Natural Hazards (2024) 120:3623–3659
https://doi.org/10.1007/s11069-023-06349-4

ORIGINAL PAPER

High-level characterisation and mapping of key climate-change hazards in European coastal cities

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Received: 24 February 2023 / Accepted: 19 November 2023 / Published online: 13 December 2023

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.

Keywords Climate change · Extreme impacts · Coastal flooding · Coastal erosion · Coastal cities · GIS · Mapping

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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 (Meehl and Tebaldi 2004; Barredo 2007; Beniston et al. 2007; Dankers and Feyen 2008; Vousdoukas et al. 2017; Hosseinzadehtalaei et al. 2020). Overall, these changes would mostly affect tidal deltas, low-lying coastal plains, sandy beaches, barrier islands, coastal wetlands, and estuaries (Ghorai and Sen 2015; J Bergillos et al. 2019a, b; Khojasteh et al. 2022). The impacts in Europe may vary from country to country, but they all affect large human and ecological values (Bergillos et al. 2020; Rodriguez-Delgado et al. 2020; García et al. 2020). Many sectors and systems are likely to be affected, adversely or positively, depending on the climate scenario, region, or sector analysed (Beniston and Tol 1998; Lückenkötter et al. 2013; Kebede et al. 2015; Martinez and Iglesias 2021).

In the last years, the European Commission has devoted particular attention, inter alia, to the concepts of integrated coastal zone management (ICZM), ecosystem-based approaches (EBA) and nature-based solutions (NBS) to address the challenge of climate change in Europe (Faivre et al. 2017; Lafortezza et al. 2018; Laino and Iglesias 2023a). These tools are critical to build the foundations for sustainable development and coastal management and to foster socio-economic development, biodiversity and ecosystem services (Rodriguez-Delgado et al. 2018, 2019a, b; Bergillos et al. 2019a, b; O'Shaughnessy et al. 2020). 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 Coastal City Living Lab (CCLL). Details on these areas and the corresponding CCLLs are given in Table 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 (Laino and Iglesias 2023b) 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.

Table 1 CCLLs partners and associated coastal area in the SCORE project

CCLL	Country	Partner's name	Geographical coastal area
Sligo	Ireland	Atlantic Technological University	Coast of County Sligo
Dublin	Ireland	University College Dublin, and Dún Laoghaire-Rathdown County Council	Coast of Great Dublin Area
Vilanova i la Geltrú	Spain	Vilanova i la Geltrú City Council, Barcelona Provincial Council, and Environment and Management (ENT)	Coast of Vilanova i la Geltrú
Benidorm	Spain	University of Alicante	Coast of Benidorm municipality
Oarsoaldea	Spain	Oarsoaldea and Naider	East coast of Guipúzcoa province
Oeiras	Portugal	Câmara Municipal de Oeiras	Tagus River estuary
Massa	Italy	Municipality of Massa	Marina di Massa
Piran	Slovenia	Science and Research Centre, Koper, Slovenia	Coast of Piran municipality
Gdańsk	Poland	University of Gdańsk	Vistula Spit
Samsun	Turkey	University of Samsun	Kızılırmak Delta

2 Materials and methods

The methodology is based on the novel concept of Coastal City Living Lab (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. Figure 1 illustrates the methodology.

The climate-related events were classified under a wide variety of categories, mainly based on the Sixth Assessment Report from the IPCC (Chapter 12) (Ranasinghe et al. 2021). 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. 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.

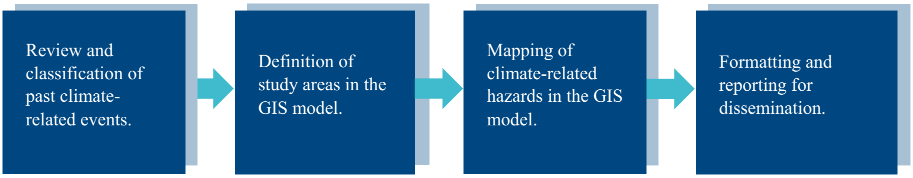

Fig. 1 Workflow of the methodology to produce the maps illustrating the key climate-hazards in the coastal cities

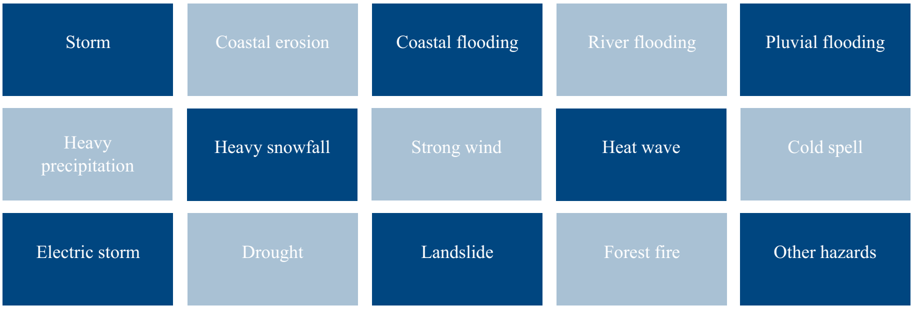

Fig. 2 Overview of the climate-change-related events identified

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.

3 Results

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 localised 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.

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 2, and a summary map illustrating the key climate-related hazards for each city is shown in Fig. 3. Complementarily, a breakdown of the number of events per category can be found in the Appendix (Tables 3 and 4).

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 (Figs. 4 and 5). The increased frequency and intensity of winter storms is the main hazard identified (Leahy and Kiely 2011). In total, forty-nine (49) past climate-related events have been registered for Sligo, as summarised in Table 5 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 (Ordnance Survey Ireland and Government of Ireland 2022). Storms, coastal and land flooding and coastal erosion are critical hazards in Dublin, too (Cooke et al. 2005; Leahy and Kiely 2011; Jeffers 2014; Al Saji et al. 2015). 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 (Commissioners of Public Works in Ireland 2022). This map provides information about the location of known flood events in Ireland and supporting information in the form of reports, photographs and press articles (Fig. 6).

