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 3.5: *Integrated Climate Change Multi-Risk Assessment at Cala Millor*

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Executive Summary

This Deliverable presents the results for the Integrated Multi Risk Assessment (MRA) in Cala Millor following the methodologies presented in D3.1, D3.2, D3.3 and D3.4 with main focus on the interactions between physical, ecological, urban and socioeconomic risks. Various climate risks, including sea-level rise, extreme weather events, coastal erosion, and ecosystem disruption are used as described in D3.4 and the methodology presented used for an integrated approach to understanding and mitigating these risks.

Regarding hazard, vulnerability and risk assessment, the developed approach incorporates four key drivers of coastal hazards: sea-level rise (SLR), extreme waves and surges, rising sea and atmospheric temperatures and the impact that the temperature increase will have on *Posidonia oceanica*. By accounting for these compound events, the methodology provides the cascading effects on infrastructures, ecosystems and in the socio economic system. The risk assessment underscores the importance of the evaluation of coastal risks across different RCPs and time horizons, taking into account various dimensions and the complexity of compound hazards. Besides, inclusion of the urban dimension in the multi-risk assessment provides a more holistic view of risk by considering the vulnerabilities of infrastructures and socio-economic systems in addition to natural hazards.

For each exposed element (beach, dunes, seagrass meadow, economic value related to cadastral parcels, population, transit infrastructure, seafront urban elements and urban elements related to drainage, hazard component and vulnerability components -in terms of sensitivity and adaptive capacity- are evaluated. Combining the exposure, the hazard and the vulnerability maps, risk maps are presented. The multi risk analysis provides the temporal evolution of average risks. The analysis developed incorporates a strong spatial component, allowing for the identification of the most susceptible areas prioritizing the conservation and adaptation efforts. The results are designed to serve as a tool to support the conceptualization, design, and selection of potential climate change adaptation measures for Cala Millor across the entire affected area.

For the **re**sults of **Permanent Flooding (Pf) in the case of the less adverse and nearest time horizon, the RCP4.5 2030,** the following key points are highlighted:

- From a broad perspective, the highest weighted MRA scores are observed in the cadastral parcels, which are indirectly affected by the combined impacts of permanent flooding and rising temperatures. These areas, though not directly exposed to flooding, experience secondary effects such as beach width and rising temperature. In contrast, the urban area generally exhibits minimal risk values, particularly in green spaces and less-developed zones. However, specific areas within the urban landscape, such as circulation zones and public spaces, may show localized increases in risk due to their connectivity and exposure

pathways. The beach itself accounts for only a small portion of the exposed elements, but its risk level is highly dependent on ongoing environmental changes.

- For the accumulated case, as expected, risk values are higher, but the spatial distribution remains unchanged. This increase reflects the compounding effects of multiple hazards acting simultaneously, amplifying the overall risk levels across exposed elements. While the general pattern of risk distribution remains consistent, the intensity of risks is significant -the highest sum value computed at one map cell is 0.66-, particularly in areas already identified as vulnerable.
- The average values for the weighted MRA are 0.22 (0.20, 0.24) which, among other risks, contemplates estimated climate change indirect socioeconomic losses of ~765,000 thousand euros.

For the results of **Permanent Flooding (Pf) in the case of the most adverse and distant time horizon, the RCP-8.5 2100,** the following key points are highlighted:

- The highest weighted MRA scores are once again observed in the cadastral parcels, which remain the most affected due to their indirect exposure to permanent flooding and rising temperatures. These areas, while not directly inundated, experience secondary effects such as loss of land value mainly due to the beach width reduction. Within the urban landscape, green spaces continue to show minimal risk values, serving as relatively stable areas in terms of exposure. However, an increase in multi-risk is particularly evident in circulation zones, where the intersection of multiple hazards amplifies potential disruptions. The central plaza stands out with elevated risk levels, likely due to its high usage, structural layout, and exposure to both direct and indirect environmental stressors. This highlights the vulnerability of key public spaces, which may require targeted adaptation measures to mitigate long-term impacts. Additionally, the permanently flooded beach area exhibits significantly higher risk values. As flooding becomes more persistent, the degradation of natural buffers, such as dunes and seagrass meadows, further exacerbates exposure to extreme weather events and long-term coastal retreat.
- For the accumulated case, as expected, risk values are higher across all dimensions -maximum accumulated value at one map cell is 1.39-, reinforcing the need for a multi-risk approach. The results emphasize the heightened vulnerability of urban areas, particularly circulation zones and public spaces, where cumulative impacts can lead to greater socio-economic and infrastructural consequences. Similarly, the beach continues to experience increasing risk.
- The average values for the weighted MRA are 0.54 (0.49, 0.64), which, among other risks, contemplates estimated climate change indirect socioeconomic losses of ~2,225,000 thousand euros.

For the results of **Extreme flooding (Ef) in the he case of the less adverse and nearest time horizon, the RCP4.5 2030,** the following key points are highlighted:

- From a broad perspective, the highest weighted MRA scores are observed in the seafront surface, which are affected by the combined impacts of sea extreme flooding, rainfall flooding ("RiskPonding") and rising temperatures. Also the main coastal roads show slight risk increases. In contrast, the urban area about 400 m away from the coast, and the dune and *P. oceanica* meadow exhibit minimal risk values.
- For the accumulated case considering the sum of all the risks interacting per map cell, as expected, risk values are higher but concentrated in these same areas. The overall risk, exceeding a sum of 2, is a result of multiple hazards interacting concurrently across susceptible exposed elements. This amplified risk reflects the combined danger of individual risks, each falling between 0 and 1.
- Averaged value for the weighted MRA is ~0.26 which, among other risks, contemplates estimated economic losses of ~830,000 thousand euros. The average results obtained of Extreme flooding are similar to those of Permanent Flooding due to the distribution of weights among a larger number of risks. However, the normalized accumulated sum value shows an approximately 20% increase in risk respect to the Pf case. The MRA maps, which display the total risk sum per cell, also show this significant increase between Ef and Pf cases.

For the results of **Extreme flooding (Ef) in the case of the most adverse and distant time horizon, the RCP-8.5 2100**, the following key points are highlighted:

- The highest weighted MRA scores are observed in the same areas (seafront and coastal roads) than in previous scenarios but now doubling the overall mean risk despite the fact that more risks are acting (see accumulated risk values). This indicates that all risks in this area are problematic for this scenario. The seafront stands out with elevated risk levels, likely due to its high usage, structural layout, and exposure to both direct and indirect environmental stressors. In addition to the permanent flooding scenarios, where the beach was already reduced almost entirely to an average width of less than 2 m, extreme flooding events now extend beyond the beach area, impacting the promenade, roads, and even overloading the drainage system when combined with periods of heavy rainfall. This is evident in the accumulated MRA mapped values for these scenarios.
- For the accumulated case, as expected, risk values are higher across all dimensions reaching a maximum accumulated value of 3.58 at a particular cell. The mean value of 0.74, calculated from all cell values within its corresponding accumulated map, indicates a high risk exposure for the area if current urban planning practices persist.

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1. Introduction

This document presents the implementation of a multi-risk assessment that integrates the multiple and the influence between different types of hazards, the vulnerability of the exposed elements and the evaluation of the cumulative risks, once the diagnostic of the study site has been assessed in Deliverable 3.4.

The ad-hoc integrated multidisciplinary methodology for the assessment of impacts and associated risks of different progressive global change projections at Cala Millor (Mallorca, Balearic Islands) urban beach, considers different elements: beach, dunes, seagrass meadow, economic value, population, roads and promenades and urban elements.

The methods implemented and the obtained results consigned in this deliverable respond to the following specific and main objectives of the LIFE ADAPT CALA MILLOR project Work Package 3 (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 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.

The content of each section is in line with the tasks described in the Action Description of Grant Agreement-101074227-LIFE21-GIC-ES-LIFE AdaptCalaMillor (p. 83 to 88), as set out in the following table:

Deliverable D3.5 Section	Task description at Grant Agreement	Major products
Definition of hazards	T.3.4.4.1 Multi-hazard assessment.	This information has been presented in D.3.4. ● Permanent marine flooding maps under RCP-4.5 and RCP-8.5 sea-level scenarios and time horizons, and different contour conditions. ● Temporal marine flooding maps related to wave storms and extremes under RCP-4.5 and RCP-8.5 sea-level scenarios and time horizons, and different contour conditions. ● Maps of *P. oceanica* extension and density decrease under RCP-4.5 and RCP-8.5 sea-water temperature scenarios.

		● Maps of urban drainage compound flooding and urban elements affected by permanent and extreme coastal flooding under RCP-4.5 and RCP-8.5 sea-level scenarios and time horizons, and different contour conditions.
2. Vulnerability assessment	T.3.4.4.2 Multi-vulnerability selection and aggregation of multiple physical, environmental and socio-economic vulnerability factors.	● Sensitivity indicators for the exposed elements ● Adaptive capacity indicators for the exposed elements. ● Determination of vulnerability evaluation. ● Maps of sensitivity and adaptive capacity indexes for each analysed element.
3. Risk assessment	T.3.4.4.3 Multi-risk assessment: selection of hazards and timeframe of analysis.	● Definition of risk. ● Maps of vulnerability to flooding of each element. ● Maps of vulnerability to rising sea temperatures. ● Maps of vulnerability to compound flooding. ● Beach flood risk maps. ● Coastal dune system risk maps related to sea flooding. ● Seagrass risk maps related to sea temperature increase. ● Population risk map related to compound flooding. ● Road risk map related to compound flooding. ● Seafront risk map related to atmospheric temperature increase. ● Seafront risk related to sea flooding. ● Urban risk related to compound flooding. ● Socioeconomic risk maps.
4. Multi-risk assessment	T.3.4.4.3 Multi-risk assessment: selection of hazards and timeframe of analysis.	● Integrated multi-risk assessment ● Tables of interaction between scenarios, temporal horizons and risks. ● Mean weight of the combined risks under extreme flooding. ● Mean weight of the combined risks under permanent flooding. ● Cumulative % of risk in the cases of extreme flooding. ● Cumulative % of risk in the case of permanent flooding.

Please note that the consideration of the urbanistic elements and the impact related to the compound flooding were not previously considered in action descriptions and the contract agreement, but they have been incorporated to improve the risk assessment, and as a basis to test the contribution of the different possible adaptation solutions to the risk mitigation.

2.   Vulnerability 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 *et al.*, 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 social 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, so here we will focus on the urban beach of Cala Millor. The analysis will be done by considering different timescales embracing mid- (2030-2050) and long-term (2100) effects as milestones.

2.1.   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 deeply explained in Deliverable 3.4.

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),

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),

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 S^i, defined as,

$$S^i = \frac{\Sigma_j^i S_j^i}{n}$$

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 the previous formula but now for the adaptive capacity indicators. Composed indexes are computed considering the normalized value (0-1) of the individual indexes.

To calculate the sensitivity index and the adaptive capacity index for each of the exposed elements, and once the corresponding sensitivity and adaptability capacity values 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 (Fig. 1).
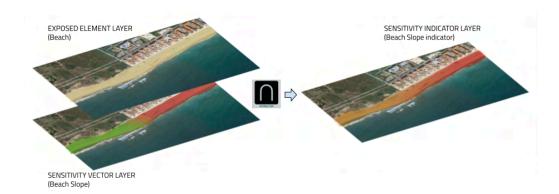
Figure 1. Example of intersection between exposed element layer (beach) and sensitivity indicator (beach slope layer), resulting in the Sensitivity index layer.

Both sensitivity and adaptive capacity indexes will 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 in Cala Millor are summarized below.

Exposed elements and vulnerability indicators according to the direct impacts that affect them:

- **Seagrass (*P. oceanica* meadow) vulnerable to sea temperature increase**
  Sensitivity: Position of the lower limit of the *Posidonia oceanica* meadow; shoot density.
  *Adaptive Capacity***:** Evaluated based on greenhouse gas mitigation measures and international agreements.

- **Dunes vulnerable to flooding**
  Sensitivity: Decrease in dune area.
  *Adaptive Capacity***:** The dune system has no capacity for adaptation, as it lacks space for natural displacement or regeneration. Therefore, adaptation measures do not mitigate vulnerability in this case.

- **Beach vulnerable to flooding**
  Sensitivity: beach slope; beach width; sediment size; beach sheltering; health of seagrass meadows; human activities.
  Adaptive Capacity: Accommodation space (backshore type); protection infrastructures; Institutional will; Education and Social awareness.

- **Urban zone/Seafront vulnerable to flooding and to atmospheric temperatures increase**
  Sensitivity: Albedo; radiation; activities and use; material typology; constructions.

  Adaptive Capacity: Adaptation to the heat island effect; permeability; recovery potential; accessibility to buildings.

- **Population vulnerable to flooding**
  Sensitivity: census population.

  Adaptive Capacity: time of the flood.

- **Roads vulnerable to flooding**
  Sensitivity: type of road.

  Adaptive Capacity: time of the flood.

- **Cadastral parcels vulnerable to flooding (diminishing beach area) and to atmospheric temperatures increase**
  Sensitivity: market value of the economic activity developed in the area; market value of the residential properties in the area.

Adaptive Capacity: time of the flood.

- **Urban drainage system Urban zone to compound flooding (coastal and rainfall flooding).**
  Sensitivity: streets and pedestrian paths slope

  Adaptive Capacity: material of streets and pedestrian, path, green areas.

The following sections break down each vulnerability indicator in detail according to ranges of its sensitivity and adaptive capacity to climate change for the final vulnerability calculation.

2.1.1. Sensitivity (S) indicators for the exposed elements

In the following, the indicators considered to address the sensitivity of each exposed element are detailed (Table 1). These indicators and their corresponding ranges have been developed, first, according to literature and expert advise, and secondly the feedback of the participant at the 1st Workshop *"How to assess the hazard, vulnerability, and risk of climate change in urban beaches?"* held within the framework of the LIFEAdaptCalaMillor WP2 Activities on Sept. 2024.

