LIFE PROJECT

"Participatory and multi-level governance process to design a transformational climate change adaptation project at Cala Millor beach from an integrated and multidisciplinary science-based approach".

DELIVERABLE NUMBER
3.1: *Ad hoc* methodology for a Multi-Risk Assessment. Strategic main lines.

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EXECUTIVE SUMMARY

This deliverable is a technical report describing the *ad hoc* methodology to evaluate the individual threats, vulnerability and risks considering different beach dimensions (i.e., physical, environmental, socio-economic) to fit the particularities of urban beaches. Meaning this, the identification and quantification of the extent and implications of global change -namely sea level rise and sea climate- on the full beach system (beach and backshore dynamics, environment, urban and socio-economic systems); and the development of replicable guidelines for an integrated multidisciplinary assessment of climate change hazards, vulnerability and risks at a local scale.

The methodological approach defines risk as the probability of an adverse event of natural or anthropogenic origin and its consequences in a period of determined time. The interaction of said event with the elements of the environment and its degree of vulnerability results in a set of impacts or effects on the population, the material, economic or environmental resources. In this sense, six risk scenarios associated with the sea level rise due to climate change and associated marine climate (minimum and maximum sea level rise projections for three time horizons). The assessment approach of risk, exposure and vulnerability, presented in this document, just concerns the coastal flooding of the sandy beaches.

In this sense, the aim of this document is to provide the general rules to be followed at a local scale approach to assess the risk associated with climate change including the sea level rise of the average level is pursued by the sea and the extreme regime. The ultimate goal is to detect the areas of greatest impact and establish priorities to guide sectoral policies.

Three time horizons and two climate scenarios should be considered from a local IPCC result data and marine climate models. For all scenarios and time horizons hazard assessment for marine data must be done assuming extreme events with a return period of 50 and 100 years with a mean sea level corresponding to a climate scenario in which greenhouse gas emissions are provided by RCP4.5 and RCP8.5 scenarios.

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INTRODUCTION

This document present an *ad hoc* methodology to evaluate the individual threats, vulnerability and risks at a local scale for each particular beach dimension (physical, environmental, socio-economic) to fit the particularities of urban beaches and following the IPCC Common Methodology (Carter et al., 1994, UNEP, 1998 IPCC, 2022). Additionally, this document aims to provide a list of the aspects that any beach in the Mediterranean basin, in which the back beach had been artificialized, but still has an important beach dynamic and well-conserved *Posidonia oceanica* seagrass meadows, can adopt.

The methodology proposed in this first deliverable, responds to the following specific and main objectives of the LIFE ADAPT CALA MILLOR project WP3:

- Identification of the extent and implications of global change -namely sea level rise and sea climate- on the full beach system (beach and backshore dynamics, environment, urban and socio-economic systems);
- Assessing potential impacts and associated risks of different climate change scenarios at the beach site embracing physical, environmental and the socio-economic dimensions individually and as a whole;
- Developing a systematic, replicable and integrated methodology to assess climate change hazards and risks at urban beaches.

Then, and following the recommendations of the IPCC Common Guidelines, an *ad hoc* methodology will be developed through these four main steps:

1. A hazard assessment to identify climate change hazards at microtidal urban beaches;
2. An exposed element assessment to identify and evaluate potential exposed elements for each beach dimension;
3. A vulnerability and risk assessment to know the damage scales; and
4. The integration of all these previous in a multi-risk assessment able to measure the effect of climate change on multiple hazards on exposed vulnerable sectors for urban beaches (Sadegh, 2018).

Later, in the course of the LIFE ADAPT CALA MILLOR project, the Multi-Risk Assessment (MRA) methodology explained in the current document will be used to assess the potential impacts and associated risks of different climate change scenarios, but particularized for the beach of Cala Millor (next Tasks 3.2 to 3.4 of WP3 in the LIFE project). Specifically, the MRA methodology will be applied for the RCP4.5 and 8.5 scenarios by years 2030, 2050 and 2100 in Cala Millor beach, and later on used, in WP4 (Task 4.4- Risk reduction assessment), to assess a catalog of possible adaptation strategies for the future Cala Millor beach ranking them by their benefit/impact on the system. This will facilitate the choice of the best measure to be considered in the participatory approach at WP5.

1.1. Concept of risk and methodological approach

The concept of risk, following the trail of the different SREX reports of the Intergovernmental Panel on Climate Change (IPCC), is understood as the probability that an adverse event of natural or anthropogenic origin (and its consequences) will occur in a given period of time. The interaction of such an event with the elements of the environment -the affected system- and its degree of vulnerability, results in a set of impacts or effects on the population, goods or environmental resources that may require an immediate response to provide a solution to basic human and socioeconomic needs, and may require external help for their recovery (IPCC, 2012).

Therefore, the risk derives from a combination of threats and the vulnerability of the exposed elements that will result in a potential for severe interruption of the society or affected element once the adverse event has materialized.

For the purposes of the methodological approach to be developed within the framework of the project, we follow the main approach described in the PIMA ADAPTA Balears project, as well as other previous national and international experiences (e.g., IH-Cantabria, 2020) developed by the Institute of Environmental Hydraulics of the University of Cantabria (IH-Cantabria). Those previous experiences dealt with natural and urban beaches at different geographical settings, and constituted a regional scale approach. On this occasion we implement a method, emphasizing the local-high resolution scale. Therefore the three dimensions of risk will be defined in terms of:

- **Danger/threats**: understood as the potential event of natural origin or caused by human activity that acts as an external risk factor on a natural and/or anthropic system, in a specific place and with a determined intensity and duration.
- **Exposure**: referring to the location of people, economic goods, means of life and production, environmental services, resources, cultural heritage, *etc.*, in the area that could be affected by an adverse event, and so exposed to impacts, loss or damage.
- **Vulnerability**: understood as the typology and inherent response capacity of an element to the negative effect of a threat.

In this sense, as shown in Figure 1, the methodological approach is organized into three modules that match these three terms.

The first of them consists of the study of natural factors which generate risk situations, by themselves or induced by anthropic activity. For this study, these are the effects of meteorological tides (also called storm waves), ocean waves and their temporal evolution (marine climate), and the rise in sea level. Because the results must be used by the managers and stakeholders of the affected areas and the elements of territorial planning need different temporary scenarios, potential risk events will be considered for two time horizons and for two climatic scenarios of greenhouse gas concentrations defined by the IPCC. Specifically, the effects of hazard for 2030, 2050 and 2100 will be addressed for both scenario RCP-4.5 and scenario RCP-8.5. They assume a slight reduction in CO2 emissions into the atmosphere, or a level of CO2 emissions into the atmosphere similar to the current one, respectively. It is worth mentioning that the worst forecasts of greenhouse gas emissions for near temporary cuts, foreseen in previous IPCC reports, have not only been reached, but exceeded (IPCC, 2013). Therefore, the most adverse scenarios proposed in this paper should not be considered as an improbable future.

The second of the modules addresses the exposure of the elements of the socioeconomic and natural system that could be the most affected by adverse event threats. This is a standard for urban beaches in the Mediterranean basin and given the importance of the tourism and residential sector in these geographical contexts, population, human activities and land uses (*i. e.*, agriculture, industry, services-commerce, leisure), as well as natural spaces, and areas of environmental interest or recreational service provided by beaches as a natural system should be addressed. It is important to remember that beaches are the pillar of the economic tourism industry and each place and work group must identify and particularize the main elements exposed to the different threats in each location.

Finally, the third of the modules, once the scope of the adverse events on each of the exposed elements has been delimited, addresses their response. Although the methods will be reported in the corresponding sections of the document, basically an attempt has been made to determine those elements that will suffer the permanent effects of the rise in sea level. As well as all those elements that will be affected by the most adverse marine climate event (defined here as that with a return period of 100 years) and what it implies in terms of affected population, damage to homes, productive sectors or the functionality of the beaches as an area of provision of recreational services.

At the end, the final risk assessment will be made up by the interaction of these three core modules and it will show in which areas adaptation measures should be implemented to reduce the risks associated with climate change.

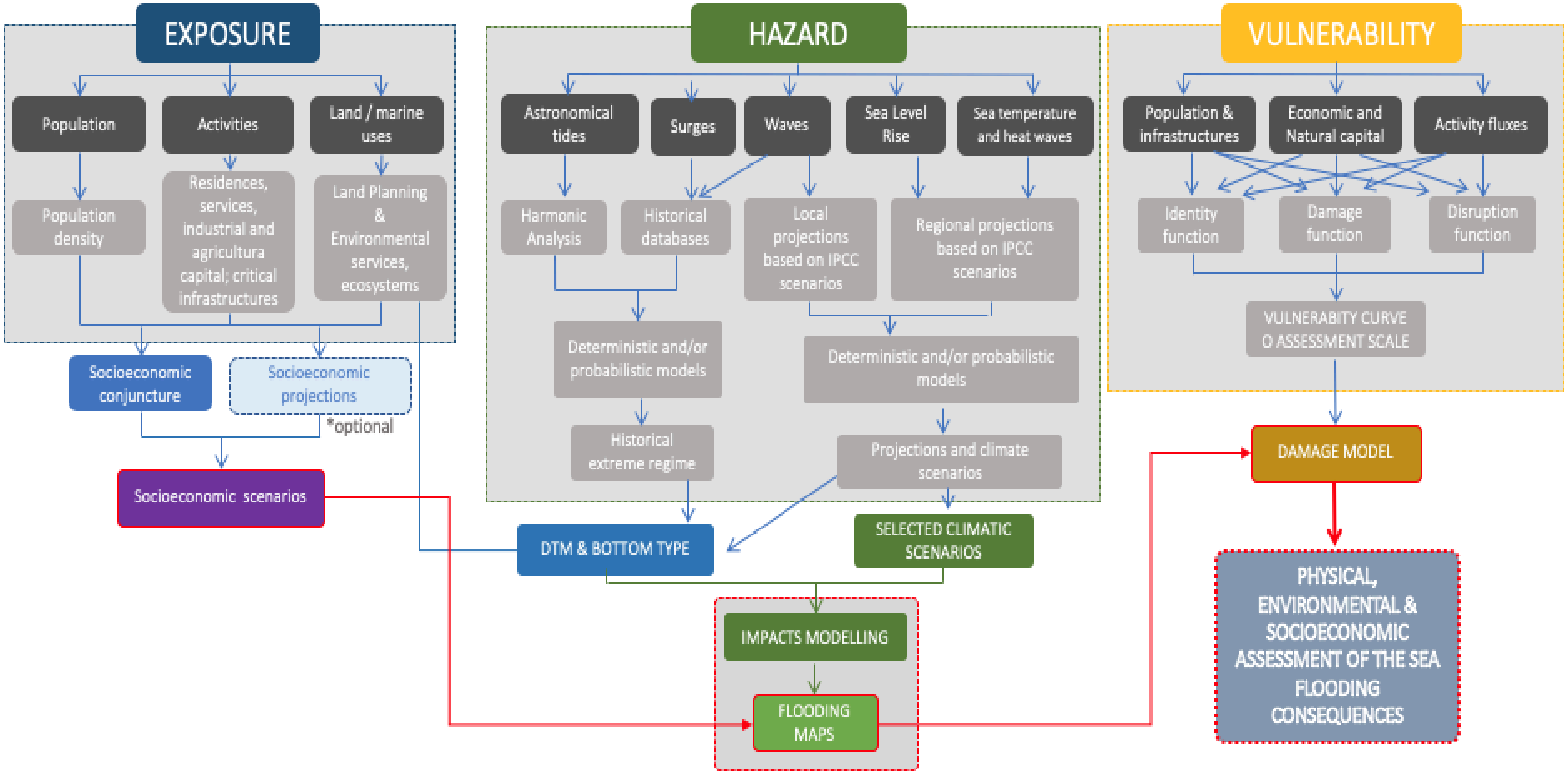

Figure 1. *Approach to implement risk assessment related to sea-level rise and global change at local scale for* beaches at the Mediterranean basin, in which the backbeach had been artificialized, but still has an important beach dynamic and well-conserved *Posidonia oceanica* seagrass meadow.

