the identification of common vulnerabilities and best practices, contributing to a more robust and universally applicable risk assessment framework.

8.4.4 Limitations and research opportunities

Despite its strengths, the MHRA methodology has several limitations. One significant limitation is the reliance on certain outdated datasets, such as the Eurosion dataset for coastal erosion, which may not accurately reflect current conditions. According to the Eurosion dataset, the coastal erosion trend in Benidorm was stable at least in the early 2000s, which might be true for Levante Beach. However, Toledo et al. (2022) shows that Poniente Beach has experienced significant erosion, particularly in its eastern zone, since 1956. This erosion was exacerbated by the 1991 beach nourishment project, which, despite initially increasing the beach width, resulted in ecological damage such as the death of Posidonia oceanica. This alteration of the beach profile has led to more severe erosion over time [581]. Recent data from 2007 to 2021 show a reduction in erosion rates, potentially due to changes in wave patterns and storm frequency. These findings underscore the importance of adaptive management strategies that can respond to evolving environmental conditions, including studying additional factors influencing coastal erosion, such as beach nourishment and the construction of breakwaters [582].

Another limitation is the complexity involved in integrating multiple hazards into a single assessment. While this provides a more comprehensive risk profile, it also requires sophisticated modelling tools and significant data inputs. The need for high-quality, granular data can be a barrier, especially in regions where data availability is limited. Additionally, the inherent uncertainties in climate projections present a challenge. Climate models vary in their predictions, and the exact magnitude and timing of climate impacts are difficult to forecast with precision. This uncertainty must be acknowledged and managed within the detailed risk assessment framework, potentially through the use of scenario analysis and sensitivity testing [554,583]. Assigning weights to indicators through correlation analysis can improve risk quantification. Incorporating a range of possible future scenarios can help to account for this uncertainty and ensure that risk management strategies are robust and flexible.

These limitations can lead to underestimations or misrepresentations of certain hazards. Continuous updates and refinements of the datasets used are essential to maintain the accuracy and relevance of the risk assessments [584–587]. The use of higher resolution satellite imagery, such as those from upcoming satellite missions, can provide more detailed and up-to-date information on land use and topography [588]. Additionally, integrating remote sensing data with real-time monitoring systems can enhance the ability to track and respond to climate-related hazards dynamically [589]. Incorporating the latest data on coastal erosion, sea-level rise, and other hazards will improve the accuracy of risk assessments [390,391,499]. Additionally, further development of the CCLL concept can enhance its effectiveness. This includes exploring new ways to engage stakeholders and integrating more advanced technologies, such as real-time monitoring and data analytics, into the risk assessment process. Furthermore, exploring the use of machine learning algorithms to analyse large volumes of remote sensing data can improve the accuracy and efficiency of hazard assessments [590]. Therefore, it is recognized that the assessment capacity of the indicators is adequate for high-level characterization but not sufficient for detailed risk studies. To better understand the limits of this methodology, it is advisable to test it with more cities.

8.5. Conclusions

This study has applied a MHRA methodology to evaluate the climate-related risks facing Benidorm, a coastal city in Spain. The findings provide significant insights into the vulnerability and resilience of the city in the context of climate change, offering both local and broader implications. The integration of remote sensing data into the MHRA methodology has proven to be highly effective in assessing and understanding climate-related hazards in Benidorm. The detailed and high-resolution information provided by these datasets enhances the accuracy of hazard indicators and facilitates the development of targeted adaptation strategies.

The study reveals that Benidorm, while generally experiencing low levels of coastal hazards compared to other European cities, faces significant risks from MSLR and extreme temperatures. The integration of multiple hazard indicators into a single framework has highlighted the susceptibility of the city to hazards such as heatwaves, flash floods and landslides.

The relatively high values for extreme high temperature thresholds, natural vegetation areas, and socio-economic indicators such as unemployment and economically active population underline the complex interplay of environmental and socio-economic factors in shaping the risk profile of the city.

A notable contribution of this research is the application of an integrative MHRA methodology, which considers multiple climate-related hazards in a unified assessment. This approach provides a comprehensive risk profile that surpasses traditional single-hazard assessments, offering a more nuanced understanding of vulnerabilities.

The incorporation of the CCLL concept represents another methodological advancement. By engaging local stakeholders, the study has ensured that the risk assessment is grounded in local realities, benefiting from diverse insights and enhancing the relevance and acceptance of the findings.

The findings of this study have critical implications for policymakers and urban planners in Benidorm and similar coastal cities. The identified risks call for updated and more stringent coastal management policies, including the reinforcement of building codes, the implementation of adaptive infrastructure, and the preservation of natural buffers.

The study underscores the importance of a participatory approach in risk assessment and urban planning. Engaging local communities and stakeholders not only enriches

the data and insights but also fosters resilience and ensures that adaptation measures are socially and culturally appropriate.

The success of the MHRA methodology in Benidorm suggests its potential for broader application. Other coastal cities can adopt this integrative approach to develop comprehensive risk profiles and inform their resilience strategies. The standardized assessment framework and the collaborative CCLL concept can be adapted to various geographic and socio-economic contexts, enhancing global urban resilience.

Extending the MHRA methodology to other coastal cities will provide valuable comparative data, helping to refine and validate the approach further. Additionally, integrating socio-economic factors more deeply into the risk assessment process will provide a fuller picture of vulnerabilities and inform more equitable adaptation strategies.

ROLE OF THE AUTHOR

The exact role of the author of the thesis includes the following CRediT terms: Writing – original draft, Writing – review & editing, Visualization, Software, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization.

Chapter 9.

