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A novel multi-hazard risk assessment framework for coastal cities under climate change

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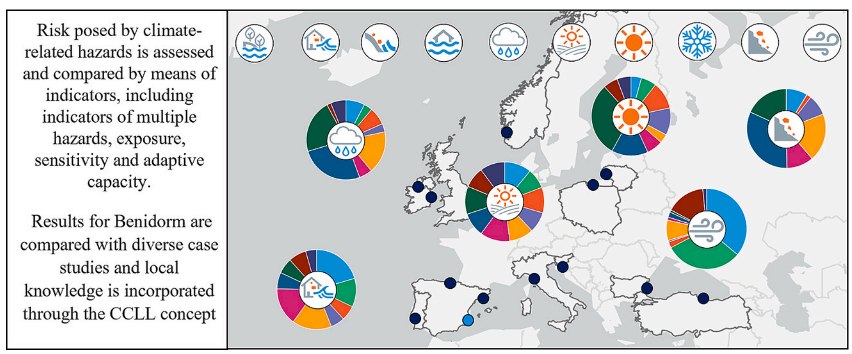
HIGHLIGHTS

- A Novel Multi-Hazard Risk Assessment framework is developed for climate-related risks.
- Local expertise is incorporated through the Coastal City Living Lab concept.
- The framework is illustrated through a case study in Benidorm, Spain.
- Results are compared with other European coastal cities.
- Specific vulnerabilities to heatwaves, coastal flooding and heavy rainfall are identified.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal cities, as centres of human habitation, economic activity and biodiversity, are confronting the ever-escalating challenges posed by climate change. In this work, a novel Multi-Hazard Risk Assessment framework is presented with the focus on Coastal City Living Labs. The methodology provides a comprehensive assessment of climate-related hazards, including sea-level rise, coastal flooding, coastal erosion, land flooding, heavy precipitation, extreme temperatures, heatwaves, cold spells, landslides and strong winds. Its application is illustrated through a case study: the Coastal City Living Lab of Benidorm, Spain. The methodology incorporates remote sensing data from various satellite sources, such as ERA5, Urban Atlas and MERIT DEM, to evaluate multiple hazards through a systematic and standardized indicator-based approach, offering a holistic risk profile that allows for comparison with other European coastal cities. The integration of remote sensing data enhances the accuracy and resolution of hazard indicators, providing detailed insights into the spatiotemporal dynamics of climate risks. The incorporation of local expertise through the Coastal City Living Lab concept enriches data collection and ensures context-specific adequacy. The integration of local studies and historical extreme climate events enhances the validity and context of the risk indicators. The findings align with regional trends and reveal specific vulnerabilities, particularly related to heatwaves, heavy rainfall, and coastal flooding. Despite its strengths, the MHRA methodology faces limitations, including reliance on outdated datasets and the complexity of integrating multiple hazards. Continuous updates and adaptive management strategies are essential to

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maintain the accuracy and relevance of risk assessments. The broader implications of the methodology for global coastal cities highlight its potential as a model for developing targeted adaptation strategies.

1. Introduction

The imperative to understand and mitigate the impacts of climate change on coastal urban environments has intensified in recent years (Lane et al., 2013; Vousdoukas et al., 2018a; Vousdoukas et al., 2018). This urgency arises from a more profound understanding of the complexities posed by climate change and its increasingly severe implications (Bergillos et al., 2019; Mentaschi et al., 2017; Rodriguez-Delgado et al., 2020). Coastal cities, as centres of human habitation, economic activity, and biodiversity, are particularly vulnerable to these changes (Mohammad and Zahra, 2017; Neumann et al., 2015). Recent studies highlight the accelerating pace and increasing severity of climate change impacts on coastal cities (Laino and Iglesias, 2023a; Nicholls, 2004; Vousdoukas et al., 2018b; Vousdoukas et al., 2017). The rise in the frequency and intensity of storms exacerbates coastal flooding and erosion (Cao et al., 2022; Kirezci et al., 2020; Kulp and Strauss, 2019; Vitousek et al., 2017). According to the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), global sea-levels have risen by approximately 20 cm since the start of the 20th century, with projections suggesting an additional rise of 30 to 60 cm by 2100 under moderate emission scenarios (Abadie, 2017; Fox-Kemper et al., 2021; Garner et al., 2021; Ranasinghe et al., 2021). These changes pose significant risks to coastal urban environments, necessitating urgent and comprehensive mitigation strategies (Bergillos et al., 2020a, 2020b; Nicholls et al., 2006; Oppenheimer et al., 2019; Vousdoukas et al., 2020).

The evolution of climate risk assessment has been marked by a transition from focusing solely on physical environmental factors to incorporating social dimensions and the application of advanced digital technologies (Argyroudis et al., 2022; Kunte et al., 2014; Laino et al., 2024; Rosendahl Appelquist and Balstrøm, 2015). The growing investment in climate change research reflects the increasing recognition of its importance (Laino and Iglesias, 2023b; Rodriguez-Delgado et al., 2019a, 2019b). Adaptation strategies have similarly evolved, showing significant variation across different geographic and socio-economic contexts (Bouaakkaz et al., 2023; Lückenkötter et al., 2013; Mafi-Gholami et al., 2019).

The integration of remote sensing technologies, such as satellite imagery and digital elevation models (DEMs), in climate risk assessments has proven to be highly beneficial, particularly for monitoring and managing environmental changes in urban and coastal areas (Cihlar et al., 2000a; Huang et al., 2017; Nguyen et al., 2018; Zhang et al., 2022). These technologies enable precise and comprehensive data collection on factors such as land use, topography, and climate variables. Remote sensing products, including datasets like ERA5, Urban Atlas, and MERIT DEM, provide high-resolution and accurate information crucial for assessing a wide range of climate-related hazards. Techniques such as satellite radar, optical imagery, and LiDAR (Light Detection and Ranging) are integral to generating datasets like Urban Atlas and MERIT DEM, which are essential for accurate topographic and land use analysis in climate risk assessments. For instance, detailed high-resolution imagery is essential for analysing urban heat islands, forest cover, agricultural areas, wetlands, and water bodies (Ozesmi and Bauer, 2002; Paranunzio et al., 2021; Sawaya et al., 2003; Weiss et al., 2020; Yuan et al., 2005). This level of detail allows for precise monitoring of changes in land use and the identification of vulnerable areas that require targeted intervention (Bauer, 2020; Chopping, 2015; Melesse et al., 2007). In coastal cities, such data is indispensable for tracking coastal waters and managing the impacts of urbanization on the natural environment (Chen et al., 2018; Kulp and Strauss, 2018; Paranunzio et al., 2022; Sharma and Bhaskaran, 2024).

The application of multi-satellite data to assess climate-related hazards is another critical advancement (Campbell and Wynne, 2011; Weng and Quattrochi, 2006; Woodcock et al., 2020; Zhu et al., 2022, 2019). Remote sensing has enabled the monitoring of storms, droughts, wildfires, hydrological hazards, sea-level rise, wave dynamics, wind patterns, and landslides, among others, with unprecedented accuracy (Bruun Christiansen et al., 2006; Chuvieco and Congalton, 1989; de Beurs et al., 2019; Hu et al., 2023; Ustin et al., 2009). For example, satellite observations can track the progression of storms and predict their potential impacts, while hydrological models informed by remote sensing data can forecast flooding events (Moradian et al., 2022, 2023, 2024; Olbert et al., 2023; Weng et al., 2014). These capabilities are particularly valuable for coastal cities, where the intersection of multiple hazards requires comprehensive and integrated management strategies (Chen et al., 2024; Sawaya et al., 2003; Sirmacek and Vinuesa, 2022; Yang et al., 2013). In this vein, satellite data products, such as those derived from ERA5, offer detailed and high-resolution information that is crucial for understanding and mitigating the impacts of climate change (Hersbach et al., 2020; Muñoz-Sabater et al., 2021; Yan et al., 2018; Yuan et al., 2021). These datasets facilitate the evaluation of sea-level rise, coastal flooding, and other extreme weather events with enhanced spatial and temporal resolution. Recent studies utilizing remote sensing data have highlighted the effectiveness of these technologies in tracking climate-induced changes and supporting urban resilience planning (Hersbach et al., 2020; Muñoz-Sabater et al., 2021; Paranunzio et al., 2024; Yamazaki et al., 2017).

Index-based methodologies represent a fundamental approach within Multi-Hazard Risk Assessment (MHRA), allowing for the articulation of the multifaceted nature of climate-related hazards (Birkmann et al., 2006; Feldmeyer et al., 2020; Laino and Iglesias, 2024a). These methodologies employ a set of independent variables to characterize key aspects of such hazards, including storm characteristics, wave regimes, sea-level changes, and temperature fluctuations (Araya-Muñoz et al., 2017; Binita et al., 2021; Birkmann, 2007; Mafi-Gholami et al., 2019). Composite indices, which aggregate these variables, offer a summarized view of the overall hazard scenario, facilitating a nuanced assessment that is both coherent and standardized (Adger, 2006; Füssel, 2007; Klein and Nicholls, 1999; Mclaughlin and Cooper, 2010; Murray et al., 2021). This approach enhances the comparability and interpretability of hazard assessments across different cases and hazard types. Despite their strengths, many existing indicator-based methodologies often exhibit limitations, such as focusing on a select range of hazards or specific vulnerability parameters (Laino et al., 2024; Owolabi and Sajjad, 2023). This specialization can overlook the interdependencies and cumulative effects of multiple hazards that concurrently affect coastal cities (Kappes et al., 2012; Wang et al., 2020). To address these gaps, modern MHRA methodologies seek to expand the traditional scope by incorporating a comprehensive set of hazards relevant to coastal cities, thus providing a more holistic view of the risk landscape (Cunha et al., 2018; Hincks et al., 2023; Laino and Iglesias, 2024a; Lung et al., 2013). This includes adapting and refining existing methodologies to meet the specific requirements of coastal urban environments (Bergillos et al., 2022; Nguyen et al., 2016).

Innovative approaches within MHRA also emphasize the integration of local and scientific knowledge (Araya-Muñoz et al., 2017; Tiepolo et al., 2019). Overall, the advancement of MHRA methodologies reflects a growing recognition of the need for comprehensive, integrative approaches to climate risk assessment and management (Ghosh et al., 2019; Ndehedehe et al., 2016; Thakur and Mohanty, 2023). By leveraging diverse data sources, incorporating innovative modelling techniques, and fostering stakeholder collaboration, these methodologies aim to enhance the resilience of coastal cities to the increasing challenges posed by climate change (Curt, 2021; Pourghasemi et al., 2019; Rusk et al., 2022). In this study, we employ a MHRA methodology to evaluate the climate-related risks facing Benidorm, a coastal city in Spain. By integrating remote sensing data with socio-economic indicators and historical climate records, we aim to provide a comprehensive assessment of the climate-related hazards, exposure and vulnerabilities of the city. The use of digital technologies such as GIS, Python, and high-resolution Digital Elevation Models (DEM) enables us to offer detailed insights into the impacts of climate change on the coastal and urban environments of Benidorm. This approach will not only enhance our understanding of local risks but also contribute to the broader discourse on urban resilience and climate adaptation.