GLOSSARY

- **Coastal protection**. Management of the risk of coastal erosion within the competences of the DGCM, seeking synergies with flood risk management and incorporating adaptation to climate change.
- **Exposed elements**. Entities or assets that are at risk, or susceptible to the effects of a hazard. These can include people, buildings, infrastructure, natural resources, economic activities, or any other elements that may be affected by the hazard. The level of exposure to the hazard determines the potential for impact and the need for protective measures.
- **Hazard**. Source, situation, or event that has the potential to cause harm, damage, or adverse effects to people, property, or the environment. Hazards can be natural, such as earthquakes, floods, or storms, and can also be human-made, such as chemical spills or industrial accidents.
- **Impact**. Consequences or effects that occur as a result of a hazard. It represents the actual or potential harm, damage, or disruption caused by the occurrence of a hazard. The impact can vary depending on the severity of the hazard, the vulnerability of the exposed elements, and the level of preparedness and resilience in place.
- **Long term**. Period of 55 years between the year 2048 (25 years after the reference year of the current situation, 2023) and the year 2103. In this case, different climate change scenarios can yield clearly differentiated results. It occurs after the completion of the current management cycle.
- **Management Cycle**. Period between the current situation (reference year 2023) and the year 2045, during which the present strategies for coastal protection in the Balearic Islands are in effect.
- **Medium term**. Period of 15 years between the year 2033 (10 years after the reference year of the current situation, 2023) and the year 2048. During this period, the various climate change scenarios are practically indistinguishable (so only the most pessimistic one is considered). It corresponds to the end of the current management cycle.
- **RCP**. Representative Concentration Pathway, each one of the scenarios used in climate research and modeling to project future greenhouse gas concentrations and their potential impacts on Earth's climate system. RCPs provide a range of plausible future pathways of greenhouse gas emissions and concentrations based on different assumptions about population growth, economic development, energy use, and technological advancements.
- **RCP4.5**. This scenario represents a future with moderate greenhouse gas emissions. It assumes some level of mitigation efforts and a gradual shift towards cleaner energy sources. It aims to stabilize greenhouse gas concentrations by the mid-21st century and limit the global average temperature increase to around 2 - 2.4 degrees Celsius above pre-industrial levels.
- **RCP8.5**. This scenario represents a future with very high greenhouse gas emissions. It assumes a business-as-usual trajectory with limited climate policies and a heavy reliance on fossil fuels. It projects the highest level of warming among the RCP scenarios, with a

global average temperature increase of around 4 - 6 degrees Celsius above pre-industrial levels.

- **Risk**. Potential for harm, loss, or negative consequences resulting from uncertain events or circumstances. The term involves the likelihood or probability of an event occurring and the potential impact or severity of its consequences. Risks can arise from internal or external factors, and are managed through various strategies to minimize negative outcomes.
- **Short term**. Period between the current situation (reference year 2023) and the year 2033. This 10-year period corresponds to the duration of technical studies and administrative processes necessary for implementing certain management measures. In the short term, the effects of climate change are considered negligible. It corresponds to the beginning of the current management cycle.
- **Vulnerability**. Degree of susceptibility or sensitivity of exposed elements to the impacts of a hazard. It represents the potential for harm or damage based on the characteristics, conditions, and resilience of the exposed elements. Vulnerability can be influenced by factors such as the physical strength of structures, socioeconomic conditions, access to resources, level of preparedness, and ability to recover from a hazardous event.

METHODOLOGY

Assessing and managing risks associated with hazards and developing strategies for hazard mitigation and resilience is crucial in a climate change scenario. Thus, all the factors should be studied and integrated as hazards represent potential sources of harm. With this consideration in mind, impacts are the consequences of hazards, exposed elements are the entities at risk, and vulnerability represents the susceptibility of exposed elements to the impacts of hazards.

This section describes a methodology for an integrated multidisciplinary hazard, vulnerability and risk assessment in front of climate change at urban beaches. Multi-risk analysis in coastal areas involves evaluating and managing multiple hazards that coexist or interact. Coastal areas are vulnerable to various natural and human-induced risks like sea-level rise, storms, tsunamis, and coastal erosion. The analysis assesses these hazards simultaneously, considering their interactions and consequences. Key aspects include hazard identification, vulnerability assessment, probability analysis, spatial mapping, and evaluating potential impacts.

1. Hazard assessment

1.1. Identify climatic, natural and human-induced impact drivers

LIFEAdaptCalaMillor project, in the framework of WP3, aims to develop an *ad hoc* methodology for a replicable multi-risk assessment of urban beaches, to assess climate change hazards at microtidal urban beaches (e.g., flooding, erosion, loss of land).

The impact drivers in coastal areas that could be taken into account, related to the climate change can be divided into climatic drivers, natural drivers and human-induced drivers being these understood as:

a) Climatic drivers such as: sea-level rise, storm waves and surges, heat waves, dry spells, and torrential rains.

b) Natural drivers such as: eolic erosion, natural hazards (tsunamis, twisters…), invasive species, freshwater shortages, etc.

c) Human-induced drivers: pollutant discharges, population, seagrass mechanical destruction, number of boats, economic model, diverse socioeconomic contingencies, urbanism and new onshore or offshore infrastructures changing the natural balance of the beach system, ecological changes with losses of biodiversity (consequent changes to functioning of ecosystems).

Since territory managers and stakeholders need to prepare proposals that integrate the degree of uncertainty or the different agents that cause risk and the associated damage, it is necessary to address each of the risk elements in different temporal scenarios and under different emissions conditions. of greenhouse gasses.

The proposal ad-hoc methodology will consider RCP4.5 and 8.5 scenarios (Representative Concentration Pathways; *vid.* van Vuuren et al., 2011), analyzed for different timescales embracing mid-term (2030 and 2050) and long-term (2100) horizons in a progressive mean sea-level rise (MSLR) process.

RCP scenarios developed by the IPCC represent different pathways of greenhouse gas emissions and their impact on climate change. RCP4.5 is an optimistic scenario where emissions peak around 2040 and decline, stabilizing atmospheric concentrations. RCP8.5 is a pessimistic scenario with high emissions throughout the century, resulting in significant climate impacts. RCP8.5 assumes limited mitigation efforts and fossil fuel-intensive development, while RCP4.5 involves significant emission reduction and international cooperation.

1.2. Definition of forcing scenarios

1.2.1. Sea-level Rise Projections

Sea-level rise projections are key for coastal hazard assessments because they provide scientifically validated estimates of potential future sea-level changes under climate change scenarios. Regionalised global mean sea-level projections allow for a more precise assessment of their potential impacts on specific coastal areas, taking into account regional factors such as land subsidence, ocean currents and spatial patterns of sea level change. By incorporating regional sea-level rise projections into coastal hazard assessments, stakeholders can make informed decisions about infrastructure planning, land use management, and disaster preparedness, which enhance the accuracy and reliability of these assessments. Moreover, using regional sea-level rise projections enables coastal communities to proactively adapt and implement strategies to mitigate the risks posed by rising sea levels, safeguarding lives, property, and ecosystems in vulnerable coastal zones. Various data portals have been implemented to communicate regional and local sea-level projections in a usable form for policy-makers. The recent IPCC AR6 report produced an interactive atlas for several climate variables, including sea level (https://interactive-atlas.ipcc.ch). In addition, NASA has published an online tool specifically for sea-level projections that provides projected changes for different periods and scenarios, and include the different sea-level drivers (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool).

One possible application of the data described above was developed by Luque et al., 2021. For instance the regional study on Balearic Islands beaches (Luque et al., 2021), the regional projections of sea-level rise for RCP4.5 and RCP8.5 at the study site of Cala Millor were obtained using Kopp et al., (2014) methodology (Figure 2). We considered 17 % and 83 % probabilities from the multi-model ensemble, defining a central 67 % probability interval ("likely" range in the IPCC report of Stocker et al., 2014).

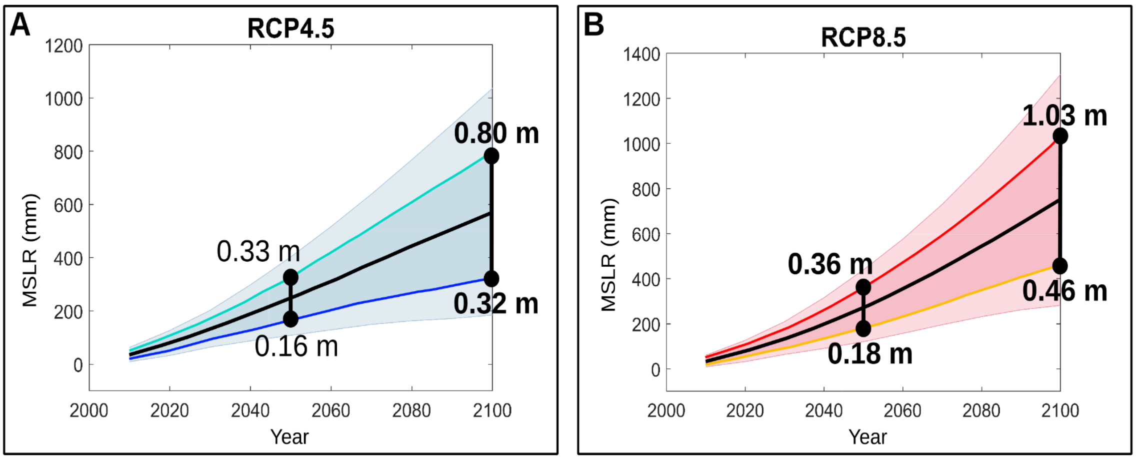

Figure 2. *Mean sea-level rise projections under RCP4.5 (panel A) and RCP8.5 (panel B) climate scenarios, computed according to Kopp et al. (2014). Black lines indicate the multi-model ensemble median and shadowed regions indicate the 17 - 83 % and the 5 - 95 % probability intervals. The four colored lines indicate the mean sea-level rise evolutions considered for the analysis of beach erosion, while the six values labeled in bold indicate the mean sea-level rise values considered for the analysis of coastal flooding.*

1.2.2. Wave forcing: mean conditions and extreme conditions

Accounting for local ocean wave and storm surge conditions alongside IPCC sea-level rise scenarios is essential for comprehensive coastal hazard assessments. While sea-level rise provides insight into long-term trends, considering local wave and surge conditions (both mean and extreme conditions) enables a more thorough evaluation of the combined effects of rising sea levels and extreme weather events. This integrated approach enhances the accuracy and robustness of assessments, allowing for effective decision-making and the development of strategies to protect against coastal hazards while enhancing coastal resilience.

- <u>**Mean wave conditions**</u>

To accurately assess mean wave climate and extreme wave and surge conditions is crucial to incorporate regional wind-wave hindcasts and measurements of wave and sea-level data. Regional wind-wave hindcasts provide valuable historical information on wave conditions and sea level, allowing for the computation of mean wave climate. These hindcasts, coupled with measurements of wave and sea-level data, enable a comprehensive understanding of the local wave climate and its variability. Furthermore, the combination of hindcasts and measurements provides better estimations of the extreme wave and surge conditions, which is essential for assessing the potential risks associated with coastal hazards.

Several hincast can be obtained currently from different research groups that have been widely published, validated and used for climatic applications. We remark that a regional reanalysis to be applied at a specific site has to be able to provide mean and extreme conditions in a reliable way and with sufficient statistical significance in terms of return periods. Some examples of such data can be obtained from the reanalysis provided by Mentaschi et al. (2017) and Vousdoukas et al. (2017), who computed waves with the wind-wave spectral model WaveWatch III (Tolman, 2002), and storm surges with the hydrodynamic model Delft3d-FLOW (Deltares, 2006), consistently forced by atmospheric pressure and surface wind fields from ERA-Interim reanalysis (hindcast spanning the period 1979–2014), and from 6 CMIP5 GCMs for the historical period (1970–1999) and future projections (2070–2099). The temporal sampling of the hindcast is 3 hours for wave data and 6 hours for surge data. Figure 3 shows as an example the dynamic models' grid points around the Balearic Islands, depicting the differences in the 50-year return period of significant wave height (left) and storm surge level between the projections and the historical records (right).

Given the unclear tendency and magnitude of the potential change, plus the lack of precision in the uncertainty characterization, we decided not to account for any projected change in sea-level extremes. In other words, we propose to assume that wave and storm surge climate will remain unaltered in the future.