Discussion, conclusions & future work

9.1 Discussion

9.1.1 Evolving understanding of climate impacts on coastal cities and existing gaps

The findings of this thesis underscore a progressive deepening of the scientific community's understanding of the complexities surrounding climate-related hazards in European coastal cities. The comprehensive literature review and scientometric analyses conducted in Chapters 2, 3 and 4 reveal a pattern where shifts in research intensity align with major global climate policy milestones, such as the establishment of the IPCC and the adoption of frameworks like the Kyoto Protocol and the Paris Agreement. These pivotal events may have consistently acted as catalysts, not only driving the volume of scholarly output but also shaping the focus of climate adaptation strategies.

However, despite the growing body of research, a critical gap remains in the integrated assessment of multiple climate hazards. Much of the existing literature remains siloed, predominantly examining singular threats such as coastal flooding, sea-level rise, or erosion in isolation. This compartmentalized approach fails to capture the compounding and cascading effects that occur when these hazards interact. The systematic review conducted in this thesis highlights the necessity for a more holistic,

multi-hazard perspective that acknowledges how interconnected stressors can amplify risks, particularly in densely populated urban coastal areas.

Similarly, it has been observed an uneven focus on various dimensions of risk assessment. There is a clear tendency in the literature to prioritize hazard characterization, such as identifying and quantifying the physical impacts of sea-level rise, storms, or heatwaves, over the equally important aspects of adaptive capacity. This imbalance suggests that while we are advancing in understanding the nature and extent of climate-induced hazards, there remains a substantial gap in how cities and communities can effectively respond to these threats.

Another key challenge identified pertains to biases in data availability and research focus. The geographical concentration of studies in countries such as the United Kingdom, Germany, and Spain reflects broader trends in climate research, which often prioritize regions with greater access to funding, institutional support, and historical data. This bias is not merely a reflection of research capabilities but also indicates underlying disparities in global attention to climate vulnerabilities. As a result, coastal cities in island territories, Eastern Europe and the Nordic countries remain underrepresented in both scientific literature and risk assessments, despite facing significant climate-related challenges.

The participatory insights obtained through the CCLLs helped to partially address these gaps by incorporating localized knowledge from stakeholders. However, the variability in data availability between cities demonstrated that relying solely on existing datasets may not always provide an accurate picture of localized risks. This imbalance restricts the generalizability of existing studies and reinforces the need for expanding field data collection efforts, particularly in regions where scientific studies are sparse or outdated.

Moreover, the findings indicate that the practical implementation of adaptation measures often lags behind theoretical advancements. While the MHRA framework

developed in this thesis provides a structured approach to assessing and prioritizing climate risks, translating these insights into actionable policy remains challenging. The lack of coherence between local, regional, and national policies further complicates the implementation of effective adaptation strategies. For instance, cities like Samsun and Gdańsk, which face acute climate risks, are constrained by limited financial resources and fragmented policy frameworks, hindering their ability to implement comprehensive adaptation measures.

9.1.2 The role of Coastal City Living Labs in contextualizing risks

The integration of CCLLs into the research framework, as explored in Chapters 3 and 5, introduced a participatory dimension that enriched the understanding of climate-related risks in European coastal cities and the identification of key climate-related hazards. This innovative approach allowed for the inclusion of local stakeholders through various collaborative activities, whose insights provided a nuanced perspective on the diverse and context-specific hazards faced by each city. The CCLLs facilitated the capture of local knowledge, which often remains underrepresented in scientific literature, thereby bridging the gap between theoretical assessments and on-the-ground realities.

By actively engaging stakeholders in cities such as Sligo and Dublin, the research identified a heightened concern regarding the intensification of winter storms and coastal flooding. Conversely, in cities like Oeiras and Piran, local experts prioritized the escalating frequency of heatwaves and droughts. These localized perspectives highlight the variability in climate impacts across regions, underscoring the importance of integrating both scientific analyses and community-based expertise when formulating adaptation strategies. This localized knowledge is crucial for tailoring interventions to the socio-economic and ecological contexts of each city, thus enhancing the effectiveness of adaptation measures.

However, the collaborative process also revealed inherent biases in both local and scientific assessments. Local agencies may prioritize risks that align with immediate economic interests, such as the protection of coastal tourism in Spanish cities, whereas scientific studies may focus on hazards with more readily available data or greater funding opportunities. This divergence suggests that while local knowledge is indispensable, it must be carefully balanced with objective scientific analysis to avoid skewed prioritizations. Recognizing and addressing these biases is vital to developing a holistic and equitable approach to climate adaptation that is both scientifically rigorous and contextually relevant.

9.1.3 The Multi-Hazard Risk Assessment framework

One of the key contributions of this thesis lies in the development of a standardized MHRA framework that seamlessly integrates both quantitative data and qualitative insights. The analysis conducted in Chapters 5 through 8 demonstrated that leveraging high-resolution geospatial datasets, such as products from ERA5 climate reanalysis and Urban Atlas land-use data, alongside participatory insights from CCLLs, results in a more holistic understanding of climate-related risks. This integrative approach addresses the limitations of conventional single-hazard assessments, which often fail to account for the multifaceted nature of urban vulnerabilities.

The application of the MHRA framework across diverse European coastal cities revealed marked heterogeneity in hazard exposure. For instance, Dublin and Gdansk were identified as highly susceptible to coastal flooding, while Benidorm and Massa exhibited a greater vulnerability to temperature-related hazards. In addition, other cities, i.e., Piran, concentrates all the previous hazards. These findings underscore the necessity of adopting a multi-hazard perspective, as traditional assessments focused on isolated hazards may overlook the cumulative effects of multiple, interacting

stressors. By capturing these compound risks, the proposed methodology offers a more robust basis for developing targeted adaptation strategies.

