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Extreme climate change hazards and impacts on European coastal cities: A review

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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. 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.

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 [1]. Climate-related disasters could affect about two-thirds of the European population annually by the year 2100 (351 million Expected Annual Number of People Exposed (EAPE) on average) compared to 5% between 1981 and 2010 (25 million EAPE on average) [2]. 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 [2]. 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 [3,4].

In the case of coastal cities, coastal storms can be considered as the main climate-related hazard, as these lead to destructive Extreme Sea-levels (ESLs), coastal flooding and coastal erosion [5–7]. A climate risk assessment performed by Abadie et al. (2016) [8] estimated the Expected Annual Damage (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 Expected Annual Damage (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 [9]. These findings align with other regional assessments conducted for coastal flooding in the German Bight [10,11], UK [12], Portugal [13], Adriatic Sea [14], Baltic Sea [15] and Balearic Sea [16]. 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 [9,13,17]. 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

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Nomenclature and abbreviations

CCLL	Coastal City Living Lab
EAD	Expected Annual Damage
EAPE	Expected Number of People Exposed
EBA	Ecosystem-Based Approach
ESL	Extreme Sea-level
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
NGO	Non-Governmental Organization
RCP	Representative Concentration Pathway
RFCT	Regional Functional Centre of Tuscany
SCORE	Smart Control of the Climate Resilience in European Coastal Cities
WoS	Web of Science

high-end warming, increasing coastal flooding risk significantly [9]. 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 [4,18], or regarding specific topics related to cities (e.g., weather [19, 20], renewable energy [21,22], energy consumption [23], infrastructure [24,25], cultural heritage [26], health [27], tourism [28], or research momentum [29]). 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 [30], historical patterns of ESL in Venice, Italy [14], or historic storms across various European coastal areas (i.e.: Belgium, Bulgaria, France, Italy, Netherlands, Poland, Portugal, Spain and the United Kingdom) [31]. 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 Coastal City Living Lab (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 [32–34]. 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.

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 synthesise 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 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.

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 Intergovernmental Panel on Climate Change (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 2). Climate change agencies focusing on international to European and national-local scales were consulted through a desktop study,

Table 1
CCLLs 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

Table 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 (IPCC)	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 (NGOs)	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

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.

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 presents the keywords tailored to the global and European context, while Table 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.

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

Table 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 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	Oeiras	Massa	Piran	Gdańsk	Samsun
Climate Change	7; 10	71; 81	0; 1	7; 7	1; 0	2; 3	7; 4	6; 5	63; 86	14; 23
Flooding	2; 2	18; 33	0; 0	0; 0	0; 0	0; 1	4; 0	4; 3	29; 57	6; 10
Coastal Erosion	0; 0	1; 0	0; 0	0; 1	0; 0	0; 0	0; 0	0; 0	23; 20	6; 0
Shoreline Retreat	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0	1; 1	1; 0
Sea-level Rise	0; 0	7; 4	0; 0	0; 0	4; 0	0; 0	0; 0	2; 1	22; 20	2; 4
Temperature rise	1; 1	4; 18	0; 0	0; 3	0; 0	0; 0	1; 1	1; 0	13; 14	3; 13
Storm	0; 0	35; 19	0; 0	12; 23	1; 0	1; 0	4; 1	2; 2	58; 42	1; 1
Climate Change Extreme Impacts	0; 0	2; 2	0; 0	1; 0	0; 0	0; 0	0; 0	0; 0	3; 2	0; 0
Drought	0; 0	8; 11	0; 0	3; 5	1; 2	1; 2	0; 0	0; 0	5; 3	12; 36
Rainfall	3; 3	30; 33		3; 4	0; 2	0; 2	8; 2	1; 1	16; 31	13; 17
Total	29	377	1	71	12	12	32	28	514	163

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 and 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 5 provides insights on the topics discussed with the CCLL partners in the development of local expertise.

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.

Table 5
Main topics of discussion with the CCLL 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.

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 [35]. 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 6 presents the climate change agencies closely related to the cities considered, including relevant documentation regarding climate change impacts.

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) [36]. Coastal flooding and erosion have a high potential of causing significant and irreparable damage. In addition, information regarding

Table 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 Instituto of Geography and Spatial Planning - University of Lisbon Environment Portuguese Agency Portuguese Institute for Sea and Atmosphere, I. P. Câmara Municipal de Oeiras	Civil Protection Municipality plan 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

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 [37] 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 [38]. 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 [39]. Furthermore, historical analyses of exposure and vulnerability to flood hazards in Irish cities (Cork, Galway and Dublin) can be found in Jeffers (2014) [40], whereas the increasing trend in extreme rainfall has been confirmed by al Saji et al. (2015) [41]. 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) [42] analyse persistent meteorological droughts in Ireland, including in the city of Dublin. For instance, the summer of 2018 brought a significant meteorological drought [43]. Particular studies of maximum temperatures in County Dublin can be found as well in O'Sullivan et al. (2020) [44], although heat-attributable deaths are very unusual in this area [45]. 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 [46]. 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 [47]. 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) [48]. 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 [49]. 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 [50]. 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 [51]. In this context, insights of Benidorm's urban development under drought-prone conditions can be found at Cremades et al. (2021) [52]. 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) [53,54]. Broadly, adaptation strategies of the hydrosocial cycles in the Mediterranean region are also reviewed and analysed in Arahuetes Hidalgo et al. (2018) [55].

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 [56]. Furthermore, the Deba area (Guipuzcoa) is intensely affected by frequent shallow landslides triggered by rainfall [57] - 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 [57] - with 1180 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 [58], 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 [59]. 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 [64]. 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 [69]. 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 [70]. This last flash flood was particularly extreme and caused important landslides [71,72]. 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 [73,74]. 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 Center 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* [65]), which periodically publishes studies on this topic [65], the RFCT also contributes to the study of local climate change.

The northern area of the Adriatic Sea is prone to storms [75], 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) [76]. 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 [78,79], and the extreme changes in temperature (both heat-waves and spell colds) affect the human mortality in the city of Gdańsk [80]. 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 [15]. For instance, a 40 cm sea-level rise would considerably increase the frequency of flooding [81]. Similarly, the amplitude of ESLs has increased during the last decades, with the highest peaks occurring in the autumn and winter months [82], and the storminess is expected to increase in the open, eastern part of the gulf, and to decrease in the sheltered, western part [83]. 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 [84]. 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 [85]. 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 [86]. 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) [93], and probabilities of extreme rainfall events are analysed in Szpakowski et al. (2018) [94], 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) [99]. The main negative consequences due to climate change in Gdańsk are well stablished [100]. 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 m. 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 [105,106]. 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 km. 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 [110,111]. 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.

4. Discussion and conclusions

Based on a novel collaborative approach through the concept of Coastal City Living Lab 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.

Authors contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by E. Laino. The first draft of the manuscript was written by E. Laino, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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