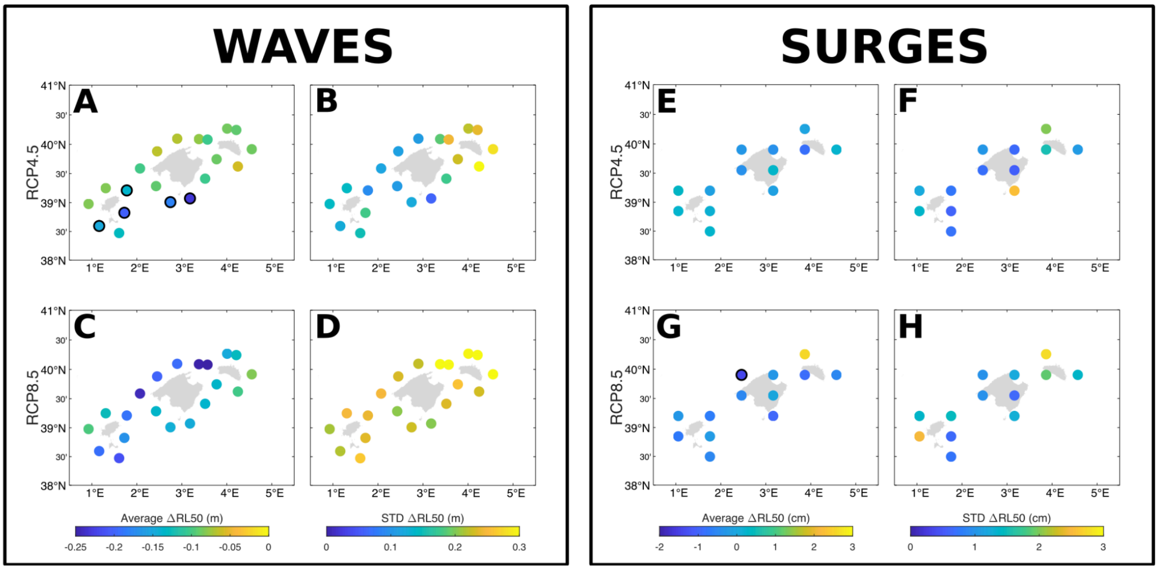

Figure 3. *Dynamic models' grid points around the Balearic Islands, depicting the differences in the 50-year return period of wave height (significant) and storm surge level between the projections and the historical records. Multi-model mean differences for wave height are shown in panel A (RCP4.5) and panel C (RCP8.5), while multi-model standard deviations of the differences are shown in panel B (RCP4.5) and panel D (RCP8.5). The same information is provided for surges in panels E to H. Results indicate that the dispersion of extreme values among the models is larger than the expected changes in most locations. Moreover, it is unlikely to extract a realistic uncertainty from such a limited number of models (the datasets used for wave height and storm surge, from Vousdoukas et al. (2017), are obtained from 6 climate models: ACCESS1.0, ACCESS1.3, CSIRO-Mk3.6.0, EC-EARTH, GFDL-ESM2G, GFDL-ESM2M).*

Regarding data it is desirable to have long term time series of meteo marine variables (including Hs, Tp, peak direction, sea level, etc.). In the case for Cala Millor there is a coastal station maintained by SOCIB which records wave and meteo parameters that provide wave data at the beach (18 m depth) since 2010 (Fernández-Mora, 2023). Regarding wind-wave hindcast, for both waves and storm surges we propose to use the CoExMed hindcast (Toomey et al., 2022) consisting in a hydrodynamic-wave coupled hindcast with an unprecedented spatial resolution for the Mediterranean reaching 200 m along the coastline. The period simulated span since1950 (updated so far until 2022), and includes for the first time the wave setup component along the coasts contributing to the coastal extreme sea levels. The modeled storm surges and waves have shown a very good skill when compared with *in-situ* and remote observations. The length and completeness of the hindcast permits the accurate computation of storm surges and wave statistics in the Mediterranean coasts separating geographical features due to its high spatial resolution, as well as their temporal variability. Provided that projected changes in storm surges and waves in the Western Mediterranean are uncertain and display a large range of inter-model variability, we use the well characterised present-day storm surge and wave climate and focus on the largest uncertainty (that from mean sea-level projections). This approach is in agreement with the majority of the existing studies (*e. g.*, Toimil et al., 2017; Sanuy et al., 2018; Enríquez et al., 2019; Ribas et al., 2023).

This data will be used to characterize:

a) Mean Wave Climate:

The mean wave climate refers to the average wave conditions observed in a specific region over a given time period. It provides statistical information about wave height, period, direction, and other parameters, serving as a baseline for understanding typical wave patterns.

b) Extreme events:

Extreme events are defined as rare, high values of wave height and/or sea level, or most importantly, their simultaneous occurrence, since those are the most harmful due to their catastrophic effects over the coastal population and their assets, *i. e.*, the effect of a big wave is worse when happens at the same time that a high tide or a high storm surge, since its landward reach is increased. The occurrence of compound events of waves and storm surges in the Mediterranean Sea (and, in general, at mid-latitudes) occurs more often that independent events because of their common mechanism of generation linked to extratropical storms (Marcos et al., 2019). Extreme events are modeled statistically fitting the upper tail of the wave or storm surge probability distribution to a theoretical distribution of extreme values, either Generalised Pareto or Generalised Extreme Value distributions that model excesses over a threshold or block maxima, respectively.The joint distribution of waves and storm surge extremes is complex and must be carried out meticulously, so it will be explained below.

If possible, it is recommended that data from reanalyses are calibrated or compared to observational data Ideally, extremes should be characterised on the basis of measurements only (e.g. Calafat and Marcos, 2020), to avoid introducing model biases. For example, in the case of Cala Millor (Balearic Islands) historical data provided by an AWAC moored at 17 m depth is used to characterize the conceptual model of the beach (Fernandez-Mora et al., 2023). For this, a two-dimensional model for wave propagation and morphological changes in the beach area will be implemented (XBeach) so as to obtain the current functioning of the beach as well as its deviation under extreme wave conditions.

- **Characterization of extremes for modeling purposes**

To develop the hazard assessment for both RCP scenarios and extreme marine events at different time-horizons, it is necessary to define individual extreme events (reference storms) as forcing of numerical models.

Given an historical time-series of wave climate and sea-level data and the characterization of extreme events (for both waves and surges), joint extreme events can be designed by means of the joint analysis of the probabilistic distributions of the tuple of variables that define a marine storm (i. e., significant wave height Hs, wave peak period Tp, wave direction θp, storm magnitude M and surge Ss). This methodology has been developed and implemented in Luque et al (2021), and allows to incorporate the information of compound extreme episodes of both waves and surges.

The reference storm can be estimated through a multivariate probabilistic analysis of the variables defined in the storm tuple and the simulation of values for individual and bivariate variables beyond the range of the extreme event data values (Goda et al., 1990; de Michele et al., 2007; Bernardino et al., 2009; Soldevilla et al., 2015; ROM 1.0, 2009; Martin-Hidalgo et al., 2014; Lin-Ye et al., 2016; Lira-Loarca et al., 2020).

1.2.3. Sea Surface Temperature Projections

Over the past century the increase in Sea Surface Temperature (SST) has been accompanied by an increase in the frequency and intensity of marine heatwaves, both globally and in European seas, with an approximate doubling from 1982 to 2016 (Oliver, 2018). This has had considerable ecological impacts, including promoting harmful algal blooms, with increased risks to human health, ecosystems and aquaculture. Marine heatwaves refer to an extended period of anomalously warm ocean temperatures in a particular region compared to the local historical average for that time of year and the specific temperature thresholds for defining a marine heatwave can vary depending on the region and the scientific study and is still upon debate in the scientific community (Figure 4). Marine heatwaves can have significant ecological, environmental, and economic impacts. They can be triggered by various factors, including atmospheric conditions, ocean currents, and climate patterns. One significant contributor is climate change, which can lead to an increase in overall ocean temperatures and create conditions conducive to heatwave events.

Marine heatwaves can have profound impacts on marine ecosystems (e.g. Garrabou et al 2022). Sudden increases in temperature can stress or kill marine organisms, including corals, fish, shellfish, and other aquatic life. This can disrupt food chains, alter species distribution, and damage sensitive habitats like *P. oceanica* meadows (Marbà and Duarte 2010) and coral reefs. Prolonged exposure to higher temperatures can lead to mass bleaching events in coral reefs, causing widespread coral mortality and affecting the biodiversity and health of these ecosystems.

Fisheries and aquaculture industries can be severely impacted as fish stocks may move to cooler areas or experience die-offs. This can lead to economic losses and affect the livelihoods of communities dependent on these industries.

Marine heatwaves can influence local weather patterns by affecting the temperature and humidity of the air above them. This, in turn, can influence weather events such as hurricanes, typhoons, and precipitation patterns. Monitoring SST is crucial for understanding the frequency, intensity, and underlying causes of these events is a need for predicting and managing their impacts in a multi risk assessment of coastal areas. Scientists use various methods to monitor and study marine heatwaves, including satellite-based measurements of sea surface temperatures and ocean temperature buoys.

In the Mediterranean Sea, the CNR MED Sea Surface Temperature (SST) from CMEMS provides SST data remapped over the entire basin at 1/16° as well as at ultra high (0.01°) spatial resolution.

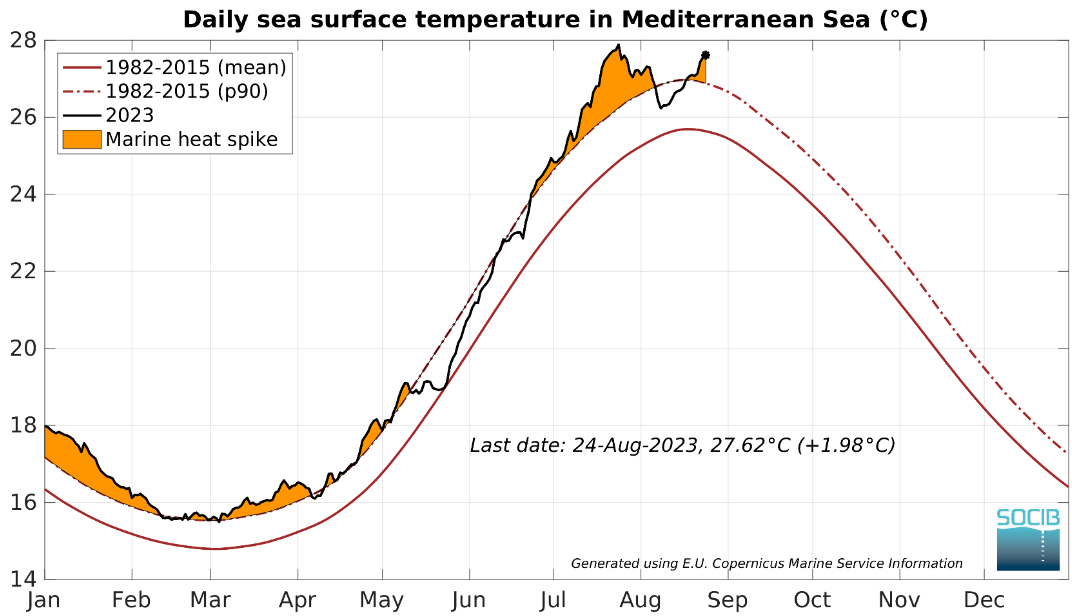

Figure 4. *Daily SST in the Mediterranean Sea. Data from Copernicus Marine Service satellite products in the Mediterranean Sea (L4) for the period between 1982 and 2015. The solid red curve indicates the mean SST for the period considered, the dashed line the 90th percentile and the solid black line the SST for 2023. Marine heat waves are defined here as the data overpassing the 90th percentile (yellow solid areas in the plot).*

1.2.4. Coastal ecosystems

Coastal vegetation offers shoreline protection from sea level rise, wave action and increased storm surges and can considerably reduce costs for coastal adaptation (van Zelst et al 2021). A key ecosystem in the marine coastal area of the Mediterranean are seagrass meadows of the phanerogam *Posidonia oceanica.* This ecosystem engineer (*sensu* Jones et al. 1994) reduces current flows in its canopies, and attenuates wave forces. The lush canopies developed by seagrass meadows affect water flow since the presence of seagrass canopies within the boundary layer alters the roughness of the bottom (Granata et al. 2001; Nepf and Vivoni 2000) as well as the vertical flow profile over the canopy, especially when canopy height represents more than 10 % of the height of the water column (Nepf and Vivoni 2000). Depending on seagrass species (plant size) and shoot density, flow reduction resulting from current deflection by the canopy ranges from two to more than ten-fold compared to water flow outside the seagrass bed (Gambi et al. 1990, Hendriks et al. 2008). The dampening effect on waves is maximal when the meadow occupies a large portion of the water column (i.e., more than 50 %; Fonseca and Cahalan 1992), however, reduction in wave energy and orbital velocity occurs even when beds are located at 5-15 m depth and the plants occupy a small portion of the water column (Verduin and Backhaus 2000, Granata et al. 2001).

The dampening of waves and currents by seagrass canopies leads to increased sediment deposition (Gacia and Duarte 2001, Gacia et al. 1999, Hendriks et al. 2008) and decreased resuspension (Lopez and Garcia 1998). Coastal vegetation offers coastline protection through its capacity to reduce coastal flooding and erosion hazards by reducing hydrodynamic energy through friction. Trapping and retaining sediment in their canopies can result in raising of the seafloor and intertidal areas (Duarte et al. 2013; Gedan et al. 2011; Moeller et al. 2014; Shepard et al. 2011; Temmerman et al. 2013).

Large-scale losses of coastal vegetation can lead to significant destabilization of the adjacent shorelines (Christianen et al. 2013, Rasmussen 1977), while restoration of coastal vegetation is likely to result in coastal stabilization.

P. oceanica is sensitive to warming (Olsen et al. 2012, Marbà et al. 2014) and meadows are already declining (Marbà and Duarte 2010, Marbà et al. 2014) and will likely severely decline over the next century (Jorda et al. 2012, Marbà et al 2022) under RCP4.6 and 8.5 scenarios. Extreme storm events are also emerging as an important driver of *P. oceanica* loss (Gera et al. 2014).