Furthermore, the inclusion of socio-economic indicators—such as GDP per capita, educational attainment, and population density from Eurostat—provided critical insights into the differential vulnerability of cities. For example, while Viana do Castelo displayed relatively lower physical exposure compared to wealthier cities like Cork, its limited adaptive capacity, driven by socio-economic constraints, resulted in a higher overall vulnerability to climate hazards. This highlights the crucial role of socio-economic context in shaping urban resilience, emphasizing that physical exposure alone does not fully encapsulate the risk profile of a city.

The integration of both standardised metrics and local expertise within a unified framework not only enriches the assessment process but also supports the development of more nuanced and context-specific adaptation strategies. Chapter 8 generally improved the understanding of climate-related risk on Benidorm, but it also highlighted particular challenges regarding the risk characterisation of coastal erosion and land flooding for this city. This comprehensive approach contributes to making climate adaptation measures not only scientifically sound but also socially relevant, addressing the unique needs and capacities of each urban area. Ultimately, this framework serves as a valuable tool for policymakers, enabling them to prioritize interventions based on a more complete understanding of the complex interplay between climate hazards, socio-economic factors, and urban resilience.

9.1.4 Planning and policy implications

A key implication for urban planning is the need for localized risk mapping. The MHRA framework developed in this research provides a structured approach for cities to comprehensively assess their risk profiles and prioritize interventions based on evidence-based assessments. The identification of specific hotspots, such as areas

vulnerable to compounded flooding in Gdansk, Benidorm and Cork or heavy precipitation and landslide risks in Oarsoaldea, Bergen and La Spezia, highlights the necessity of targeted, localized assessments. By mapping these high-risk areas, urban planners can better allocate resources to the most vulnerable zones, particularly in densely populated urban regions where the potential for damage is greatest. This approach ensures that adaptation strategies are not only efficient but also context-specific, thereby enhancing their effectiveness.

In addition, the thesis findings emphasize the role of green and blue infrastructure in mitigating climate-related hazards. Enhancing green spaces and coastal buffers can significantly reduce the impacts of extreme events such as heavy rainfall and heatwaves. For example, cities like Oarsoaldea, Piran and Sligo stand to benefit from ecosystem-based adaptation measures, including the restoration of wetlands and dune systems. These natural solutions provide cost-effective flood defences while simultaneously enhancing biodiversity and improving urban liveability. Integrating such ecosystem-based strategies into urban planning can help cities build resilience in a sustainable manner.

Furthermore, zoning and land use regulations emerged as critical factors in enhancing urban adaptability. Cities with flexible zoning frameworks, such as Benidorm, have demonstrated a greater capacity to adjust to evolving climate risks. The incorporation of climate risk assessments into zoning laws can prevent maladaptive developments in high-risk areas, particularly in flood-prone coastal zones. Establishing stringent guidelines for land use can help mitigate the long-term risks associated with unplanned urban expansion, thereby safeguarding both human lives and economic assets.

From a policy perspective, the participatory approach adopted in this research, particularly through the CCLLs, revealed that fragmented policy frameworks often hinder the effective implementation of adaptation measures. Ensuring policy coherence across different governance levels—from local to regional and national—

is essential for coordinated climate action. The integration of findings from this thesis into broader studies, such as the SCORE project, could enhance resilience-building efforts by aligning local adaptation strategies with overarching climate goals. This alignment not only promotes consistency but also ensures that cities receive the support needed to implement localized adaptation measures.

Another critical policy implication is the need for enhanced financial mechanisms for climate adaptation. The results indicate that cities like Samsun and Varna face considerable challenges due to limited financial resources. Establishing dedicated funds and incentives for adaptation projects, particularly in economically constrained cities, is imperative to accelerate climate action. Leveraging public-private partnerships can provide additional funding streams and stimulate innovation in resilience strategies.

9.2 Conclusions

This thesis has developed a novel MHRA framework tailored specifically to the needs of European coastal cities, providing a tool to address the increasingly complex climate-related risks these urban areas face. By integrating quantitative indicators with qualitative insights from CCLLs, the framework has demonstrated its capability to capture the multifaceted nature of climate-related hazards.

The integration of high-resolution datasets and collaborative local expertise proved invaluable in contextualizing the varied risks of diverse European coastal cities. This combination of scientific rigor and local knowledge not only enhanced the accuracy of the risk assessments but also fostered a more inclusive, stakeholder-driven approach to climate adaptation. These participatory insights emphasized that adaptation strategies must align with local socio-cultural contexts to be effective, fulfilling Objective II of this research.

A key contribution of this thesis lies in its ability to bridge the gap between isolated hazard assessments and a holistic, multi-hazard approach. The analysis revealed that cities with strong socio-economic resilience are better equipped to manage climate risks, while others face greater challenges despite having lower physical exposure. By incorporating socio-economic indicators into the MHRA framework, this research provides a more comprehensive view of urban vulnerability, highlighting the need for tailored adaptation policies that account for both physical and social factors. This fulfils Objective III by enabling cross-regional comparative analyses, which are essential for effective resource allocation.

Furthermore, the study underscores the transformative potential of integrating emerging technologies such as AI, IoT, and digital twins to enhance urban climate resilience. These technologies, when combined with the MHRA framework, can provide dynamic, real-time risk assessments, enabling cities to adapt more effectively to evolving climate conditions. This technological dimension represents a promising avenue for future research, particularly in enhancing predictive capabilities and fostering proactive urban planning.

Despite the strengths of the MHRA framework, the study also highlighted key challenges, particularly regarding data availability and the underrepresentation of adaptive capacity indicators. Addressing these gaps is essential to ensure the robustness of future risk assessments. The findings emphasize the need for continuous monitoring and adaptive management to maintain the relevance of risk models as climate conditions evolve.