There has been a rise of innovative concepts in climate resilience, such as MHRA, Ecosystem-Based Approach (EBA), Nature-Based Solutions (NBS), digital twins, citizen science, and Coastal City Living Lab (CCLL) (Gharbia et al., 2016; Laino and Iglesias, 2023b; Munang et al., 2013; Riaz et al., 2023; Riera-Spiegelhalder et al., 2023). Specifically, the CCLL concept represents an expansion of the Living Labs model, offering a comprehensive framework for addressing the unique challenges faced by coastal cities, including sea-level rise, coastal erosion, and extreme climate events (Tiwari et al., 2022). This approach fosters collaborative innovation among various stakeholders in both physical and virtual settings. In response to these challenges, Benidorm has established a CCLL through the SCORE (Smart Control of the Climate Resilience in European Coastal Cities) project (Laino and Iglesias, 2023c; Toledo et al., 2024a).

Benidorm, located on the Mediterranean coast of Spain, presents a compelling case study for examining climate-related hazards due to its unique combination of geographic and socio-economic factors (Martínez-Ibarra, 2015; Nolasco et al., 2020). The city is characterized by a densely populated urban area, a thriving tourism industry, and significant coastal infrastructure, all of which are vulnerable to climate impacts such as sea-level rise, storm surges, and extreme weather events (Nolasco et al., 2020; Olcina and Miró Pérez, 2017). Additionally, the proactive stance of Benidorm on climate adaptation, exemplified by the establishment of the CCLL through its participation in the EU-funded SCORE project, makes it an ideal candidate for this study (Laino and Iglesias, 2023c). In this context, remote sensing devices play a pivotal role in providing real-time data and long-term environmental monitoring. These labs are designed to foster innovation and collaboration among various stakeholders, including scientists, policymakers, and local communities. By leveraging remote sensing technologies, CCLLs can enhance their ability to monitor environmental changes, assess risks, and develop adaptive strategies that are informed by accurate and up-to-date information. The efforts of the city of Benidorm to implement and test innovative resilience strategies will provide valuable insights for other coastal cities facing similar challenges (Toledo et al., 2024a).

Besides, despite the wealth of research on individual climate-related hazards in coastal cities, there is a notable gap in studies that integrate these hazards within a comprehensive assessment framework (Kappes et al., 2012; Laino et al., 2024; Ranasinghe, 2016; VijayaVenkataRaman et al., 2012). Existing literature often focuses on singular aspects, such as the hydrodynamic modelling of storm surges or the socio-economic impacts of coastal erosion (Abadie et al., 2016; Mendoza and Jiménez, 2009; Rangel-Buitrago et al., 2020). However, the interconnected nature of climate hazards necessitates a holistic approach to accurately assess risks and inform adaptation strategies (Gallina et al., 2016; Gill and Malamud, 2014). This research aims to bridge this gap by employing a novel MHRA methodology that synthesizes various hazard data into a unified risk profile for Benidorm. The MHRA methodology employed in this study represents an advanced approach to climate risk assessment, integrating multiple data sources and analytical techniques to provide a comprehensive understanding of hazards. This methodology involves the systematic collection and analysis of climatic, geographic, and socio-economic data, combined with advanced modelling tools such as GIS and hydrodynamic simulations. By evaluating the combined effects of multiple hazards, MHRA offers a nuanced perspective on risk that is essential for developing effective adaptation strategies. This approach is particularly valuable in the context of coastal cities, where overlapping risks from sea-level rise, extreme weather, and human activities converge.

While there is a substantial body of research addressing individual climate-related hazards in Benidorm, such as increased storm intensity, flooding, and erosion (Camarasa-Belmonte et al., 2020; Diez et al., 2013; Fernández Montes and Sánchez Rodrigo, 2014; Gonzalez-Hidalgo et al., 2007; Imeson et al., 1998; Toledo et al., 2022), there is a noticeable gap in studies that integrate these various hazards within a comprehensive framework. This paper aims to fill this gap. It builds on the existing foundation of scientific and legislative understanding, alongside a record of historical climatic events. Utilizing an innovative MHRA methodology that includes a collaborative partnership with the city of Benidorm, this study seeks to dissect the multifaceted impact of climate change on the city. This paper also aims to validate the MHRA methodology employed by comparing the results of its application in Benidorm with existing studies. Additionally, it seeks to contribute standardized and systematic results on Benidorm within a European context. In this manner, this study not only assesses the multifaceted impact of climate change on Benidorm but also provides a robust framework that can be applied to other coastal cities, enhancing the overall resilience of urban environments against climate-related hazards. The ultimate objective is for this methodology to become a powerful decision-making tool, enabling Public Administrations to propose advanced and holistic solutions to enhance the resilience of Benidorm against the mounting challenges posed by climate change.

2. Materials and methods

Benidorm, located on the Mediterranean coast of Spain, is the focal point of this study (Fig. 1). The city is known for its high-density urban planning and high-rise buildings, developed in the 1960s during the rise of mass tourism, which remains its main economic activity (Femenia-Serra and Ivars-Baidal, 2021). The success of Benidorm is partly due to its two beaches, Poniente and Levante, characterized by fine sediment and averaging over 2 km in length and 50 m in width (Toledo et al., 2022)). These beaches are part of a closed coastal system forming a promontory cove, with abundant *Posidonia oceanica* seagrass meadows on sandy and rocky seabed (Blanco-Murillo et al., 2022). The area is in a microtidal zone where storm surges are more significant than astronomical tides (Toledo et al., 2024a). Ravines in the city flow into these beaches, and extensive urbanization has altered the hydrological and hydraulic behaviour of the basins, increasing risks (Toledo et al., 2024a).

Benidorm is particularly susceptible to climate impacts such as sea-level rise, storm surges, and extreme weather events. These phenomena can significantly damage coastal infrastructure, including street furniture and the seafront. These natural hazards and their consequences have been recorded over time (Tros-de-Ilarduya, 2013). Its proactive approach to climate adaptation, demonstrated by its participation in the SCORE project and the establishment of a CCLL, makes Benidorm an ideal setting to apply and validate the MHRA methodology developed in Laino and Iglesias (2024b).

The MHRA methodology represents an advanced, systematic approach to assessing climate-related hazards. For this assessment, the spatial extents of Benidorm were derived from the Urban Atlas dataset (Copernicus Land Monitoring Service, 2012), which provides high-resolution satellite imagery for detailed land use and land cover (LULC) analysis. The Urban Atlas dataset utilizes Very High Resolution (VHR) satellite imagery, which offers high-resolution optical images suitable for urban planning and environmental monitoring. Besides, a representative point for the city was identified using OpenStreetMap

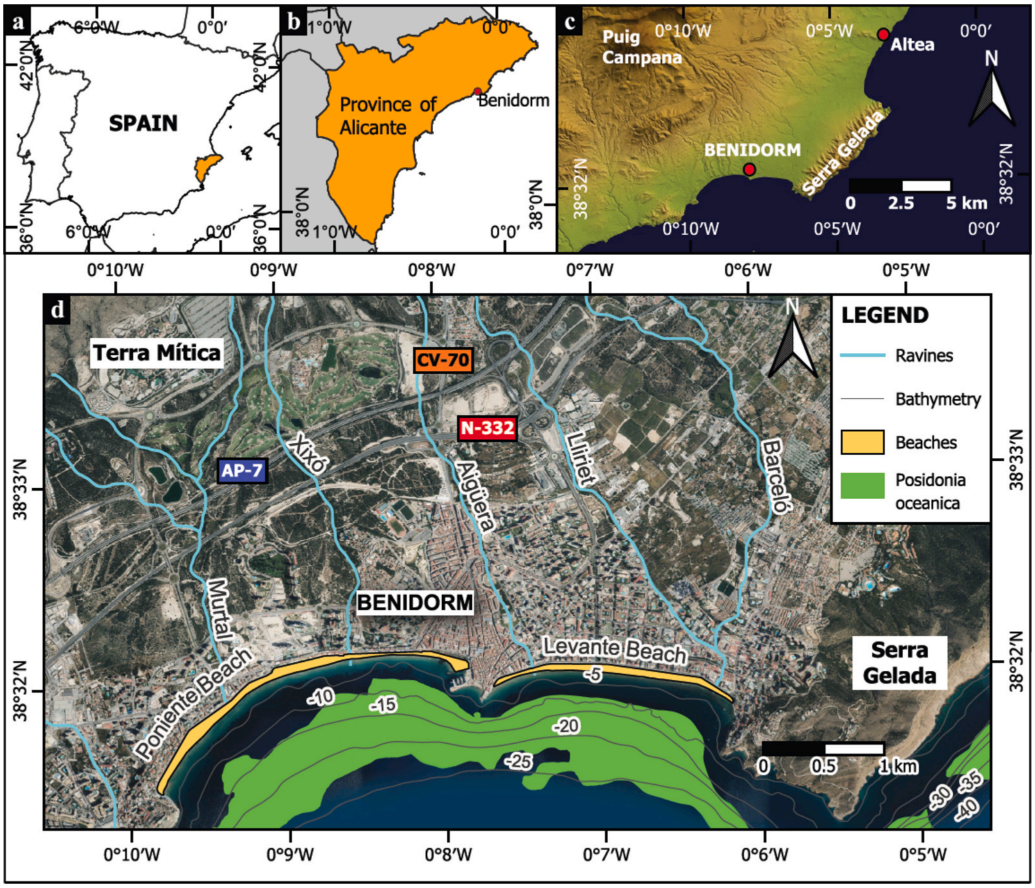

Fig. 1. (a) Study area located in Spain, (b) location in the province of Alicante, (c) detail of the study area, and (d) locations of Poniente Beach, Levante Beach, and the ravines within Benidorm.

data and the geopy library in Python. These coordinates were used to calculate various hazard indicators.

Comprehensive data on climatic, geographic, and socio-economic factors were initially collected, including historical climate data, GIS data, and socio-economic indicators relevant to Benidorm and comparable to other European coastal cities. These indicators were categorized under the risk parameters of hazard, exposure, and vulnerability, where vulnerability encompasses sensitivity and adaptive capacity (Ranasinghe et al., 2021).