Also direct human impacts on seagrasses are threatening their habitat, particularly in densely populated areas (Borum et al., 2004). Direct impacts from human activity include: i) fishing and aquaculture (Delgado et al., 1999; Díaz-Almela et al., 2008; Holmer et al., 2008), ii) introduced exotic species (e.g. Borum et al., 2004), iii) boating and anchoring (Abadie et al., 2016; Francour et al., 1999), and iv) habitat alteration due dredging, reclamation and coastal construction (Ruiz & Romero, 2003). Other factors that impact the ecological status of *P. oceanica* meadows are nutrients and particulate organic matter discharges to coastal waters. Major anthropogenic sources include sewage effluent, septic system seepage, stormwater outfalls, industry (abattoirs, steel works, fertilizer processing plants), aquaculture (particularly sea cage-culture and prawn farms), and agricultural runoff (Ralph et al., 2006). Particulate organic matter, when deposited In seagrass sediments will degrade through aerobic mineralization and sulfate reduction, which causes anoxic sediment conditions and elevated concentrations of sulfide (Frederiksen et al., 2007). The combined effects of sulfide and anoxia have been shown to significantly affect seagrass growth and survival and are considered major causes of seagrass die-back events (Calleja et al., 2007, Frederiksen et al., 2007). The effects of sulfides are buffered in iron-rich sediments by the precipitation of pyrite as sulfides combine with iron (Marba et al., 2007), however, around Mallorca, sediments are iron-deficient and sulfite accumulates (Marbà et al., 2002; Mazarrasa et al., 2017). Sediment sulfides can diffuse through the rhizosphere directly affecting the below-ground root tissues (Ralph et al., 2006).

Seagrass beach cast, largely accumulating after fall and winter storms, contributes to shoreline protection (i) by providing calcareous skeletons from epiphytes and calcium carbonate deposited on seagrass leaves and rhizomes that become beach sand and (ii) may prevent beach erosion when beach cast deposits are some meters thick. In addition, export of seagrass beach cast to adjacent dune systems enhances dune stabilization and subsidizes vegetation growth (del Vecchio et al 2013, Jiménez et al 2017).

After meadow loss, other macrophytes might be able to stabilize the sediment where *P. oceanica* meadows were present, especially species more resistant to warmer temperatures like *Cymodocea nodosa.* However, this species has a limited engineering capacity compared to *P. oceanica*. Invasive species, like *Halimeda incrassata* have also shown to stabilize the sediment and provide ecosystem functions (Marx et al. 2021), but due to their marked seasonality offer limited sediment stabilization during fall, when most wave action is expected. In addition, wave attenuation will not be to the same extent due to differences in size and lack of shedding in fall, causing beach protection through the accumulation of beach wrack (Gómez-pujol et al., 2013; Beltran et al., 2020).

1.2.5. Socioeconomic: population, economic model, diverse contingencies

Global climate change studies rely on numerous assumptions and factors related to policy options and social developments. Shared Socioeconomic Pathways (SSPs) have been developed during the last years (O'Neill et al.,2014; 2015) describing plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change. SSPs aim to describe how the future can evolve under a consistent set of assumptions based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development (Riahi et al., 2017). In the context of the present ad-hoc multi-risk assessment methodology, SSP2 is set as the Reference scenario. The SPP2 scenario represents a continuation of the main economic, demographic and social trends that characterize the world today. That is why it has also been coined as Middle of the Road, Dynamics as Usual, Current Trends Continue, or Continuation.[1]

In this context, and given the frequent tourist specialization of Mediterranean coastal areas, it is important to consider how climate change will affect tourism demand in these destinations. The relevance of climate in Mediterranean tourism is evidenced through the typical seasonality pattern, that peaks during the summers and falls in winter. Whether through the direct effects of climate change -such as temperature and precipitation- or through secondary effects -such as vegetation, stream flows, reservoir levels, wildlife populations and miles of beaches-, it can be expected that the spatial and temporal pattern of outdoor recreation activities will adjust. Despite the uncertainties related to projecting social phenomena in the long run, different quantitative studies have analyzed the effects of climate change on tourism flows. Three main approaches have dominated the literature (Rosselló-Nadal, 2014): Time series analysis, discrete choice modeling and aggregated tourism demand modeling.

[1] For a more specific description of SSP, see Fricko et al. (2016)

Within the context of time series analysis, it is preferable to talk about weather rather than climate since the most popular approach is to attempt to capture some kind of short-term relationship between tourism demand and extreme weather events (Rosselló et al, 2011; Kulendran and Dwyer, 2012; Otero-Girálde et al., 2012; Goh, 2012; Rosselló and Waqas, 2016). In this sense, this project will focus especially on this type of literature to analyze the effects of extreme events, without prejudice to other types of methodologies that have also aimed to analyze the effects of extreme events on tourism (Rosselló et al, 2020).

Discrete Choice Models try to answer the question why people choose a particular destination. Tourism choices are considered to be a process of both quantitative and qualitative consumption. The quantitative unit of tourism consumption can be represented by the length of stay in a particular destination, the number of visits, etc. The qualitative unit of tourism consumption is represented by the bundle of characteristics provided by destinations, including climate conditions. Using a survey of European households, Eugenio-Martín and Campos-Soria (2010) investigated the relationship between climate in the home area and the choice of taking a holiday in the tourist's home region or abroad, showing that the climate in the home region is a strong determinant of holiday destination choices. They show that residents in regions with better climate indexes have a higher probability of domestic travel and a lower probability of traveling abroad, while residents of colder regions tend to travel abroad more often than residents of warmer ones. Bujosa and Rosselló (2013) investigate the impact of climate change on destination choice decisions within a context of domestic summer coastal tourism in Spain. Once the destinations have been characterized in terms of the travel cost and coastal 'attractors' (temperature and beach related attributes), the observed pattern of interprovincial domestic trips is modeled, showing trade-offs between temperature and attractiveness in the likelihood of a particular destination being chosen. Using A1FI and B1 climate change scenarios they show that Spain's colder northern provinces would benefit from rising temperatures, while provinces in the south would experience a decrease in the frequency of trips. This project will benefit from these previous results to contextualize future projections of tourism demand in coastal areas.

Within the context of time series analysis Madison's (2001) presents a cross-sectional model of destinations chosen by British tourists, using classic price determinants of tourism demand and incorporating climate variables in terms of attractors. The model's estimation allows the trade-off between climate and holiday expenditure to be quantified and, through the introduction of nonlinear effects , the 'optimal' climate for generating British tourism is identified. Taking a global perspective, Hamilton et al., (2005a, 2005b) present what is known as the Hamburg Tourism Model (HTM), consisting of the estimation of two equations for international tourist departures and arrivals for a specific year. Despite the relatively high level of complexity of the specification and estimation process, using specific projected climatic, population and economic data related to A2, B1 and B2 scenarios, Rosselló and Santana-Gallego (2014) forecast tourist arrivals for 2080 (Figure 5), finding similar results to previous works and thus providing more evidence that climate change would imply a weakening of the currently predominant international tourism flow from North to South. Recently, Matei et al. (2023) simulate the impacts of future climate change on tourism demand for four warming levels (1.5°C, 2°C, 3°C, and 4°C) under two emissions pathways (RCP4.5 and RCP8.5) finding a north-south pattern in tourism demand changes, with northern regions benefiting from climate change and southern regions facing significant reductions in tourism demand. This project will benefit also from these previous results to contextualize future projections of tourism demand in coastal areas.

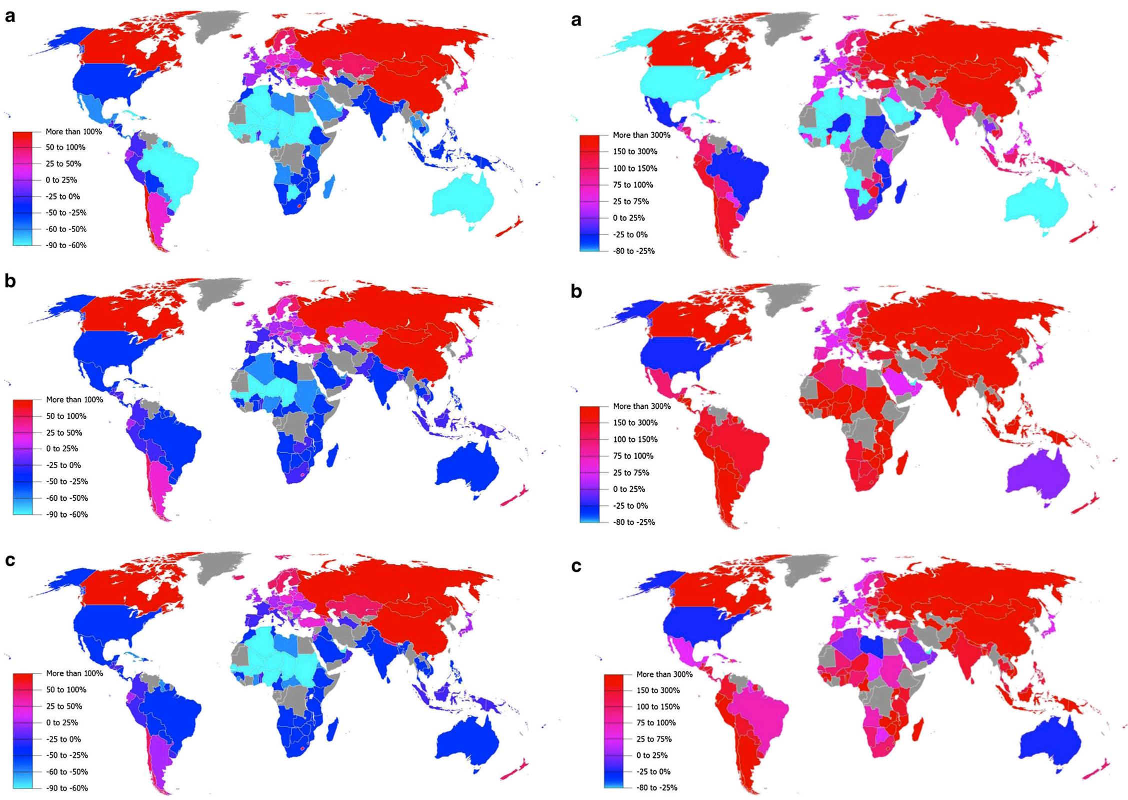

Figure 5. *Left: Percentage variation in tourist arrivals caused by changes in temperatures. Percentage change in tourist arrivals for 2080, compared to arrivals in 2007, considering only the effect of temperature for scenarios A2 (a), B1 (b), and B2 (c) . Right: Percentage variation in tourist arrivals caused by change in temperatures and the Gross Domestic Product per capita. Percentage change in tourist arrivals for 2080, compared to arrivals in 2007, considering scenarios A2 (a), B1 (b), and B2 (c). Source: Rosselló and Santana-Gallego (2024)*

Regarding data it is desirable to have projections of tourism demand for the country (and region if available) to characterize future economic environments. These projections will be derived from the empirical literature mentioned above and thus considering time series models, discrete choice models and aggregated tourism demand modeling. Additionally, descriptive statistical data to characterize the region both from an economic and sociological point of view will be used from using the regional statistical institute.

1.3. Definition of the hazard assessment methodology for each beach dimension.

Coastal hazard assessment is a critical tool for protecting coastal communities and ensuring their long-term sustainability. As the impacts of climate change continue to intensify, the need for accurate, up-to-date assessments becomes increasingly urgent. Through a combination of historical analysis, technological advancements, and community involvement, coastal hazard assessments empower societies to make informed decisions, mitigate risks, and build resilient coastal communities that can thrive even in the face of nature's challenges. These assessments are not just a matter of safety; they are an investment in the future of our coastal regions, economies, and ecosystems. Coastal systems and beaches will experience an increase in the potential impacts during the 21st century due to extreme events flooding as well as from the eventual erosion resulting from the sea level rise. It is accepted that population growth in coastal areas as well as the importance of services and infrastructures will increase the risks and hazards in coastal systems (IPCC, 2014).

Under this perspective, a wide range of methodological frameworks are emerging for the socioeconomic assessment of the risks and consequences of flooding and erosion at different scales. The classical methodology applied to the analysis of extreme weather risks has resulted in a generalized conceptual framework (IPCC, 2014) based on the combination of hazard, exposure and vulnerability. There is not a unique methodology to assess each risk component, and the existing approaches are strongly dependent on the availability of data, the spatial scale, the impact modeling strategy considered, and the type of statistical analysis required, among others. In addition, the management and planning of the territory is always made on a regional scale, which translates into the need to integrate risks and consequences in a given area. In this regard, the challenge lies mainly in treating a set of socio-economic sectors in an integrated way, especially if these sectors are of a different nature.

The multi-hazard assessment approach is divided into the physical component, the environmental and the socio-economic dimensions in order to evaluate the potential influences among different types of hazards, taking into account possible interactions that may amplify the overall risk. It is performed through these steps: a selection of the hazards and the timeframe of analysis; an analysis of hazard probabilities; an assessment of the hazard interactions; and finally the aggregation and normalization of the multi-hazard score.

The hazards and timeframe to be considered in the MRA depend on the scope of the study and the data availability. Single hazard metrics can be derived from climate models (e.g., temperature or precipitation projections) and physical impact models (e.g., sea-level rise, currents velocity, and bottom stress), or by reviewing single-hazard scenarios available from previous projects in the considered region. The selected metrics should represent the intensity of the hazard (e.g., projected water level for inundation and wave energy for coastal erosion) and capture the influence of climate change (e.g., anomalies between baseline and future scenarios).