In conclusion, this thesis has successfully developed a standardized yet flexible approach to multi-hazard risk assessment, addressing significant gaps in current methodologies. The findings offer critical insights for policymakers, urban planners, and researchers, providing a robust tool to guide the development of resilient, adaptive coastal cities in the face of accelerating climate change. Moving forward, further

refinement of the MHRA framework—particularly through the integration of adaptive management practices and emerging technologies—will be essential to sustain long-term urban resilience.

9.3 Future work

While this thesis makes strides in advancing the understanding of multi-hazard risks in coastal cities, several areas warrant further investigation:

9.3.1 Enhancing data availability and granularity

One of the primary limitations identified in this study was the reliance on existing datasets, which may not always reflect the most current conditions, especially in rapidly changing coastal environments. Future research should prioritize the development and integration of higher-resolution, real-time data sources. Leveraging remote sensing technologies, such as satellite imagery from upcoming missions, can improve the spatial and temporal resolution of datasets, particularly for underrepresented regions like Eastern Europe and the Scandinavian coastline. Additionally, the inclusion of open-source geospatial data and enhanced use of crowd-sourced information from local communities could bridge existing data gaps.

9.3.2 Expanding the Multi-Hazard Risk Assessment framework to include future climate projections

The current MHRA framework developed in this thesis primarily focused on assessing risks under present-day conditions. However, given the rapidly changing climate, future studies should incorporate projections based on different climate scenarios. Integrating climate models that predict changes in sea levels, temperature extremes, and precipitation patterns would allow cities to prepare for long-term risks. This would involve developing methods to project indicators like coastal erosion, heatwave

intensity, and flood extents, ensuring that adaptation measures remain robust against future uncertainties.

9.3.3 Improving the assessment of adaptive capacity

While this thesis integrated socio-economic indicators to assess vulnerability, the measurement of adaptive capacity was relatively underdeveloped. Future research should focus on creating more comprehensive indicators that capture social resilience, community networks, and institutional capacities. For example, integrating measures of social cohesion, public health infrastructure, and access to resources can provide a more nuanced understanding of a city's ability to adapt. This could also include assessing how factors like governance, public participation, and local leadership influence adaptive capacity.

9.3.4 Leveraging emerging technologies for dynamic risk assessment

The rapid evolution of technologies such as AI, ML, and the IoT presents opportunities to enhance the MHRA framework. Future work could explore how AI and ML models can be applied to large datasets to improve the predictability of compound hazards. Additionally, deploying IoT-based sensors in coastal cities to monitor real-time changes in sea levels, storm intensity, and temperature fluctuations could enable dynamic updates to risk assessments. The development of digital twins for cities, allowing simulations of various climate scenarios, is another promising area that could optimize resource allocation and planning.

9.3.5 Expanding the framework to non-European coastal cities

While this research focused on European coastal cities, the MHRA framework has the potential to be applied globally. Future studies could test its applicability in other

regions with different socio-economic, climatic, and environmental conditions. For instance, cities in Southeast Asia or the Caribbean, which are highly vulnerable to sea-level rise and extreme weather events, could benefit from a localized adaptation of the framework. Comparative studies between regions would also provide insights into how different urban settings and governance structures affect climate resilience.

9.3.6 Incorporating socio-cultural factors into adaptation strategies

The role of socio-cultural factors in shaping adaptation responses emerged as a critical insight from this research. Future work should delve deeper into how cultural heritage, social norms, and local traditions influence climate resilience. Developing participatory approaches that engage local communities in data collection, decision-making, and implementation of adaptation measures can enhance the social acceptability and sustainability of these efforts. Expanding the concept of CCLLs to incorporate cultural dimensions could lead to more holistic adaptation strategies.

9.3.7 Exploring the role of financial mechanisms in supporting climate adaptation

The research highlighted the need for dedicated financial resources to support adaptation, especially in cities with limited budgets like Samsun, Gdańsk and Varna. Future studies could explore the development of financial mechanisms such as climate adaptation funds, insurance schemes, and public-private partnerships. Additionally, evaluating the effectiveness of existing funding programs under the European Green Deal and other international frameworks can provide insights into scaling up investment in resilience projects.

9.3.8 Integrating long-term monitoring and adaptive management

To ensure that the MHRA framework remains relevant, it is crucial to incorporate mechanisms for continuous monitoring and adaptive management. Future research should focus on developing methodologies for periodic reassessments based on new data and evolving climate conditions. Scenario analysis and sensitivity testing can be incorporated to explore the impact of different adaptation strategies over time. Establishing a feedback loop where cities can adjust their strategies based on real-time data and updated assessments can potentially enhance urban resilience.

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Appendix

Table A.1. Breakdown of the number of past climate-related events collected per event category for Sligo, Dublin, Benidorm, Oarsoaldea and Vilanova i la Geltrú CCLLs. Period of analysis included in brackets.

Climate-related event category	**Sligo (1973-2021)**	**Dublin**	**Benidorm (1980-2020)**	**Oarsoaldea (1900-2022)**	**Vilanova i la Geltrú (1988-2021)**
Storm	15	0	0	21	2
Coastal erosion	2	0	5	0	0
Coastal flooding	0	0	22	1	0
Land flooding	9	0	5	13	6
Heavy precipitation	6	0	2	12	0
Heavy snowfall	2	0	0	1	0
Drought	3	0	0	4	0
Cold spell	2	0	0	2	0
Heat wave	1	0	0	11	0
Landslide	0	0	1	10	0
Strong winds	0	0	2	0	3
Forest fire	0	0	0	0	4
Compound event	6	0	0	0	0
Other	3	0	0	0	0
Total	49	0	37	75	15

Table A.2. Breakdown of the number of past climate-related events collected per event category for Oeiras, Massa, Piran, Gdansk and Samsun CCLLs. Period of analysis included in brackets.