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. 7) (Lopez-Bustins et al. 2013; Versini et al. 2013; Ballesteros et al. 2018). Although most of the SLR studies in the Spanish Mediterranean coast are focussed 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 (Portillo Juan et al. 2022). 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 (Servei Meteorològic de Catalunya). In addition, the document *Vilanova i la Geltrú Climate Change Adaptation Plan* holds information on extreme temperatures (ERF Estudi Ramon Folch i Associats et al. 2018). 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. 6). 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 (Institut Cartogràfic i Geològic de Catalunya and Generalitat de Catalunya—Departament de la Vicepresidència i de Polítiques Digitals i Territori). In addition, two (2), three (3), six (6) and four (4) episodes

Table 2 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

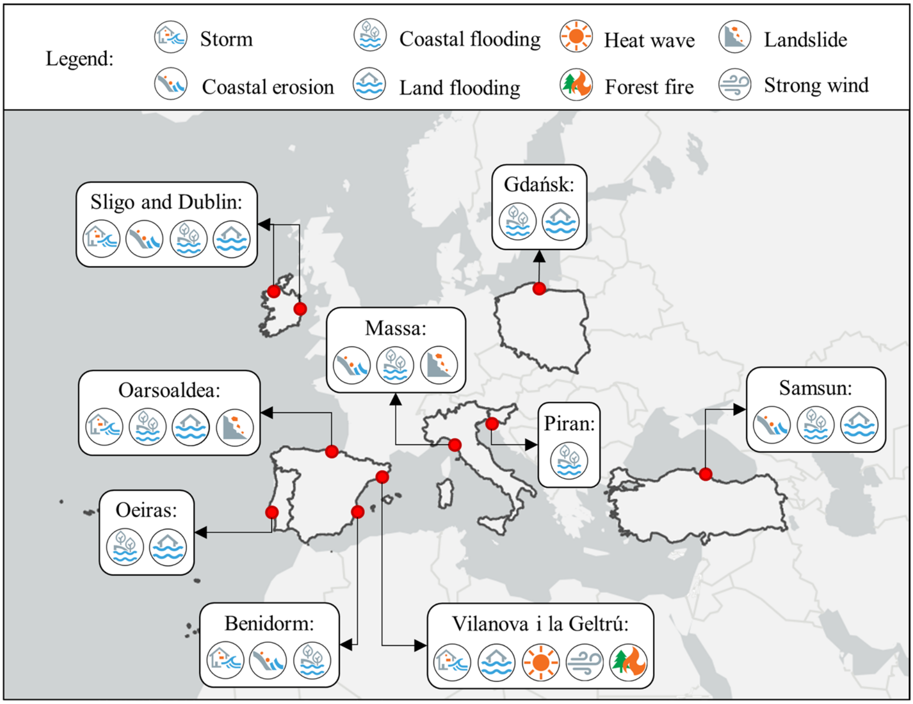

Fig. 3 Schematic representation of the key climate-related hazards identified in the ten coastal cities studied

Table 3 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 4 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

of storms, strong winds, land flooding, and forest fires, respectively, have been registered (Table 6 in Appendix). The geographical data were retrieved from the National Institute of Geography of Spain (Instituto Geográfico Nacional).

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 (Imeson et al. 1998; Gonzalez-Hidalgo et al. 2007; Diez et al. 2013; Fernández Montes and Sánchez Rodrigo 2014; Camarasa-Belmonte et al. 2020; Toledo et al. 2022). 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. 8 and Table 7 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 (Institut Cartogràfic Valencià and Generalitat Valenciana). The shapefiles representing the three beaches (Levante, Poniente and Cala Finestrat) were provided by the Benidorm CCLL. The

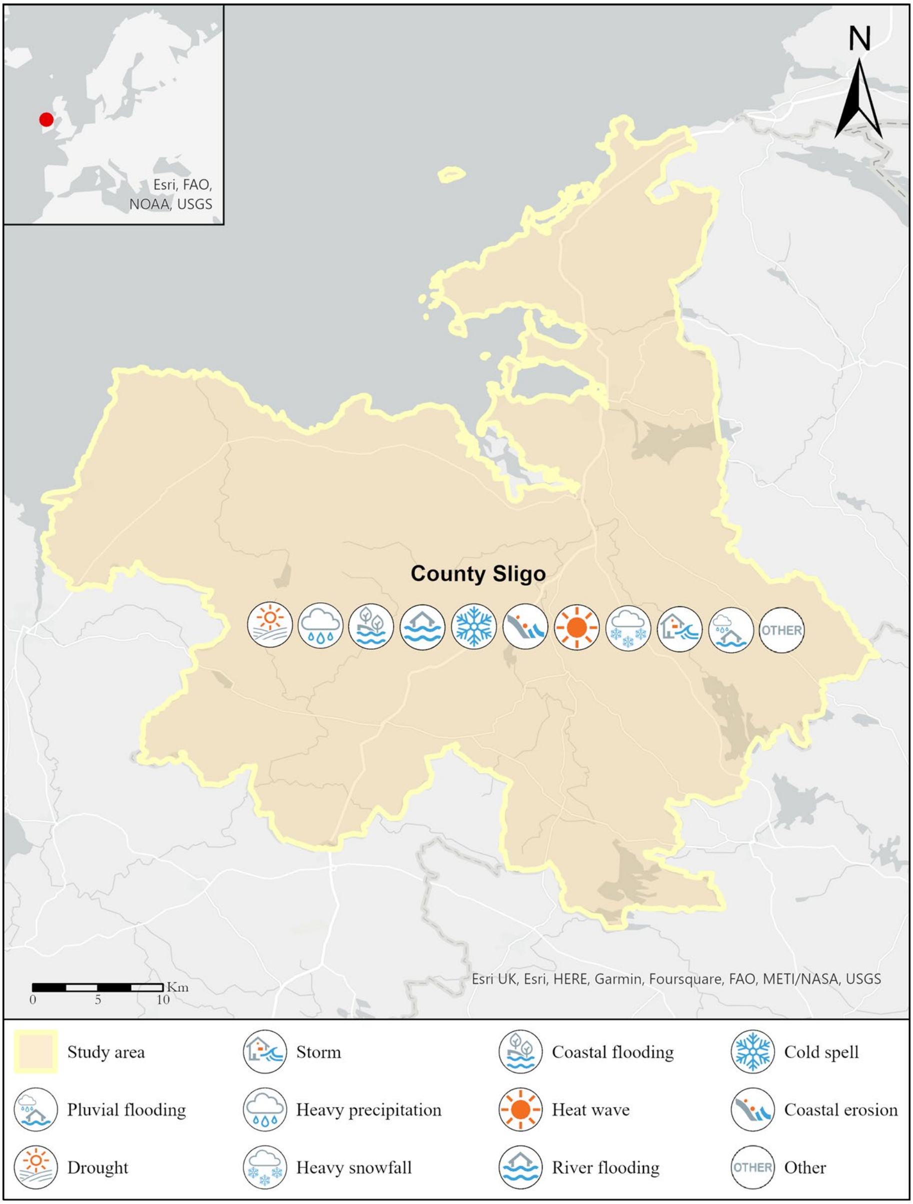

Fig. 4 Schematic representation of the climate-related hazards identified in Sligo, Ireland

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.