In the following, we describe for each dimension the hazard assessments.

1.3.1. Physical Dimension

The coastal areas and especially the sandy beaches are a space of great socio-economic relevance since they concentrate a large part of the human activities linked to the coast, a high population density, at the same time that they are one of the largest areas of biodiversity on the planet. In addition to their contribution or role as support for ecosystems, beaches are mainly elements of natural protection of the coasts against extreme marine events (Vousdoukas et al., 2017).

The beaches are characterized by their great dynamic variability, responding relatively quickly to wave changes and, at the same time, subject to long-term changes in which the complex interactions between morphodynamics play an important role (i.e., changes in the topographic profile and plan of the beach) and forcings (e.g. tides, waves and currents). In order to improve the understanding of the physical processes in the beaches and to be able to anticipate the possible changes in their morphology in response to external forces, it is necessary to monitor and analyze the state of these systems. Ultimately, this information is relevant to inform coastal management decisions.

One of the most visible and potentially damaging consequences of climate change resulting from human activity is the gradual rise in mean sea level. Sea level has been rising since the beginning of the 20th century in response to increased concentrations of greenhouse gasses in the atmosphere, and observations and models suggest that it will continue to do so for decades and centuries to come (IPCC, 2019). In addition, climate change is linked to variations in weather patterns that control the storm regimes that affect the coasts. Among other factors, changes in the average marine climate (wave height, wave period or direction) as well as in the regime of extremes, affect the processes that govern the dynamics of the beaches. That is why, in order to have a strategy for adapting coastal uses and resources, as well as for mitigating the effects of climate change, it is necessary to quantify future changes in these forcings (Figure 6).

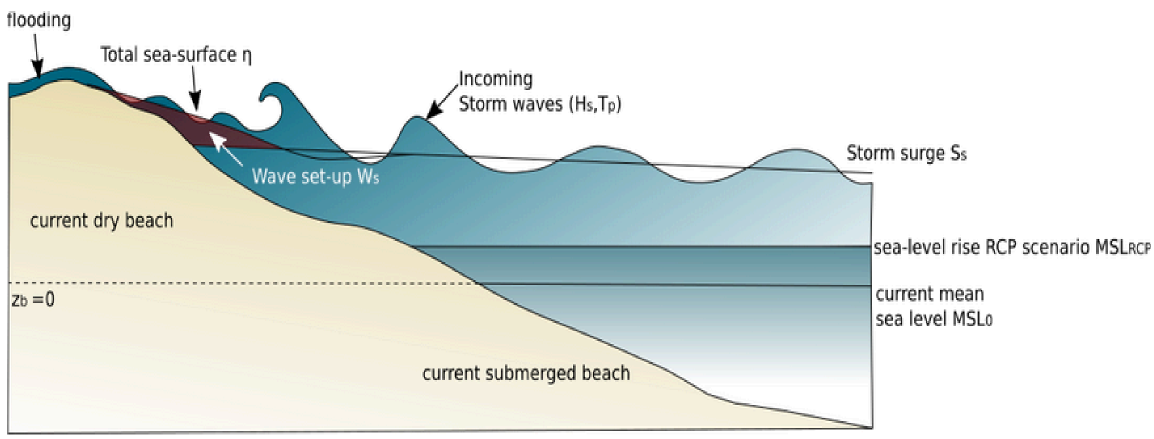

Figure 6. *Schematic view of the different components affecting the flooding in a typical beach profile (source: Fernández-Mora and Bonet, 2023).*

Hazard assessment aims to anticipate the effect on inundation and erosion of beaches in the face of changing forcings consistent with climate change scenarios from the physical point. Specifically, in this section a methodology is presented for estimating changes in a microtidal mediterranean beach during this century. To this end, the climate scenarios for the evolution of greenhouse gas emissions known as RCP-4.5 and RCP-8.5 (Representative Concentration Pathways; vid. van Vuuren et al. 2011) have been used. The considered forcings include the rise of the mean sea level, storm waves (storm surges) and waves. The astronomical tide is considered as an invariant[2]. These agents affect the state of the beach through flooding, erosion and, in the event that there is sufficient accommodation space, causing the setback of the beach-dune system; after all,

[2] In those beaches where the tidal component provides a significant value of the sea level it has to be included in any analysis.

modifying the coastline. Its impact has been quantified using numerical models applied at the local (beach) scale and forced from regionalized global climate model outputs.

Main hazards related to sea-level rise and waves and surges action are the coastal flooding and erosion. For a sake of simplicity in the following we are providing some definitions related to the main physical hazards:

- Permanent coastal flooding refers to the long-term inundation of coastal areas due to a rise in sea levels. It occurs when the sea level rises to a point where low-lying coastal regions become permanently submerged, making them uninhabitable or unsuitable for human activities. This type of flooding typically results from climate change-induced sea-level rise.
- Extreme coastal flooding, on the other hand, refers to severe and exceptionally high floods that occur along coastal areas (Caruso and MArani, 2021). These floods are often associated with extreme weather events such as hurricanes, cyclones, or intense storm waves and surges. Extreme coastal flooding can cause significant damage to coastal infrastructure, result in the displacement of communities, and pose significant risks to human life and property, and
- Beach erosion refers to the gradual or rapid loss of sand or sediment from a beach, resulting in a decrease in its width and volume.

Hazard assessment methodology:

a. Beach diagnostic: morphodynamic model and interannual evolution.

The analysis of the actual state and seasonal and interannual evolution of beaches in response to mean wave conditions and sea levels is crucial for developing a comprehensive hazard assessment. By understanding how beaches interact with these environmental factors, we can assess the potential risks and vulnerabilities associated with coastal hazards.

Incorporating data on beach state and behavior into hazard assessments provides a comprehensive understanding of coastal vulnerability. This information assists in identifying high-risk areas, prioritizing resources, and implementing effective measures to mitigate hazards. For this, a sequential methodology has to be implemented:

1. Marine climate and extremes characterization (in-situ data or model hindcast).
2. Analysis of mid/long term morphodynamics for different time-scales (inter-annual and seasonal):
   a. Shoreline evolution: analysis of available shoreline data (e.g. using time series of video monitoring, orthophotos, DGPS , satellite imagery , etc.).
   b. Sediment budget: analysis of available topo bathymetry data.
3. Beach morphodynamics modeling:
   a. Mean wave climate (data and/or numerical models): beach morphodynamics (currents, transport, morphodynamic patterns...).
   b. Storm conditions: beach response (erosion/accretion patterns, sand bar dynamics, storminess and recovery time).

4. Beach conceptual model from the integration of 1, 2 and 3.

b. Hazard Assessment:

Analyzing the behavior of beaches in the face of sea-level rise and extreme events is a complex task that requires considering various local factors. These factors can significantly influence how a beach responds to changing conditions and impact the potential for coastal flooding. Urban beaches, in particular, present additional complexities due to the presence of built infrastructure along the coastline. To study **coastal flooding and beach erosion** accurately, it is necessary to account for **bidimensional (2D) processes**. Coastal flooding involves complex interactions between sea-level rise, storm surge, wave dynamics, tides, and local topography. Traditional one-dimensional (1D) models may not capture the spatial variations and interactions accurately. Therefore, 2D modeling approaches, such as numerical hydrodynamic models, allow for a more comprehensive understanding of flood patterns, flow velocities, and sediment transport across the coastal zone. These models consider the influence of local factors and provide insights into how coastal flooding may impact urban beaches and associated infrastructure.

Near-shore morphodynamic models have become one of the main tools in unraveling the complex dynamics of coastal environments. These models encompass a spectrum of approaches, each offering unique insights into near-shore evolution. Process-based models integrate fundamental principles of fluid dynamics and sediment transport to simulate the intricate mechanisms governing beach evolution (Falqués et al., 2007; González et al., 2007; Roelvink et al., 2009). RANS (Reynolds-Averaged Navier-Stokes) models delve deeper into fluid dynamics, providing a numerical framework to analyze turbulence effects and wave-structure interactions (Higuera et al., 2013, Jacobsen et al., 2014a, b). DNS (Direct Numerical Simulation) models offer even finer-grained resolution by directly solving fluid equations, enabling accurate depiction of small-scale coastal phenomena. Machine learning models, a recent innovation, harness the power of data-driven algorithms to extract patterns from extensive datasets, enhancing predictive capabilities and capturing nonlinear coastal behaviors (Goldstein et al., 2018).

From this background we propose a process-based model, the XBEACH model (Roelvink et al., 2009) which is nowadays confirmed as a reference for coastal flooding and beach erosion. Its capabilities in simulating wave and hydrodynamic processes, sediment transport, and morphological changes allow for a comprehensive understanding of coastal dynamics. By providing valuable insights into beach behavior under varying conditions, XBEACH supports decision-making, coastal management, and the development of strategies to mitigate coastal hazards and protect coastal environments.

The proposed scenarios to evaluate the hazards for the physical beach component are summarized in Table 1.

***Table 1**. Scenarios and time horizons proposed to evaluate the hazards for the physical component*[3].

IPCC Sc	Forcing	Actual (2023)	2030	2050	2100
RCP4.5	Sea-level	(no RCPs); 2 maps: EXTREME T50 & T100	PERMANENT (3 int) = 3 maps	PERMANENT (3 int) = 3 maps	PERMANENT (3 int)= 3 maps
	Sea-level + wave and storm surge T50 and T100		EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6
	Sea-level + wave and storm surge T50 and T100 Corresponding *P. oceanica* meadow state		EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6
RCP8.5	Sea-level		PERMANENT (3 int) = 3 maps	PERMANENT (3 int) = 3 maps	PERMANENT (3 int)= 3 maps
	Sea-level + wave and storm surge T50 and T100		EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6
	Sea-level + wave and storm surge T50 and T100 Corresponding *P. oceanica* meadow state		EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6	EXTREME (3 int x 2 T) =6

1.3.2.Environmental Dimension

Seagrass meadows in the Mediterranean Sea can extend from less than 1 meter of water depth down to 45 m in clear waters such those in the Balearic Islands, and along several kilometers perpendicular to the seashore. These ecosystems enhance sediment accretion and can act as natural coastal defenses against the physical hazards identified above, due to their role on sediment stabilization and currents, wave height and wave energy attenuation. The provision of coastal protection by seagrass meadows is constrained by seagrass abundance (extent, and shoot density) and meadow submergence ratio (vegetation height/water height), thus plant size.

Global warming and heat waves are threatening the persistence of some seagrass meadows globally (Marbà et al 2022). Current warming in the Mediterranean sea, which doubles to triple that in the global ocean, is already enhancing the decline of the abundance of *Posidonia oceanica* (Marbà and Duarte 2010, Garrabou et al 2022), the dominant seagrass species in the region. Projections of *P. oceanica* abundance under RCP scenarios reveal massive declines that may lead to functional extinction of these Mediterranean seagrass meadows (Jordà et al 2012). Conversely, the Mediterranean warming projected for the current century under RCP scenarios might trigger the spread of another seagrass, *Cymodocea nodosa*, a warm-affinity species, present in the Mediterranean but currently much less abundant and smaller than *P. oceanica*. Losses of *P. oceanica* abundance, as well as possible shifts in seagrass flora triggered by warming and heat waves are expected to affect the role of seagrass meadows on coastal defense and thus coastal flooding and erosion. Global warming and heat waves, together with extreme storm events, could also constrain the magnitude of seagrass beach cast deposits and dynamics.

[3] Note that each scenario defined in Table 1 has to be computed for the mean, minimum and maximum value of SLR. This means 3 simulations for 32 forcing scenarios by the three probability intervals.

To note that its mandatory to get the physical and biological interaction with seagrass meadows in the Mediterranean context. Following the example of Cala Millor (Infantes et al., 2012) hydrodynamical data to obtain wave climate, wave energy and current attenuation in seagrass meadows was compiled from the literature or in dedicated experiments. In this sense, sediment accretion/erosion in the seagrass meadow over the last 100 years can be assessed from estimates derived from 210-Pb dated sediment cores (i.e. Arias-Ortiz et al., 2018)). Declining rates of shoot abundance triggered by warming can also be assessed using available relationships of seawater summer temperature and net shoot population growth and mortality rates in the literature and derived from long term monitoring (>20 years) of *P. oceanica*. The presence or absence of *P. oceanica* and *C. nodosa* meadows under projected RCP warming scenarios can thus be assessed using compiled thermal thresholds for survival and growth, defined by the thermal niche, of populations of these species in each study site (i.e. Marbà et al., 2022). As an example, the current distribution of seagrasses in Cala Millor can be obtained from the Balearic Islands cartography recently conducted by the Government of the Balearic Islands as well as from current estimates of shoot densities across the depth gradient of *P. oceanica* meadows in the Balearic Islands. It is highly recommended for the areas under study to analyze the temporal dynamics of seagrass beach cast deposits and their role as dune subsidies.