The remote sensing data were utilized to derive various hazard indicators, such as mean sea-level rise (MSLR), storm surge, significant wave height (Hs), annual highest high tide (AHHT), coastal flooding extents, coastal erosion, river flooding extents, heavy precipitation events, droughts, extreme high and low temperatures, heatwaves, cold spells, strong winds, and landslides. The ERA5 products from Copernicus Climate Change Service (C3S) provide high-resolution climate reanalysis data, offering hourly estimates of a large number of atmospheric, land, and oceanic climate variables at a spatial resolution of circa 31 km. Details on these indicators, including their spatiotemporal resolution, coverage, and source references, are provided in Table 1, with further information available in Laino and Iglesias (2024a).

The indicators of exposure and vulnerability encompass various measures, including the low-elevation coastal zone (LECZ), LULC, population and socio-economic factors, and the presence of critical infrastructure elements (Table 2). The LECZ, defined as land contiguous to the sea and below 10 m in elevation, is highly susceptible to sea-level rise, storm surges, and coastal flooding (Mcgranahan et al., 2007). The LECZ was calculated using GIS software and the Multi-Error-Removed Improved-Terrain (MERIT) DEM dataset, expressed as a percentage of the total city area (MacManus et al., 2021; Yamazaki et al., 2017). The MERIT DEM dataset is generated using satellite radar data from missions such as the Shuttle Radar Topography Mission (SRTM) and the Advanced Land Observing Satellite (ALOS).

The LULC categories from Urban Atlas were reclassified into residential areas, critical infrastructure, transportation infrastructure, agricultural areas, open spaces, natural vegetation, wetlands, water bodies, and other miscellaneous uses as per Laino and Iglesias (2024b). These area calculations were performed for both the entire study area and the LECZ, expressed as percentages to create standardized indicators for cross-city comparisons. The socio-economic indicators, derived from Eurostat data, include population density, percentages of the population under 5 and over 65 years old, GDP per capita, rates of economically active population and unemployment, and levels of high educational attainment. The presence and distribution of power plants, airports, ports, and railway stations within Benidorm were mapped and analysed using open-source geospatial data from OpenStreetMap via Overpass Turbo.

Risk was calculated following the approach established in Laino and Iglesias (2024b), aligning with the IPCC paradigm of risk as a function of hazard, exposure, and vulnerability. The indicators were normalized between $[0,1]$ using a linear scale transformation of the min-max method (Hwang and Yoon, 2012). The extremities of the interpolated interval are determined by the maximum and minimum observed values for each indicator across a series of benchmarking cities: Bergen (Norway), Cork (Ireland), Klaipeda (Lithuania), La Spezia (Italy), Varna (Bulgaria), and Viana do Castelo (Portugal). These cities represent diverse climatic, socioeconomic conditions, and varied urban settings within Europe. For the indicators measuring the presence of critical infrastructure elements, scores of 0 or 1 were assigned to indicate absence or presence, respectively.

Table 1
Summary of hazard indicators, including units and spatial and temporal resolution and coverage.

Indicator (units)	Spatial resolution and coverage	Temporal resolution and coverage	Data source
MSL rate (mm/year)	1-degree grid; global	Decade; 2020 relative to a 1995-2014 baseline	NASA Sea-Level Projection Tool (Garner et al., 2021; Intergovernmental Panel on Climate Change (IPCC), 2023; Kopp et al., 2023)
Storm surge level (m)	0.1-degree grid; Europe	Value corresponding to the 50th percentile of the 50-year return period from 2001 to 2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century (Caires and Yan, 2020; Hersbach et al., 2020; Yan et al., 2020)
Significant wave height (m)	0.1-degree grid; Europe	Average value between the 90th and 100th percentiles from 2001 to 2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century Wave (Caires and Yan, 2020; Hersbach et al., 2020; Yan et al., 2020)
Annual highest high tide (m)	0.1-degree grid; Europe	Value corresponding to the 50th percentile of the 50-year return period from 2001 to 2017 ERA5 reanalysis	Indicators of water level change for European coasts in the 21st Century Wave (Caires and Yan, 2020; Hersbach et al., 2020; Yan et al., 2020)
Coastal flooding extents (%)	100-m; most Europe	Values corresponding to the 50-year return period and 36-h duration storm	ECFAS Pan-EU Flood Catalogue (Le Gal et al., 2022, 2023)
Coastline length undergoing erosion (%)	200 m; Europe	Single values reflecting conditions up to the early 2000s	Eurosion (Lenôtre et al., 2004)
Land flooding area (%)	100 m; Europe and its surrounding areas	Values for the 100-year return period based on daily river flows between 1990 and 2016	River flood hazard maps for Europe and the Mediterranean Basin region (Dottori et al., 2021)
Heavy rainfall frequency (day/year)	0.25-degree; Europe	Day; 1981-2019	Extreme precipitation risk indicators for Europe and European cities from 1950 to 2019 (Hersbach et al., 2020; Mercogliano et al., 2021)
Drought frequency (month/year)	1-degree; global	Month; 1981-2020	Global Drought Observatory (European Commission, Joint Research Centre (JRC), 2021)
Extreme high temperature threshold (°C)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory (Lavaysse et al., 2018)
Extreme low temperature threshold (°C)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory (Lavaysse et al., 2018)
Heatwave frequency (day/year)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory (Lavaysse et al., 2018)
Cold spell frequency (day/year)	0.25-degree; Europe	Day; 1981-2020	European Drought Observatory (Lavaysse et al., 2018)
Strong winds frequency (event/year)	1 km; 20 W-35E, 35 N-70 N regular latitude-longitude grid	Hour; 1981-2020	Winter windstorm indicators for Europe from 1979 to 2021 derived from reanalysis (Copernicus Climate Change Service, Climate Data Store, 2022; Hersbach et al., 2020)
Landslide-prone area (%)	200 m; Europe	Single values reflecting conditions pre-2018	ELSUS v2 (Wilde et al., 2018)

Table 2
Summary of exposure and vulnerability indicators, including their units and corresponding parameter of risk.

Indicator	Units	Parameter of risk
Area	km^2	Exposure
Population density	inhabitants/km^2	Exposure
Residential area	% of total area	Exposure
Open areas	% of total area	Vulnerability (adaptive capacity)
Critical infrastructure area	% of total area	Exposure
Transportation infrastructure area	% of total area	Exposure
Agriculture area	% of total area	Exposure
Forest area	% of total area	Exposure
Wetland area	% of total area	Exposure
Presence of power plant	Yes/No	Vulnerability (sensitivity)
Presence of airport	Yes/No	Vulnerability (sensitivity)
Presence of port	Yes/No	Vulnerability (sensitivity)
Presence of railway	Yes/No	Vulnerability (sensitivity)
LECZ area	% of total area	Exposure
Residential area (LECZ)	% of LECZ area	Exposure
Open areas (LECZ)	% of LECZ area	Vulnerability (adaptive capacity)
Critical infrastructure area (LECZ)	% of LECZ area	Exposure
Transportation infrastructure area (LECZ)	% of LECZ area	Exposure
Agriculture area (LECZ)	% of LECZ area	Exposure
Forest area (LECZ)	% of LECZ area	Exposure
Wetland area (LEC)	% of LECZ area	Exposure
Presence of power plant (LECZ)	Yes/No	Vulnerability (sensitivity)
Presence of airport (LECZ)	Yes/No	Vulnerability (sensitivity)
Presence of port (LECZ)	Yes/No	Vulnerability (sensitivity)
Presence of railway station (LECZ)	Yes/No	Vulnerability (sensitivity)
Population over 65 years old	% of total population	Vulnerability (sensitivity)
Population under 5 years old	% of total population	Vulnerability (sensitivity)
Unemployment	% of total population	Vulnerability (sensitivity)
GDP per capita	% of total population	Vulnerability (adaptive capacity)
Economically active population	% of total population	Vulnerability (adaptive capacity)
Higher education	% of total population	Vulnerability (adaptive capacity)

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

$$S_i = \frac{(S_{i,max} - S_{i,min})(I_i - I_{i,min})}{I_{i,max} - I_{i,min}} + S_{i,min} \quad (1)$$

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

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

$$A_{C_k} = \frac{\sum_{i \in C_k} S_i}{N_{C_k}} \quad (2)$$

wherein indicators for each category are equally weighted and aggregated, a common practice (Bagdanavičiūtė et al., 2019; Godwyn-Paulson et al., 2022; Hagenlocher et al., 2018; Sahoo and Bhaskaran, 2018; Tiepolo et al., 2019). N_{C_k} denotes the number of indicators within the risk category C_k (hazard, exposure and vulnerability), and thus $k = 1, 2$, 3. The indicators of adaptive capacity were subtracted from 1, as they have a reverse effect on vulnerability.

The partial scores were integrated into the European Multi-hazard Index (*EMI*) score of risk through multiplicative aggregation:

$$EMI = \prod_k A_{C_k} \quad (3)$$

where *EMI* denotes the risk for Benidorm.

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

The findings from the MHRA methodology were further refined and validated through local knowledge obtained via the Benidorm CCLL. The collaborative process involved reviewing and synthesizing the relevant local documents and legislative frameworks to ensure the results aligned with existing policies and regulations, especially with the Climate Change Adaptation Plan (CCAP) of Benidorm. This step was crucial for integrating the MHRA methodology within the local context and ensuring its practical applicability. A comprehensive record of historical extreme weather events in Benidorm was also compiled. These historical data provided valuable context and served to further validate the risk indicators calculated through the MHRA methodology. By comparing past events with the indicators, the study could assess the accuracy and relevance of the methodology.