The main climate-related hazards identified in Oarsoaldea are storms, coastal and land flooding, and landslides (Chust et al. 2009; Ocio et al. 2016; Rivas et al. 2020). 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

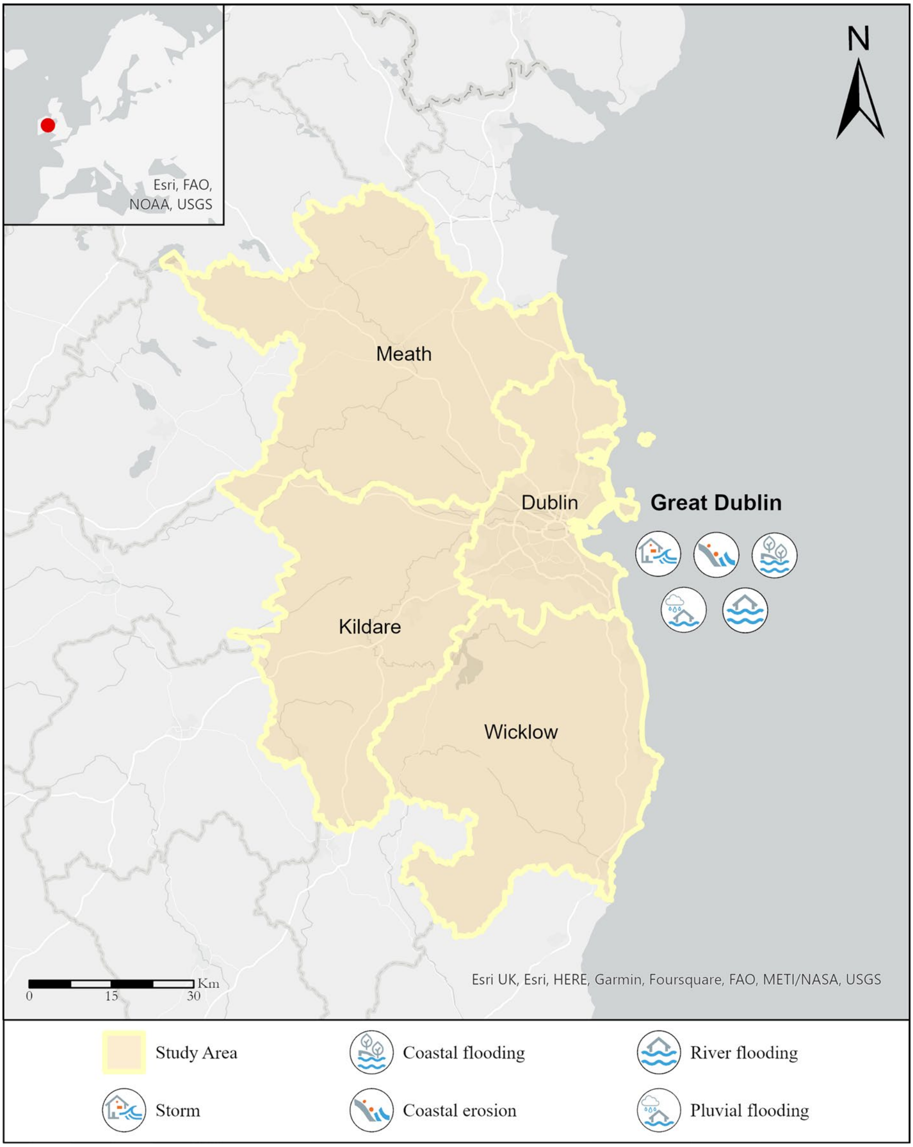

Fig. 5 Schematic representation of the climate-related hazards identified in Dublin, Ireland

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. 9 and Table 8 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.

Table 5 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	–

Table 5 (continued)

Event ID	Climate-related hazard category	Date	Additional information
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	–

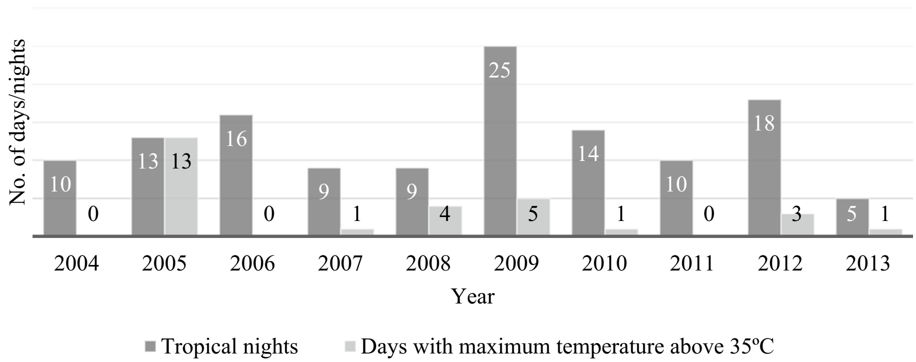

Fig. 6 Evolution of the number of tropical nights and hot days at the Sant Pere de Ribes weather station (2004–2013). From: Vilanova i la Geltrú Climate Change Adaptation Plan

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 (geoEuskadi).

Coastal and land flooding are the most relevant climate-related hazard in Oeiras (Santos et al. 2010; Martins et al. 2012; Leal et al. 2018; Tavares et al. 2021). However, as explained hereinafter, other hazards are also important (Fig. 10). The main information sources on past climate events for Oeiras is the DISASTER database (Zêzere et al. 2014), 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 (Autoridade Nacional de Emergência e Proteção Civil), and the *Civil Protection Municipality Plan* (Proteção Civil de Oeiras), containing, respectively, a wide variety of natural and technological related hazards which occurred in Portugal since 2006, and