Exposed element - BEACH				
Sensitivity Indicator	**Definition**	**Source**	**Ranges**	**Index value estimate**
Beach Slope	The beach slope influences the extent of flooding and erosion rates.	Slope map/ Topobathymetry	>20º (steep)	0.2 (low)
			6-20º (gentle slopes)	0.6 (medium)
			0-6º (plain)	1 (very high)
Beach Width / shoreline evolution[1]	The width of a beach (distance between the maximum shoreline and the dune foot or the promenade in Cala Millor) is a fundamental indicator of its ability to absorb wave energy and provide a buffer against storm surges and erosion.	Erosion/flooding/evoluti on trend map	advancing coast; > 30m	0.2 (low)
			stable coast; approx. 30 m	0.5 (medium)
			coast in erosion; < 30 m	1 (very high)
Sediment 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	Coarse (>0.5 mm)	0.3 (low)
			Medium (0.25-0.5 mm)	0.6 (medium)
			Fine (0.15-0.25 mm)	1 (very high)
Beach sheltering level	The exposure degree of beaches to incoming waves influences the effects of storms (coastal flooding and erosion).	Cartography	Sheltered beach	0.2 (low)
			Semi-enclosed beach	0.6 (medium)

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[1] Indicator depending on time-horizon and RCP scenario

			Exposed beach	1 (very high)
Health of seagrass meadows[2]	The presence/absence and health state of the seagrass meadows in the submerged beach controls wave energy dissipation rates.	Vegetation cover maps	Dense and healthy *P. oceanica* meadow	0.2 (low)
			Weakened *P. oceanica* meadow	0.6 (medium)
			Degraded or non-existent *P. oceanica* meadow	1 (very high)
Human activities	The intensity of human activities on the beach (both in water and on land) leading to increased vulnerability to erosion	https://www.platgesdebalears.com/; Socorristes (Safebeach)	One person per more than 8 square meters	0.2 (low)
			One person per 8 square meters	0.6 (medium)
			One person per 4 square meters	1 (very high)
Exposed element - DUNE				
Decrease in dune area	Coastal dunes act as natural barriers protecting inland areas from storms and waves, but their effectiveness depends on their size, volume and area. When they lose surface area due to erosion or flooding, their protective capacity decreases, their function as a habitat for biodiversity is affected, and their natural recovery is limited, especially in built-up areas where they have no space to regenerate.	Topobathymetry	Optimum decrease in dune area for the conservation of the dune system. < 12,5 %	0.2 (low)
			Medium decrease in dune area for the conservation of the dune system. 12,5 -33,3 %	0.5 (medium)
			Dangerous decrease in dune area for the conservation of the dune system >33,3%	1 (very high)

[2] Indicator depending on time-horizon and RCP scenario

Exposed element - SEAGRASSES				
Indicator	**Definition**	**Source**	**Ranges**	**Index Value**
Position of the lower limit of the *Posidonia oceanica* meadow	The position of the lower limit of the meadow reflects the environmental conditions necessary for its survival. If the boundary recedes towards shallower areas, it suggests a deterioration in water quality due to factors such as pollution, turbidity or human activities, demonstrating how the meadow responds to changes in its environment and its vulnerability to these impacts.	Orthophotography, satellite images, drone images, underwater transects, cartography.	*Posidonia oceanica* lower boundary under human and natural pressures: >35 m. (optimal)	0.2 (low)
			Posidonia oceanica lower boundary under human and natural pressures: 35-30 m	0.5 (medium)
			Posidonia oceanica lower boundary under human and natural pressures: Pressures. <30 m (critical)	1 (high)
Shoot Density	Shoot density affects bottom roughness and friction velocity and wave attenuation. Sensitivity to storms and extreme temperature events.	Shoot counts	Dense beds. >400 shoots/m²	0 (low)
			Dispersed beds: 400-300 shoots/m² (dynamic equilibrium)	0.5 (medium)
			Very sparse beds: <300 shoots/m² (regression)	1 (high)
Exposed element - CADASTRAL PARCELS				
Market value according to direct effects	The direct effect of climate change: Floods negatively affect the market value of each cadastral plot.	Forecasts of flooding scenarios	Permanent and temporal floods generate a direct effect on the market value of each cadastral plot	0 (permanent flooding)
				1 (no flooding)

Market value according to indirect effects	The indirect effect of climate change: Reductions in the size of the beach and higher temperatures will decrease the attractiveness of the area to tourists affecting the economic activity in the area and therefore the value of the economic activity developed in each cadastral plot.	Forecasts of beach area and temperature scenarios generated by the team of this project.	The sensibility of tourism demand to temperature increases and beach area reductions determine the reduction in the market value of each cadastral plot. This sensibility is obtained from tourist surveys (SOCIB).	1 minus the percentage of market value lost in case of an increase in temperature and a reduction in beach area (0 to 1).

Exposed element - POPULATION				
Registered population	Number of inhabitants registered in a postal address as long as they exceed the number of three people so as not to violate statistical secrecy.	Institut d'Estadística de les Illes Balears (IBESTAT). Official Population Census 2021.	Postal address with 3 or less registered inhabitants	0.1 (low)
			Postal address with 4 to 10 registered inhabitants	0.6 (medium)
			Postal address with more than 10 inhabitants	1 (high)

Exposed element - ROADS				
Transportation Infrastructure	Category and function of the type of communication infrastructure	Institut Cartogràfic i Geogràfic de les Illes Balears (ICGIB). CDE Xarxa de transport de les Illes Balears i Viari unificat de les Illes Balears (VUIB)	Rural road	0.1 (low)
			Urban street	0.5
			Urban avenue	0.8
			Coastal Urban Boulevard and regional road	1 (high)

Exposed element - Urban Zone/SEAFRONT				

Albedo	The albedo effect depending on the material of the urban element makes it more or less sensitive to rising temperatures.	Mapping from orthophotographs and topographic cartography 1:1000 (ICGIB)	Grass; Trees (vegetation); Ponds and ponds; Wooden ramp.	0.33 (low)
			Concrete (stairs, ramps, wall); Tile (bike lane and walkway); Concrete base and ophitic gravel (paving stone); Recycled rubber (playgrounds); Artificial stone curb	0.66
			Asphalt	1 (high)
Radiation	The radiation level depends on the material of the urban element making it more or less sensitive to rising temperatures.	Insolation data from LIDAR	< 4	0 (low)
			4 to 8	0.33
			8 to 12	0.66
			> 12	1 (high)
Activities and uses	The use of land or the activity carried out in a given urban element makes it more or less sensitive to flooding due to rising sea levels.	Mapping from literature analysis/technical reports	Active mobility	0.33 (low)
			Motorized mobility	0.66
			Terraces; playground areas	1 (high)
Materials typology	Depending on the materials with which an urban element is built, this can be more or less sensitive to spoil by flooding due to rising sea levels.	Mapping from literature analysis/technical reports	Concrete (stairs, ramps, wall); Tile (bike lane and walkway); Concrete base and ophitic gravel (paving stone); Asphalt; Artificial stone curb	0.33 (low)
			Grass	0.66

			Trees (vegetation); Recycled rubber (playgrounds); Wooden ramp.	1 (high)
Constructions	The type of construction makes it more or less sensitive to spoil by flooding due to rising sea levels and extreme events.	Mapping from literature analysis/technical reports	Restaurants, public toilets and tourism office	0.33 (low)
			EBAR and booster pump	1 (high)
Exposed element - Urban Zone/Drainage system				
Slope	Street and pedestrians paths slope controls rain water run-off direction and velocity and potential ponding areas	High-resolution (2.5x2.5 m) lidar topography of Cala Millor from the IGN	> 20º (sloped areas)	0.2 (low)
			0º (flat areas)	1 (high)

Table 1. *Sensitivity indicators considered for the different exposed elements.*

2.1.2. Adaptive Capacity (AC) indicators for the exposed elements

Similarly to sensitivity indicators, In the following, the indicators considered to address the adaptive capacity of each exposed element are detailed (Table 2). These indicators and their corresponding ranges have been developed, first, according to literature and expert advice, and secondly the feedback of the participant at the 1st Workshop *"How to assess the hazard, vulnerability, and risk of climate change in urban beaches?"* held within the framework of the LIFEAdaptCalaMillor WP2 Activities on Sept. 2024.

Exposed element - BEACH				
Indicator	**Definition**	**Source**	**Ranges**	**Index value**

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	Mature dune system	1 (high)
			Incipient dune system	0.2 (medium)
			Hard-boundary (structures)	0 (low)
Protection Infrastructures	Existence of artificial barriers: Breakwaters, dikes and other coastal defense systems. Drainage systems: Presence of efficient drainage systems.	Topographic beach survey	existence and efficient	1 (high)
			existing but insufficient	0.3 (medium)
			non-existence or inefficient	0 (low)
Adaptive policy frameworks/ Institutional capacity & management	Integrating management plans into local policies and regulations to ensure sustained protection and adaptation measures/ Political will.	SOCIB survey to stakeholders from the public sector. List of projects planned or carried out in the two municipalities, in the Cala Millor bay.	Political will and projects aligned with climate issues	1 (high)
			Lack of political will and non-aligned projects with climate change	0 (low)
Social awareness (Annex 1)	Education of the population and implementation of best practices to help ensure that beaches can be resilient to climate change.	SOCIB survey to education centers, and degree of involvement of citizen associations.	Aware	1 (high)
			Conscienceless	0 (low)
Exposed element - DUNE				

No capacity for adaptation	The dunes of Cala Millor lack adaptive capacity as they are confined by infrastructure that prevents their natural migration and regeneration. Limited space and reduced sediment supply further restrict their ability to respond to erosion and rising sea levels. Although management measures exist, they cannot compensate for the dunes' inability to shift, meaning their vulnerability depends solely on their sensitivity to environmental impacts.	Literature analysis/technical reports	Not applicable.	0 (none)
			Not applicable.	0 (none)
			Not applicable.	0 (none)
Exposed element - SEAGRASSES				
Climate Mitigation Policies & Global Agreements	Unlike other ecosystems, where adaptive capacity can be influenced by direct management actions, the adaptation of *Posidonia oceanica* meadows depends entirely on climate change mitigation at a global scale. Since the species cannot actively adapt to rising sea temperatures, its resilience is indirectly determined by emission reduction policies and international agreements.	Climate projections (RCP 4.5,P25 & P50); (RCP 8.5, P50 & P75)	**Optimal Adaptive Capacity:** Strong climate mitigation policies are fully implemented, such as those in the Paris Agreement (equivalent to 25th percentile of the RCP 4.5 scenario).	1 (high)
			Medium Adaptive Capacity: Some mitigation policies are applied but are insufficient to ensure high resilience of the meadow (equivalent to the 50th,75th percentile of the RCP 4.5 scenario and 25th percentile of the RCP 8.5 scenario).	0.5 (medium)

				Null Adaptive Capacity: No mitigation measures are taken (corresponding to the 50th and 75th percentiles of the RCP 8.5 scenario)	0 (low)

Exposed element - CADASTRAL PARCELS				
The market value of cadastral parcels according to direct effects	The direct effect of climate change: Floods negatively affect the market value of each cadastral plot	Forecasts of flooding	Permanent floods destroy the whole market value of a cadastral plot. However, the owners react to the temporal floods recovering their functionality	0 (in case of permanent flood)
				1 (in case of temporal flood)
The market value of cadastral parcels according to indirect effects	The indirect effect of climate change: Reductions in the size of the beach and higher temperatures will decrease the attractiveness of the area to tourists affecting the economic activity in the area and therefore the value of the economic activity developed in each cadastral plot	Forecasts of beach area and temperature generated by the team of this project.	The owners of each cadastral parcel cannot reverse the reduction of the attractiveness of the area to tourists due to increases in temperature and reductions in beach area.	0 (reduction in market value due to the indirect effects of climate change and a decrease in the area's attractiveness)

Exposed element - POPULATION				
Registered population	The effects of coastal flooding affect access to or and the use of homes where the census population resides as their main home	Literature analysis / technical reports	Permanent coastal flooding: There is no option to repair or recover damage caused by coastal flooding given its permanent nature.	0

			Temporal coastal flooding: There are some viable options to repair or recover damage caused.	0.5
Exposed element - ROADS				
Transportation Infrastructure	Coastal flooding may impact transit infrastructure accessibility and use.	Literature analysis / technical reports	Permanent coastal flooding: There is no option to repair or recover damage caused by coastal flooding given its permanent nature.	0
			Temporal coastal flooding: There are some viable options to repair or recover damage caused by coastal flooding given its sporadic nature.	0.5
Exposed element - Urban Zone/SEAFRONT				
Adaptation to the heat island effect	According to uses and activities, an urban element can adapt better to temperature increase.	Literature analysis / technical reports	Playground areas	0.33 (the materials that make up the playground areas tend to heat up significantly, making it impossible to play).
			Active mobility	0.66 (there is adaptive capacity but it differs when there are zones with a lack of cooling amenities)

			Terraces and motorized mobility	1 (there is adaptive capacity)
Permeability	Depending on the type of material, it will be more or less permeable to flooding.	Literature analysis / technical reports	Concrete (stairs, ramps, wall); Tile (bike lane and walkway); Concrete base and ophitic gravel (paving stone); Asphalt; Artificial stone curb, Recycled rubber (playgrounds); Wooden ramp.	0
			Grass	0.66 (Grass can retain a little bit more)
			Vegetation (trees)	1 (Vegetation minimizes the stress on drainage systems and slow down raindrop impact during flooding events)
Recovery potential	Each material reacts differently to flooding, as does its recovery potential, which varies in terms of durability, cost of repair, cleaning or replacement, etc.	Literature analysis / technical reports	Recycled rubber (playground)	0.33 (Prolonged exposure to water may cause mould growth or other problems requiring extensive cleaning or replacement)
			Wooden ramp and grass	0.66 (Wood is susceptible to warping, rotting, or structural damage and grass may become waterlogged)

			Concrete (stairs, ramps, wall); Tile (bike lane and walkway); Concrete base and ophitic gravel (paving stone); Asphalt; Artificial stone curb.	1 (these materials are more resistant to flooding and have higher recovery potential)
Accessibility to constructions		Literature analysis / technical reports	Restaurant; Public toilets; EBAR and booster pump; Tourism office.	1 (there is adaptive capacity)
Exposed element - Urban Zone - Drainage				
Response capacity to flooding	Materials can facilitate the infiltration of ponded water	Literature analysis / technical reports	Concrete, asphalt	0.33
			Tiles	0.66
			Green areas	1

Table 2. *Adaptive capacity indicators considered for the different exposed elements.*

2.2. Determination of vulnerability evaluation

Vulnerability of an exposed element is defined as:

$$V^i = S^i - AC^i$$

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. An element will be more vulnerable to hazards (rank 1) the higher its sensitivity index and the lower its adaptive capacity.