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

The application of this comprehensive and collaborative framework aimed to validate the MHRA methodology proposed by Laino and Iglesias (2024b). By comparing the results of its application in Benidorm with those from other European cities, the study sought to demonstrate

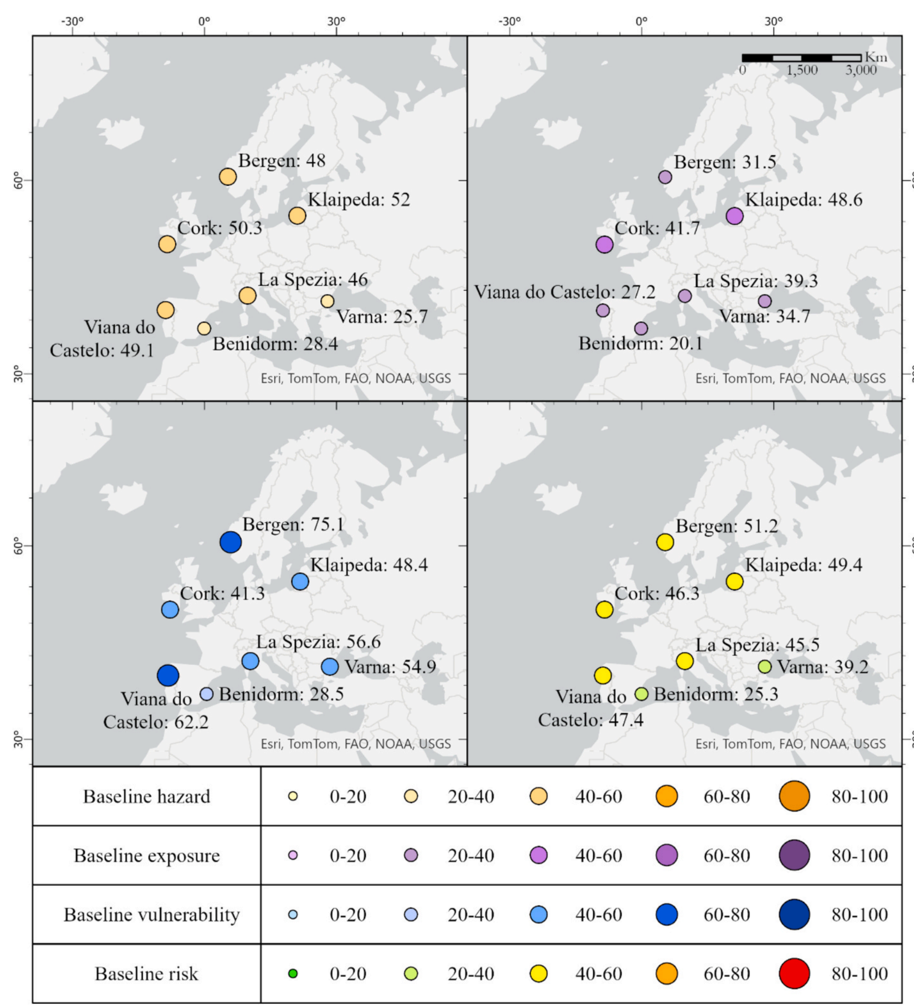

Fig. 2. Scores of hazard, exposure, vulnerability and risk for diverse European coastal cities, including Benidorm, Spain.

the robustness and utility of the methodology. Additionally, the standardized and systematic results contribute valuable insights into the specific climate-related risks for Benidorm, enhancing the overall resilience of the city against such hazards.

3. Results

3.1. Normalization of indicators and scores of risk

The risk index EMI and its partial scores for Benidorm are compared with other European coastal cities in Fig. 2. A cubic root transformation was applied to the calculated risk values to enhance interpretability. The findings indicate a low risk profile for Benidorm, with all risk parameters ranging between 20 and 30 points. This contrasts with higher values observed in the other cities, particularly in vulnerability scores, where Bergen scores 75.1 points compared to 28.5 points for Benidorm. Due to the nascent stage of the MHRA methodology, these results should be interpreted cautiously. A key aim of this study is to validate these results, which are discussed subsequently.

The scores are based on indicators presented in Table 3, which includes the minimum and maximum thresholds derived from the assessment of other European coastal cities, providing a comparative context for the results for Benidorm. These cities were selected to represent diverse climatic and socioeconomic conditions across Europe, ensuring a comprehensive benchmarking process. Based on these thresholds, results have been normalized on a scale from 0 to 1. The risk profile of Benidorm is characterized by relatively high values in indicators such as extreme high temperature thresholds, natural vegetation areas, unemployment, and economically active population.

These normalized results are thematically grouped in Fig. 3 and will be critically discussed hereinafter. Among the coastal hazard indicators, the MSLR rate is particularly notable, while other hazards register low values within the European context. This is logical given the Mediterranean location of Benidorm, which generally experiences less severe coastal hazards compared to the Atlantic or North Sea regions. Regarding land hazards, indicators for heatwaves and extreme high temperatures are elevated, consistent with the position of Benidorm in southern Europe, which is prone to such extreme weather conditions.

3.2. LULC

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

The presence of significant green spaces within Benidorm is noteworthy, given the dense urbanization of the city. These green spaces, including natural parks and open areas, contribute to the overall resilience of the city by providing ecological benefits and recreational opportunities. The Serra Gelada Natural Park, in particular, is a critical asset for biodiversity conservation and serves as a natural barrier against coastal erosion and other environmental hazards. The urban planning of Benidorm has managed to balance development with the preservation of natural areas, which is reflected in its land use indicators. The limited

Table 3
Results of the indicator-based assessment for Benidorm, Spain, including thresholding and scoring after min-max normalization to a range of 0-1.

Indicator	Value	Lower threshold	Upper threshold	Score (0-1)
Mean sea-level rate (mm/year)	3.4	0	6	0.57
Coastline length undergoing erosion (%)	0	0	90	0
Significant wave height (m)	2.3	1	8	0.19
Surge level (m)	0.5	0.3	2	0.12
Annual highest high tide (m)	0.1	0.1	3	0
Landslide-prone area (%)	17.8	0	66.7	0.27
Land flooding area (%)	0	0	10	0
Strong winds frequency (event/year)	0.1	0	2.5	0.04
Heavy rainfall frequency (day/year)	2.7	0	50	0.05
Extreme high temperature threshold (°C)	34.4	24	38.2	0.73
Extreme low temperature threshold (°C)	−1.8	3	−20	0.21
Heatwave frequency (day/year)	2.4	0	3.6	0.67
Cold spell frequency (day/year)	0.5	0.3	2.5	0.09
Drought frequency (month/year)	1.6	1.5	2.3	0.13
Area (km^2)	38.6	25	650	0.02
LECZ area (%)	3	2.5	50	0.01
Population density (inhabitant/km^2)	4062.8	250	4000	1
Residential area (%)	16.1	10	40	0.2
Open areas (%)	9.4	0	15	0.63
Critical infrastructure area (%)	9.3	2	30	0.26
Transportation infrastructure area (%)	6	3	15	0.25
Agriculture area (%)	10.4	10	15	0.08
Natural vegetation area (%)	45.8	0	50	0.92
Wetland area (%)	0	0	10	0
Presence of power plant (0 or 1)	0	0	1	0
Presence of airport (0 or 1)	0	0	1	0
Presence of port (0 or 1)	0	0	1	0
Presence of railway station (0 or 1)	1	0	1	1
Residential area (LECZ) (%)	20.5	10	40	0.35
Open areas (LECZ) (%)	40.9	0	15	1
Critical infrastructure area (LECZ) (%)	7.4	2	30	0.19
Transportation infrastructure area (LECZ) (%)	3.9	3	15	0.08
Agriculture area (LECZ) (%)	4.8	10	15	0
Forest area (LECZ) (%)	7.3	0	30	0.24
Wetland area (LECZ) (%)	0	0	30	0
Presence of power plant (LECZ) (0 or 1)	0	0	1	0
Presence of airport (LECZ) (0 or 1)	0	0	1	0
Presence of port (LECZ) (0 or 1)	0	0	1	0
Presence of railway station (LECZ) (0 or 1)	0	0	1	0
Population over 65 years old (%) (2022)	19.4	14.5	26.5	0.41
Population under 5 years old (%) (2022)	3.5	2.6	6.4	0.24
Unemployment (%) (2020)	8.91	0.9	12	0.72
GDP per capita (2021)	19,700	8000	150,000	0.08

(continued on next page)

Table 3 (*continued*)

Indicator	Value	Lower threshold	Upper threshold	Score (0-1)
Economically active population (%) (2020)	48.7	25.8	55	0.72
Higher education (%) (2020)	14.6	5	30	0.38

presence of critical infrastructure in the LECZ reduces the potential impact of coastal hazards on essential services and facilities. However, this also highlights a potential vulnerability in terms of connectivity and accessibility, as the transport infrastructure of the city is not as extensive as in other European coastal cities.

3.3. Coastal hazards

The results concerning coastal flooding and the LECZ indicate that coastal hazards primarily impact the beaches and do not extend far inland in Benidorm (Fig. 4). This contrasts with other European coastal cities, where these hazards tend to have a more extensive impact (Laino and Iglesias, 2024a, 2024b). In Benidorm, the coastal flooding areas identified in the ECFAS Pan-EU Flood Catalogue cover only 0.1 % of the total municipal area, located at the eastern end of Poniente Beach. The LECZ, representing 3 % of the total area, encompasses small coves under Serra Gelada and the Levante and Poniente beaches, extending into the highly urbanized promenade area. While the Eurosion dataset does not indicate significant coastal erosion in Benidorm, recent evidence suggests otherwise (Toledo et al., 2022). Additionally, the seabed in this region, mostly composed of unconsolidated very fine-grained sediments such as sand, is part of a protected natural area, which increases its sensitivity.

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

Since 1980, episodes of coastal erosion have been frequent, typically affecting the beaches and the promenade, as shown in Table 4. The significant importance of the beaches as a tourist destination elevates the vulnerability of Benidorm to these hazards. The economic dependence of the city on tourism means that even minor erosion events can have substantial economic impacts. Additionally, the local government has implemented various mitigation measures, such as beach