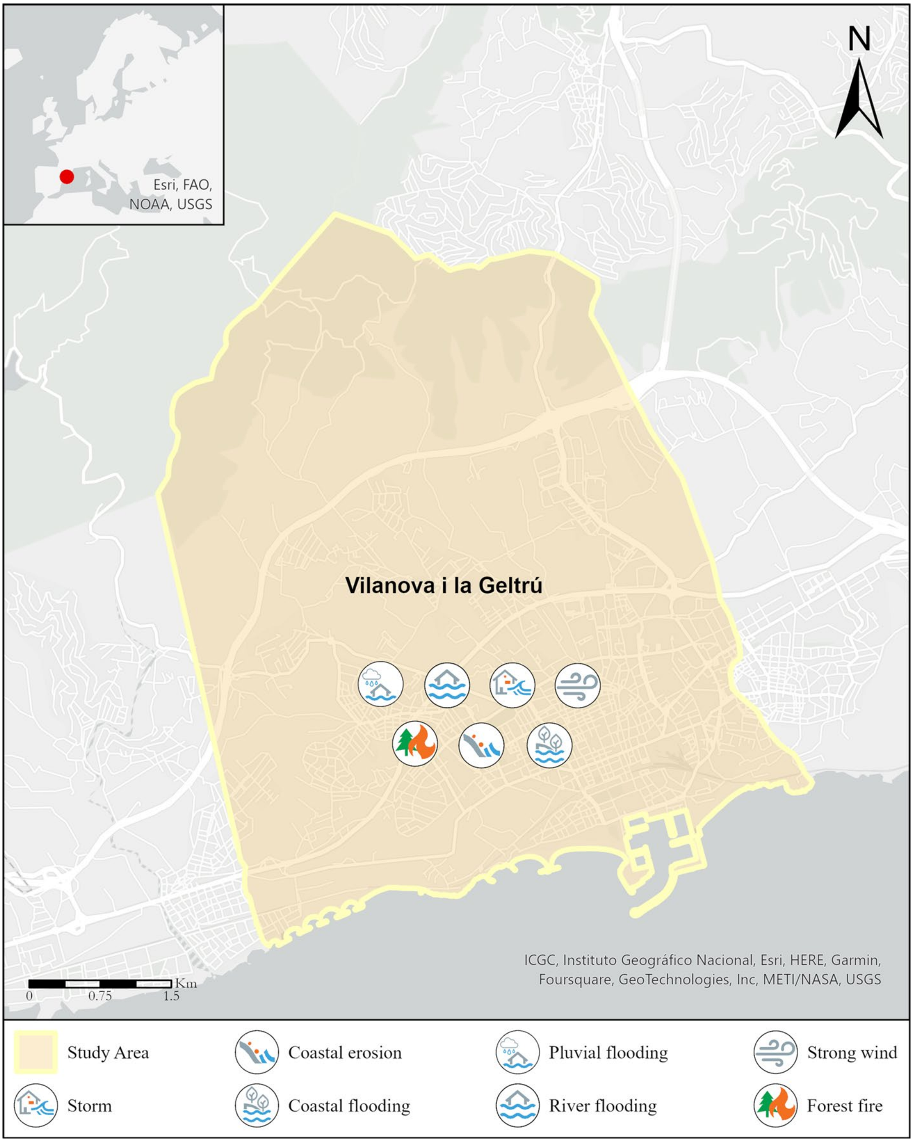

Fig. 7 Schematic representation of the climate-related hazards identified in Vilanova i la Geltrú, Spain

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 9 in Appendix). Most of the events are concentrated along the coastline, in the parishes of Oeiras e São

Table 6 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

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).

As regards 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 (Brunetti et al. 2004; Rudari et al. 2005; Anfuso et al. 2011; D'Amato Avanzi et al. 2013; Pranzini et al. 2018; Caporali et al. 2021). 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 (Regional Functional Centre). The past events identified include the categories of heavy precipitation, coastal storm, coastal erosion, river flooding, pluvial flooding, landslides and strong winds (Fig. 11). 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 10 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

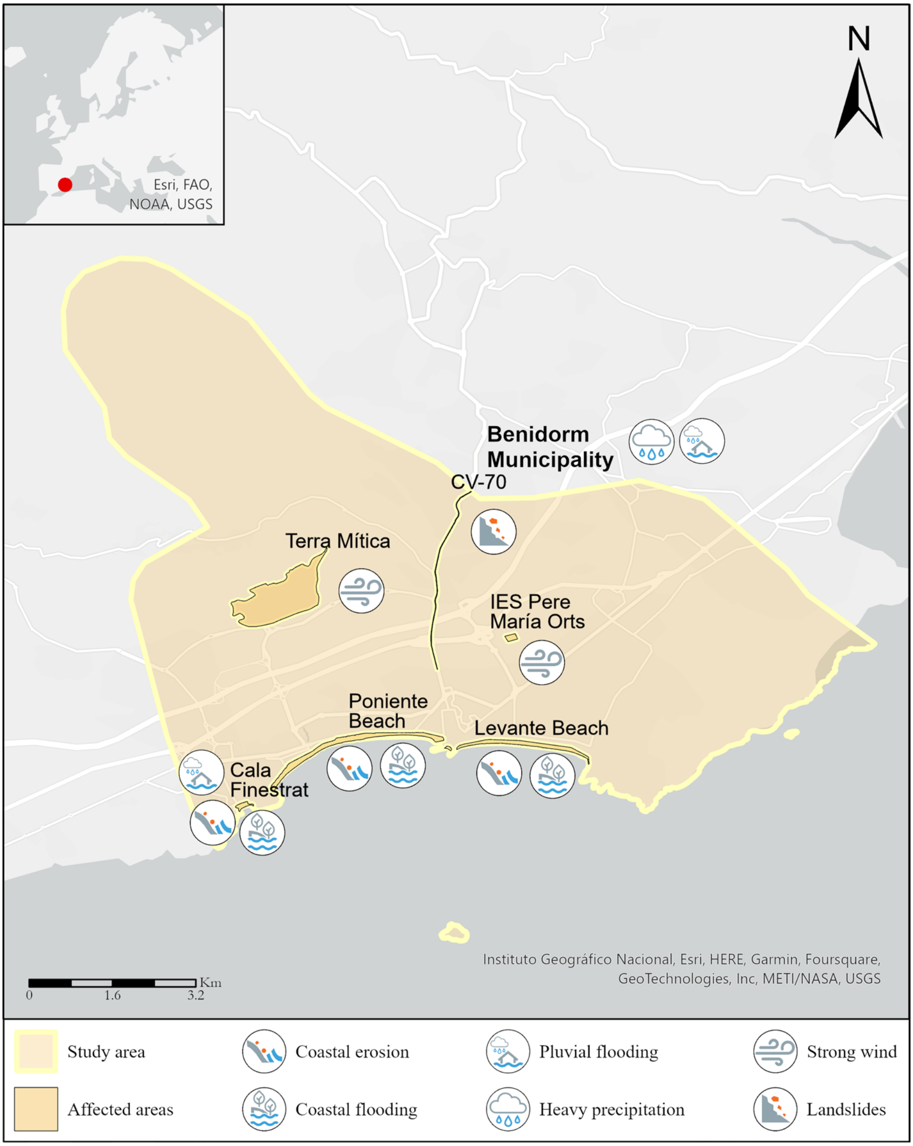

Fig. 8 Schematic representation of the climate-related hazards identified in Benidorm, Spain

landslides, which are publicly available on a web-viewer (District Basin Authority of the Northern Apennines). The geographical data representing the municipality of Massa were downloaded from the National Institute of Statistics of Italy (National Institute of Statistics of Italy).

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. 12) (Kovačič et al. 2016; Lionello et al. 2016; Brečko Grubar et al. 2019). The main source providing information is the platform managed by the Administration of the