This section details the steps involved in creating each vulnerability map that will be included later on in Section 3.2 of the current document. All the layers (sensitivity and adaptive capacity data) and figure maps are available as Annex 2.

2.2.1. Beach

The vulnerability of the beach element will be calculated using the following formula, which incorporates the various sensitivity (Section 2.1.1) and adaptive capacity (Section 2.1.2) indexes, as detailed in the following paragraphs in the order in which they appear in the formula:

$$V^i = [S] - [CA] =$$

$$= \left[\frac{(Width + Slope + SizeSed + Sheltering + PosidoniaHealth + Occupancy)}{6} \right.$$

$$\left. - \left[\frac{(0.5*Accom.Space + 0.2*Protection + 0.2*Policies + 0.1*Awareness)}{4} \right] \right];$$

Section 3.2 compiles the Beach Vulnerability maps (V^i) considering the mean interval of the RCP scenarios.

The beach sensitivity indexes exhibit both spatial and temporal variability, specifically "Beach Width" and "Posidonia Health". It is also worth noting that the cartographic-dependent variables—namely "Beach Width", "Beach Slope", "Sediment Size", "Municipal Policies", and "Social Awareness"—are the primary contributors to spatial variability, as the remaining five indexes are assigned a constant value across the entire beach area. The following paragraphs provide a detailed description of each of these indexes.

- **Sensitivity Beach width (7 maps):** Beach Width is an spatio-temporal variable computed from the permanent flooding results of the different RCP scenarios and time-horizons and considering only the P50 RCP interval. The 'Sensitivity beach Width' has been computed following the description in Section 2.1.1. Higher sensitivity values stand for smaller beach

width values. Figure 2 illustrates the sensitivity indicator for the current state of Cala Millor. Figures 3-7 show some of the evaluated cases for the different considered scenarios.

- **Sensitivity Beach slope (1 map) :** Following the description and classification in Section 2.2.1, sensitivity beach slope exhibits an inverse proportionality to beach slope. Since dry beach evolution in time and in the different scenarios is not considered in the current analysis, beach slope sensitivity is considered constant. Figure 8 shows the resulting sensitivity value of current beach slope computed considering in-situ high-resolution topography.

- **Sensitivity map for Sediment size (1 map):** The sensitivity indicator related to sediment grain size has been computed considering the mean grain size from in-situ sediment samples collected from 2011 till 2022 (Fernández-Mora *et al.*, 2023), and according to the description of the sensitivity sediment grain size description in previous sections. The sensitivity values are based on the classification detailed in Section 2.1.1 (Fig. 9). Higher sensitivity to erosion is caused by thinner particles.

- **Sensitivity map for the Sheltering level:** Due to its exposure as a semi-enclosed beach, the Cala Millor bay was assigned a single sensitivity value of 0.6 regarding the sheltering level of the bay, meaning . This value will be applied to the entire study polygon representing the beach element.

- **Sensitivity maps depending on Posidonia health** : We follow the hypothesis that, given the current state of Posidonia, the beach is still relatively resilient and not highly vulnerable. In other words, we consider that this variable, in its current state, continues to protect the beach. Based on this hypothesis for the current scenario, the following sensitivity values are projected for future scenarios. They indicate that as the condition of Posidonia deteriorates due to the effects of climate change (primarily rising sea temperatures), the beach's sensitivity will increase. The values considered for this index are time and scenario-dependent and constant along the beach. Table 3 details the sensitivity values corresponding to each case:

RCP scenario	Time-horizon	N (#/m^2)	Sensitivity value
No changes (Current state)		589	0.01
RCP-4.5	2030	432	0.27
	2050	219	0.63
	2100	14	0.98
RCP-8.5	2030	382	0.35
	2050	175	0.70
	2100	1.5	0.99

Table 3. Sensitivity indicator to P. oceanica health (as a function of N) for each time-horizon and scenario.

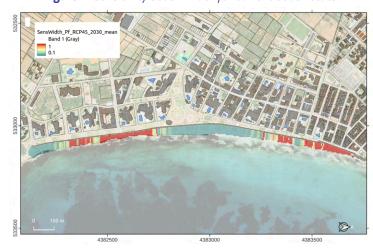**Figure 2.** *Sensitivity beach width for current beach state.*

Figure 4. *Sensitivity beach width for the scenario RCP-4.5 in 2050.*

Figure 3. *Sensitivity beach width for the scenario RCP-4.5 in 2030 (same as the map for RCP8.5 2030[3]).*

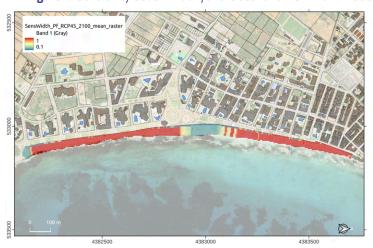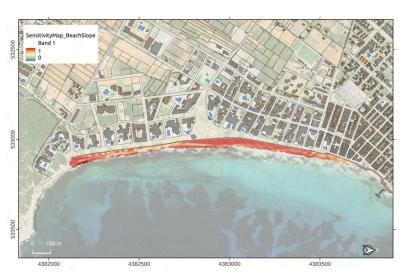**Figure 5.** *Sensitivity beach width for the scenario RCP-4.5 in 2100.*

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[3] *The RCP scenarios share the same sea level value in 2030 (see Table 10 in Deliverable 3.4).*

Figure 6. *Sensitivity beach width for the scenario RCP-8.5 in 2050.*

Figure 8. *Sensitivity of the beach slope.*

Figure 7. *Sensitivity beach width for the scenario RCP-8.5 in 2100.*

Figure 9. *Sensitivity sediment grain size.*

- **Sensitivity depending on Human activities/occupation:** An attempt was made to obtain data from lifeguards to provide information on the occupancy of the monitored beaches, allowing us to categorize Cala Millor by sectors, but finally this data was not available. Therefore, it was decided to use a single value for the entire beach, considering Cala Millor as a beach zone with the highest occupancy value and therefore a maximum value of sensibility (equal to 1).

- **Adaptive Capacity map according to the Accommodation space:** Based on the current cartography of the Cala Millor, anthropic structures (promenade wall) along the beach backshore prevents the beach from capacity of accommodation in front of sea-level rise. In this case, it is considered a minimum score set to 0.

- **Adaptive Capacity map according to protection infrastructures:** Regarding beach protection infrastructure, the beach's adaptation capacity is very low, scoring 0.3 on the indicator (CA=0.3). This is due to outdated drainage systems that continue to inefficiently vent onto the beach, and the lack of other protective infrastructure, as reflected in current cartography of Cala Millor.

- **Adaptive Capacity map according to the Institutional will:** This indicator is addressed as a weighted average of:

1) The answers collected from the surveys carried out to the public sector (addressed in WP2, in the Governance framework) about their perceptions and intentions regarding climate change. Note that, since surveys were not originally designed with this priority in mind, this score is weighted as a 0.1 from the total score.
2) The qualification of the different urban projects planned in Cala Milor, before and during the LifeAdaptCalaMillor project (weighing 90% due to taking care of these actions is essential to the project development and success).

	1) Institutional capacity and support			2) Effectiveness of the actions and strategies carried out	Final Score
	Average interest	Average influence	Interest + influence		
Sant Llorenç des Cardassar Council	0.86	0.70	0.78	0.19	0.249
Son Servera Council	0.68	0.54	0.61	0.3	0.331

Table 4. *Adaptive Capacity values related to Institutional will.*

Regarding the first point "1) Institutional capacity and support": these surveys were conducted by SOCIB in *"Task 2.1.2 Understanding the stakeholders from the public sector"* of the project WP2. These surveys have provided insight into the perception of climate change effects and the level of influence and interest in the project from representatives of

stakeholders in the public sector. Additionally, the surveys have assessed the degree of involvement of administrations in the Cala Millor area by analyzing the interest-influence matrix and conducting a subsequent analysis using a semantic differential scale (see Tables 6 and 7 of the report by Pericàs-Palou *et al.*, 2024a). Among the results, we will focus on the average values for the interest and influence scores obtained from the Sant Llorenç des Cardassar and the Son Servera town councils, based on the responses from the interviewees. These values will be assigned to the entire municipality on the "Institutional Capacity and Support" map for the exposed element of the beach.

Regarding the second point "2) Effectiveness of the actions and strategies carried out". Projects related to the renovation/modification of the promenade (Table 5) are rated "0" because they do not consider the effects of climate change at any point; they are contrary to climate change adaptation projects. Projects related to street drainage renovation are rated as 0.3, since although the objective appears to be achieving efficient urban drainage, the interaction with the beach system and the impacts of climate change are not considered.

The final average values of the scores are shown in Table 4.

Planned Projects/Strategies in Cala Millor			
Sant Llorenç	Score	**Son Servera**	Score
2023_PE_CarrilBici_Sant Llorenç	0.3	2023_PE_CalleSol_Son Servera	0.3
2021_PE_ConexiónVíaVerde_Sant Llorenç	0.3	2023_PE_SUDSCalleFetget_Son Servera	0.3
2023_PE_CalleLlum-Bonança_Sant Llorenç	0.3	2023_PE_SUDSCalleSol+Fetget_Son Servera	0.3
2023_PE_CallePlatja-Dofí_Sant Llorenç	0.3	Proyecto Constructivo de Renovación Urbana Sostenible de la Calle Vinya del Mar	0.3
2023_PE_CalleCaravel.les-Flor_Sant Llorenç	0.3	Proyectos calles Ca s'Hereu i Na Penyal	0.3
2021_PE_CalleCristofolColom_Sant Llorenç	0.3	Proyecto calle Binicanella	0.3
2021_PE_ Paseo Marítimo_Plaza fase1	0.3	2020_PE_PM TramI_Son Servera	0.3
2020.12_PE_ Paseo Marítimo_Plaza	0	2023_PE_PM TramII_Son Servera	0.3
2020_Remodelación Paseo Marítimo_esquema	0	2023_PE_PM TramIII_Son Servera	0.3
2020_Mejora Tramo Paseo Marítimo Cala Millor	0		
2014_Remodelación Paseo Marítimo Cala Millor	0		
Score	**0.19**	Score	**0.3**

Table 5. Scores rating Planned projects and strategies for both municipalities at Cala Millor Beach.

Figure 10 reflects the quite low adaptive capacity values of both municipalities, highlighting the significance of the LifeAdaptCalaMillor governance project.
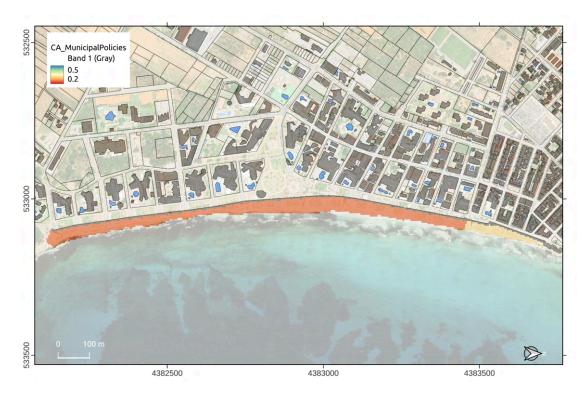
Figure 10. Adaptive capacity in terms of institutional will along Cala Millor.

- **Adaptive Capacity map according to Social awareness :** For this indicator, the information collected from surveys conducted with the society within the framework of the LifeAdaptCalaMillor Project (WP2 T2.2.2) will be used. Due to the need for geographic components to map the indicator of citizen awareness, we cannot consider the responses from tourists and employees in the tourism sector because we do not have this information. Therefore, we will only use the responses from students of six educational centers (five schools and one high school, as detailed in the Pericàs-Palou *et al.,* 2024b), as well as from four summer schools (Pericàs-Palou *et al.,* 2023), along with the involvement of associations of senior citizens, neighborhood groups, and parents' associations. This allows for the calculation of an average awareness level per municipality. The scores from different groups regarding their consciousness and good practices about climate change are summarized in Table 9 and further broken down in Annex 1. These average values are mapped on Figure 11.

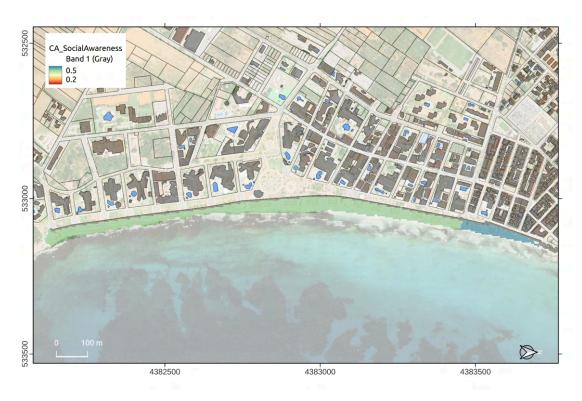|	Interest of associations	Awareness of students in educational centers	Awareness of students in summer schools	Averaged Value
Sant Llorenç des Cardassar Council	0.65	0.21	0.42	**0.43**
Son Servera Council	0.80	0.17	0.46	**0.48**

Table 6. Scores rating Social awareness.

Figure 11. Adaptive capacity in terms of Social awareness along Cala Millor.