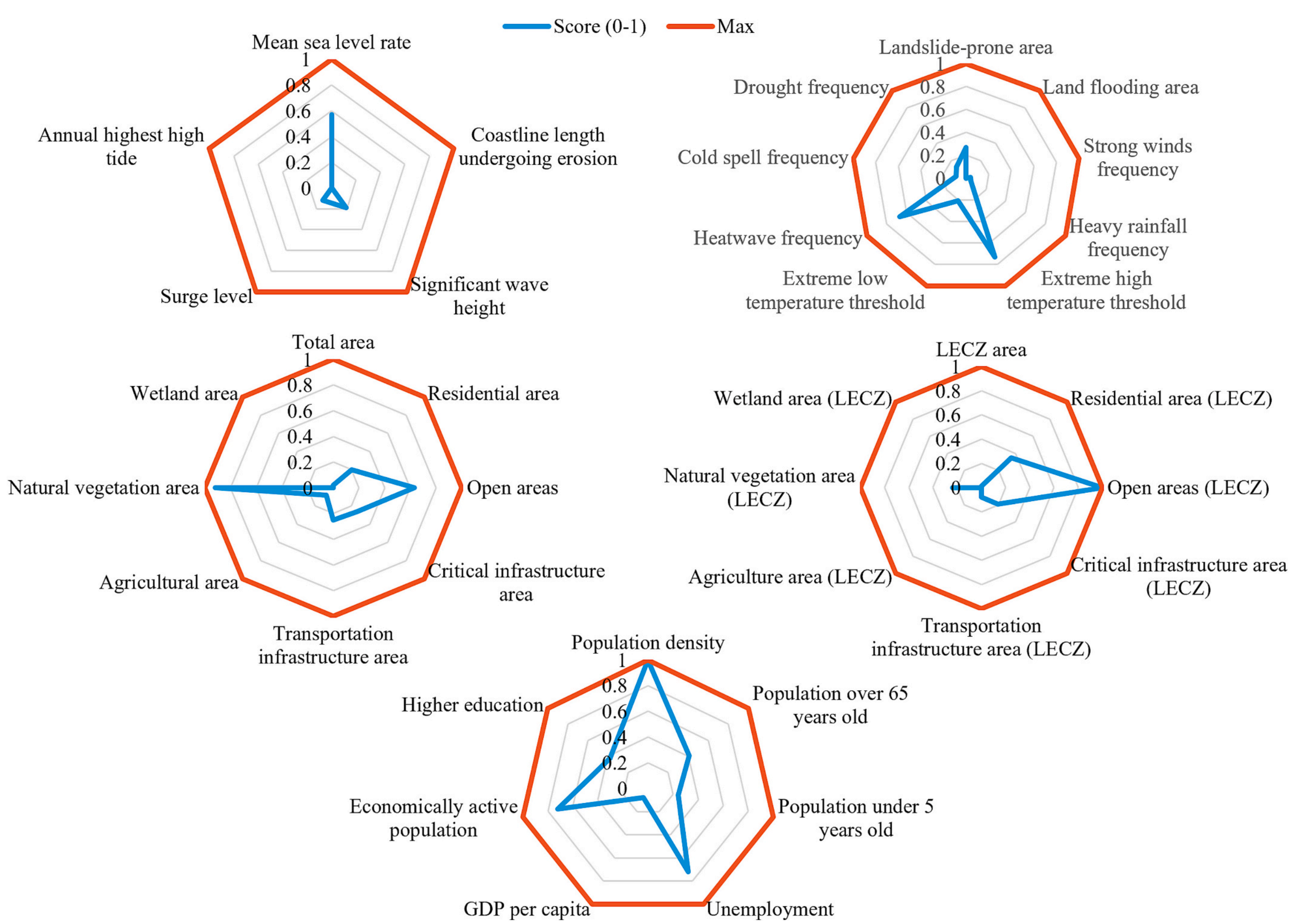

Fig. 3. Normalization of risk indicators based on thresholds from the assessment of diverse European coastal cities for Benidorm, Spain, as per Laino and Iglesias (2024b).

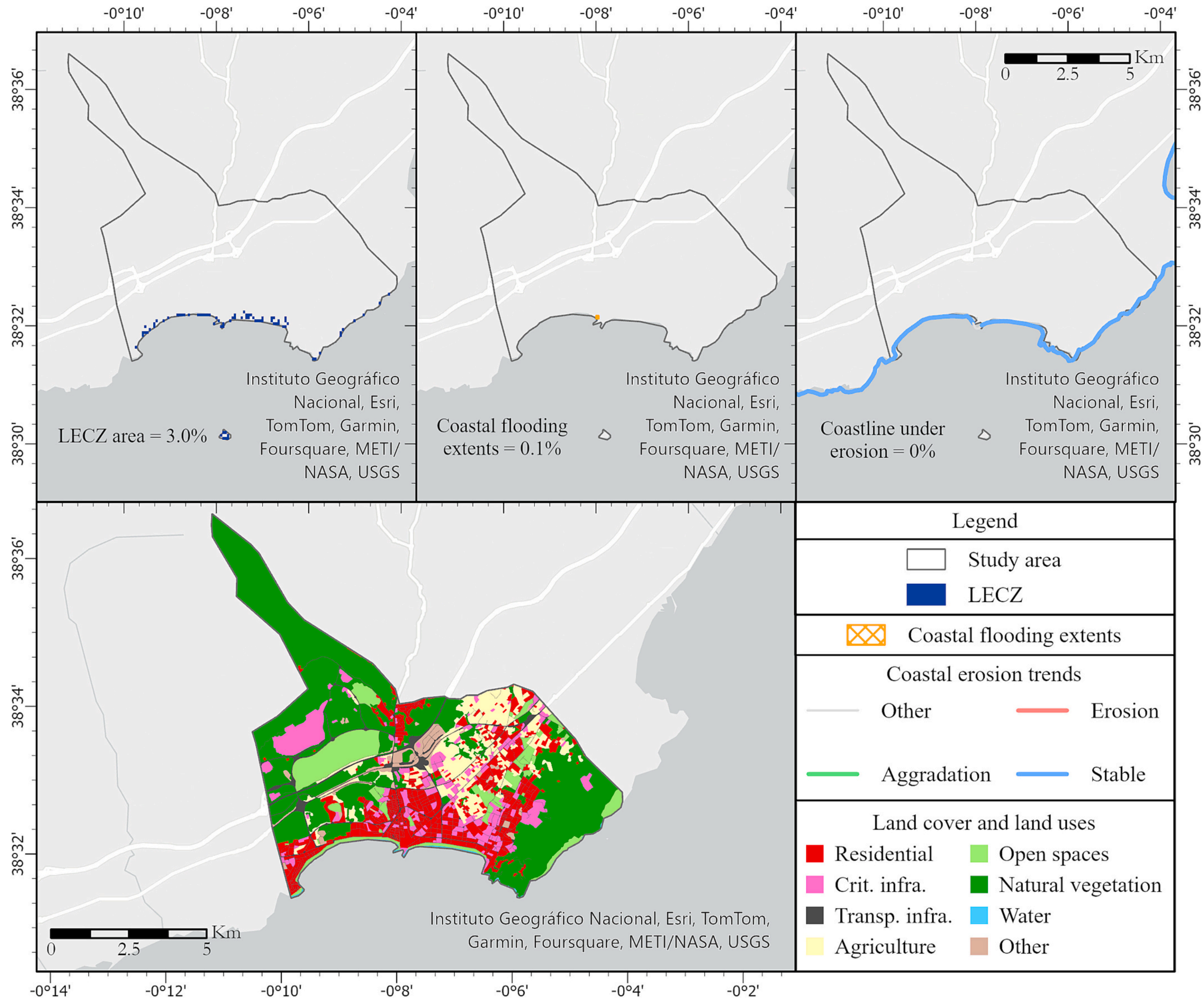

Fig. 4. Low-elevation coastal zone, coastal flooding extents, coastal erosion trends and land use of Benidorm, Spain.

nourishment and coastal defences, to protect these vital areas. However, these measures have varying degrees of success and longevity, requiring continuous monitoring and adaptation.

Water level indicators in Benidorm are not particularly high (Fig. 5), which is typical for the Mediterranean. However, as indicated in the CCAP, these values are sufficient to cause flooding episodes. The AHHT has a median value of 0.109 m. The significant wave height for the median between the 90th and 100th percentiles ranges from 1.9 to 3.0 m, with a median of 2.365 m. The surge contribution is approximately 0.46-0.48 m, with a median of 0.47 m. This aligns with the coastal flooding event on January 19th, 2020, when the sea level rose by half a meter. In a worst-case scenario, where these three contributions coincide, extreme sea-level values between 2.5 and 3.6 m could occur, primarily driven by wave height.

3.4. Temperature-related hazards

Heatwave and cold spell events are defined as those exceeding the temperature threshold for three consecutive days or more – the 99th percentile of the daily maximum temperature series between 1981 and 2000 for heatwaves (34.4 °C), and the 1st percentile of the daily minimum temperature series between 1981 and 2000 for cold spells (-1.8 °C). Fig. 6 shows the variation in heatwave and cold spell events between 1981 and 2020, indicating the total days of each event per year. The heatwave data do not reveal clear trends, except that heatwaves were frequent between 1984 and 1994 and from 2015 to the present. Conversely, no cold spell has occurred since 1988, suggesting a shift towards a warmer climate. The compilation of past extreme climate events does not include heatwaves or cold spells. However, the Benidorm CCAP examines the maximum and minimum average temperatures for the quinquennia from 2000 to 2020, based on data from the Altea meteorological station, part of the IVIA Network of the Generalitat Valenciana, located 10 km from the study area and with records from 1999 to the present. The conclusions indicate a significant increase in minimum temperatures during the warm months, associated with the warming of the Mediterranean Sea. No significant changes are observed for the other months, with stable or slightly increasing maximum temperatures during the summer and slightly increasing maximum temperatures during the winter months.

3.5. Droughts and heavy precipitation events

The number of drought months shows a decreasing trend between 1981 and 2020, while the number of extreme precipitation events has an

Table 4
Past coastal flooding and coastal erosion events in Benidorm, as provided by Benidorm CCLL.

Date	Short description
27/12/1980	The sky-cable platform disappears; two Red Cross boats are rescued in Rincón de Loix; the wind knocks down two ice cream kiosks; the waves flood a locutorio del Rincón; the waves flood the road between Torrechó and Pachá; the beach is flooded and covered with dirt; the furniture disappears; the waves rip out the sewage pipes.
02/01/1982	Poniente Beach is filled with dead remains of *Posidonia oceanica*.
04/10/1984	Evicted bathers at the risk of being swept away by the huge waves that break out in 15 min in Poniente Beach.
21/02/1985	Important loss of sand in the Torrechó; undermining the foundations of City Hall.
14/11/1985	Floods in Avda. de la Marina Española; damage to beach furniture; a freighter takes refuge in the bay.
27/09/1986	Beach flooding: the rupture of a pipe causes discharges of sewage into the sea.
03/11/1987	Flooding of the beach and damage to the foundations of a Telefónica booth.
17/10/1988	Misalignment of the buoys in the bathing area of Levante Beach. Undermining of foundations of the promenade in Fontanelles (Poniente Beach); damage to the promenade railing and beach furniture; undermining of the foundations of the promenade in La Cala; a British sailboat runs aground in Fontanelles and suffers damage.
04/09/1989	The beach furniture is removed so that the waves do not wash it away; damage to the retaining wall of Avda. de Alcoy and storm drains in Levante Beach. Damage to street furniture in La Cala (Poniente Beach); the waves exceed the beach and cause damage to the road; significant loss of sand in Fontanelles (1 km of beach disappears); flooding of Avda. de la Marina Española; large deposit of sand accumulated by the sea next to the promenade of La Cala.
20/02/1992	New profile of the beach, 1 km of «llosar» and a pipe in the cable-ski area are exposed (Levante Beach). Important loss of sand in the Cala (Poniente Beach); pile of sand near the port.
06/01/1994	Significant loss of sand (sections from 30 to 8-10 m wide); the "llosar" is exposed; damage to street furniture.
22/09/1994	Damage to the leisure platform.
11/11/1996	Beach flooding of Levante and Poniente beaches; significant loss of sand in the Torrechó; damage to beach furniture, which is thrown onto the promenade like projectiles.
08/04/1997	The waves come up to the boardwalk; beach furniture removed; significant loss of sand in the Torrechó.
30/09/1997	Moderate damage to the boardwalk; sand losses, the pipes are left in the air.
06/11/1997	A large portion of Levante beach is flooded, damage to accesses and beach facilities. The waves reach the wall of the Paseo de Colón in Poniente Beach; an area is flooded; beach furniture removed.
10/11/2001	Damage to disabled access.
30/10/2003	Important loss of sands; damage to furniture on the promenade.
27/03/2004	Accumulation of tons of dead remains of Posidonia.
03/12/2004	Losses for the tourism sector; visitors shorten their stay during the bridge of the Constitution.
19/01/2020	The sea-level rises half a meter, strong waves in the Torrejó area and the waves break directly against the promenade. Cleaning services have had to remove debris from walkways and beach furniture.