Table 7 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

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,

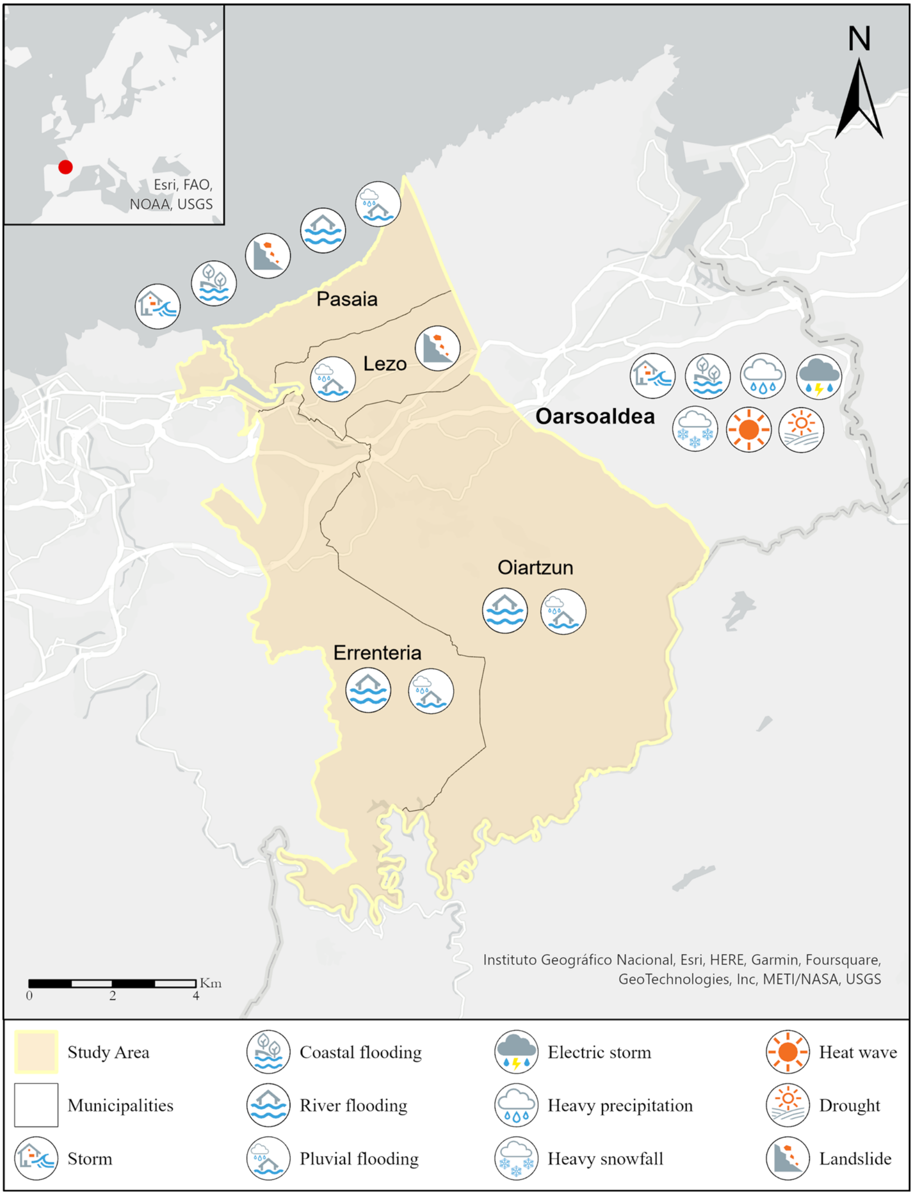

Fig. 9 Schematic representation of the climate-related hazards identified in Oarsoaldea, Spain

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

Table 8 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

Table 8 (continued)

Event ID	Climate-related hazard category	Date	Affected area
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

Table 8 (continued)

Event ID	Climate-related hazard category	Date	Affected area
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)

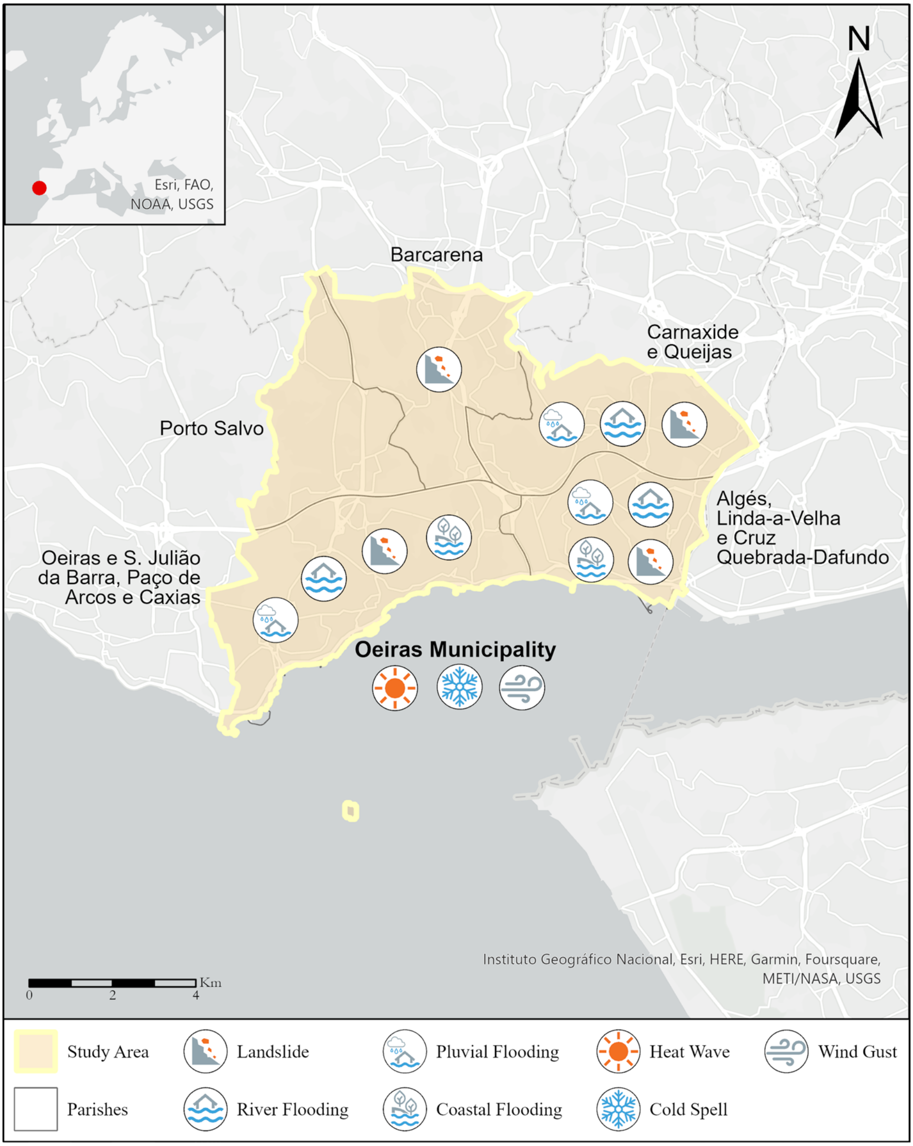

Fig. 10 Schematic representation of the climate-related hazards identified in Oeiras, Portugal

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 (Ministry of the Environment and Spatial Planning–Directorate of the Republic of Slovenia for Water). Besides, the document *Analysis of landslide occurrence in Slovenia and preparation of landslide probability* provides significant information on the landslide hazard in the city (Administration of the Republic of Slovenia for Protection and Rescue). The probability scenarios included in the document show the negligible, very low, low, medium, high and very high

Table 9 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

Table 9 (continued)

Event ID	Climate-related hazard category	Date	Affected area
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

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 (Gallina et al. 2020). The shapefile representing Piran municipality was retrieved from the University of Texas at Austin portal (Robert J. Hijmans–University of California (Berkeley)–Museum of Vertebrate Zoology 2015).