2.2.2. Dunes

Beach sensitivity and adaptive capacity indexes for the dune system are detailed:

- **Sensitivity to Decrease in dune area (S):** To estimate the sensitivity of coastal dunes, a single indicator has been considered: the proportion of the dune that remains after a flood event. Given that the adaptive capacity of dunes is practically null due to the lack of space for their recovery, attributable to intense urbanisation, their sensitivity and vulnerability are assumed to be equivalent. In this context, any significant reduction in the size of the dune critically compromises its functionality and its ability to perform its essential ecosystem services.

- **Adaptive capacity of dune systems** depends on the availability of space for their displacement or reconstruction following erosion events. However, in urbanised areas, fixed infrastructure obstructs this natural retreat. This issue hampers the processes of dune migration and regeneration, leaving these ecosystems trapped between the advancing sea and human development.

In the case of the Cala Millor dune system, intense urbanisation has been observed to completely restrict the dunes' capacity for recovery, as insufficient space prevents their regeneration. Consequently, the sensitivity and vulnerability of the dunes in this context are considered equivalent, since any loss of structure or volume directly impacts their functionality, leaving no possibility for natural adaptation. Saying that, we introduce for completeness the dune sensitivity plots below for the RCP-4.5 (Fig. 12) and RCP-8.5 (Fig. 13) for time horizons 2030, 2050 and 2100.
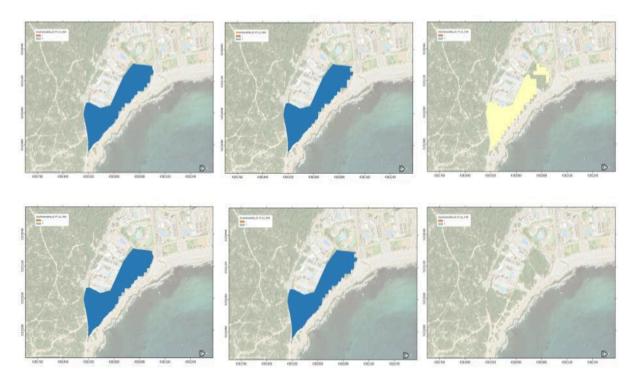

Figure 12. Sensitivity maps under Extreme Flooding under RCP-4.5 (top row) for 2030 (left), 2050 (center) and 2100 (right). The same for RCP-8.5 (bottom row) for 2030 (left), 2050 (center) and 2100 (right).
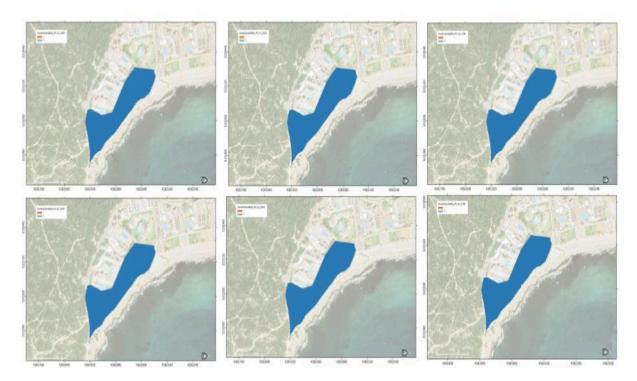
Figure 13. *Sensitivity maps under Permanent Flooding under RCP-4.5 (top row) for 2030 (left), 2050 (center) and 2100 (right). The same for RCP-8.5 (bottom row) for 2030 (left), 2050 (center) and 2100 (right).*

To determine the vulnerability of the dunes, we have used data on permanent and extreme inundation, including various sea level rise (SLR) scenarios and climate change projections. This data allows us to assess both the long-term effects of sea level rise and the impacts of extreme events, such as storms and marine phenomena, which can severely affect the dunes in short periods of time. Additionally, the influence of *Posidonia oceanica* has been considered in these scenarios, helping to assess the interaction between marine ecosystems and dunes, thereby improving the accuracy of the analysis.For dynamic reasons and in order to apply a conservative criterion, the maximum sea level rise projection within each scenario has been considered. This decision responds to the highly mobile nature of dune sediments and the fact that floods not only affect the base of the dune, but can also transport sediments towards the emerging part, altering its structure and stability in the long term.

In this context, a reduction in the size of the dunes following a flood event directly translates into a loss of their protective capacity against future impacts. Therefore, vulnerability is assessed using a proportional relationship between the initial size of the dune and its post-flood state, establishing three levels of normalised vulnerability (ranging from 0 to 1):

● High vulnerability (Vulnerability = 1): When the decrease in the size of the dune reaches or exceeds 33.3% of its initial volume (leaving less than two-thirds intact). The loss of one-third of the volume results in a critical reduction in its energy-buffering capacity, significantly exposing coastal areas to the direct impact of storms and waves. Moreover, losses of this magnitude are often not naturally recoverable, especially in highly anthropized environments.

- Moderate vulnerability (Vulnerability = 0.5): When the decrease in size of the dune is between 12.5% and 33.3% of its initial volume. In this range, although the dune still retains some functional capacity, the loss of volume is sufficient to partially compromise its protective effectiveness.
- Low vulnerability (Vulnerability = 0): When the reduction is less than 12.5% of the initial size of the dune. In this case, the structure of the dune remains practically intact, ensuring the continuity of its protective and ecological functions. This level represents a minimal impact, which is common in well-preserved dune systems or in environments with active sediment dynamics.

The determination of these levels allows for a clear and quantitative assessment of the vulnerability of dunes to inundation events. This approach highlights the urgency of mitigating stress factors and preserving dune systems, especially in highly urbanised areas, where the scope for recovery is practically non-existent.

2.2.3. *Posidonia oceanica* meadow

To estimate the sensitivity of *Posidonia oceanica* meadows, two fundamental indicators have been considered: the lower limit of the meadow and the density of shoots (shoot/m²). These indicators are crucial for assessing the resilience and structural integrity of seagrass ecosystems, as they reflect both environmental conditions and the physiological state of the meadow.

Meadows in areas with higher turbidity and eutrophication tend to have shallower lower limits due to increased light attenuation, whereas those in clearer waters extend to greater depths (Pergent *et al.*, 1995). This makes the lower depth limit a reliable proxy for long-term environmental changes affecting the meadow.

Shoot density, on the other hand, provides a direct measure of the meadow's structural condition and response to environmental stressors. Temporal variations in shoot density reflect the cumulative impact of factors such as sedimentation, mechanical damage, and temperature stress. To classify meadow sensitivity based on shoot density, we have applied an adapted classification system from Buia *et al.* (2004), which groups meadows into four categories based on depth, environmental conditions, and anthropogenic pressures:

- **Equilibrium Beds:** Density is within normal limits (normal density, ND) relative to a theoretical density or exceptionally high (highest subnormal density, HSD), indicating a stable state with no significant degradation.
- **Disturbed Beds:** Meadows present reduced density due to limiting factors, such as moderate disturbances or suboptimal environmental conditions (lowest subnormal density, LSD).
- **Highly Disturbed Beds:** Meadows display abnormally low density (abnormal density, AD), often as a result of chronic stress or extreme environmental degradation.

This classification provides a standardized framework for assessing meadow sensitivity across different environmental conditions and climate change scenarios.

The adaptive capacity of *Posidonia oceanica* meadows has been assessed in terms of external factors that determine their resilience to climate change, in particular greenhouse gas mitigation policies and international climate agreements. As these meadows cannot modify their physiological thresholds to respond to rising water temperatures and increasing anthropogenic pressures, their adaptive capacity depends directly on the evolution of global emissions and the strategies adopted to reduce them. To quantify this adaptive capacity, Representative Concentration Pathways (RCPs), projections developed by the IPCC that model different GHG concentration scenarios depending on the policies implemented, have been used. Based on these projections, three levels of adaptive capacity have been defined:

- **Optimal Adaptive Capacity:**
  This scenario assumes full implementation of climate mitigation policies, such as those outlined in the Paris Agreement, aimed at limiting global temperature rise. Here, we consider the 25th percentile of the RCP-4.5 scenario, which reflects a trajectory where emissions stabilize and begin to decline in the latter half of the 21st century. Under these conditions, *Posidonia oceanica* meadows are expected to maintain higher resilience due to slower temperature increases and improved environmental conditions.
- **Medium Adaptive Capacity:**
  In this state, some mitigation policies are in place, but they are insufficient to ensure high resilience. This corresponds to the 50th and 75th percentiles of the RCP-4.5 scenario, as well as the 25th percentile of the RCP-8.5 scenario, reflecting moderate yet significant warming with adverse implications for meadow functionality.
- **Null Adaptive Capacity:**
  This scenario represents the absence of mitigation measures or compliance with recommendations, as in the RCP-8.5 scenario. The simulations use the 50th and 75th percentiles of this scenario, projecting a continued rise in sea temperature and a marked decline in the adaptive capacity of grasslands, accelerating their mortality and reducing their natural resilience. This state highlights the maximum vulnerability due to inaction in the face of climate change.

After defining the eighteen scenarios of adaptive capacity and sensitivity, the vulnerability of the meadows is estimated using the following criteria:

- A **vulnerability of 1** is assigned when shoot density falls below 10% of its current value. At this threshold, the grassland is considered non-functional, as such a drastic decline compromises its structural integrity.
- A **vulnerability of 0.5** is assigned when shoot density decreases to between 10% and 20% of its current value. Although the meadow remains partially functional, it is experiencing ecological stress that reduces its resilience and increases its susceptibility to further degradation.

- A **vulnerability of 0** is assigned if shoot density exceeds 20% of the current density, suggesting that the meadow retains some level of functionality despite environmental stressors.

Figure 14, shows the vulnerability map for percentile 50 and medium adaptive capacity corresponding to RCP 4.5 (top row) for 2030, 2050 and 2100 (right). In the same plot, the bottom row displays the null adaptive capacity corresponding to percentile 50 and RCP 8.5 for 2030, 2050 and 2100 (right).
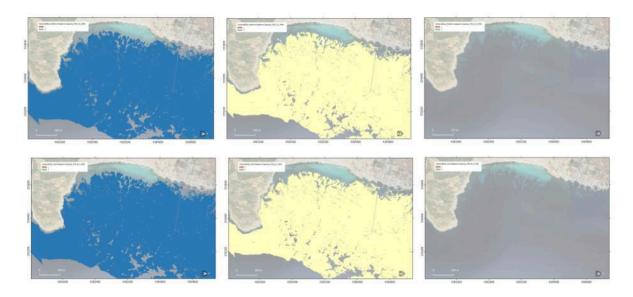

Figure 14. Vulnerability maps for percentile 50 and medium adaptive capacity corresponding to RCP-4.5 (top row) for 2030 (left), 2050 (center) and 2100 (right). The same for null adaptive capacity corresponding to percentile 50 and RCP-8.5 (bottom row) for 2030 (left), 2050 (center) and 2100 (right).

Figure 15, displays the vulnerability maps for percentile 75 and null adaptive capacity corresponding to RCP-8.5 (top row) for 2030, 2050 and 2100. In the bottom row it is shown the vulnerability maps for percentile 25 and optimal adaptive capacity corresponding to RCP-4.5 for 2030, 2050 and 2100.
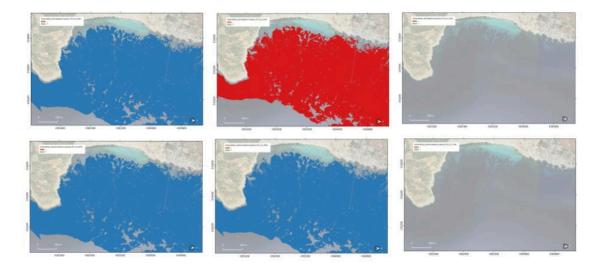
Figure 15. Vulnerability maps for percentile 75 and null adaptive capacity corresponding to RCP-8.5 (top row) for 2030 (left), 2050 (center) and 2100 (right). The same for percentile 25 and optimal adaptive capacity corresponding to RCP-4.5 (bottom row) for 2030 (left), 2050 (center) and 2100 (right).

Figure 16, displays the vulnerability maps for percentile 75 and medium adaptive capacity corresponding to RCP-4.5 (top row) for time horizons of 2030, 2050 and 2100. In the bottom row it is shown the vulnerability maps for percentile 25 and medium adaptive capacity corresponding to RCP-8.5 for 2030, 2050 and 2100.
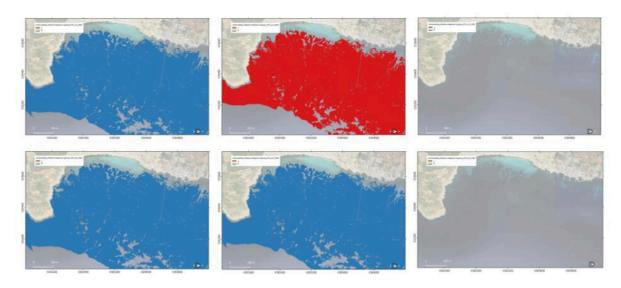

Figure 16. Vulnerability maps for percentile 75 and medium adaptive capacity corresponding to RCP-4.5 (top row) for 2030 (left), 2050 (center) and 2100 (right). The same for percentile 25 and medium adaptive capacity corresponding to RCP-8.5 (bottom row) for 2030 (left), 2050 (center) and 2100 (right).

2.2.4. Population

The vulnerability of the population element will be calculated using the following formula, which incorporates the sensitivity (Section 2.1.1) and adaptive capacity (Section 2.1.2) indexes, as detailed in the following paragraphs, following the order in which they appear in the formula:

$$V^i = [S] - [CA] = [\%population - ExposureTime];$$

Ultimately, Section 3.2 will present a Population Vulnerability map. In scenarios of permanent flooding, these vulnerability maps will be equivalent to the % population Sensitivity map as the Adaptive Capacity index for flooding exposure would be zero. However, the analyzed scenarios presents no risk of permanent flooding to the population.