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

Records of heavy precipitation or pluvial flooding events begin with an event on November 3rd, 2006, where 89 l/m^2 of precipitation fell in less than 12 h. Since then, data include five pluvial flooding events and another heavy precipitation event, all described in Table 5. The extreme nature of these events is reflected in figures such as 74 mm/day on November 1st, 2015, or 177 mm over four days in April 2019. These events cause significant damage to buildings, infrastructure, beaches, and urban furniture, traffic disruptions, and even loss of life.

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

3.6. Land flooding

The indicator for river flooding areas (Dottori et al., 2021) shows no significant results for Benidorm. However, land flooding in Benidorm is characterized by the sudden overflow of several ravines that traverse the municipality from north to south during intense torrential rain events (Sánchez-Almodóvar et al., 2023). Therefore, land flooding is largely driven by these heavy precipitation events, which lead to flooding at the outlets of the ravines. For this reason, a map based on the findings from the regional flood study PATRICOVA, which provides a more detailed analysis of land flooding hazards, has been included (Fig. 7). This map shows the envelope of different land flooding-prone areas, including the extent of the 100-year return period flood event with a water depth of 0.8 m, the 500-year return period flood event with the same depth, and runoff areas. The land flooding hazard is concentrated in the downstream sections of the Lliret-Derramador and Barcelo ravines, which are densely populated. Critical elements within this area include hotels, campsites, traffic infrastructure, green areas, residential and commercial buildings, and the Levante Beach and its associated services. Additionally, there is the potential for compound flooding in this area due to the interaction of land and coastal flooding.

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

3.7. Landslides

The assessment of landslide hazard using the ELSUS v2 dataset shows varying susceptibility values (Fig. 8). The highest values are concentrated in the northwestern extremes of the municipality. Serra Gelada also records high susceptibility values. The periphery of the beaches registers medium values, particularly Poniente Beach. The central areas of the municipality show low to very low values. The list of past events includes only one landslide that occurred on November 12th, 2012, leading to the temporary closure of the regional road CV-70. The CCAP does not analyse this hazard in great detail, though it occasionally references landslides. For instance, it mentions that landslides can affect certain sectors, such as industry and construction, due to the increase in extreme phenomena resulting from climate change. In particular, the exacerbation of erosive processes on cliffs may generate more frequent landslides during large storms along the coastal sector of Benidorm and

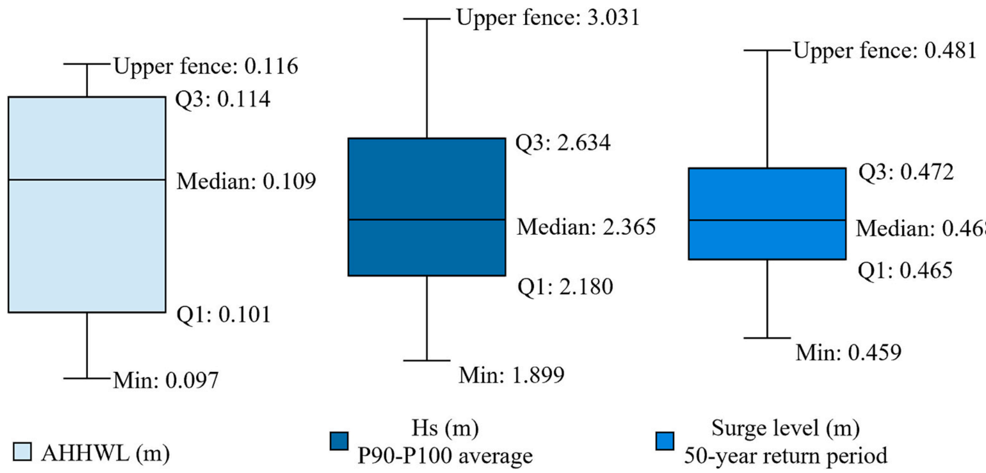

Fig. 5. Indicators of extreme water levels, including annual highest high-water level (AHHWL), significant wave height (Hs) and surge level for Benidorm, Spain.

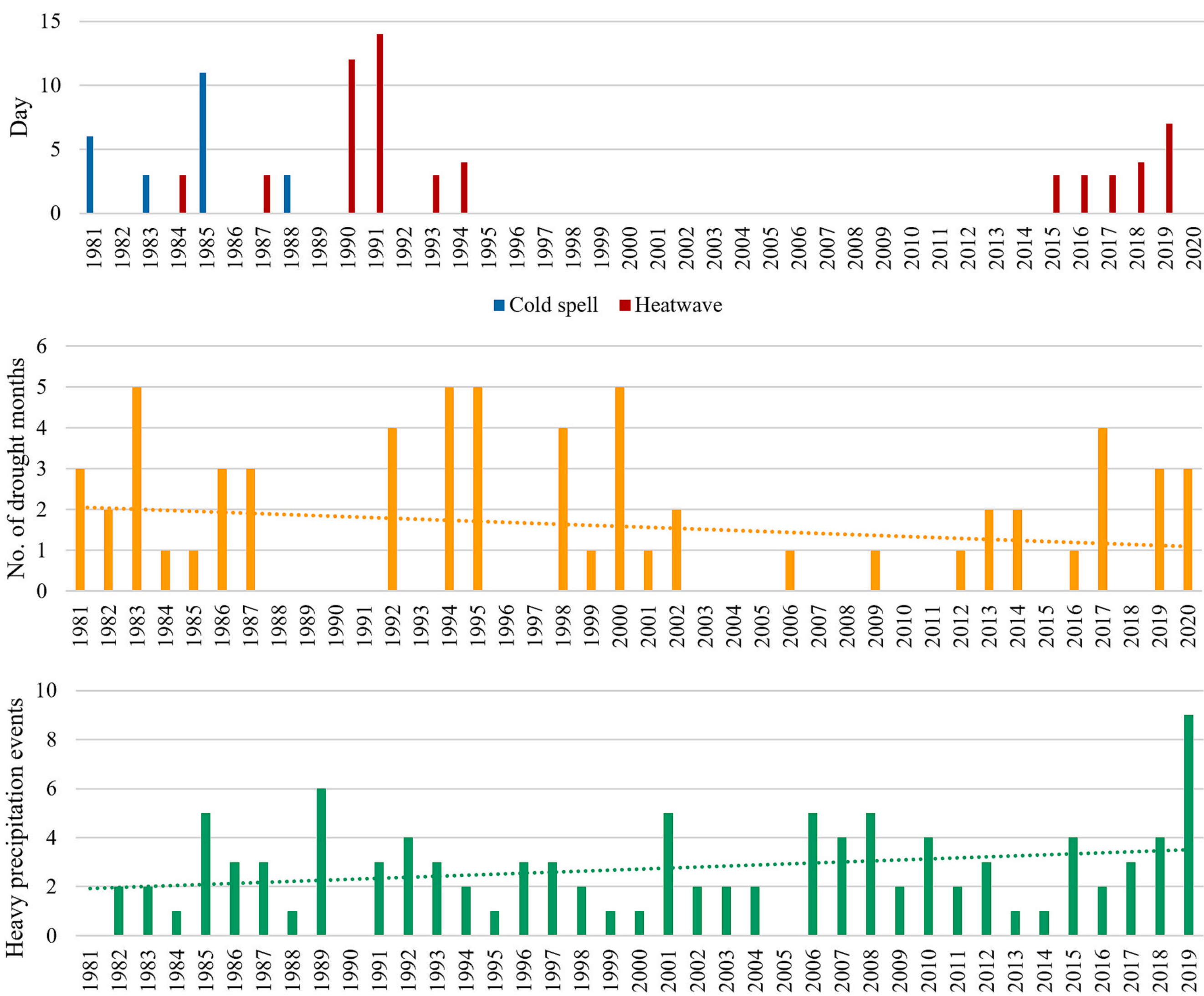

Fig. 6. Yearly evolution of cold spell and heatwave days, drought months and heavy precipitation events for Benidorm, Spain.

Table 5
Heavy precipitation events leading to flooding in Benidorm, as collected by Benidorm CCLL.

Date	Short description
03/11/2006	89 l/m^2 of precipitation fell in less than 12 h.
13/10/2007	Two small hotels were evicted as a result of flooding.
21/10/2011	Two British tourists killed and five injured in a flood in Cala Finestrat. The water swept people and vehicles.
01/11/2015	The town has collected a total of 74 l per square meter in the La Cala area. The rain damages an access staircase from the Plaza de la Senyoría to the Mal Pas beach and causes traffic cuts on Toledo Street at its intersection with Bernat de Sarriá and on El Murtal avenue.
18/12/2016	A deceased by a flood in the street that ends in Cala de Finestrat. Heavy rains also forced the evacuation of some 89 caravans from a campsite in the Rincón de Loix area.
17/01/2017	Various municipal buildings and facilities, public lighting, trees, El Tossal de La Cala, pumping stations, beaches and the Rincón de Loix health centre were affected.
19/04/2019	Benidorm collects 177 l per square meter in four days. The rains have caused several potholes in the road, the occasional closure of traffic on some streets due to accumulation of water, the fall of some trees, and damage to one of the perimeter fences of the 'Antonio López' football fields.

Serra Gelada. In light of these findings, the local government has initiated slope stabilization projects and monitoring systems in high-risk areas to prevent future landslides. These projects involve reinforcing cliff faces, installing drainage systems to reduce water infiltration, and continuous monitoring to detect early signs of ground movement.