Climate-related event category	**Oeiras (1865-2021)**	**Massa (1994-2021)**	**Piran (2005-2021)**	**Gdańsk (1892-2017)**	**Samsun (1963-2012)**
Storm	0	8	0	0	0
Coastal erosion	0	0	0	0	0
Coastal flooding	0	0	0	0	0
Land flooding	45	7	16	23	11
Heavy precipitation	0	4	0	0	0
Heavy snowfall	0	0	0	0	0
Drought	0	0	0	0	0
Cold spell	0	0	0	0	0
Heat wave	0	0	0	0	0
Landslide	6	12	0	0	0
Strong winds	0	0	0	0	0
Forest fire	0	0	0	0	0
Compound event	0	0	0	0	0
Other	0	0	0	0	0
Total	51	31	16	23	11

Table A.3. Summary of the past climate-related events collected in Sligo, including identification code, categorisation, date and additional information.

Event ID	**Climate-related hazard category**	**Date**	**Additional information**
SL-CO-1	Compound event	February 1990	Storm and heavy precipitation.
SL-CO-2	Compound event	February 2002	Storm surge and coastal flooding.
SL-CO-3	Compound event	September 2003	Flooding and landslide.
SL-CO-4	Compound event	Summer 2008	Heavy rain and flooding.
SL-CO-5	Compound event	Winter 2013/14	Winter storms and storm surges.
SL-CO-6	Compound event	Summer 2018	Heatwave and drought.
SL-CE-1	Coastal erosion	01/02/2014	-
SL-CE-2	Coastal erosion	January 2022	-

SL-CS-1	Cold spell	Winter 2009/10	-
SL-CS-2	Cold spell	November and December 2010	-
SL-DR-1	Drought	October 1974 - August 1976	-
SL-DR-2	Drought	Summer 1995	-
SL-DR-3	Drought	2007	-
SL-LF-1	Flood	November 1973	-
SL-LF-2	Flood	October 1987	-
SL-LF-3	Flood	June 1993	-
SL-LF-4	Flood	August 1997	-
SL-LF-5	Flood	December 1998	-
SL-LF-6	Flood	November 2000	-
SL-LF-7	Flood	November 2002	-
SL-LF-8	Flood	November 2009	-
SL-LF-9	Flood	26/02/2020	-
SL-HW-1	Heat wave	Summer 2006	-
SL-OT-1	Other	February 1988	Storm force winds.
SL-OT-2	Other	December 1998	Hurricane force winds.
SL-OT-3	Other	Winter 2016/17	Driest winter in 25 years.
SL-HP-1	Heavy precipitation	November 1980	-
SL-HP-2	Heavy Precipitation	October 1989	-
SL-HP-3	Heavy precipitation	October 2011	-
SL-HP-4	Heavy precipitation	Summer 2012	-
SL-HP-5	Heavy precipitation	January 2016	-
SL-HP-6	Heavy precipitation	August 2017	-
SL-ST-1	Storm	January 1976	-
SL-ST-2	Storm	January 1974	-
SL-ST-3	Storm	August 1976	-
SL-ST-4	Storm	July 1985	-
SL-ST-5	Storm	August 1986	-
SL-ST-6	Storm	January 1991	-
SL-ST-7	Storm	March 1995	-
SL-ST-8	Storm	December 1997	-
SL-ST-9	Storm	February 2014	-
SL-ST-10	Storm	October 2017	-
SL-ST-11	Storm	March 2018	-
SL-ST-12	Storm	September 2018	-
SL-ST-13	Storm	7-8 December 2021	-

SL-ST-14	Storm	17-18 February 2022	-
SL-ST-15	Storm	20/02/2022	-
SL-SF-1	Heavy snowfall	January 1982	-
SL-SF-2	Heavy snowfall	January 1987	-

Table A.4. Summary of past climate-related events collected in Vilanova i la Geltrú, including identification code, categorisation and date.

Event ID	**Climate-related hazard category**	**Date**
VI-ST-1	Storm	20/01/2020
VI-ST-2	Storm	23/11/2021
VI-SW-1	Strong winds	12/08/2019
VI-SW-2	Strong winds	12/08/2019
VI-SW-3	Strong winds	12/08/2019
VI-LF-1	Land flooding	Autumn 1962
VI-LF-2	Land flooding	September 2004
VI-LF-3	Land flooding	September 2005
VI-LF-4	Land flooding	August 2019
VI-LF-5	Land flooding	August 2022
VI-LF-6	Land flooding	October 2020
VI-FF-1	Forest fire	02/09/1988
VI-FF-2	Forest fire	03/07/1989
VI-FF-3	Forest fire	13/05/1997
VI-FF-4	Forest fire	12/06/2012

Table A.5. Summary of the past climate-related events collected in Benidorm, including identification code, categorisation, date and affected area.

Event ID	**Climate-related hazard category**	**Date**	**Affected area**
BE-CF-1	Coastal flooding	27/12/1980	Levante Beach.
BE-CF-2	Coastal flooding	02/01/1982	Poniente Beach.
BE-CF-3	Coastal flooding	04/10/1984	Poniente Beach.
BE-CE-1	Coastal erosion	21/02/1985	Levante Beach.
BE-CF-4	Coastal flooding	14/11/1985	Poniente Beach.
BE-CF-5	Coastal flooding	27/09/1986	Levante Beach.
BE-CF-6	Coastal flooding	03/11/1987	Levante Beach.
BE-CF-7	Coastal flooding	17/10/1988	Levante Beach.