In contrast, when extreme flooding occurs, vulnerability will be determined as the formula indicates. It means by subtracting the total number of people exposed and susceptible to the risk from the exposed population's capacity to adapt to the timing of the event.
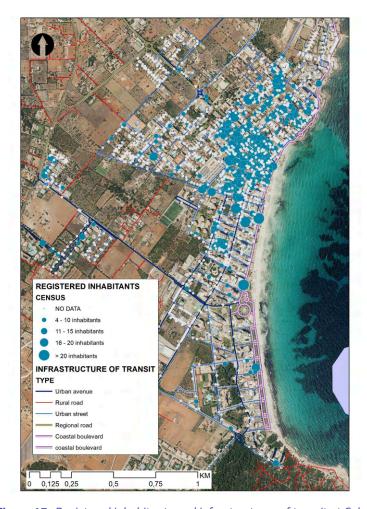

Figure 17. *Registered inhabitants and infrastructures of transit at Cala Millor.*

- **Sensitivity map depending on the population:**

The 2021 official Population Census data from the Institut d'Estadística de les Illes Balears (IBESTAT) was used to create this sensitivity map collecting the number of registered inhabitants at a postal address, only when there are more than three people, to maintain statistical confidentiality (Fig. 17). Then, from these values, the sensitivity map (Fig. 18) is derived according to the classification explained in Section 2.1.1 into three ranges; being the highest sensitivity layer in that postal code with more than 10 inhabitants.

It is important to note that the most densely populated and residential area is located in the northern part of the town, primarily within the municipality of Son Servera, or along the second and third lines of the beach. In contrast, the southern part, which falls within the municipality of Sant Llorenç, has fewer registered inhabitants. However, in the southern sector, there are several hotel establishments with registered residents. These establishments reflect two distinct situations: some accommodate long-term or permanently rented apartments/rooms, while others provide lodging for their employees.
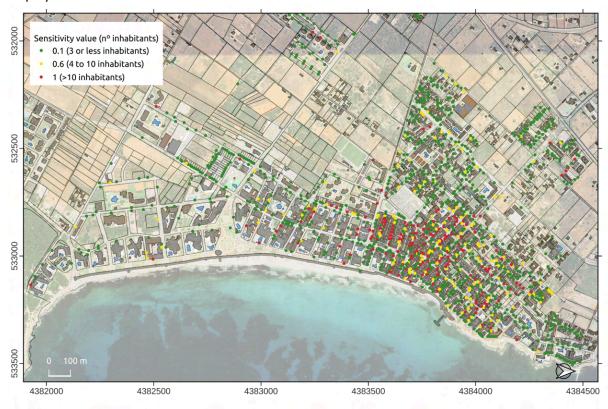

Figure 18. *Population sensitivity map at Cala Millor.*

- **Adaptive capacity map depending on the flooding exposure time:**

Coastal flooding impacts the accessibility and use of primary residences but we consider it as a problem only when these floodings are permanent. In this case, it implies that there is no option to

repair or recover the damages caused given its permanent nature and the adaptive capacity value is established as null (CA=0), being thus maximum its vulnerability. However, if the flooding is temporal it is assumed that the damage caused is possible to repair or recover and therefore the adaptive capacity value is medium (CA=0.5) thus reducing vulnerability to hazards.

2.2.5. Roads

The vulnerability of the roads element will be calculated using the following formula, which incorporates the sensitivity (Section 2.1.1) and adaptive capacity (Section 2.1.2) indexes, as detailed in the following paragraphs, following the order in which they appear in the formula:

$$V^i = [S] - [CA] = [RoadType - ExposureTime];$$

Ultimately, Section 3.2 will present a Road Vulnerability map. In scenarios of permanent flooding, these vulnerability maps will be equivalent to the Road Type Sensitivity maps, as the Adaptive Capacity index for flooding exposure will be zero. However, as in the population case, the analyzed scenarios presents no risk of permanent flooding to the roads. Conversely, in scenarios of temporary flooding events, vulnerability will be determined as the formula indicates: the level of sensitivity the road has to the risk minus the capacity of the road to recover from the risk determines the vulnerability.

- **Sensitivity Road Typology map:**

The road categorization data is sourced from the Institut Cartogràfic i Geogràfic de les Illes Balears (ICGIB), specifically from the "Xarxa de transport de les Illes Balears i Viari unificat de les Illes Balears (VUIB)" database. The road's class and sensitivity value are determined by its category and function within the communication infrastructure. These values are based on the ranges established in section 2.2.1 giving a higher sensitivity value the busier the road is. Figure 19, displays the derived sensitivity map.
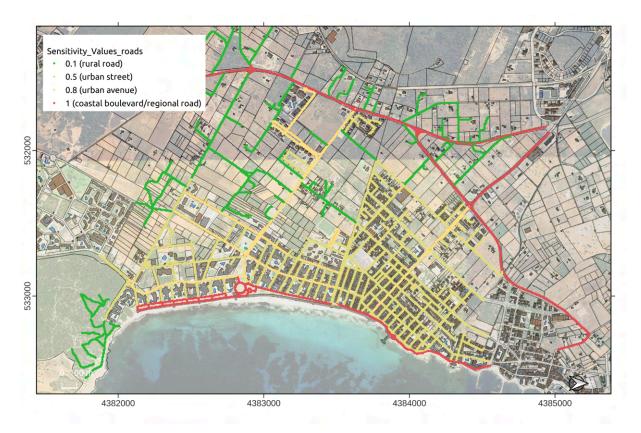
Figure 19 *Transportation infrastructure sensitivity map at Cala Millor.*

- **Adaptive capacity map of the Roads depending on the flooding exposure time:**

In the same way as was hypothesized for the population, coastal flooding impacts transit infrastructure accessibility and use but this it is considered as a problem only when these floodings are permanent. In this case, it implies that there is no option to repair or recover the damages caused given its permanent nature and the adaptive capacity value is established as null (CA=0). However, if the flooding is temporal it is assumed that the damage caused is possible to repair or recover and therefore the adaptive capacity value is medium (CA=0.5) thus reducing vulnerability to hazards.

2.2.6. Urban Zone/Seafront

The vulnerability of the Cala Millor bay's seafront component to increasing temperatures (V^t) or flooding (V^f) is assessed using the formulas below that incorporates sensitivity and adaptive capacity indexes. These indexes, listed in Tables of sections 2.1.1 and 2.1.2, are here explained in detail following the order they appear in the formulas:

$$V^t = [S] - [CA] =$$

$$= [\frac{Albedo + Radiation\ exposure)}{2}] - [Adaptation\ to\ high\ temperatures];$$

44

$$V^f = [S] - [CA] =$$

$$= \left[\frac{Sens.\ of\ infraestructures\ relatives\ to\ uses\ \&\ activities + Material\ typology + Sens.\ of\ constructions)}{3} - \left[\frac{(permeability + recovery\ potencial + accesibility\ to\ buildings)}{3}\right]\right];$$

At the end, a total of two Seafront Vulnerability maps will be shown in Section 3.2, one according to the temperature increase and the other, conforming to the flooding impact. The following paragraphs describe each of the indexes considered, all of which provide a uniform value per land feature throughout the area due to consistent conditions, with the exception of solar radiation, which is spatially variable. In the following, indexes according to the rising temperatures V^t and to the flooding impact (V^f) are detailed.

a) **Rising temperatures indexes:**

- **Albedo sensitivity index:** The albedo values used in Seafront are classified according to their ability to absorb and reflect solar radiation. High albedo surfaces reflect more sunlight and absorb less heat, while low albedo surfaces retain more heat, increasing their sensitivity to temperature increases. The thermal properties of the materials used in the seafront, such as their ability to absorb and retain heat, have been taken into account in the assessment of this index. Materials such as asphalt tend to have a higher sensitivity (score 1), while materials with low heat retention (f.i. grass) have a low sensitivity (score 0.33).

Asphalt	Concrete, Tiles, Cobblestone, Recycled rubber, Artificial stone curbs	Grass, Vegetation, Ponds and water features, Wooden ramps	NoData
1	0.66	0.33	0

Table 10. *Albedo sensitivity indexes for the different materials.*

- **Radiation exposure sensitivity index:** Radiation exposure measures the amount of solar radiation received by an area. Factors such as orientation, shading, and geographic location influence this index, with higher radiation levels of radiation correlating with increased sensitivity. The radiation values were recorded on July 1, 2024 at 12:00 PM, derived from LIDAR data.

Then, integrating these two first sensitivity indexes, Figure 20, shows the overall sensitivity values for the seafront area with respect to the impact associated with atmospheric temperature increasing.
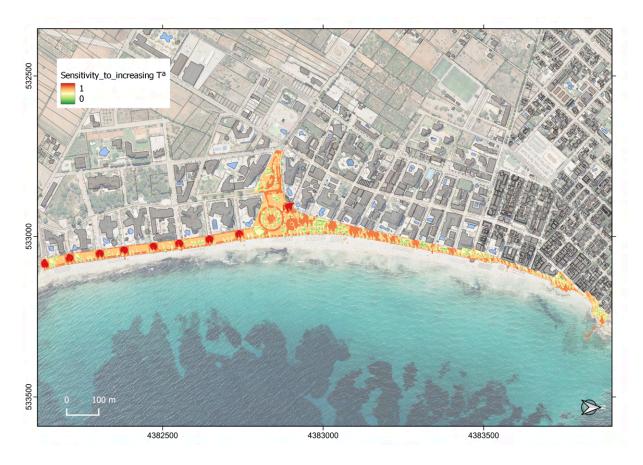
Figure 20. *Radiation exposure sensitivity index.*

- **Adaptive Capacity index to high temperatures:** The adaptive capacity indexes are quantified in relation to the specific uses and activities that take place along the seafront. These measure the extent to which they can be used in case of extremely high temperatures.

Terraces and motorized mobility	Active mobility (walking, cycling)	Playground	NoData
1	0.66	0.33	0

Table 11. *Adaptive Capacity to high temperature*

Figure 21, shows the adaptive capacity values for the seafront area with respect to the impact of the increasing atmospheric temperatures.

Figure 21. *Adaptive Capacity to high temperature.*

b) **Flooding indexes.**

● **Uses and Activities sensitivity index:** Different uses and activities in the seafront contribute to different levels of sensitivity to flooding. For example, areas designated for play or terraces will be more sensitive than areas for active mobility, because they won't be able to be used during a flood event.

Terraces and Playground	Motorized mobility	Active mobility (walking, cycling)	NoData
1	0.66	0.33	0

Table 12. *Activities sensitivity index*

● **Material typology sensitivity index:** The typology of materials used in the Seafront influences its sensitivity to flooding. Materials such as recycled rubber or wooden ramps are more susceptible to flooding than more impervious surfaces such as concrete or asphalt.

Vegetation, Recycled	Grass	Concrete,Tiles, Cobblestone, Artificial stone	NoData

rubber, Wooden ramps		curbs, Asphalt	
1	0.66	0.33	1

Table 13. Material typology sensitivity indexes

- **Constructions sensitivity index:** The sensitivity of constructions is determined by their essentiality during a flood event. Critical infrastructures like pumping stations are highly sensitive, as they are indispensable for managing floodwaters. In contrast, recreational facilities are less sensitive.

Critical infrastructure (pumping stations)	Restaurant, Tourism office & public toilets	No Data
1	0.33	0

Table 14. Constructions sensitivity index

Figure 22, shows the integration of sensitivity values for the seafront area with respect to the flooding impact.

Figure 22. Sensitivity values for the seafront area with respect to the flooding impact.

- **Material permeability adaptive capacity index:** The permeability of materials determines their ability to absorb water or allow it to drain away. Impermeable surfaces will have the lowest score.

Vegetation	Grass	Concrete,Tiles, Cobblestone, Artificial stone curbs, Recycled rubber, Wooden ramps, Asphalt, NoData
1	0.66	0

Table 15. *Material permeability scores*

- **Recovery potential adaptive capacity index:** Recovery potential measures material resilience, as well as how quickly and effectively different components can return to normal after flooding.

Vegetation, Concrete, Tiles, Cobblestone, Artificial stone curbs, Asphalt	Grass, Wooden ramps	Recycled rubber	NoData
1	0.66	0.33	1

Table 16. *Recovery potential scores*

- **Accessibility to Constructions adaptive capacity index:** This index measures the ease with which these infrastructures can be accessed during a flood event.

Critical infrastructure, Restaurant, Public toilets, Tourism office	NoData
1	0

Table 17. *Accessibility to Constructions scores.*

Then, integrating these three last indexes, Figure 23 shows the overall adaptive capacity values for the seafront area with respect to the flooding impact.

Figure 23. *Adaptive capacity values for the seafront area with respect to the flooding impact.*

2.2.7. Urban zone / Compound flooding

Vulnerability in terms of compound flooding (coastal and rainfall flooding) due to drainage systems failure is computed as:

$$V = max(0.1, [S] - [CA]) = max[0.1, Slope - Materials];$$

The following parameters are considered:

- **Sensitivity to slope:** Sensitivity of the urban area to ponding is considered directly over the streets and pedestrian paths , considering the following terms:
  - **Slope:** Streets with steep slopes can exacerbate runoff velocity, increasing the risk of flash flooding and overwhelming drainage systems. Conversely, streets located in flat or gently sloping areas may experience slower water movement, leading to water accumulation and prolonged inundation.

  - **Depression areas or low-lying zones:** they naturally collect runoff, making them prone to ponding and localized flooding.

Sensitivity is computed as a linear function in terms of slope, considering the high-resolution 2.5x2.5 m DEM from IGN, and setting a maximum for flat areas (0º) of 1 and a minimum of 0.2 for slopes higher than 20º.

- **Adaptive Capacity of Materials:** Adaptive Capacity for compound flooding depends on usages and materials of streets. In this sense, it has been categorized following the material typology described in section 2.2.6 and considering the following concepts and values (Table 18):
    - **Vegetation, Grass and Green Infrastructure:** The presence of vegetation, green spaces, and bioswales increases runoff absorption and thus flooding amount and time are reduced.
    - **Concrete, Tiles and Asphalt:** Areas covered with these materials have less infiltration capacity.

Vegetation and grass	Tiles, Cobblestone	Concrete, Asphalt	NoData
0.66	0.46	0.33	0

Table 18. Adaptive capacity of material in front of compound flooding.