3.8. Strong winds

The measurements of extreme wind events associated with winter storms, defined as those with 3-s, 10-m gusts exceeding 20 m/s, indicate 0 to 4 events over 40 years within the municipality. This value is very low compared to other coastal cities facing the Atlantic Ocean (Laino and Iglesias, 2024a). The list of past climatic events reflects two such episodes. One occurred on December 13th, 2009, with gusts up to 90 km/h (25 m/s), causing damage in the popular theme park Terra Mitica, especially to roofs, street furniture, shaded areas, landscaping, signage, and office buildings. The second event occurred on January 19th, 2013, with recorded gale winds (around 20 m/s), where strong gusts ripped open the walls and roof of the barracks. The CCAP explains that maximum average wind speeds usually occur in winter months and are typically associated with the general westward circulation, usually from the NW component. This finding supports the validity of the wind indicator for Benidorm. To mitigate wind-related damage, Benidorm has enforced stricter building codes to enhance structural resilience against high winds. The city also promotes the use of windbreaks and other landscape features to reduce wind speed and protect vulnerable areas.

3.9. Socioeconomic indicators

The evolution of various socioeconomic indicators, based on data from Eurostat, is illustrated in Fig. 9. The proportion of the population under five years old shows a downward trend, while the population over 65 years old is increasing. This demographic shift results in an inverted population pyramid, which is typically more vulnerable to the impacts

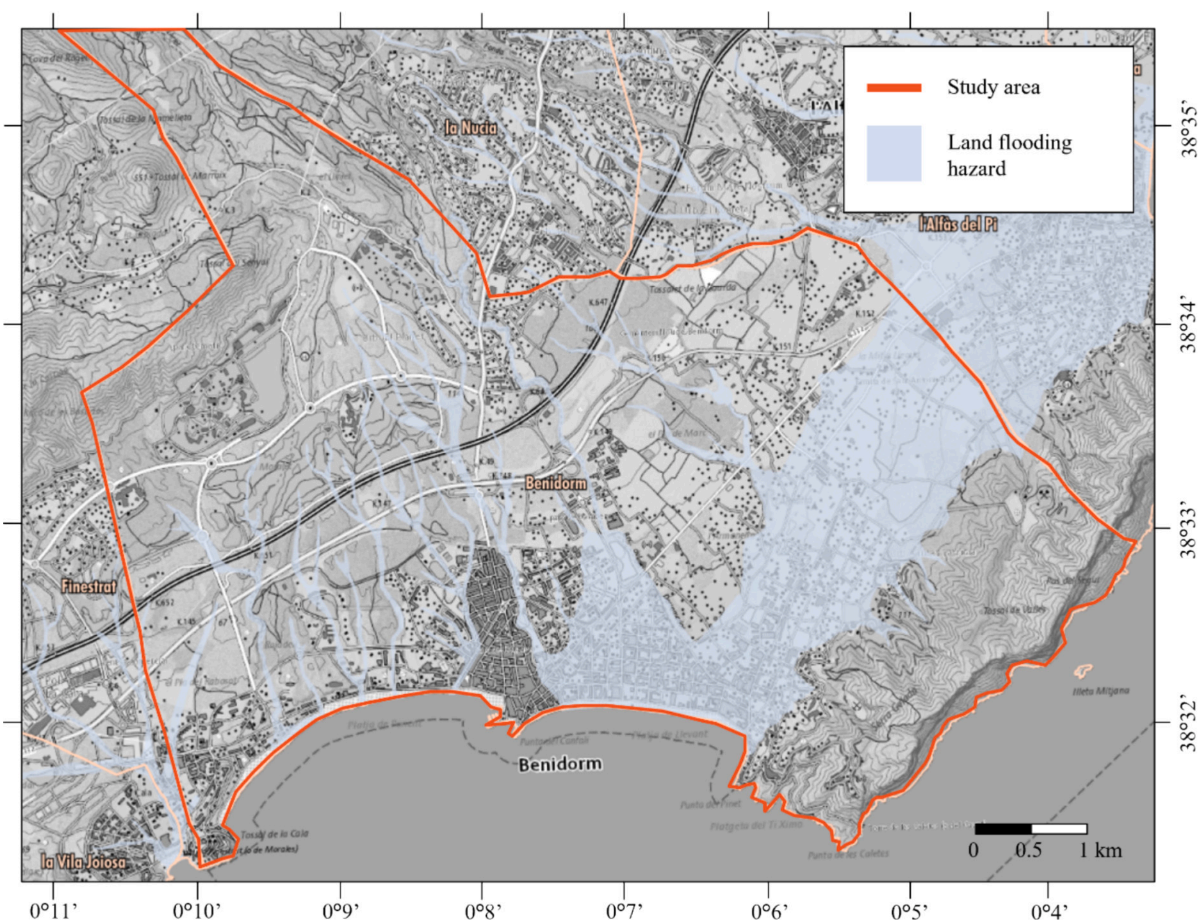

Fig. 7. Areas exposed to land flooding in Benidorm, Spain, according to PATRICOVA. Source: Flood Hazard Envelope. Sectoral territorial action plan on flood risk prevention in the Valencian Community – PATRICOVA 2015 CC BY 4.0 © Institut Cartogràfic Valencià, Generalitat and Grey basemap 2019 CC BY 4.0 © Institut Cartogràfic Valencià, Generalitat.

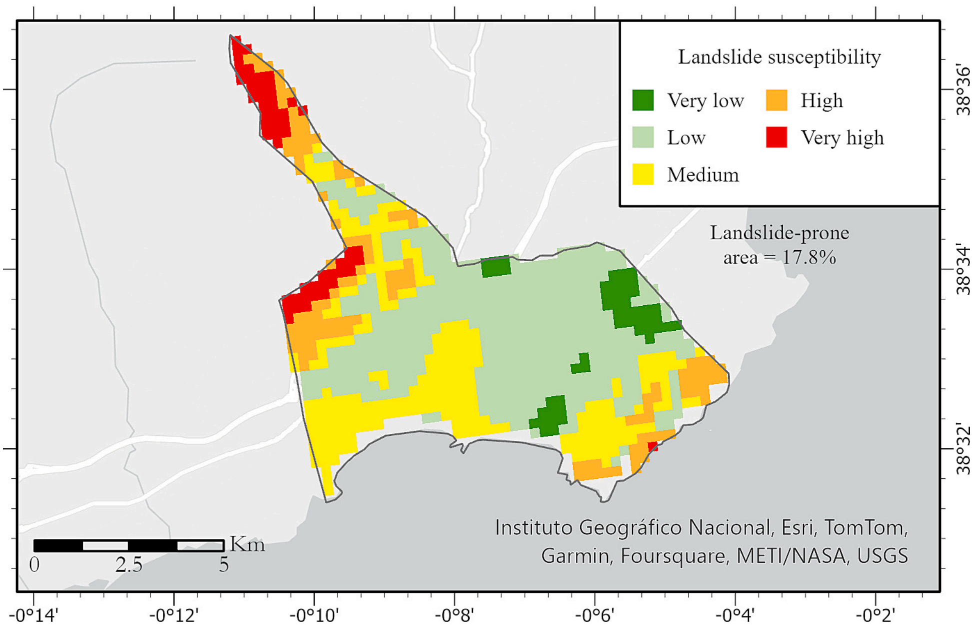

Fig. 8. Landslide susceptibility in Benidorm, Spain. Source: ELSUS v2.

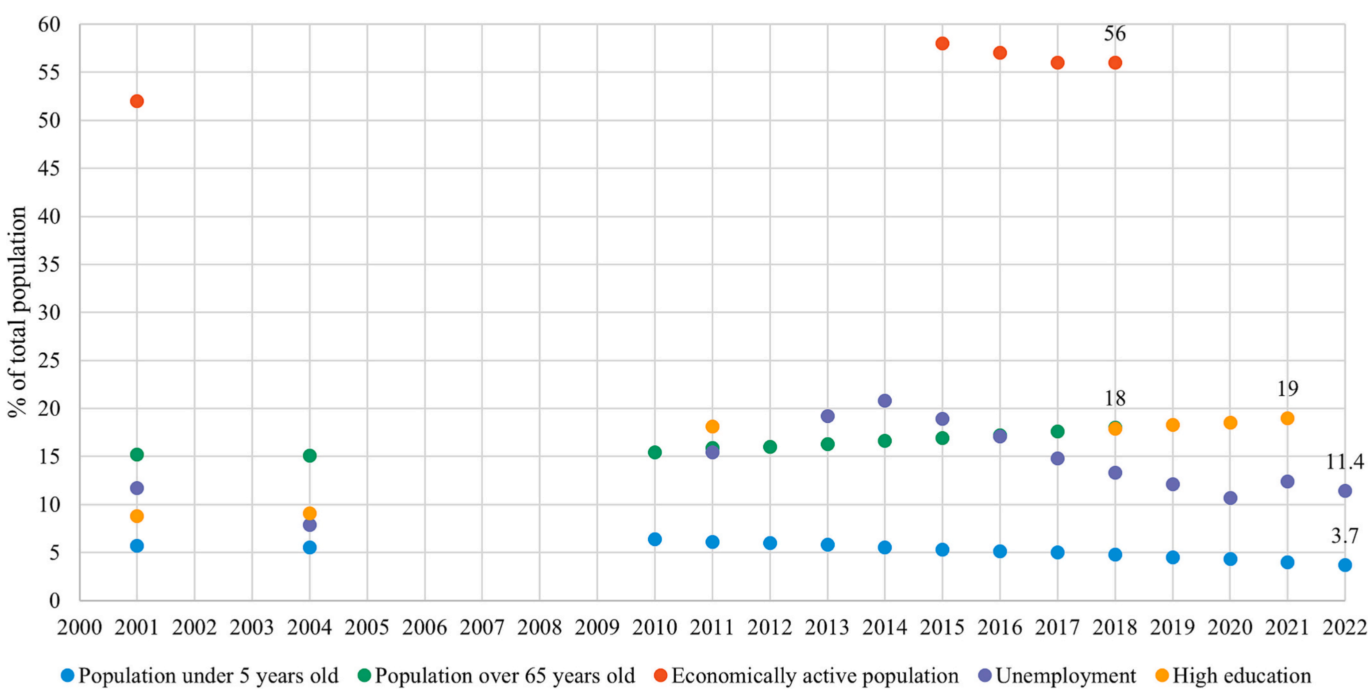

Fig. 9. Evolution of indicators on the population of Benidorm, Spain. Source: Eurostat.

of climate change due to the higher dependency ratio and increased health risks associated with an aging population.