BE-CF-8	Coastal flooding	17/10/1988	Poniente Beach.
BE-CF-9	Coastal flooding	04/09/1989	Levante Beach.
BE-CF-10	Coastal flooding	04/09/1989	Poniente Beach.
BE-CE-2	Coastal erosion	20/02/1992	Levante Beach.
BE-CE-3	Coastal erosion	20/02/1992	Poniente Beach.
BE-CE-4	Coastal erosion	06/01/1994	Levante Beach.
BE-CF-11	Coastal flooding	22/09/1994	Levante Beach.
BE-CF-12	Coastal flooding	11/11/1996	Levante Beach.
BE-CF-13	Coastal flooding	11/11/1996	Poniente Beach.
BE-CF-14	Coastal flooding	08/04/1997	Levante Beach.
BE-CF-15	Coastal flooding	30/09/1997	Levante Beach.
BE-CF-16	Coastal flooding	06/11/1997	Levante Beach.
BE-CF-17	Coastal flooding	06/11/1997	Poniente Beach.
BE-CF-18	Coastal flooding	10/11/2001	Levante Beach.
BE-CE-5	Coastal erosion	30/10/2003	Levante Beach.
BE-CF-19	Coastal flooding	27/03/2004	Poniente Beach.
BE-CF-20	Coastal flooding	03/12/2004	Levante Beach.
BE-HP-1	Heavy precipitation	03/11/2006	Benidorm.
BE-PF-1	Pluvial flood	13/10/2007	Benidorm.
BE-SW-1	Strong winds	13/12/2009	Terra Mítica theme park.
BE-PF-2	Pluvial flood	21/10/2011	Cala Finestrat.
BE-LA-1	Landslide	12/11/2012	CV-70 road.
BE-SW-2	Strong winds	19/01/2013	Pere María Orts High School.
BE-PF-3	Pluvial flood	01/11/2015	Benidorm.
BE-PF-4	Pluvial flood	18/12/2016	Cala Finestrat.
BE-PF-5	Pluvial flood	17/01/2017	Benidorm.
BE-HP-2	Heavy precipitation	19/04/2019	Benidorm.
BE-CF-21	Coastal flooding	19/01/2020	Levante Beach.
BE-CF-22	Coastal flooding	19/01/2020	Poniente Beach.

Table A.6. Summary of the past climate-related events collected in Oarsoaldea, including identification code, categorisation, date and affected area.

Event ID	**Climate-related hazard category**	**Date**	**Affected area**
OA-RF-1	River flooding	01/04/1915	Town of Errenteria.
OA-RF-2	River flooding	01/09/1917	Town and fields of Errenteria.
OA-RF-3	River flooding	01/04/1918	Errenteria and Oiartzun.

OA-RF-4	River flooding	01/06/1933	Pasaia.
OA-RF-5	River flooding	23/10/1933	Town of Errenteria, Oiartzun and Pasaia (San Juan District).
OA-RF-6	River flooding	01/10/1949	Errenteria and riverside of Oiartzun river.
OA-RF-7	River flooding	01/10/1953	Town centre of Errenteria.
OA-RF-8	River flooding	01/01/1981	Errenteria and Oiartzun.
OA-CF-1	Coastal flooding	01/02/2014	Pasaia (San Juan District).
OA-PF-1	Pluvial flooding	01/06/1992	Central areas of Errenteria, Pasaia and Oiartzun.
OA-PF-2	Pluvial flooding	01/06/1997	Central areas of Errenteria, Pasaia and Lezo.
OA-PF-3	Pluvial flooding	01/08/2002	Pasaia.
OA-PF-4	Pluvial flooding	01/05/2019	Errenteria centre, Oiartzun and Pasaia.
OA-PF-5	Pluvial flooding	01/12/2021	Town centre of Errenteria.
OA-HS-1	Heavy snowfall	01/01/1985	Shire/county of Oarsoaldea.
OA-CS-1	Cold spell	01/02/1956	Shire/county of Oarsoaldea.
OA-CS-2	Cold spell	01/01/1985	Shire/county of Oarsoaldea.
OA-HW-1	Heat wave	01/07/1982	Province of Guipúzcoa.
OA-HW-2	Heat wave	01/09/1987	Province of Guipúzcoa.
OA-HW-3	Heat wave	01/07/1989	Province of Guipúzcoa.
OA-HW-4	Heat wave	01/07/1990	Province of Guipúzcoa.
OA-HW-5	Heat wave	01/07/1991	Province of Guipúzcoa.
OA-HW-6	Heat wave	01/08/1998	Province of Guipúzcoa.
OA-HW-7	Heat wave	01/06/2003	Province of Guipúzcoa.
OA-HW-8	Heat wave	01/08/2003	Province of Guipúzcoa.
OA-HW-9	Heat wave	01/08/2012	Province of Guipúzcoa.
OA-HW-10	Heat wave	01/08/2016	Province of Guipúzcoa.
OA-HW-11	Heat wave	01/07/2019	Province of Guipúzcoa.
OA-HP-1	Heavy precipitation	01/06/1992	Shire/county of Oarsoaldea.
OA-HP-2	Heavy precipitation	01/05/1993	Shire/county of Oarsoaldea.
OA-HP-3	Heavy precipitation	01/06/1997	Shire/county of Oarsoaldea.
OA-HP-4	Heavy precipitation	01/06/2010	Shire/county of Oarsoaldea.
OA-HP-5	Heavy precipitation	01/10/2012	Shire/county of Oarsoaldea.
OA-HP-6	Heavy precipitation	01/02/2014	Shire/county of Oarsoaldea.
OA-HP-7	Heavy precipitation	01/01/2015	Shire/county of Oarsoaldea.
OA-HP-8	Heavy precipitation	01/03/2016	Shire/county of Oarsoaldea.
OA-HP-9	Heavy precipitation	01/02/2018	Shire/county of Oarsoaldea.
OA-HP-10	Heavy precipitation	01/05/2019	Shire/county of Oarsoaldea.
OA-HP-11	Heavy precipitation	01/11/2021	Shire/county of Oarsoaldea.
OA-HP-12	Heavy precipitation	01/12/2021	Shire/county of Oarsoaldea.