Since the few studies conducted so far reveal that extreme storm events may also trigger losses of *P. oceanica* meadows (Gera et al 2014), historical changes in aerial cover and position of the upper depth limit of *P. oceanica* meadow in each location will be examined in relation to storm events. Similarly, a time series of 4 decades of *P. oceanica* vertical growth, a proxy for changes in sediment accretion-erosion fluctuations, will be analyzed and the relation of inter-annual variability in growth with extreme events will be explored.

The results of the effect of seagrass meadow structure, abundance and morphology on wave attenuation and hydrodynamics at present and in the future, considering vegetation changes triggered by RCP scenarios, will be embedded in the physical models described in the previous sections.

1.3.3.Socio-economic dimension

The spatial and temporal pattern of tourism demand can be expected to adjust to environmental changes, either as a result of the direct effects of climate change, such as rising temperatures, or due to secondary effects, such as impacts on the landscape, bathing water quality, jellyfish proliferation or rising sea levels. While in the first case (the direct effects of the change in temperature and other climatic conditions on tourism demand) this project will take as reference the available statistical models described in section 1.2.5, in the second case (the indirect effects of climate change through the change in sea levels on tourist demand), this project will take the results of the physical and environmental dimensions described in previous sections about consequences on the size of the beaches and hazard assessment on different urban structures as reference to evaluate the consequences on local economy.

To achieve this objective, it is necessary, on the one hand, to try to regionalize as much as possible the results of aggregate models that measure the direct effects of climate change on tourism and, on the other hand, to consider the dependence on the physical and environmental conditions of tourist activity. Consequently, given the aggregate nature of the regional economic accounts, it will be necessary to obtain information through surveys that allow this dependence to be evaluated in order to rigorously transfer the results from tourist demand to the economic evaluation of the climate impact on the local economy.

1.4. Hazard likelihood

Computing hazard likelihood is a crucial component of risk assessment, as it provides a quantitative understanding of the probability of a hazardous event occurring. Incorporating hazard likelihood into risk assessment enhances our ability to identify vulnerabilities, design effective mitigation strategies, and develop resilient systems that can withstand and respond to potential threats.

1.4.1. Physical dimension

As detailed in section 1.3, hazards related to the physical dimension include permanent flooding, extreme flooding, and beach erosion. The probability associated with these hazards is directly linked to the likelihood of the drivers considered in section 1.2: the IPCC RCP scenarios and extreme wave and surge reference storms with return periods of T50 and T100.

Thus, considering the current approach:

a. Regarding the IPCC RCP sea-level rise scenarios, the likelihood of both scenarios will be addressed considering the current state-of-the-art works on probability of RCP scenarios (Capellán-Pérez et al., 2016, Jackson & Jevrejeva,2016)
b. Regarding the extreme events (reference wave and surge storms for a given return period), since they are defined independently of the RCP scenarios, the associated probability is directly related to the return period for which they are designed.

Since both types of drivers are considered simultaneously yet remain independent, the joint probability is computed as the product of the probabilities of the individual events happening "$P(A \cap B)=P(A)*P(B)$". Probabilities should be computed considering the time-horizons 2030, 2050 and 2100.

1.4.2. Environmental dimension

As detailed in 1.3.2 section, the presence, abundance and type of flora of seagrass meadows is constrained largely driven by seawater thermal conditions exceeding seagrass thermal tolerance upper limit. A similar approach as described for the physical dimension will be followed to assess hazard likelihood in the environmental dimension:

Regarding the IPCC RCP marine warming and heatwaves scenarios, the likelihood of both scenarios will be addressed considering the current state-of-the-art works on probability of RCP scenarios.

1.4.3. Socio-economic dimension

As detailed in previous sections 1.2.5. and 1.3.3 the economy of the study area is conditioned by the potential tourist demand of the area and by the infrastructure (natural and urban). To evaluate the probability of danger in the economic dimension, on the one hand, the latest works on the impact on tourism demand under climatic change scenarios will be taken. On the other hand, the probabilities of the physical and environmental dimensions will be used as reference in the evaluation of the economic effects of the infrastructure damage.

1.5. Output: Hazard maps

Once the hazards have been defined and analyzed, as well as their inner hazard probabilities, it remains to turn the results into a hazard raster map per beach dimension and for each scenario, where each pixel has a normalized score (range 0-1). Keep in mind that hazard maps, considered as events or physical trends related to the climate or its physical impacts (IPCC, 2014), have to show the spatial and temporal distribution of a certain variable in the different proposed climate change scenarios.

As an example, the hazard map of the physical dimension obtained by the forcing “Sea-level + wave and surge storm T50”, will return a flooding raster map where each pixel will indicate if it is flooded (1) or not (0) for that particular scenario and with its associated probability of occurrence.

Then, from this first hazard assessment Table 2 summarizes the resulting maps:

Table 2. *Expected outputs from the hazard assessment.*

Physical dimension	(32*3 SLR) = 96 maps[4] (detailed in Table 1)
Environmental dimension	2 scenarios RCP (for summer temperature projections)*min/max/mean * 4 time steps (current state,2030, 2050, 2100) = 24 seagrass presence/absence maps 2 scenarios RCP (for summer temperature projections)*min/max/mean * 4 time steps ((current state, 2030, 2050, 2100) = 24 seagrass shoot density maps
Socio-economic dimension	Depending on the number of hazards: 96 economic valuation maps derived from the scenarios of the physical dimension

All these raster maps cartography the same study area, so each pixel could be affected by none, one, or multiple hazards. The pixel values will be 0 (no hazard) or 1 (there is threat), and note that the probability of occurrence also has to be indicated for each hazard and scenario.

2. Exposed elements

The methodological approach to determine the impact degree that occurs on a specific study area bases on the combination of hazard and exposure maps. For example, the impact of coastal flooding arising from sea level rise and storm surge, will consist of crossing layers of spatial information of diverse origin and scale with the spatial layers of the flooded areas for each of the time horizons and IPCC climate scenarios. Following the methodological framework described in the Methodology section and illustrated in Fig. 1, the risk assessment focuses on determining the scope of the risk on the receptors such as population, buildings, critical infrastructures, residential land, agricultural land, land dedicated to activities of services, hotels and other economic activities, protected natural spaces and habitats, and on the environmental resources of the beaches.

From a general point of view in this section we should identify, for each study site, some major groups of exposed elements (land use classes). Those belonging to the physical dimension (i.e. beach surface, study site extremely detailed topography), to infrastructures (i.e. critical infrastructures as roads, power stations, hospitals, etc.), to the natural dimension (i.e. seagrass meadow extension, natural parks, protected habitats and taxons) or to the socio-economic

[4] 3 (SLR_intervals) per 32 forcing scenarios, becomes 96 different hazard maps; + their 96 associated hazard probabilities.

dimension (i.e. population, economic activities, land use). Once selected, these cartographic data (vector or raster layers) will be expected to be exposed and potentially affected by the hazards of Section 1. Then, by expert criteria, these data will be prepared and, if possible, categorized in five levels of exposure (ranging 0 to 1) according to the economic value of land uses: 0 (unexposed), 0.25 (low exposure), 0.5 (medium), 0.75 (high exposure), to 1 (fully exposed).

2.1. Definition of data requirements, data sources and temporal resolution to evaluate exposed elements

Exposed elements in order to be crossed with a hazard layer should be provided as spatial data, both, vector or raster type. The data resolution as we are dealing with local approach should be the maximum resolution available (i.e. DEM 2x2 m enriched with detailed information on structures that can interact with sea flooding). The minimum desired requirements are shown at Table 3 as an example.

***Table 3**. Example of type of exposed elements, data sources and temporal scale for each dimension (to be site adapted).*

Variable (exposed element)	Data source	Desired Spatial resolution	Desired Temporal resolution
Physical dimension			
Digital Elevation Model (DEM) -> derived slope map	Official cartographic Institute or municipality	The maximum available (1:1000 or 3 x 3 m rasters)	According availability
Topo-Bathymetry	Official or developed for project purposes	High resolution, according to the beach length.	According availability
Hydrological basins	Official cartographic Institute or municipality	The maximum available (1:1000 or 3 x 3 m rasters)	According availability
Infraestructures			
Roads	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000); vector type.	According availability
Power infrastructures	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000); vector type.	According availability
Hospitals	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000) ; vector type.	According availability
Education centres	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000); vector type.	According availability
Cemeteries	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000); vector type.	According availability
Ports / airports	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000); vector type.	According availability

Environmental			
Natural habitats	Official cartographic Institute or municipality	The maximum available (1:5000 or 3 x 3 m raster)	According availability
Protected areas/ Special Areas of Conservation (SACs)	Official cartographic Institute or municipality	The maximum available (1:5000 or 3 x 3 m raster)	According availability
Species distribution	Official cartographic Institute or municipality	The maximum available (1:5000 or 3 x 3 m raster)	According availability
Socio-economic			
Population	Population Census or JRC products	The maximum available. Urban block.	According availability
Buildings	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000)	According availability
Land use	Official cartographic Institute or municipality	The maximum available (1:5000 or 3 x 3 m raster)	According availability
Economic activities	Official cartographic Institute or municipality	The maximum available (1:5000 or 1:1000)	According availability

2.2. Output: Exposure map

An exposure map shows the presence of people, livelihoods, species, or ecosystems, environmental functions, services and resources, infrastructure, or economic, social or cultural assets in places and environments that could be negatively affected (IPCC, 2014).

Thus, the final exposure map of the study site will be a compendium of different cartographic data that experts, from each beach dimension, decide for being potentially threatened by the different hazards and are therefore considered to be elements at risk. Each expert will be responsible for the information layers within its scope by data curating and by classifying the different elements into an exposure level according to the economic value of land uses (Estrela-Segrelles et al. 2021).

As exemple, for an elevation map or DEM, it is clear that the exposure value will decrease with the elevation. However, within a layer of natural habitats, the class "bare ground" will have lower value and consequently lower exposure level than a lagoon, a wetland or a dune area. Note that these categories will be associated with values from 0 to 1 this way: 0 (unexposed), 0.25 (low exposure), 0.5 (medium), 0.75 (high exposure), and 1 (very high exposure level).

Later on, by adding all these information layers, a final raster exposure map will be performed reflecting on each pixel (range 0-1 after being normalized) the number of exposed elements (receptors) at risk for the three beach dimensions, as well as their weights depending on the land value, if applicable. Before normalization, a pixel will have an exposure value equal to 0 if no receptors are present in the investigated cell; a pixel value of 3 if overlap three receptors fully exposed; whereas an exposure value equal to 0.5 could refer , to the presence of one receptor with medium exposure level, or the presence of two receptors both with a "low exposure level".

The exposure map will be unique for the various scenarios, this means that same cartographic data (representing the current mapping) wil be used for crossing with all the different sets of hazard maps in order to know about the impact degree that occurs on a specific area for each climate scenario.

3. Vulnerability and risk assessment

According to the framework proposed by the natural hazard community (The United Nations International Strategy for Disaster Reduction; UNISDR, 2009), the analysis of the likely impacts or risks related to coastal hazards involves the evaluation of two main components: hazard (i.e. an event or phenomenon with the potential to cause harm, such as loss of life, social and economic damage or environmental degradation) and the system vulnerability, i.e. the characteristics of a system that increase its susceptibility to the impact of climate-induced hazards (Torresan, 2012). In this context, vulnerability is often expressed in a number of quantitative indexes, and is a key step toward risk assessment and management.

Coastal vulnerability is a multifaceted concept encompassing physical, ecological, and societal aspects. It involves not only the susceptibility of coastal environments to natural hazards but also the capacity of communities to adapt and respond to these threats. Vulnerability can vary significantly from one region to another based on factors such as geology, climate, infrastructure, and governance. Risk assessment is not a one-size-fits-all process; it must be tailored to the specific characteristics and challenges of each coastal region. The primary goal is to identify, analyze, and prioritize risks, enabling informed decision-making and resource allocation.

The methodological approach defines risk as the probability of an adverse event of natural or anthropogenic origin and its consequences in a determined period of time. The interaction of said event with the elements of the environment and its degree of vulnerability results in a set of risks on the population, the material, economic or environmental resources.

A vulnerability assessment is the process of identifying, quantifying, and prioritizing vulnerabilities in systems, networks, applications, or physical assets. Vulnerabilities are weaknesses or flaws that could be exploited by threats (such as hackers, malware, or natural disasters) to compromise the confidentiality, integrity, or availability of an asset. Risk assessment is a broader process that involves identifying, analyzing, and evaluating risks to an organization. It considers not only vulnerabilities but also threats, the potential impact of those threats, and the likelihood of those threats occurring. Both vulnerability and risk assessments are crucial for maintaining the security and resilience of an organization's operations, whether in the context of information security, disaster preparedness, or other areas where risk management is essential.

The assessment of risk, exposure and vulnerability, which are characterized in the present work, result from the modeling of the coastal flooding for the entire of the sandy beaches, excluding the rest of coastline typologies out of the scope of this work (ie., steep coasts and beaches of blocks). The methodology to assess climate change vulnerability and risks at microtidal urban beaches, by considering the RCP4.5 and RCP8.5 scenarios. The analysis will be done by considering different timescales embracing mid- (2030-2050) and long-term (2100) effects as milestones.