The most serious threat in Gdańsk is the occurrence of sudden urban floods (flash floods), river floods and coastal flooding events (Fig. 13) (Marosz 2007; Urbański and Ślimak 2008; Wiśniewski et al. 2009, 2011; Suligowski and Nawrot 2018). 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* (Government of Poland). 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 11 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 (Paprotny and Terefenko 2017). Additional important threats that affect Gdańsk are the occurrence of strong gusts of wind and torrential rains due to intense storms (Badur and Cieślikiewicz 2018; Szpakowski and Szydłowski 2018; Tylkowski and Hojan 2018), and the increasing frequency of heat waves and hot days (Swiatek 2019; Grelowska and Kozaczka 2020; Kuchcik 2021).

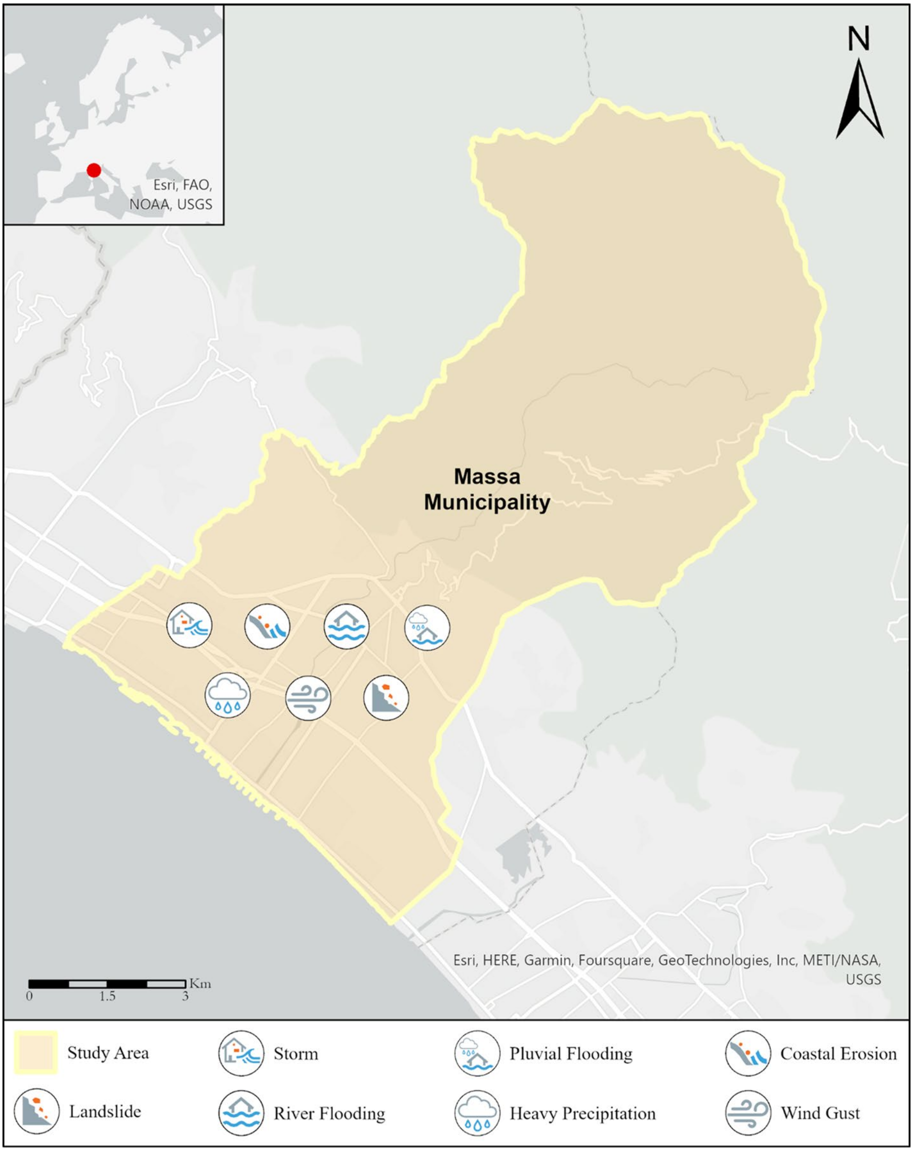

Fig. 11 Schematic representation of the climate-related hazards identified in Massa, Italy

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. 14) (Demir and Kisi 2016; Beden and Ulke 2020). 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 in the Kızılırmak Delta (Samsun). Satellite imagery and three different methods were used to determine the

Table 10 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

shoreline changes. Secondly, a similar study was developed by (Ozturk and Sesli 2015) 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 in 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

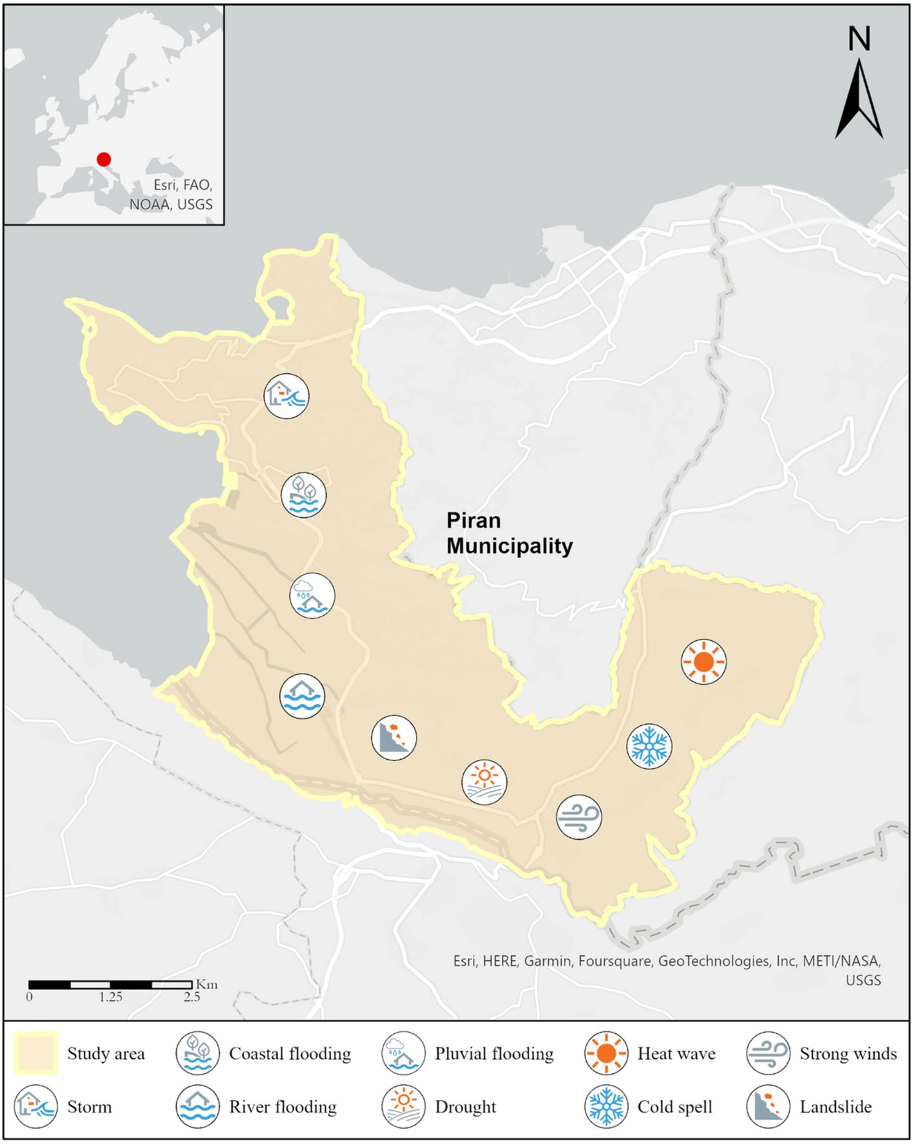

Fig. 12 Schematic representation of the climate-related hazards identified in Piran, Slovenia

in the area for the period 1963–2012 (Table 12 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 (Regional IM Working Group—Europe).