OA-ST-1	Storm	01/11/2009	Pasaia Harbour area
OA-ST-2	Storm	01/01/2019	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-3	Storm	01/11/2019	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-4	Storm	01/12/2019	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-5	Storm	01/02/2020	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-6	Storm	01/09/2020	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-7	Storm	01/12/2020	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-8	Storm	01/01/2021	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-9	Storm	01/02/2021	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-10	Storm	01/12/2021	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ST-11	Storm	01/01/2022	Shire/county of Oarsoaldea, especially the coastline and the harbour
OA-ES-1	Electric storm	01/07/2015	Shire/county of Oarsoaldea.
OA-ES-2	Electric storm	01/06/2017	Shire/county of Oarsoaldea.
OA-ES-3	Electric storm	01/07/2018	Shire/county of Oarsoaldea.
OA-ES-4	Electric storm	01/07/2019	Shire/county of Oarsoaldea.
OA-ES-5	Electric storm	01/08/2019	Shire/county of Oarsoaldea.
OA-ES-6	Electric storm	01/01/2020	Shire/county of Oarsoaldea.
OA-ES-7	Electric storm	01/05/2020	Shire/county of Oarsoaldea.
OA-ES-8	Electric storm	01/06/2021	Shire/county of Oarsoaldea.
OA-DR-1	Drought	1900-1905	Province of Guipúzcoa.
OA-DR-2	Drought	1944-1949	Province of Guipúzcoa.
OA-DR-3	Drought	1987-1991	Province of Guipúzcoa.
OA-DR-4	Drought	01/06/2017	Province of Guipúzcoa.
OA-LS-1	Landslide	01/05/1993	Coastal cliff in Pasaia.
OA-LS-2	Landslide	01/06/2010	District of Antxo (Pasaia).
OA-LS-3	Landslide	01/10/2012	South slope of Ulia mountain, district of Trintxerpe (Pasaia) and Arraindegi street.
OA-LS-4	Landslide	01/02/2014	East side of the mouth of the Harbour, Alabortza rock beach and San Juan district.

OA-LS-5	Landslide	01/01/2015	East side of the mouth and lighthouse of Pasaia Harbour.
OA-LS-6	Landslide	01/03/2016	Westside of the mouth of Pasaia Harbour and Ondartxo avenue.
OA-LS-7	Landslide	01/02/2018	Road Gi-3440 and district of San Juan (Pasaia).
OA-LS-8	Landslide	01/02/2018	District of Trintxerpe (Pasaia) and Azkuene street.
OA-LS-9	Landslide	01/05/2019	Road GI-3440, between Lezo and district of San Juan (Pasaia).
OA-LS-10	Landslide	01/12/2021	Road GI-3440, between Lezo and district of San Juan (Pasaia).

Table A.7. Summary of the past climate-related events collected in Oeiras, including identification code, categorisation, date and affected area.

Event ID	**Climate-related hazard category**	**Date**	**Affected area**
OE-LF-1	Land flooding	22/01/1881	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-2	Land flooding	07/11/1907	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-3	Land flooding	22/12/1909	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-4	Land flooding	15/01/1924	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-5	Land flooding	05/01/1940	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-6	Land flooding	16/10/1946	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-7	Land flooding	07/02/1951	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LS-1	Landslide	31/03/1952	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-8	Land flooding	16/12/1953	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-9	Land flooding	16/12/1953	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-10	Land flooding	26/11/1865	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-11	Land flooding	19/01/1895	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-12	Land flooding	17/03/1916	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-13	Land flooding	02/01/1940	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-14	Land flooding	04/11/1942	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-15	Land flooding	18/11/1945	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-16	Land flooding	16/10/1946	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-17	Land flooding	13/04/1959	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-18	Land flooding	10/10/1962	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.

OE-LF-19	Land flooding	20/11/1937	Carnaxide and Queijas.
OE-LF-20	Land flooding	02/01/1940	Carnaxide and Queijas.
OE-LF-21	Land flooding	16/10/1946	Carnaxide and Queijas.
OE-LF-22	Land flooding	16/10/1946	Carnaxide and Queijas.
OE-LF-23	Land flooding	14/01/1966	Barcarena.
OE-LF-24	Land flooding	25/11/1967	Barcarena.
OE-LS-2	Landslide	08/01/1996	Barcarena.
OE-LF-25	Land flooding	18/11/2011	Barcarena.
OE-LF-26	Land flooding	15/01/1964	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-27	Land flooding	15/01/1964	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-28	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-29	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-30	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-31	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-32	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-33	Land flooding	25/11/1967	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-34	Land flooding	19/11/1983	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LS-3	Landslide	08/01/1996	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-35	Land flooding	08/01/1996	Oeiras, S. Julião da Barra, Paço de Arcos and Caxias.
OE-LF-36	Land flooding	18/02/1966	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-37	Land flooding	25/11/1967	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-38	Land flooding	25/11/1967	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-39	Land flooding	25/11/1967	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-40	Land flooding	25/11/1967	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LS-4	Landslide	13/03/1969	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LS-5	Landslide	18/03/1969	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LS-6	Landslide	03/03/1978	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-41	Land flooding	18/11/1983	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-42	Land flooding	30/10/1993	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-43	Land flooding	08/01/1996	Algés, Linda-a-Velha and Cruz Quebrada-Dafundo.
OE-LF-44	Land flooding	25/11/1967	Carnaxide and Queijas.
OE-LF-45	Land flooding	25/11/1967	Porto Salvo.