3.1. Sensitivity and adaptation capacity for the exposed elements

Sensitivity relates to the characteristics of exposed elements that are dependent on specific environmental conditions, and the degree to which it will likely be affected by climate change. Adaptive capacity means ability of an element to cope and persist under changing conditions through local, dispersal or migration, adaptation (e.g., behavioral shifts), and/or evolution. **Sensitivity and adaptive capacity indicators** are selected considering the framework of the analysis, in this case climate change related hazards.

The selection of a sensitivity indicator for coastal flooding is a crucial step in assessing the vulnerability of coastal areas to potential inundation events. This indicator plays a pivotal role in understanding how various elements within the coastal zone, such as infrastructure, ecosystems, and human settlements, might react to the impacts of flooding. A well-chosen sensitivity indicator should encompass a range of factors including topography, land use, infrastructure resilience, and ecological characteristics.

These components should be defined for each exposed element considering the following terms:

1. **Sensitivity (S^i):**
   Definition of the sensitivity of a given element: a definition of its sensitivity,
   Indicator: qualitative or quantitative metric that evaluates the sensitivity of the element. This indicator should be easily normalized (from 0 to 1, the more sensitivity),
   Computing method,
   Units: units of the no-normalized indicator.

2. **Adaptive capacity (AC^i):**
   Definition of the adaptive capacity of a given element: a definition of its adaptive capacity,
   Indicator: qualitative or quantitative metric that evaluates the adaptive capacity of the element. This indicator should be easily normalized (from 0 to 1, the more adaptability),
   Computing method,
   Units: units of the no-normalized indicator.

Sensitivity and adaptive capacity indicators of each type of exposed element will be defined in a single fact-sheet considering the terms listed above. An example of a fact-sheet is found in Figure 6.

Note that an exposed element may have multiple sensitivity and/or adaptive capacity indicators. In this sense we define the following indexes:

- the composed sensitivity index CS^i, defined as,

$$CS^i = \frac{\Sigma_j^i S_j^i}{n} \qquad \text{Eq. 1}$$

where *j* stands for the *jth* sensitivity indicator of the *ith* exposed element, and *n* is the number of sensitivity indicator considered,

- the composed adaptive capacity index AC^i, defined as Eq. 1 but now for the adaptive capacity indicators.

Composed indexes are computed considering the normalized value (0-1) of the individual indexes.

EXPOSED ELEMENT: BEACH

SENSITIVITY INDICATOR 1

Name: Beach slope
Definition: The slope of the beach shoreface influence on flooding extents and erosion rates.
Indicator: Beach shoreface slope
Calculus: Rated from 0-1 depending on slope ranges:

Slope ranges	Sensitivity index value
>20° (steep)	0.2 (low)
6-20° (moderate-gentle slopes)	0.6 (medium)
0-6° (plain)	1 (very high)

Units: adimensional

ADAPTIVE CAPACITY INDICATOR 1

Name: Accommodation space (back-face)
Definition: The type of elements in the back-face of the beach determine if it have space to accommodate in front SLR effects
Indicator: Presence-absence of dune systems
Calculus: Rated from 0-1 depending on:

Back-face	Adaptive capacity value
Mature dune system	1 (high)
Incipient dune system	0.5 (medium)
Hard-boundary (structures)	0 (low)

Units: adimensional

SENSITIVITY INDICATOR 2

Name: Beach sheltering level
Definition: The level of exposure of the beach to extreme wave conditions controls extreme flooding and erosion
Indicator: Type of beach sheltering level
Calculus: Rated from 0-1 depending on:

Sheltering level	Sensitivity index value
Sheltered beach (sheltered by structures / very indented)	0.2 (low)
Moderately Indented beach	0.5 (medium)
Semi-enclosed beach	0.75 (high)
Exposed beach	1 (very high)

Units: adimensional

Figure 7. *Example of Sensitivity and Adaptive Capacity Indicators Fact-sheet for the exposed element 'Beach'.*

To calculate the sensitivity index and the adaptive capacity index for each of the exposed elements, and once the corresponding sensitivity and adaptability capacity indicators have been defined, the geospatial layers of each element are intersected with the layers that define each indicator. The various intersections between layers and the sum of the values taken by the indicators at each pixel will result in the sensitivity and adaptability capacity layers (Figure 8).

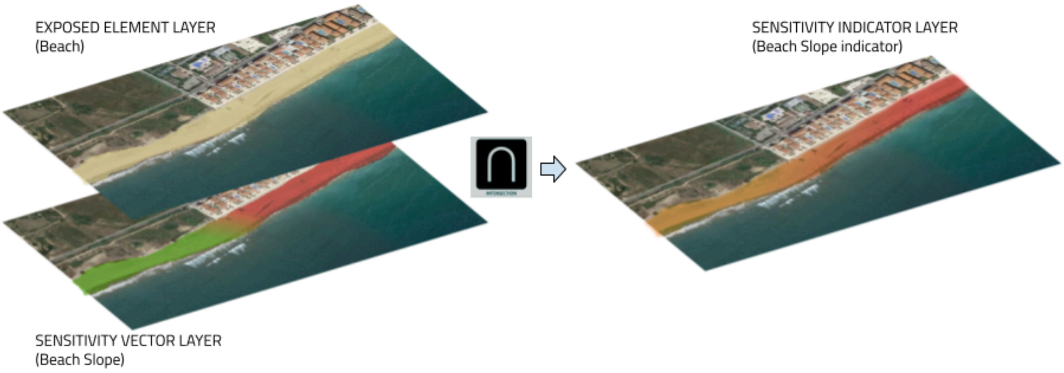

Figure 8. *Example of intersection between exposed element layer (beach) and sensitivity indicator (beach slope layer), resulting in the Sensitivity index layer.*

Both sensitivity and adaptive capacity indexes should be represented in GIS format considering the resolution provided by each exposed element. This will allow developing a geospatial database of the key components to determine vulnerability and further determining the geospatial multi risk assessment.

Note that some indicators can be time-dependent (time-horizons) or scenario dependent (RCP scenarios). This should be considered on the calculus of indexes and will result in variable indexes.

Some examples of sensitivity and adaptive capacity indexes to be considered for each beach dimension are summarized below.

3.1.1 Physical dimension

a. Sensitivity indicators

***Table 4**. summarizes the basic sensitivity indicators to consider on evaluating the sensitivity index of the most relevant exposed elements in the physical dimension.*

Exposed element - BEACH		
Indicator	**Definition**	**Source**
Beach Width and Slope	The width and slope of a beach are fundamental indicators of its ability to absorb wave energy and provide a buffer against storm surges and erosion. Wider, gently sloping beaches are generally more resilient.	Slope map / Topobathymetry
Sediment composition and size	The composition and grain size of beach sand influence its stability and ability to resist erosion. Coarser sands are often more resistant to wave action.	Grain Size distribution
Beach sheltering level	The exposure degree of beaches to incoming waves influences the effects of storms (coastal flooding and erosion).	Cartography
Beach morphodynamic state	Beach state and the presence/absence of submerged morphodynamic patterns control wave energy dissipation rates.	Wave climate and d50
Seagrass meadows	The presence/absence of submerged seagrass meadows in the submerged beach controls wave energy dissipation rates.	Vegetation cover maps
Human activities	Urban development, construction, and tourism-related activities can alter natural beach processes, leading to increased vulnerability to erosion.	Cartography and socioeconomic maps
Exposed element - DUNE		
Vegetation cover	The presence and health of vegetation on dunes, such as grasses and shrubs, contribute to their stability by preventing erosion and promoting sand accumulation.	Vegetation cover maps
Dune height and volume	The height and volume of dunes are critical indicators of their ability to provide protection against storm surges and coastal flooding. Higher and larger dunes generally offer better resistance to inundation.	Topobathymetry
Dune stability	Indicators of dune stability include factors like erosion rates, sand compaction, and slope angle. Stable dunes are less likely to be breached during storm events.	Topobathymetry
Beach profile	The relationship between the dune crest, beach, and shoreline is critical for dune effectiveness. A wider beach profile can help absorb wave energy before it reaches the dunes.	Topobathymetry

Exposed element - WETLANDS		
Wetland type and morphology	Different types of wetlands, such as marshes, swamps, and tidal flats, respond differently to flooding and erosion due to their unique characteristics.	Topobathymetry
Wetland configuration	The arrangement, shape, and connectivity of wetland areas affect their ability to absorb and dissipate wave energy during flooding events	Topobathymetry
Elevation and topography	The elevation of wetland areas above sea level and their relative topography play a crucial role in determining their vulnerability to coastal flooding and erosion.	Topobathymetry
Wave exposure	The degree of exposure to waves and storm surges influences the potential impact of coastal flooding on wetlands	Topobathymetry
Vegetation health	The health and resilience of wetland vegetation, such as reeds, grasses, and trees, influence their ability to stabilize sediment and resist erosion.	Vegetation cover

b. Adaptive indicators

Table 5 *summarizes the basic adaptive indicators to consider on evaluating the sensitivity index of the most relevant exposed elements in the physical dimension.*

Exposed element - BEACH		
Indicator	**Definition**	**Source**
Accommodation space (backshore type)	The presence of sand dunes along a beach can enhance its resilience by providing additional protection against storm surges and erosion. The presence of public amenities, such as walkways, access points, and recreational facilities, can affect the intensity of human impact on the beach environment.	Land use maps and aerial photogrammetry. Cartography
Management flexibility/Adaptive policy frameworks	Possibility of integrating management plans into local policies and regulations to ensure sustained protection/adaptation measures.	Sectorial plans
Exposed element - DUNE		
Management and protection measures	The presence and effectiveness of dune management strategies, such as dune restoration, and vegetation planting, indicate the level of human intervention and protection for these natural features.	Literature analysis/technical reports
Management flexibility/Adaptive policy frameworks	Possibility of integrating management plans into local policies and regulations to ensure sustained protection/adaptation measures.	Technical reports

Exposed element - WETLANDS		
Hydrological restoration	Efforts to restore or enhance hydrological patterns, allowing wetlands to absorb and dissipate floodwaters.	Literature analysis/technical reports
Management flexibility/Adaptive policy frameworks	Possibility of integrating management plans into local policies and regulations to ensure sustained protection/adaptation measures.	Literature analysis/technical reports

3.1.2. Environmental dimension

a. Sensitivity indicators

Table 6 *summarizes the basic sensitive indicators to consider on evaluating the sensitivity index of the most relevant exposed elements in the environmental dimension.*

Exposed element - MARINE VEGETATION		
Indicator	**Definition**	**Source**
Seagrass areal extent	The presence of vegetation in the littoral adjacent to beaches, such as seagrasses, contributes to sediment stability and prevents coastal erosion. Their dense canopy attenuates coastal waves, enhances sand accumulation and, together with the thick network of rhizome and roots, prevents sediment resuspension. Sensitivity to storms and extreme temperature events.	Ortophotographs, satellite images, drone images, underwater transects, cartography
Water Depth of upper seagrass limit	The water depth of the upper seagrass limit affects the role of the ecosystem on wave attenuation. Sensitivity to storms and extreme temperature events.	Ortophotographs, satellite images, drone images, underwater transects, cartography
Fragmentation	Meadow fragmentation affects bottom roughness and friction velocity	Ortophotographs, satellite images, drone images, underwater transects, cartography
Shoot Density	Shoot density affects bottom roughness and friction velocity and wave attenuation. Sensitivity to storms and extreme temperature events.	Shoot counts
Shoot mortality rate	Shoot excessive mortality triggers the decline of seagrass density, and fragmentation and areal extent at long term. Sensitivity to storms and extreme temperature events.	Analysis of population age structure using retrospective approaches, repeated shoot censuses
Shoot size	Shoot size affects bottom roughness and friction velocity. Seasonal sensitivity and sensitivity to species shifts.	Species leaf length
Seagrass burial/uprooting	Seagrass burial/uprooting constrains seagrass survival and reflects sediment dynamics (e.g. driven by storms).	*In situ* measurements, analysis of time-series of seagrass vertical growth.

Beach cast	The areal extent and volume of beach cast may prevent beach erosion and the export of its materials subsidize, provide structure and moisture to adjacent dune systems	analysis of historical images and *in situ* measurements.

b. Adaptive indicators

Table 7 *summarizes the basic adaptive indicators to consider on evaluating the sensitivity index of the most relevant exposed elements in the environmental dimension.*

Exposed element - SEAGRASS MEADOWS AND DUNE SYSTEM		
Indicator	**Definition**	**Source**
Management and protection measures	The presence and effectiveness of seagrass management strategies, such as effective and improved WWTP treatments, protection from physical damage (anchoring) by increased patrolling, and real mitigation of climate warming.	IPCC report, local governments.
Dune restoration success	Success of dune restoration projects, assessing the degree to which dunes have been restored to a healthy and stable state.	Reports, literature review

3.1.3 Socioeconomic dimension

In terms of the socioeconomic dimension, the risk exposure comes from two sources; one from modifications in the coastline (with flooded areas), and the other is from modifications in the average temperature in the area. The probabilities of such events will be based on the projections of RCP4.5 and 8.5. The exact modifications of the coastline and the average temperature to be considered will come from the analysis of the physical dimension.