Benidorm stands out for its high population density, economically active population, and unemployment rates. However, data on the economically active population are scarce and have not been updated since 2018, making it challenging to understand the current state of this variable, especially considering the potential impact of COVID-19 on labour markets (Braga et al., 2022). The unemployment rate has shown a decreasing trend over the past decade, which may indicate an increase in the resilience of the population. Similarly, the proportion of the population with higher education has grown to around 20 %. Despite these improvements, the overall percentage of the population with higher education remains lower compared to cities like Klaipeda, Lithuania, and Varna, Bulgaria.

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

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

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

4. Discussion

4.1. Relevance of the assessment

This study extends and demonstrates the utility of the MHRA methodology developed by Laino and Iglesias (2024b) in providing a comprehensive assessment of climate-related risks in Benidorm. By evaluating multiple hazards through a systematic and standardized indicator-based approach, the methodology offers a holistic risk profile that traditional single-hazard assessments lack. This approach facilitates the comparison of results with different coastal cities across Europe, serving as a valuable tool for policymakers and decision-makers at various levels. The application of remote sensing data, such as ERA5, Urban Atlas, and MERIT DEM, enhances the accuracy and resolution of hazard assessments in Benidorm (Chuvieco, 2020; Cihlar et al., 2000b; Moreno-de-las-Heras et al., 2023; Tang et al., 2009). These datasets provided comprehensive and high-resolution information on land use, topography, and climate variables, which are crucial for assessing a wide range of climate-related hazards. The integration of results with local studies, including a database of past climate events, further enhances the assessment by providing historical context and validation for the risk indicators. This comprehensive view is crucial for understanding the full spectrum of climate-related risks and developing effective adaptation strategies (Wang et al., 2023).

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

The participatory approach through the CCLL concept is particularly noteworthy. Engaging local stakeholders enriches the data and insights while also building community resilience and ensuring that adaptation measures are culturally and socially appropriate. This model of inclusive, science-based planning can be replicated in diverse urban contexts, enhancing global resilience to climate change. Further development of the CCLL concept can enhance the effectiveness of the methodology, including exploring new ways to engage stakeholders and integrating advanced technologies such as real-time monitoring and data analytics into the risk assessment process (Pereira et al., 2024b).

4.2. Comparison with previous works

The assessment of the various indicators calculated in this study generally aligns with previous research, confirming known vulnerabilities and revealing new insights through its integrative approach. The indicators related to coastal flooding and extreme sea levels show results similar to existing studies. For instance, the distribution of wave height and wave direction for the most unfavourable storm, as noted in Toledo et al. (2024a, 2024b), shows values around 2.5 m on the Levante and Poniente beaches for wave heights with a 0.137 % probability of being exceeded. This is comparable to the significant wave height values corresponding to the median between the 90th and 100th percentiles calculated in this study using ERA5 reanalysis data. Furthermore, the surge levels proposed are consistent with values reported in past climate events from Laino and Iglesias (2023c) (approximately half a meter) and Toledo et al. (2024a, 2024b) (0.63 m). The results regarding the extent of coastal flooding, based on the calculation of the LECZ and coastal flooding extents from ECFAS data, are also coherent with the flood studies of Toledo et al. (2024a, 2024b), which indicate that coastal flooding primarily affects the promenade and barely advances inland. However, the results from our study are not capable of distinguishing the differences in the impact of coastal flooding between the different beaches.

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

The study by Fernández Montes and Sánchez Rodrigo (2014) on climate variability in the southeast Iberian Peninsula provides valuable context for understanding temperature and precipitation trends in Benidorm. The pattern of torrential rainfall described in their work aligns with the results presented in this study. In Benidorm, river flooding areas identified by Dottori et al. (2021) are negligible, making heavy rainfall indicators particularly important in evaluating land flooding. The significant increases in daily maximum and minimum temperatures, especially in highly urbanized areas like Alicante-Murcia, reflect broader regional trends driven by urbanization and land-use changes. These findings are consistent with the observed increase in heatwave frequency and intensity in Benidorm. Additionally, the slight recovery in precipitation since the 1980s, primarily during winter months, suggests a complex interaction between climate variability and local environmental changes. This recovery could mitigate drought conditions to some extent but also indicates a trend towards more extreme precipitation events, as shown in this study, which can lead to increased flooding and soil erosion. These findings call for comprehensive adaptation plans that integrate sustainable urban planning, improved water resource management, and enhanced monitoring systems to mitigate the impacts of climate change.

4.3. Implications of the findings

Demographic and socio-economic factors highlight both the strengths and vulnerabilities of the population of Benidorm in the context of climate resilience. The increasing proportion of higher-educated individuals and the decreasing unemployment rate are positive signs of socio-economic resilience. However, the challenges posed by an aging population and lower GDP per capita must be addressed through comprehensive and inclusive adaptation planning. Integrating socio-economic factors more deeply into the risk assessment process can provide a fuller picture of vulnerabilities (Mathew et al., 2020; Thakur and Mohanty, 2023). Understanding how climate risks intersect with issues such as poverty, inequality, and health disparities is crucial for developing comprehensive and equitable adaptation strategies.

The implications of these findings are critical for regulatory bodies and urban planners in Benidorm. The highlighted risks necessitate the revision and strengthening of existing coastal management policies. The inclusion of comprehensive climate risk assessments in urban planning and the establishment of stricter building codes in vulnerable areas are essential steps (Pereira et al., 2024a). The Benidorm CCAP already outlines measures to address some of these risks, but the data from this study can provide more detailed and targeted insights to enhance these strategies. Collaboration with regional and national bodies can ensure that adaptive measures are harmonized and effectively implemented. Detailed studies are vital for a better understanding of risk, as exemplified by the flood patterns in Benidorm mentioned earlier (Tu et al., 2017).

The findings from this study align with those from similar coastal cities, reinforcing the need for an integrative approach to climate risk assessment (Olcina and Miró Pérez, 2017; Sánchez-Almodóvar et al., 2023). Studies on erosion dynamics in Guardamar and San Juan Beaches emphasize the critical role of sedimentological factors and the impact of human interventions (Pagán et al., 2018; Toledo et al., 2024b). Comparing these results with those from Benidorm highlights that while localized solutions are essential, broader regional strategies must also be developed to address common vulnerabilities and enhance overall resilience. Cities with similar vulnerabilities, such as Alicante, Valencia, and other Mediterranean coastal cities, can adopt this methodology to enhance their resilience planning.

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

4.4. Limitations and research opportunities

Despite its strengths, the MHRA methodology has several limitations. One significant limitation is the reliance on certain outdated datasets, such as the Eurosion dataset for coastal erosion, which may not accurately reflect current conditions. According to the Eurosion dataset, the coastal erosion trend in Benidorm was stable at least in the early 2000s, which might be true for Levante Beach. However, Toledo et al. (2022) shows that Poniente Beach has experienced significant erosion, particularly in its eastern zone, since 1956. This erosion was exacerbated by the 1991 beach nourishment project, which, despite initially increasing the beach width, resulted in ecological damage such as the death of *Posidonia Oceanica*. This alteration of the beach profile has led to more severe erosion over time (Aragonés et al., 2015). Recent data from 2007 to 2021 show a reduction in erosion rates, potentially due to changes in wave patterns and storm frequency. These findings underscore the importance of adaptive management strategies that can respond to evolving environmental conditions, including studying additional factors influencing coastal erosion, such as beach nourishment and the construction of breakwaters (Sande et al., 2018).

Another limitation is the complexity involved in integrating multiple hazards into a single assessment. While this provides a more comprehensive risk profile, it also requires sophisticated modelling tools and significant data inputs. The need for high-quality, granular data can be a barrier, especially in regions where data availability is limited. Additionally, the inherent uncertainties in climate projections present a challenge. Climate models vary in their predictions, and the exact magnitude and timing of climate impacts are difficult to forecast with precision. This uncertainty must be acknowledged and managed within the detailed risk assessment framework, potentially through the use of scenario analysis and sensitivity testing (Ai et al., 2024; Moradian et al., 2022). Assigning weights to indicators through correlation analysis can improve risk quantification. Incorporating a range of possible future scenarios can help to account for this uncertainty and ensure that risk management strategies are robust and flexible.

These limitations can lead to underestimations or misrepresentations of certain hazards. Continuous updates and refinements of the datasets used are essential to maintain the accuracy and relevance of the risk assessments (de Beurs and Henebry, 2004; Roy et al., 2014; Wulder et al., 2019; Zhu and Woodcock, 2014). The use of higher resolution satellite imagery, such as those from upcoming satellite missions, can provide more detailed and up-to-date information on land use and topography (Wei et al., 2022). Additionally, integrating remote sensing data with real-time monitoring systems can enhance the ability to track and respond to climate-related hazards dynamically (Senf et al., 2015). Incorporating the latest data on coastal erosion, sea-level rise, and other hazards will improve the accuracy of risk assessments (Bergillos et al., 2019a, 2019b; Weng et al., 2014). Additionally, further development of the CCLL concept can enhance its effectiveness. This includes exploring new ways to engage stakeholders and integrating more advanced technologies, such as real-time monitoring and data analytics, into the risk assessment process. Furthermore, exploring the use of machine learning algorithms to analyse large volumes of remote sensing data can improve the accuracy and efficiency of hazard assessments (Hethcoat et al., 2019). Therefore, it is recognized that the assessment capacity of the indicators is adequate for high-level characterization but not sufficient for detailed risk studies. To better understand the limits of this methodology, it is advisable to test it with more cities.

5. Conclusions

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

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

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

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

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

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

The study underscores the importance of a participatory approach in risk assessment and urban planning. Engaging local communities and stakeholders not only enriches the data and insights but also fosters resilience and ensures that adaptation measures are socially and culturally appropriate.

The success of the MHRA methodology in Benidorm suggests its potential for broader application. Other coastal cities can adopt this integrative approach to develop comprehensive risk profiles and inform their resilience strategies. The standardized assessment framework and the collaborative CCLL concept can be adapted to various geographic and socio-economic contexts, enhancing global urban resilience.

Extending the MHRA methodology to other coastal cities will provide valuable comparative data, helping to refine and validate the approach further. Additionally, integrating socio-economic factors more deeply into the risk assessment process will provide a fuller picture of vulnerabilities and inform more equitable adaptation strategies.

CRediT authorship contribution statement

Emilio Laino: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ignacio Toledo:** Writing – review & editing, Investigation, Formal analysis. **Luis Aragonés:** Writing – review & editing, Formal analysis. **Gregorio Iglesias:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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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