3. Risk Assessment in Cala Millor

This section presents the results of how climate change hazards (analyzed in D3.4) affect the mapped elements. These effects depend on the vulnerability of the elements and the duration of exposure to the hazard. The risk degree for each element and climate scenario has been mapped. This allows for the quantification, integration, and comparison of multiple risk pathways for a selected set of hazards. The ultimate goal is to enhance cross-sectoral decision-making, climate proofing, and adaptation planning. Therefore, the risk assessment is valuable for prioritizing the implementation of climate change adaptation measures.

3.1. Mapping the analysed exposure elements

The number of receptors at risk analysed according to the current cartography of Cala Millor are mapped in Figure 24: cadastral parcels from Son Servera and Sant Llorenç des Cardassar -limiting the area by the western main road limit, Punta de n'Amer and the perpendicular street that separates Cala Bona-, registered inhabitants, road infrastructure, urban seafront, urban drainage system, the beach area, dune area, and *P. oceanica* meadow. Then, the final vulnerability score of each of these receptors or exposed elements (Section 3.2) are determined by their intrinsic characteristics and/or external factors that condition it (Sensitivity and Adaptive Capacity indexes), which were analyzed in Section 2. These characteristics influence the degree of risk they face depending on the specific hazard.
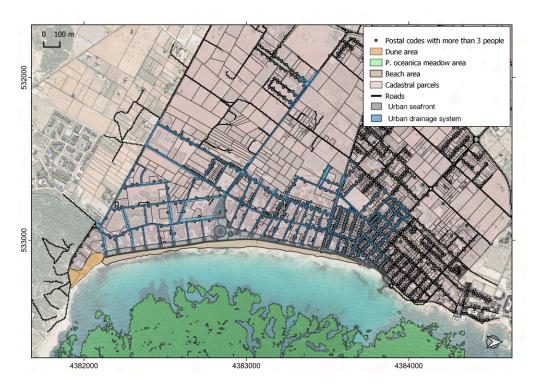

Figure 24. *Exposed elements at Cala Millor.*

Noteworthy, at a starting level of analysis, the exposed elements for the different dimensions considered were:

- **Physical Dimension:** Beach
- **Environmental Dimension:** *P. oceanica* meadow
- **Socio-economic Dimension:** Cadastral parcels (value)

However, on a first analysis of hazards and their interaction, and a preliminary risk assessment evidenced that further hazards (compound flooding) and exposed elements should be considered to really capture the potential risks in the study area. In this way, a new dimension was considered (urban dimension) and the final exposed elements considered are:

- **Physical Dimension:** Beach
- **Environmental Dimension:** *P. oceanica* meadow, Dunes
- **Socio-economic Dimension:** Cadastral parcels (value), Roads, Population
- **Urban dimension:** Urban zone (roads and pedestrian paths), Drainage system.

3.2. Vulnerability maps of each element

This section displays the final vulnerability maps, which illustrate the vulnerability of each exposure element to the analyzed climate change hazards. The maps use a scale of 0 to 1 to represent the level of vulnerability for each climate scenario and time horizon. The vulnerability scores, which are determined using the formulas specified in Section 2.2, indicate the susceptibility of a given system exposed to particular hazards. The scores also reflect the system's inherent characteristics, including its ability to respond, resist, and recover. All the resulting vulnerability layers and figure maps are available as Annex 2.

3.2.1. Beach vulnerability maps to flooding impacts

The first set of vulnerability maps (Annex 2) correspond to seven vulnerability maps of the beach area -derived from the permanent flooding hazard maps-: vulnerability of the current state (2024), and vulnerabilities in both RCP4.5 and RCP8.5 for 2030, 2050 and 2100 time horizons. These maps are available in both TIF (georeferenced raster file) and PNG formats (to display it as a figure for easier viewing). For Cala Millor, the maps explain an average vulnerability value of 0.5 for the current beach width -and considering the current state of *P. oceanica*-, and ranges between 0.55 to 0.74 respectively for the "RCP4.5 2030" and "RCP8.5 2100" climatic scenarios. Note that the differences in vulnerability between the beaches are due solely to the climate scenario-dependent indexes of "beach width" and "Posidonia Health" as explained in section 2.2.1.

3.2.2. Dune vulnerability to flooding

Next maps correspond to twelve vulnerability maps of the dune system (Annex 2) derived from the permanent flooding (Pf) and extreme flooding hazard maps with scenario-dependent state of *P. oceanica* (Ef_Pt): vulnerabilities in both RCP4.5 and RCP8.5 for the 2030, 2050 and 2100 time horizons. These maps are available in TIF and PNG format, with the PNGs specifically designed as figure maps.

Note that the differences in vulnerability between dunes are only due to the climate scenario-dependent 'Decrease in dune area' indexes (explained in section 2.2.2). In cases where the dune system has entirely disappeared due to flooding, no raster is generated, as the dune is no longer present.

3.2.3. *Posidonia oceanica* meadow vulnerability to rising sea temperatures

Also available are eighteen maps with the vulnerability of *Posidonia oceanica* meadows— RCP4.5 and RCP8.5—covering the time horizons of 2030, 2050, and 2100, and considering three confidence intervals (percentiles P25, P50, and P75). These maps are available in both TIF and PNG formats, with the PNGs specifically designed as figure maps (those embedded in the document).

Note that the differences in vulnerability between *Posidonia oceanica* meadows are exclusively attributed to the scenario-dependent indexes of "shoot density" and "lower depth limit." In cases where the *Posidonia oceanica* meadow has entirely disappeared due to excessive sea temperature increases, no raster is generated, as the meadow is no longer present. These criteria are described in detail in section 2.2.3.

3.2.4. Population and Roads vulnerability maps to compound flooding

The vulnerability maps for population and roads are dependent on the duration of the flooding hazard, which results from the combined effects of coastal and rainfall-induced flooding. This was explained previously in sections 2.2.4 and 2.2.5. In scenarios of permanent flooding, the risk to population and roads would be zero as these elements are not affected by the hazard (no hazard). However, this risk exists for those scenarios of extreme flooding where the impact will be greater or lesser depending on the vulnerability. In this instance, the vulnerability map follows the same distribution as the sensitivity map but less severe due to the adaptive capacity constant value associated with the temporary nature of the hazard.

3.2.5. Seafront vulnerability

The vulnerability map to rising atmospheric temperatures (Fig. 25) shows the areas that are vulnerable to increased temperatures along the Cala Millor seafront, possibly due to the urban heat island effect or lack of shading [see section 2.2.6.1. for causes]. We note that hard landscaping materials such as asphalt, tiles and concrete contribute to heat vulnerability due to their high heat absorption and retention, and their exposure to pedestrian and vehicular traffic, which can further heat these materials and increase the urban heat island effect (UHI). In addition, green spaces and vegetated areas play an important role in mitigating the effects of heat. As well as providing natural shade and reducing the amount of solar radiation absorbed by surfaces such as asphalt or concrete, vegetation can reduce temperatures and increase humidity through evapotranspiration.

Figure 26, highlights areas along the seafront that are vulnerable to flooding. These areas are identified using the Sensitivity (S) and Adaptive Capacity (AC) indexes explained in Section 2.2.6.2. Vulnerability is likely to be higher in areas composed of materials that are less resistant to water damage, such as wooden ramps and recycled rubber. In the case of recycled rubber, vulnerability is increased by the presence of a play area, which is a sensitive element as it can't be used during and after a flood event. Although concrete, tile and asphalt surfaces are less susceptible to these events than other materials, they contribute to the lack of permeability in these areas. Finally, it's important

to consider critical infrastructure such as EBAR or booster pumps, which are highly sensitive to flooding due to their essential role in urban systems. Flooding can disrupt their operation and require costly repair or replacement after the event.
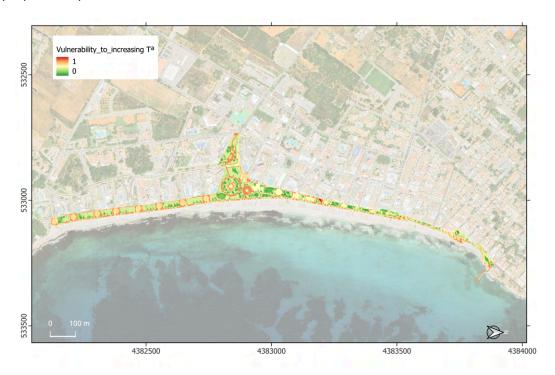

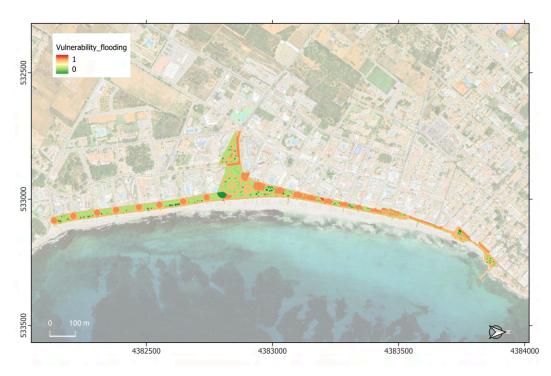*Figure 25.* Urban zone vulnerability in front rising atmospheric temperature.

Figure 26. Urban zone vulnerability in front of coastal flooding.

3.2.6. Urban vulnerability to compound flooding

The susceptibility of the urban drainage system to ponding as a result of compound flooding, arising from the combined effects of coastal and rainfall-induced flooding, is mapped in Figure 27 according to the guidelines set out in section 2.2.7.
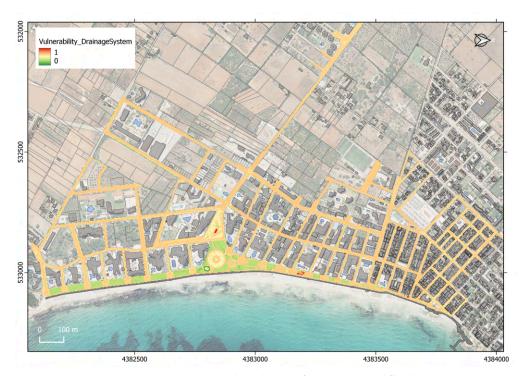

Figure 27. *Urban zone vulnerability in front compound flooding.*

3.3. Risk assessment

3.3.1. Definition of risk

As stated in Deliverable D3.1, 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.

Following this definition, we consider the risk on a exposed element associated to each hazard detailed in D3.4 as:

$$R_{i,RCPj} = P_{RCP} H_{RCP,j} V_i$$

Where P_{RCP} is the probability of the hazard associated with the RCP scenario, $H_{RCP,j}$ is the hazard j at the corresponding RCP and V_i is the vulnerability of the exposed element i.

Estimating the precise probabilities of future greenhouse gas concentration scenarios, such as RCP-4.5 and RCP-8.5, is inherently challenging due to uncertainties surrounding socio-economic developments, technological advancements, and policy decisions. Nevertheless, studies have made attempts to assess the plausibility of these scenarios:

- **RCP-4.5**: This scenario describes a stabilization of radiative forcing at 4.5 W/m² by 2100, assuming moderate mitigation efforts. While specific probability estimates are not widely available, RCP4.5 is often considered a plausible intermediate pathway, dependent on the successful implementation and effectiveness of global mitigation strategies.
- **RCP-8.5**: Representing a high greenhouse gas concentration trajectory, RCP8.5 is often associated with the 90th to 98th percentile of baseline scenarios that assume no additional climate policies. This suggests it is a less likely, but still possible, outcome if current emission trends continue unabated.

Currently, there is no consensus on assigning specific probabilities to Representative Concentration Pathway (RCP) scenarios. RCPs are intended to reflect a range of possible greenhouse gas concentration trajectories, not probabilities of their occurrence. Consequently, they are typically used for comparative analysis rather than probabilistic forecasting. This approach allows researchers and policymakers to explore potential climate outcomes under different emission pathways without implying any specific probability distribution among them. Huard *et al*. (2022) examined the probability of various RCP and Shared Socioeconomic Pathway (SSP) scenarios using different model simulations. However, they cautioned that their approach and results should not be interpreted as practical likelihood estimates. Instead, their work aimed to demonstrate the potential of Integrated Assessment Models (IAMs) to inform scenario probabilities.

In this analysis, risk is evaluated based on impact and vulnerability, without explicitly incorporating the probabilities of RCP-4.5 and RCP-8.5 scenarios. This approach is justified for several reasons:

- **High Uncertainty in Scenario Probabilities**: Estimating the probability of different RCPs is fraught with uncertainty due to the complexities of future emissions, policy shifts, and socio-economic dynamics. Assigning precise probabilities to RCP4.5 and RCP8.5 could inadvertently introduce subjective biases and a false sense of certainty in otherwise uncertain projections.
- **Scenario-Based Risk Assessment**: The RCP framework is designed for exploratory scenario analysis, not probabilistic forecasting. While RCPs represent plausible pathways for greenhouse gas concentrations and their associated climate impacts, they do not specify the likelihood of occurrence. Therefore, risk assessments should focus on the potential consequences of each scenario, rather than attempting to estimate their probabilities.
- **Precautionary Principle and Decision-Making**: Risk assessments often prioritize worst-case or high-impact scenarios to ensure that systems are prepared for a broad range of outcomes. By emphasizing the severity of impacts and system vulnerabilities, rather than uncertain

probabilities, decision-makers can adopt robust adaptation and mitigation strategies that remain effective across a variety of possible futures.

- **Consistency with Deterministic Approaches**: It is common in climate risk assessments to evaluate impacts under specific scenarios without assigning probabilities. This ensures that planning and policy decisions are based on the potential consequences of different scenarios, rather than uncertain likelihoods, making the assessment more actionable and practical for real-world decision-making.

In the following, the risks associated with each element identified in the current Cala Millor cartography need to be quantified. This will involve calculating a risk score based on the vulnerability and hazard for each element, taking into account different climate scenarios and exposure durations. The risk will be calculated as: Risk = Hazard ∩ Vulnerability (exposure time). The risk maps generated for each exposure element and for all the scenarios analyzed are available. Annex 2 contains links to all these data. Only a selection of these available maps are shown in the following subsections.