Table A.8. Summary of the past climate-related events collected in Massa, including identification code, categorisation, date and affected area.

Event ID	**Climate-related hazard category**	**Date**	**Affected area**

MA-HP-1	Heavy precipitation	06/11/1994	Hilly area.
MA-HP-2	Heavy precipitation	10/11/1994	Hilly area.
MA-CS-1	Coastal Storm	14/05/1995	East coast.
MA-CS-2	Coastal Storm	01/07/1997	East coast.
MA-CS-3	Coastal Storm	09/02/1998	East coast.
MA-CS-4	Coastal Storm	28/12/1999	East coast.
MA-CS-5	Coastal Storm	08/11/2001-09/11/2001	West coast.
MA-PF-1	Pluvial Flood	21/09/2002-22/09/2002	City centre and coastal area.
MA-PF-2	Pluvial Flood	23/09/2003	Mountain areas.
MA-CS-6	Coastal Storm	October 2003	West coast.
MA-LS-1	Landslide	10/04/2004-11/04/2004	Mountain areas.
MA-LS-2	Landslide	27/02/2007-28/02/2007	Mountain area of Guadine.
MA-LS-3	Landslide	05/03/2008	Hilly and mountain areas.
MA-LS-4	Landslide	19/05/2008-20/05/2008	Mountain area (Belvedere).
MA-PF-3	Pluvial Flood	30/10/2008-31/10/2008	City centre and hilly area.
MA-PF-4	Pluvial Flood	04/11/2008	City centre and hilly area.
MA-PF-5	Pluvial Flood	10/12/2008	Hilly and mountain areas.
MA-LS-5	Landslide	20/01/2009	Hilly and mountain areas.
MA-LS-6	Landslide	02/02/2009	Hilly and mountain areas.
MA-RF-1	River flood	29/07/2009-30/07/2009	Coastal area.
MA-LS-7	Landslide	10/01/2010	Hilly and mountain areas.
MA-HP-3	Heavy precipitation	31/10/2010-01/11/2010	Coastal area.
MA-LS-8	Landslide	24/10/2011-25/10/2011	Hilly and mountain areas.
MA-RF-2	River Flood	10/11/2012-11/11/2012	Coastal area.
MA-HP-4	Heavy precipitation	27/11/2012	Coastal area (Ricortola) and hilly area (Romagnano).
MA-LS-9	Landslide	04/01/2014-05/01/2014	Mountain area (Casette, Forno).
MA-LS-10	Landslide	20/01/2014	Mountain areas.
MA-LS-11	Landslide	30/01/2014	Mountain areas.
MA-LS-12	Landslide	14/01/2014	Mountain areas.
MA-LS-13	Landslide	01/02/2014	Mountain areas.
MA-CS-7	Coastal Storm	04/03/2015 05/03/2015	Coastal area.
MA-CS-8	Coastal Storm	26/09/2021	City centre and coastal area.

Table A.9. Summary of the past climate-related events collected in Gdańsk, including identification code, categorisation, and date.

Event ID	**Climate-related hazard category**	**Date**

GA-PF-1	Pluvial flooding	11/07/1992
GA-PF-2	Pluvial flooding	10/09/1994
GA-PF-3	Pluvial flooding	11/07/2000
GA-PF-4	Pluvial flooding	09/07/2001
GA-PF-5	Pluvial flooding	28/05/2002
GA-PF-6	Pluvial flooding	28/07/2003
GA-PF-7	Pluvial flooding	21/07/2004
GA-PF-8	Pluvial flooding	19/09/2006
GA-PF-9	Pluvial flooding	13/08/2007
GA-PF-10	Pluvial flooding	01/07/2009
GA-PF-11	Pluvial flooding	18/07/2009
GA-PF-12	Pluvial flooding	03/08/2010
GA-PF-13	Pluvial flooding	27/09/2010
GA-PF-14	Pluvial flooding	07/13/2011
GA-PF-15	Pluvial flooding	24/08/2011
GA-PF-16	Pluvial flooding	07/07/2012
GA-PF-17	Pluvial flooding	03/08/2012
GA-PF-18	Pluvial flooding	20/08/2012
GA-PF-19	Pluvial flooding	23/06/2013
GA-PF-20	Pluvial flooding	05/08/2014
GA-PF-21	Pluvial flooding	08/09/2014
GA-PF-22	Pluvial flooding	14/11/2015
GA-PF-23	Pluvial flooding	14/07/2016

Table A.10. Summary of the past climate-related events collected in Samsun, including identification code, categorisation, and date.

Event ID	**Climate-related hazard category**	**Date**
SA-PF-1	Pluvial flooding	17/02/1963
SA-PF-2	Pluvial flooding	09/06/1971
SA-PF-3	Pluvial flooding	31/07/1972
SA-PF-4	Pluvial flooding	04/07/1977
SA-PF-5	Pluvial flooding	04/07/1977
SA-PF-6	Pluvial flooding	06/18/2010
SA-PF-7	Pluvial flooding	04/07/2012
SA-PF-8	Pluvial flooding	04/07/2012
SA-PF-9	Pluvial flooding	07/08/2012
SA-PF-10	Pluvial flooding	07/08/2012

SA-PF-11	Pluvial flooding	07/08/2012