Regarding the measurement of the exposure of socioeconomic elements, we will focus on the revenues generated by companies in the area being analyzed. In the type of Urban Beach being analyzed in this study, most of the economic activity is based on the tourism industry, although there are other activities in other industries (e.g., hair salons). The companies located in the area develop economic activities and generate revenues that sustain most of the socioeconomic elements. These revenues generate cash flow to pay the wages of their workers, pay the suppliers (i.e., farmers producing vegetables), and even pay taxes to the public administrations, also the local ones, that sustain many services to the population (e.g. schools). Without this economic activity, the local population would leave the area and the public administrations would reduce the services provided to the local population. Therefore, the revenues generated by all the companies in the urban beach area are a quite complete measure of the overall exposure of all socioeconomic elements in the area. Revenues are generated continuously, and usually are summarized on an annual basis. Therefore, the overall exposure, from the socioeconomic point of view, will be computed as the present value of the annual revenues generated in the future under the assumption that the coastline and the average temperature remain constant (there is no climate change). This is a baseline to detect the effects of climate change. Then we could study how this value would change when the coastline and the average temperature change. We will use standard valuation methods to measure the present value of the expected future cash flows (e.g., Ross, Westerfield, and Jordan, 2022). To determine the discounting interest rate needed for this measurement, we will use the Capital Asset Pricing Model, developed simultaneously by Treynor (1961, 1962) Sharpe (1964), Lintner (1965), and Mossin (1966), based on the portfolio theory (Markowitz, 1999).

Given that each company is located in a specific area, we estimate the present value of the expected future revenues in this area as a summary of the overall exposure of the socioeconomic elements in this area. These revenues, and the socioeconomic elements, are exposed to the two sources of risk mentioned above, derived from modifications in the coastline and in the average temperature.

Modifications in the average temperature generate sensitivity of the present value of all revenues (socioeconomic elements) in the urban beach. All of them will be sensitive to such modifications, and there may be differences in the adaptative capacity of different socioeconomic elements. For example, hotels could move their activity toward winter months if the temperature increases enough. Detecting whether this is possible will depend on the overall tendencies of the tourism industry, and in the case of the specific urban beach under study, on the preferences of the habitual customers.

Modifications in the coastline will generate direct sensitivity in the socioeconomic elements located in the flooded areas (the present value of the revenues generated in such areas), and indirect sensitivity in the remaining elements. The socioeconomic elements located in the flooded areas will be totally affected and their adaptability will depend on the possibility of moving such elements to non-flooded areas (e.g., if the local administrations allow construction in new areas). For the socioeconomic elements located outside the flooded areas, the degree of sensitivity will depend on different determinants. For example, a hotel situated in a non-flooded area may be less attractive to tourists if the beach disappears. The adaptability of the socioeconomic elements in front of modifications in the coastline will depend on factors such as the overall tendencies of the tourism industry and on the preferences of habitual customers.

In summary, to detect the exposure, sensitivity, and adaptability of the socioeconomic elements in the analyzed urban beach area, we will need to value the overall economic activity generated in the area, to study the overall tendencies in the tourism industry, to survey the habitual customers (to estimate their reaction to modifications in the coastline and the average temperature in the Urban beach area), and also to consider the reaction of different actors, such as the public administrations (especially to evaluate the adaptability).

3.2. Determination of vulnerability evaluation

Vulnerability of an exposed element is defined as:

$$V^i = S^i - AC^i \quad \text{Eq. 2}$$

where S^i is the final sensitivity index (single index or composed index) and AC^i is the final adaptive capacity index (single index or composed index), and *i* represents the *ith* exposed element.

The vulnerability index will be provided in GIS format with the resolution appropriate to its corresponding exposed element for each beach dimension.

3.3. Output: Vulnerability maps

It is expected to have at this point, a vulnerability map ranging 0 to 1 values for each beach dimension (-physical, environmental and socioeconomic- where each group of experts have dealt with the information layers for the exposed elements of its scope of study).

Then, the last step of the vulnerability assessment will consist on average this three beach dimensions and compute a score for each cell that measures the level of multi-vulnerability which will depend on what receptor is, what its characteristics are and how it will be able to deal with the hazards for a particular scenario.

4. Integrated Multi-Risk assessment

Ad hoc methodology for a Multi-Risk Assessment (MRA) to measure the effect of climate change on multiple (interacting) hazards on exposed vulnerable sectors (Gallina et al., 2020) for urban beaches (local scale). The implementation of a MRA methodology allows to quantify, integrate, and compare multiple risk pathways for a selected set of hazards, with the final aim of improving cross-sectorial decision-making, climate proofing, and adaptation planning.

The integrated multi-risk assessment methodology proposed in this study is a methodology in which hazard, exposure, and vulnerability will be developed individually and for each of the three beach dimensions, converging to obtain risk estimates for a coastal zone. Thus, the risk assessment is useful to prioritize where to apply climate change adaptation measures. The areas where the level of risk is very high will be the first where risk reduction measures should be established.

Risk = Hazard ∩ Exposure ∩ Vulnerability

where “Hazard” refers to the degree of a disaster, such as sea level rise projections; “Exposure” refers to the land uses or environments exposed to hazard; and “Vulnerability” refers to the sensitivity of a system exposed to certain hazards as well as its inherent characteristics, such as its response, resistance, and resilience ability.

Figure 8 shows the flow diagram to be followed to **first** obtain the multi-hazard map by combining all the hazard maps of Section 1 considering their interrelationships and hazard probabilities. **Secondly**, based on the exposed elements already defined in Section 2, and the consequent exposure map mapping the number of receptors at risk, the information will be crossed with the hazard maps, and this combination determines the impact maps whose values manifest the effects of hazards on natural and human systems. **Thirdly**, for each receptor or exposed element, a vulnerability score has been assigned according to the different vulnerability factors (Sensitivity and Adaptive Capacity) that condition it to a greater or lesser extent depending on the hazard that threatens it (results of vulnerability maps of Section 3).

Finally, the synergy of these three multi-hazard, multi-exposure, and multi-vulnerability will lead to a multi-risk map, showing the damage caused by the effects of climate change depending on what and how elements are exposed in the coastal zone. In this way, the multi-sectoral consequences of climate change for a set of risk scenarios can be obtained and quantified as a result.

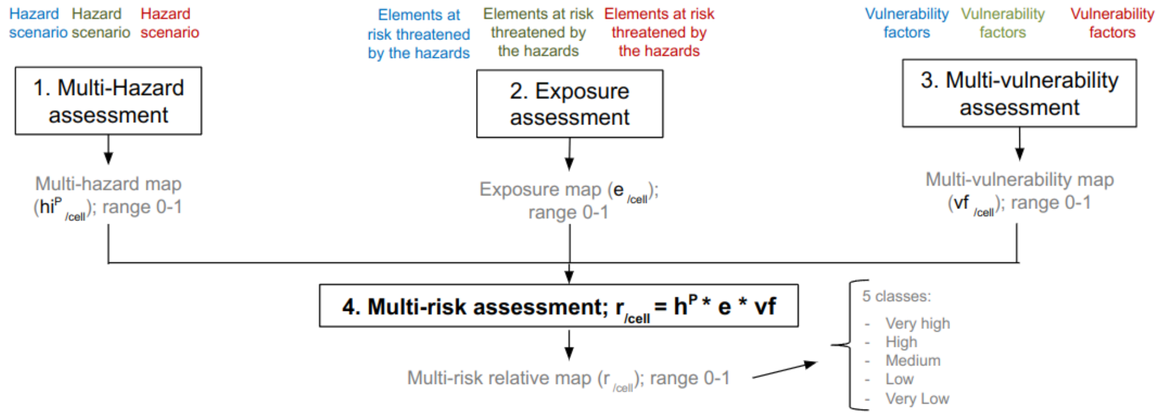

Figure 8. MRA example (Gallina et al., 2020) for a particular RCP and year projected scenario by considering the physical dimension (in blue), the environmental dimension (in green), and the physical dimension (in red).

The result of the MRA will be as many MRA maps for the studied beach area as multi-hazard maps there are; so one MRA map per climate scenario.

4.1. Definition of multi-hazard assessment methodology

Focusing on the first assessment called "Multi-hazard", the steps mentioned already in Section 1.3 were the selection of the hazards and the timeframe of analysis, an analysis of hazard probabilities, an assessment of the hazard interactions, and finally the aggregation and normalization of the multi-hazard score.

The first two have already been addressed being the outputs of Section 1. So the steps to follow now focus on establishing the interactions between hazards and obtaining the total hazard score for each pixel. For that purpose, the definition of a hazard influence matrix is the way to get common metrics for climate change threats considering the different beach dimensions and temporal scales (e.g., how a hazard could be negatively affected by another operating in the same area and in the same temporal window).

The matrix below pretends to be an example that defines if there is (value 1) or not (value 0) relationship among the hazards (hi) through the configuration of a hazard influence matrix which may vary for each climate change scenario, if considered.

	Sea level rise + storm surge (h1)	Boats number (h2)	Pollutant spill (h3)	Temperature increase (h4)	Posidonia extinction (h5)	… hazard (hi)
Sea level rise + storm surge (h1)	1	0	0	0	1	
Boats number (h2)	0	1	1ª	0	1^	
Pollutant spill (h3)	0	0ª	1	0	1	
Temperature increase (h4)	1	1	1	1	1	
Posidonia extinction (h5)	0	1*	0	0	1	
… hazards (hi)						1

<u>*Explanation of examples*</u>:
1: The Posidonia extinction is related to the Boat number. This will reduce due to the striking blue color that Posidonia causes and tourism will reduce.*
1^: The Boat number relates to Posidonia. the greater the number of boats (more anchors in action), the greater the danger to Posidonia oceanica.
0ª: Pollutant spill doesn't relate to the number of boats. However,
1ª: The Boats number relates with the pollutant spills because there is more risk.

Once the relations among hazards are established by consensus of the experts for each beach dimension, this matrix will have to integrate the hazard probabilities P(hi) in order to compute the joint probability between hazards:

	Sea level rise + storm surge (h1)	Boats number (h2)	Pollutant spill (h3)	Temperature increase (h4)	Posidonia extinction (h5)	… hazard (hi)
Sea level rise + storm surge (h1)	P1	0	0	0	P1*P5	
Boats number (h2)	0	P2	P2*P3	0	P2*P5	
Pollutant spill (h3)	0	0	P3	0	P3*P5	
Temperature increase (h4)	P4*P1	P4*P2	P4*P3	P4	P4*P5	
Posidonia extinction (h5)	0	P5*P2	0	0	P5	
… hazards (hi)						P(hi)

Finally, to reach a multi-hazard score per pixel this will be computed as follow:

1. Intersect all the output hazard maps (values 0, 1) and generate a vector with so many ones as hazards arrive at that pixel.
2. Multiply the probability hazard matrix by the hazard vector.

Following the previous example but considering now only three hazards and the Posidonia extinction not affecting for this pixel, then the multi-hazard score for this pixel will remain:

Sea level rise + storm surge	Temp. increase	Posidonia extinction

$$\begin{pmatrix} P1 & 0 & P1*P5 \\ P4*P1 & P4 & P4*P5 \\ 0 & 0 & P5 \end{pmatrix} \times \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} = \begin{pmatrix} P1 \\ P4*P1 + P4 \\ 0 \end{pmatrix}$$

hP= Multi-hazard score/pixel = (P1+P4*P1+P4)/ nº hazards.

In the end, the multi-hazard map (ranging between 0 and 1) will show the distribution of the hazards for the study area at pixel level, taking into account their probability of occurrence.

4.2. Definition of multi-risk methodology

After the multi-hazard assessment, the resulting maps should be crossed with the map of exposed elements derived from Section 2. This multi-exposure map is obtained by intersecting all the selected data potentially at risk, and so, their values, ranging from 0 to 1 (after normalized), quantify the number of exposed elements (receptors) at risk for the three beach dimensions, as well as their weights depending on the exposure levels, if applicable.

Having these two previous maps, the third consists of the multi-vulnerability map which is an average of the three vulnerability maps for each beach dimension (Section 3 outputs), ranging from 0 to 1. Then, for each pixel, this map measures the level of multi-vulnerability achieved as the interaction between all the vulnerability factors and hazards affecting that cell for a particular scenario.

The result of the multi-risk methodology will be then a numeric map (one for each climate scenario), that must classify at different levels the risk to which each cell is subjected. Five levels of risk will be established: Total, High, Medium, Low, and no risk.

A risk score that has been obtained as the result of multiplying the “Multi-hazard map” (hP) or danger level distribution, the “Multi-Exposure map” (e) or number of potential elements at risk, and the “Multi-Vulnerability map” (vf) or the adaptability and sensitivity level of the receptors against hazards.

$$r_{/cell} = h^{P} * e * vf$$

Note the importance of accurate risk maps to prioritize where to act. It is clear that the areas where the level of risk is very high will be the first where risk reduction measures and climate change adaptation strategies should be established.

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