3.3.2. Beach flood risk maps

The risk associated with the beach element according to the best and worst scenarios (RCP4.5_2030 and RC8.5_2100 respectively, both considering the mean confidence interval) of Permanent Flooding (Pf) and Extreme Flooding (Ef_Pt) are shown in Figures. 28-31.

3.3.3. Dune system risk maps related to sea flooding

The risk associated with the dune element according to the best and worst scenarios (RCP4.5_2030 and RCP8.5_2100 respectively, both considering the mean confidence interval) of Permanent Flood (Pf) and Extreme Flood (Ef_Pt) are shown in Figures 32-35.

3.3.4. *P. oceanica* meadow risk maps related to sea temperature increase

The associated risk for the *P. oceanica* meadow element for seawater temperature rise based on the three different adaptive capacities at the 2030 and 2100 time horizons are shown in Figures 36-41.

3.3.5. Population risk map related to compound flooding

The risk associated with extreme flooding (Ef_Pt) for the population under the best (RCP 4.5_2030) and worst (RC8.5_2100) scenarios, both using the mean confidence interval, are shown in Figures 42-43.

3.3.6. Road risk map related to compound flooding

The risk associated with extreme flooding (Ef_Pt) for roads under the best (RCP 4.5_2030) and worst (RC8.5_2100) scenarios, both using the mean confidence interval, are shown in Figures 44-45.

3.3.7. Seafront risk related to atmospheric temperature increase

The risk to the urban seafront area from rising atmospheric temperatures can be determined by combining the vulnerability map with the normalized values of expected temperatures for each scenario (see Table 3 in Deliverable D3.4). Figure 46, mapped the risk for the worst scenario (RC8.5_2100 respectively).

3.3.8. Seafront risk related to sea flooding

The risk associated for the urban seafront area according to the best and worst scenarios (RCP4.5_2030 and RC8.5_2100 respectively, both considering the mean confidence interval) of extreme flooding (Ef_Pt) are shown here in Figures 47-48. The risk maps generated for permanent flooding scenarios show that the flooding does not significantly impact the seafront, even in the worst-case scenario.
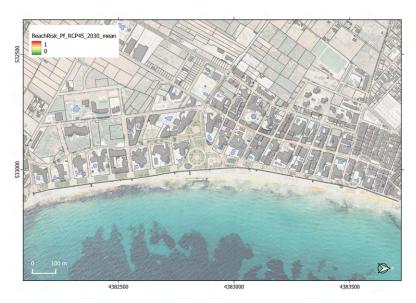
Figure 28. *Permanent flooding: Pf_RCP4.5_2030.*

Figure 30. *Extreme flooding: Ef_Pt_RCP4.5_2030.*

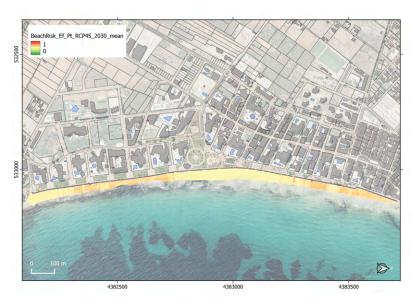**Figure 29.** *Permanent flooding: Pf_RCP-8.5_2100.*

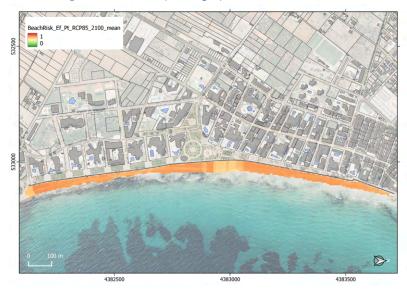**Figure 31.** *Extreme flooding: Ef_Pt_RCP-8.5_2100.*
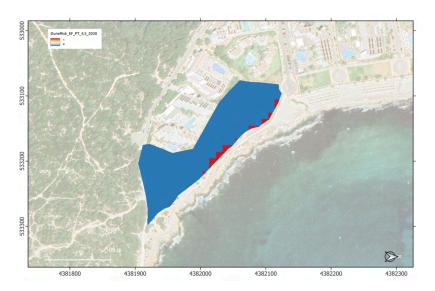
Figure 32. Extreme flooding: Ef_Pt_RCP-4.5_2030.

Figure 34. Permanent flooding: Pf_RCP-4.5_2030.

Figure 33. Extreme flooding Ef_Pt_RCP-8.5_2100.
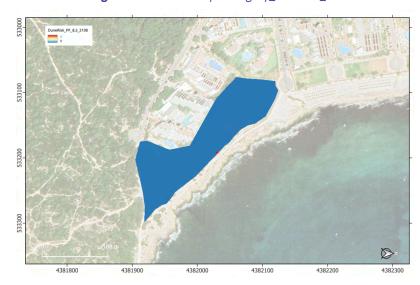
Figure 35. Permanent flooding: Pf_RCP-8.5_2100.
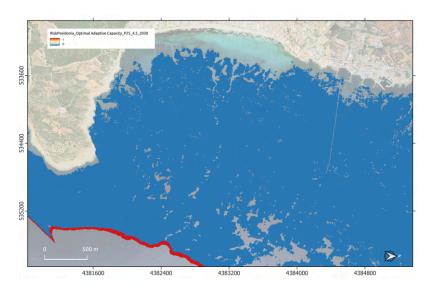
Figure. 36 *Optimal adaptive capacity_ RCP-4.5_ 2030.*

Figure 38. *Medium adaptive capacity_ RCP-4.5_ 2030.*

Figure 37. *Optimal adaptive capacity_RCP-4.5_ 2100.*
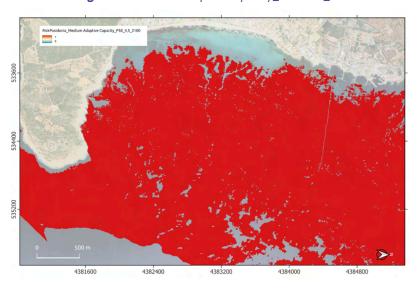
Figure 39. *Medium adaptive capacity_ RCP-4.5_ 2100.*
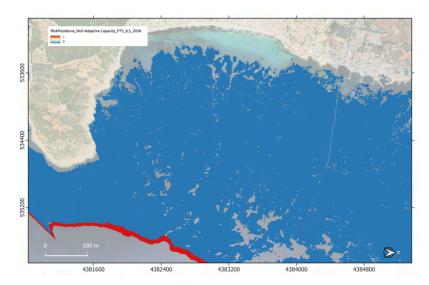
Figure 40. Null adaptive capacity_ RCP-8.5_ 2030.
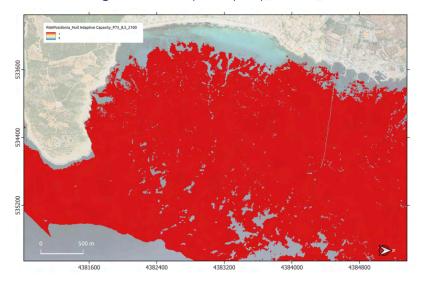
Figure. 41 Null adaptive capacity_ RCP-8.5_ 2100.
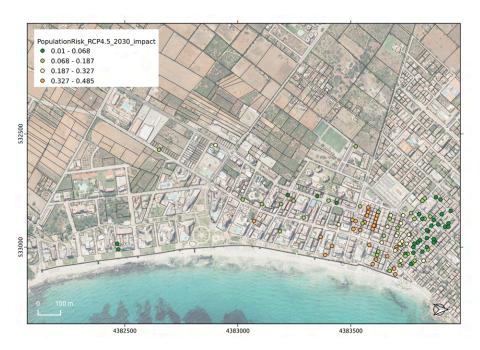
Figure 42. Population Risk: Ef_Pt_RCP-4.5_2030.
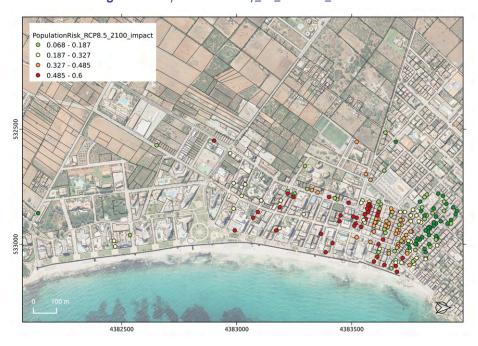
Figure 43. Population Risk: Ef_Pt_RCP-8.5_2100.

Figure 44. *Compound flooding: RCP-4.5 2030.*

Figure 45. *Compound flooding: RCP-8.5 2100.*
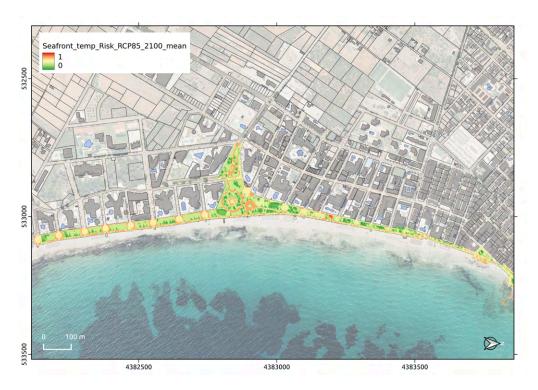
Figure 46. *Sea-front risk to temperature .*
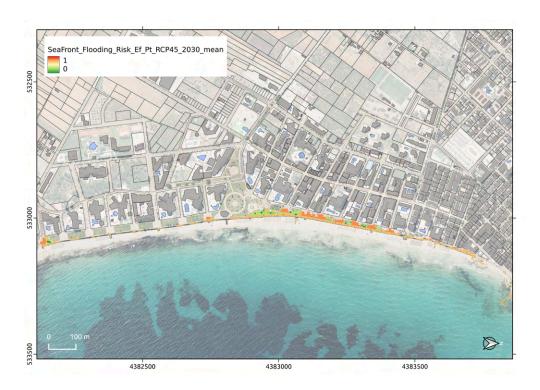
Figure 47. *Seafront-risk to flooding: RCP-4.5 2030.*

Figure 48. *Seafront-risk to flooding: RCP-4.5 2030.*

### 3.3.9.	Urban risk related to compound flooding

The risk associated for the drainage system according to the best and worst scenarios (RCP-4.5_2030 and RCP-8.5_2100 respectively, both considering the mean confidence interval) of extreme compound flooding (Ef_Pt) are shown here:

Figura 49. *Compound flooding: RCP-4.5 2030.*

Figure 50. *Compound flooding: RCP-8.5 2100.*

3.3.10.   Socio-economic Risk

The socioeconomic methodology explained in Section 2.3.4 of Deliverable 3.4 of the LifeAdaptCalaMillor project yielded the results shown here. These results, also available in the links provided in Annex 2, aim to demonstrate how floodings due to sea level rise and storm surges, atmospheric temperature increases, and beach width reduction affect the Cala Millor's economy. Direct financial losses were only calculated for cadastral parcels where land is permanently flooded. This means that only the impacts related to sea level rise were considered and not those related to extreme flooding. Parcel owners have a high adaptive capacity in case of temporary flooding events. Indirect financial losses were calculated for all cadastral parcels and depend on beach width reductions and atmospheric temperature increases.

This section presents the maps with the socioeconomic land value per each cadastral parcel in the current year (2024) and for each corresponding climatic scenario. Additionally, maps were created to illustrate the expected socio-economic losses -as a percentage- between each scenario and the current state. These maps show the differences along the cadastral parcels within the municipal areas of Sant Llorenç des Cardassar and Son Servera. Figures 52-57 show the predicted economic value at different scenarios and the corresponding % of loss with respect to the current state (Fig. 51).
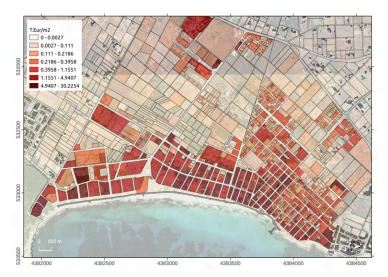
Figure 51. *Current economic value in thousands of euros per m2: [total amount= 2,673.468 euros]*

Figure 53. *Economic value losses in 2030; RCP-4.5 scenario with respect to current state*
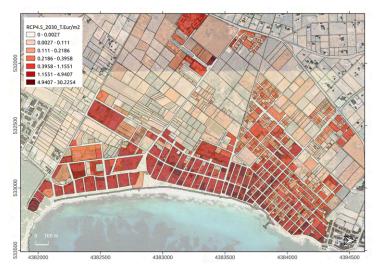
Figure 52. *Economic value (T.Eur/m2) in 2030; RCP-4.5 scenario: [total amount= 1,908.459 T.Eur]*
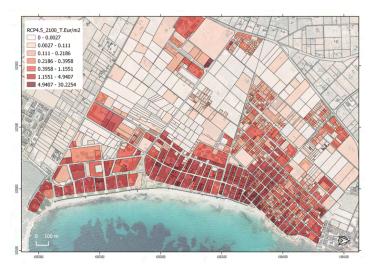
Figure 54. *Economic value (T.Eur/m2) in 2100; RCP-4.5 scenario: [total amount= 1,352.088 T.Eur]*

Figure 56. *Economic value (T.Eur/m2) in 2100; RCP-8.5 scenario: [total amount= 1,166.632 T.Eur]*

Figure 55. *Economic value losses in 2100; RCP-4.5 scenario with respect to current state:.*
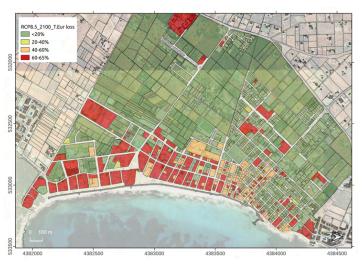
Figure 57. *% Economic value losses in 2100; RCP-8.5 scenario with respect to current state*

4. Integrated multi-risk assessment in Cala Millor

The implementation of a Multi-Risk Assessment (MRA) methodology enables the quantification, integration, and comparison of multiple risk pathways for selected hazards. This approach enhances cross-sectoral decision-making, climate-proofing, and adaptation planning. The proposed methodology assesses risk by analyzing hazard, exposure, and vulnerability across different beach dimensions (physical, environmental, socioeconomic, urban and urban infrastructure…), ultimately providing risk estimates for coastal zones. This assessment helps prioritize climate adaptation measures, with high-risk areas requiring immediate intervention.