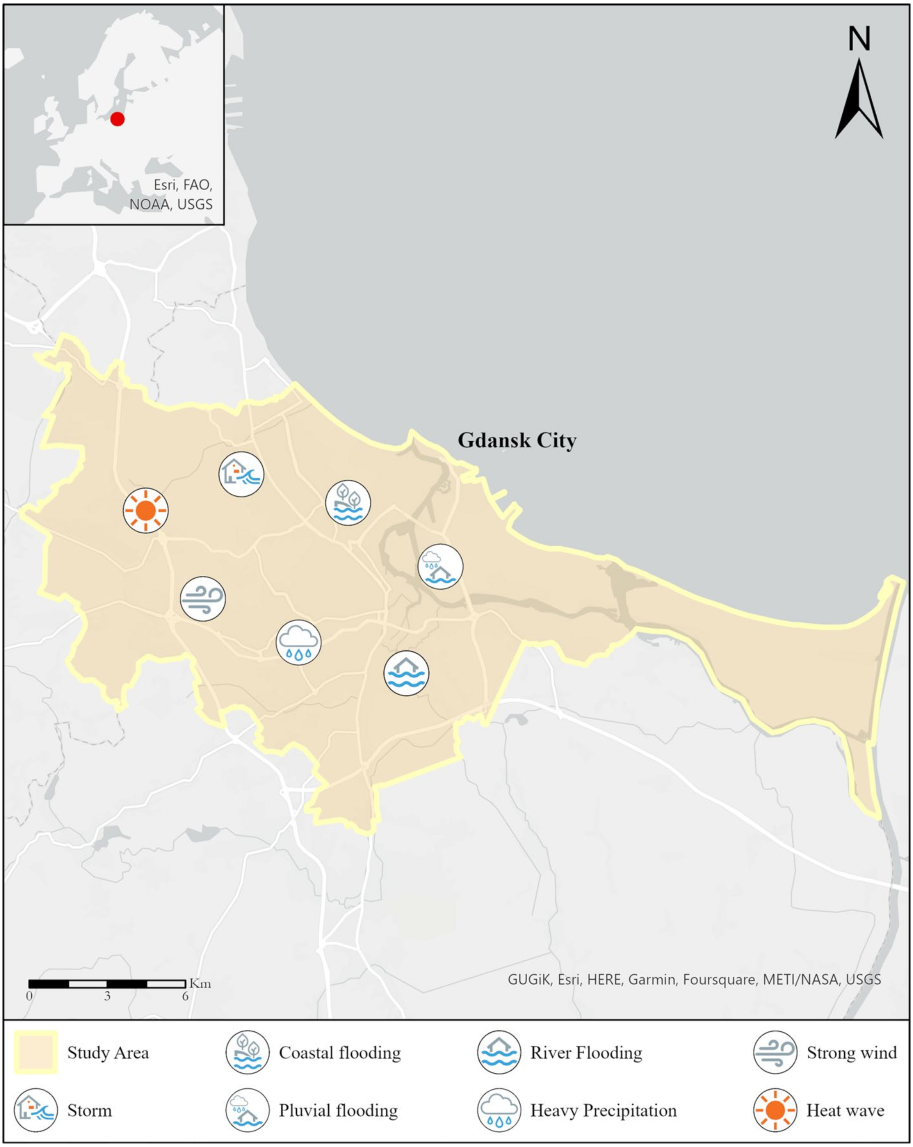

Fig. 13 Schematic representation of the climate-related hazards identified in Gdańsk, Poland

4 Conclusions

Planning for coastal adaptation and the management of coastal defences and ecosystems requires a comprehensive understanding of the hazards affecting coastal cities. A high-level identification of the key hazards derived from climate change in ten European coastal cities was carried out following an approach based on the establishment, and liaison with, ten Coastal City Living Labs (CCLLs), encompassing diverse climatic regions and socioeconomic realities within Europe.

Table 11 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

A methodology to assess climate-related hazards in coastal areas involving the participation of the CCLLs was developed. The use of local expertise enhanced the detection of the specific challenges related to sea-level rise, coastal erosion, and extreme events through the interaction of CCLL with complex local administrations and other relevant agents. A database containing past extreme climate-related events was produced, and the results were summarised graphically through maps representing climate-related hazards and the respective areas affected for each CCLL. The cooperation with the CCLLs was of great help in dealing with issues related to the adequacy of the data received (e.g. content, format, language, confidentiality, and level of detail). It also allowed the level of detail for some of the cities to be increased through zoning based on administrative boundaries (municipalities in Oarsoaldea and parishes in Oeiras), elements of the city (Benidorm) or qualitative areas (Massa). The methodology is flexible enough to enable the identification of critical areas or city elements. These findings may be used to devise future adaptation measures or design actions within the city. This methodology was applied to ten European coastal cities in this work, but it may be applied elsewhere.

Relative sea-level rise and associated extreme sea levels during storms or meteotsunamis pose a major hazard to human life, property, and infrastructure in coastal cities. Their

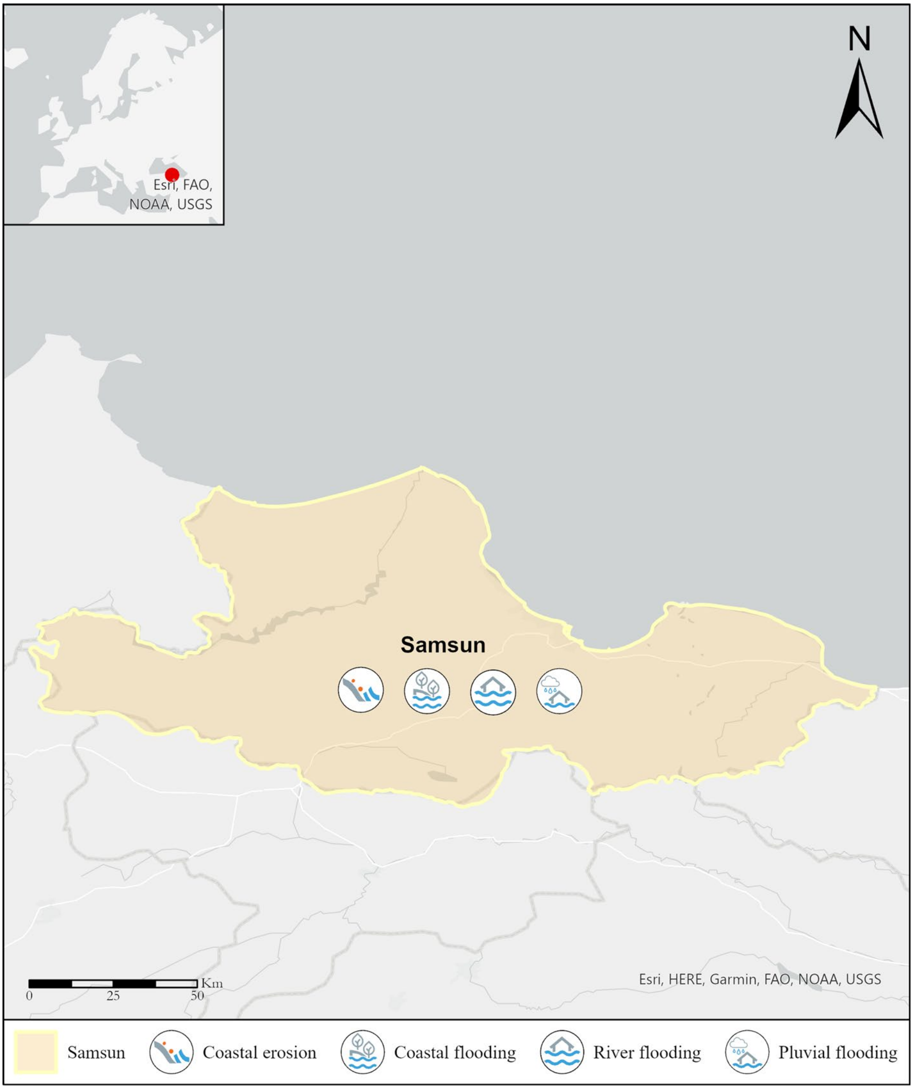

Fig. 14 Schematic representation of the climate-related hazards identified in Samsun, Turkey

effects may include coastal flooding, coastal erosion, and saltwater intrusion into surface and groundwater, negatively affecting the water supply, agriculture and ecosystems. Rising extreme sea levels may trigger new or more devastating coastal flooding events, putting at risk people, ecosystems, assets, and critical infrastructure, including water supply systems. Coastal defences have generally been designed to withstand floods whose frequency and intensity are now increasing, for which their effectiveness can be drastically reduced. As coastal flooding is expected to become more frequent and more intense especially in northern and western Europe, but also in northern Adriatic Sea regions, it is a key hazard

Table 12 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

in Sligo, Dublin, Piran and Gdansk, although it cannot be neglected in the rest of the coastal cities considered. Coastal erosion was found to be a critical hazard in Samsun due to the prevalence of agricultural activity and the presence of several Ramsar sites in the Kızılırmak Delta.

Heatwaves pose a risk to human health and affect productivity. These were identified as a significant hazard in Sligo, Oarsoaldea, Oeiras, Piran and Gdansk. This result is in line with the EEA, which has informed that hot extremes and humid heatwaves are projected to increase rapidly across Europe. Heatwaves also increase forest fire risk, which is especially relevant in Vilanova i la Geltrú, and negatively affect agriculture and ecosystems.

Land flooding may trigger losses of human lives, infrastructure, buildings, facilities, services, cultural heritage, industry, agriculture, and ecosystems. Flood levels depend directly on the intensity of rainfall; however, they are also affected by non-climatic factors, such as land cover and use, changes to river basins, natural water flow characteristics and soil conditions. In some cases, land flooding may be aggravated by landslides. In general, heavy precipitation events are expected to increase in frequency and intensity in northern Europe, and in intensity in central Europe, whereas mixed changes are projected for southern Europe. Land flooding is of particular concern in Benidorm, Oarsoaldea, Oeiras and Massa.

Somewhat counterintuitively, the drought hazard is compatible with the land flooding hazard when precipitation occurs in few, short and intense episodes during the hydrological year. Droughts have the potential to affect socioeconomic activities, ecosystems, soil characteristics and water availability. Although they may potentially affect all regions in Europe, the drier climate in Southern Europe is in principle more prone to droughts. The CCLLs for which droughts are a significant hazard are found to be Vilanova i la Geltrú, Benidorm, Oeiras, Massa and Piran.

Although all the cities studied belonged to a European context, significant differences were found between the relevant climate-related hazards. The intensification of winter storms is the main hazard identified in Sligo and Dublin. Coastal and land flooding and coastal erosion are other important threats for the Irish cities. Storms, land flooding, heat waves, strong winds and forest fires have been identified as the main hazards affecting Vilanova i la Geltrú. The main concerns related to climate change in Benidorm are storms, coastal flooding and coastal erosion. In the case of Oarsoaldea, storms, coastal and land flooding, and landslides are seen as major threats. Coastal and land flooding pose the major threat for Oeiras, with coastal erosion, landslides, droughts, heat waves, cold spells and strong winds identified as additional relevant hazards. The most dangerous climate-related hazards in Massa are represented by coastal and land flooding and coastal erosion. The main concern for the Slovenian city of Piran is coastal flooding. The most serious threat in Gdańsk is coastal and land flooding. Finally, for Samsun coastal erosion is the most important concern, although coastal and land flooding are also relevant.

As part of an integrated coastal zone management framework under the SCORE project, this work lays the first stone in the development and implementation of coastal city early warning systems for extreme events, spatial digital twin solution prototypes, EBAs, smart coastal city policies, resilience plans and dynamic adaptation pathways according to local legislation, in a network of cities learning from each other. Nevertheless, further work is required for the development of these measures. The identification of key climate-related hazards in this work must be combined with vulnerability and exposure studies to develop a baseline risk assessment. Indicators of the exposure and vulnerability of the human and natural systems associated with the coastal cities include the presence of critical infrastructure, public, residential and commercial assets, and human and environmental indicators (Balica et al. 2012; Gallina et al. 2016; Papathoma-Köhle et al. 2016). This baseline risk assessment would constitute the foundation for a subsequent complete analysis of risk, and thus become a kick-starter for the development of future adaptation measures in the coastal cities, with the overall objectives of protecting them from increasing climate and sea-level risks and enhancing their overall long-term resilience. Hence, future work will be aimed towards the development of vulnerability and exposure indicators for European coastal cities.

Appendix

See Tables 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.

Acknowledgements E. Laino acknowledges the support of the European Commission through the SCORE project, SMART CONTROL OF THE CLIMATE RESILIENCE IN EUROPEAN COASTAL CITIES, H2020-LC-CLA-13-2020, Project ID: 101003534. The authors are grateful to the SCORE consortium and, in particular, the Coastal City Living Labs for the valuable local knowledge.

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

Funding This work was supported by the SCORE project, SMART CONTROL OF THE CLIMATE RESILIENCE IN EUROPEAN COASTAL CITIES, H2020-LC-CLA-13-2020. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003534. This output reflects the views of the authors, and the European Commission is not responsible for any use that may be made of the information contained therein.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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