Risk is defined as the intersection of hazard, exposure, and vulnerability. Hazard refers to disaster intensity, such as sea level rise projections. Exposure accounts for land use or environments at risk, while vulnerability reflects a system's sensitivity, resistance, and resilience.

The methodology follows a structured approach: first, a multi-hazard map is created by integrating hazard maps and their interrelationships. Next, an exposure map is generated by identifying exposed elements and crossing this data with hazard maps, producing impact maps. Finally, vulnerability scores are assigned to receptors based on sensitivity and adaptive capacity. The combination of multi-hazard, multi-exposure, and multi-vulnerability data results in a multi-risk map, which quantifies climate change impacts and informs risk management strategies for coastal areas.
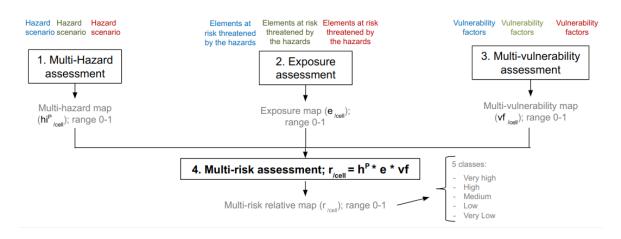
*Figure 58. MRA example (Gallina et al., 2020) for a particular RCP and year projected scenario by considering the physical dimension (blue), the environmental dimension (green), and the physical dimension (red).*

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. Hazards interaction

Analyzing coastal risks is inherently complex due to the interplay of multiple hazards, including sea-level rise, extreme wave and surge events, and rising sea and atmospheric temperatures. These factors interact in nonlinear and often unpredictable ways, amplifying their overall impact and increasing the uncertainty of risk assessments.

Our approach addresses these hazards in two ways: first, by evaluating them as individual threats when appropriate, and more importantly, by integrating their interconnections to better capture real-world dynamics. For instance, the approach of coastal flooding during extreme events not only accounts for sea-level rise but also considers the direct impact of rising sea temperatures on *P. oceanica* meadows. In this context, the hazard interaction matrix described in D3.1 is inherently incorporated into impact estimation, ensuring a more comprehensive assessment of derived risks.

The following tables (Tables 19-20) show the different hazards interaction and how they are connected to the different beach dimensions and risks:

	SLR	Waves storm T100	Sea temp. rise	Atm. temp. rise	Rainfall
SLR	1:1	Non-linear		Linear	Non-linear
Waves storm	Non-linear	1:1	Non-linear	Linear	Non-linear
Sea temp. rise		Non-linear	1:1		Non-linear
Atm. temp. rise	Linear	Linear		1:1	Linear
Rainfall	Non-linear	Non-linear	Non-linear	Linear	1:1

■ 1:1 interaction   ■ Non-linear coupling   ■ Linear interaction (risk assessment)

***Table 19**.. Hazards (drivers) interaction scheme*

Driver	PHYSICAL	ENVIRONMENTAL		SOCIO-ECONOMIC			URBAN	
	Beach	*P. oceanica*	Dune	Cadastral value	Population	Roads	Seafront	Drainage system
SLR	■		■	■			■	
SLR+Wave storms	■		■		■	■	■	■
Sea Temp.		■						
Atm. Temp.				■			■	
Rainfall					■	■	■	■

Table 20. *Hazards considered on the different dimensions and corresponding exposed elements.*

4.2. Multi-risk Assessment

The workflow of the multi-risk assessment has been designed to initially consider hazards as affecting different exposed elements separately. However, in the current dimensional analysis, most exposed elements are impacted by multiple hazards simultaneously. As a result, the use of an interaction matrix is unnecessary, as these interactions are inherently accounted for in the hazard simulations. Additionally, compound hazards interact in a nonlinear manner, avoiding the oversimplification of assigning weight values to hazards based on subjective expertise.

For example, in the **physical dimension**, coastal flooding results from the nonlinear interaction of extreme waves (driver) propagating over rising sea levels (driver) across a *Posidonia oceanica* meadow, which is further affected by increasing sea temperatures. In the **socio-economic dimension**, land value loss risk considers multiple contributing hazards, including coastal flooding driven by sea-level rise, extreme events, rising sea temperatures, and increasing atmospheric temperatures. In the **urban dimension**, compound flooding emerges from the complex interplay of sea-level rise, extreme events, rising sea temperatures, and intensified rainfall.

Given this, the decision has been made to analyze the resulting risks of each exposed element across all dimensions collectively.

At this step, it is important to note that **the concept of zero risk is not plausible**, as no system or environment analyzed is entirely free from hazards, exposure, or vulnerability. Even with extensive mitigation and adaptation measures, residual risk always remains due to uncertainties, unforeseen events, and the dynamic nature of environmental and socio-economic systems. Cascading and compounding risks can emerge from the interactions of multiple factors, and thus absolute null risk elimination is impossible.

In the risk assessment approach, a crucial aspect of both risk and multi-risk analysis is the definition of vulnerability. If an exposed element is impacted by a hazard, it cannot be entirely invulnerable. Therefore, **vulnerability can never be zero.**

However, when analyzing risk results individually, it becomes evident that in the environmental dimension (seagrass meadows and dunes), the consideration of plausible null vulnerability values leads to risk values of zero. Since the goal of the multi-risk assessment is to integrate risks across all dimensions, these results can distort the overall assessment by masking or underestimating the true magnitude of multi-risk impacts. To minimize potential bias, a minimum risk value of R = 0.05 has been set, corresponding to the order of magnitude of the lowest reported risk across other dimensions.

The challenge in multi-risk assessment relies in determining the most effective method to combine individual risks into a single multi-risk value. Various approaches have been tested, ranging from simple methods like arithmetic and geometric means to more sophisticated techniques like fuzzy logic-based aggregation[4] (Nandalal *et al.*, 2011).

However, these methods do not emphasize the significance of cascade and compound impacts, and unweighted risks may again lead to the masking of results. After analyzing the interactions of drivers and the risks derived from their compound interaction over the exposed elements, the multi-risk has been defined as:

$$MR \;=\; \sum_{i}^{l} \frac{n_i}{\sum_{i}^{l} n_i} R_i$$

where *n* is the number of drivers of the *Risk* of the element *i* and *l* is the number of risks considered. One of the hazards considered is coastal flooding, which has been analyzed in terms of Permanent Flooding (Pf) and Extreme Flooding (Ef). Given its cross-sectional impact across all dimensions, the multi-risk assessment has been conducted separately for cases involving Pf and Ef. Table 21 summarizes the risks considered in both multi-risk assessments, along with the corresponding weight values for each risk in both scenarios.

Following this approach, a total of 36 Multi-Risk raster maps have been generated. Each map represents a weighted average value of the risks involved in each scenario, per pixel. 18 multi-risk raster maps related to Permanent flooding were computed. As Table 21 summarizes, these are the result of a weighted average of the risks acting for these cases that are: beach, dune, *P. oceanica*, Loss of Land Value, and Seafront Temperatures risk maps (derived from 6 different climatic drivers). The other 18 multi-risk raster maps are related to Extreme Flooding. These were calculated as the weighted average of all the risk maps acting in those extreme cases that are: beach, dune, *P. oceanica*, Population, Loss of Land Value, Roads, Seafront Temperature, Seafront flooding, and drainage system risk maps (derived from 27 different climatic drivers).

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[4] Model risk levels as linguistic variables (e.g., low, medium, high) and applying fuzzy rules to derive a comprehensive multi-risk value

	Cases Crossings with Permanent flooding (Pf)		Cases Crossings with Extreme floodings (Ef_Pt)	
Interacting Risks	**Number of Drivers acting**	**Risk weight**	**Number of Drivers acting**	**Risk weight**
Risk Beach	SLR	0.16	SLR. Wave Storms T100. Sea Temp. <- (*P. oceanica* death).	0.11
Risk Duna	SLR.	0.16	SLR. Wave Storms T100. Sea Temp. <- (*P. oceanica* death).	0.11
Risk *P. oceanica*	Sea Temp.	0.16	Sea Temp.	0.04
Risk Population	—	—	SLR. Wave Storms T100. Sea Temp. <- (*P. oceanica* death). Rainfall.	0.15
Risk Loss of land Value	SLR. Atmos. Temp.	0.33	SLR. Wave Storms T100. Sea Temp. <- (*P.oceanica* death). Atmos. Temp.	0.15
Risk Roads	—	—	SLR. Wave Storms T100. Sea Temp. <- (*P.oceanica* death). Rainfall.	0.15
Risk Drainage system	—	—	SLR. Wave Storms T100. Sea Temp. <- (*P. oceanica* death). Rainfall.	0.15
Risk Seafront Flood	—	—	SLR. Wave Storms T100. Sea Temp. <- (*P. oceanica* death).	0.11
Risk Seafront Temp	Atm. Temp.	0.16	Atmos. Temp.	0.04

Table 21. *Summary of risk and compound drivers and corresponding weight values for the Permanent and Extreme climate scenarios.*

4.3. Multi-risk Results

In the following, the results of the weighted MRA are presented.

a) **Cases of Permanent flooding (Pf):**

The results of the MRA analysis in terms of weighted and cumulative MRA for the mean interval (P50) of RCP4.5 2030 and RCP8.5 2100 scenarios are shown in Figures 59-62. The weighted averages and accumulated (sum of risks) maps have been computed per cell map. Note that graphic scales have truncated values for better visual comparison between maps. All the rest of scenarios are available as raster files (18 in total for Pf) in the links detailed in Annex 2.

To simplify the interpretation of spatial results, the average risk values are shown in Table 22 separately for each individual risk considering its particular spatial coverage -thus means average considering the number of pixels affected-. Then, from these averaged values, an overall mean risk value per scenario and a normalized total risk sum are computed in last highlighted columns of Table 22. The normalized sum values were calculated using the maximum accumulated mean risk of the Ef cases to ensure a proper comparison with those cases. The stacked values within the columns of Figure 58 represent the average values for individual risks, which can also be found in the initial five columns of Table 22.

For the results of Pf for the RCP4.5 2030 (Figs. 59-60), the following key points are highlighted:

- From a broad perspective, the highest weighted MRA scores are observed in the cadastral parcels, which are indirectly affected by the combined impacts of permanent flooding and rising temperatures. These areas, though not directly exposed to flooding, experience secondary effects such as beach width and rising temperature. In contrast, the urban area generally exhibits minimal risk values, particularly in green spaces and less-developed zones. However, specific areas within the urban landscape, such as circulation zones and public spaces, may show localized increases in risk due to their connectivity and exposure pathways. The beach itself accounts for only a small portion of the exposed elements, but its risk level is highly dependent on ongoing environmental changes.
- For the accumulated case, as expected, risk values are higher, but the spatial distribution remains unchanged. This increase reflects the compounding effects of multiple hazards acting simultaneously, amplifying the overall risk levels across exposed elements. While the general pattern of risk distribution remains consistent, the intensity of risks is significant -the highest sum value computed at one map cell is 0.66-, particularly in areas already identified as vulnerable.
- The average values for the weighted MRA are 0.22 (0.20, 0.24) which, among other risks, contemplates estimated climate change indirect socioeconomic losses of ~765,000 thousand euros.

For the results of Pf for the RCP8.5 2100 (Figs. 61-62), the following key points are highlighted:

- The highest weighted MRA scores are once again observed in the cadastral parcels, which remain the most affected due to their indirect exposure to permanent flooding and rising temperatures. These areas, while not directly inundated, experience secondary effects such as loss of land value mainly due to the beach width reduction. Within the urban landscape, green spaces continue to show minimal risk values, serving as relatively stable areas in terms of exposure. However, an increase in multi-risk is particularly evident in circulation zones, where the intersection of multiple hazards amplifies potential disruptions. The central plaza stands out with elevated risk levels, likely due to its high usage, structural layout, and exposure to both direct and indirect environmental stressors. This highlights the vulnerability of key public spaces, which may require targeted adaptation measures to mitigate long-term impacts. Additionally, the permanently flooded beach area exhibits significantly higher risk values. As flooding becomes more persistent, the degradation of natural buffers, such as dunes and seagrass meadows, further exacerbates exposure to extreme weather events and long-term coastal retreat.
- For the accumulated case, as expected, risk values are higher across all dimensions -maximum accumulated value at one map cell is 1.39-, reinforcing the need for a multi-risk approach. The results emphasize the heightened vulnerability of urban areas, particularly circulation zones and public spaces, where cumulative impacts can lead to greater socio-economic and infrastructural consequences. Similarly, the beach continues to experience increasing risk.
- The average values for the weighted MRA are 0.54 (0.49, 0.64), which, among other risks, contemplates estimated climate change indirect socioeconomic losses of ~2,225,000 thousand euros.

It is noteworthy that the risk associated with the environmental dimension is minimal, and since its area is quantitatively larger than the other exposed elements (see weight values in Table 21), it masks the resulting weighted MRA. This is observable in Figure 58, where cumulative risk values for the different exposed elements are shown (average values of each risk). To avoid this masking effect, and given that the primary climate change adaptation measures will be implemented in higher-risk areas (i.e., urban zones and the beach itself), a secondary average MRA has been calculated. This secondary average, referred to as the MRA_{urban}, represents the average risk in these critical areas.

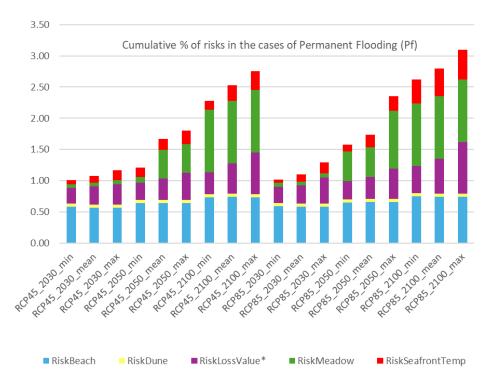**Figure 58.** *Cumulative R scores for the calculation of MRA values in the 18th scenarios with Permanent flooding.*
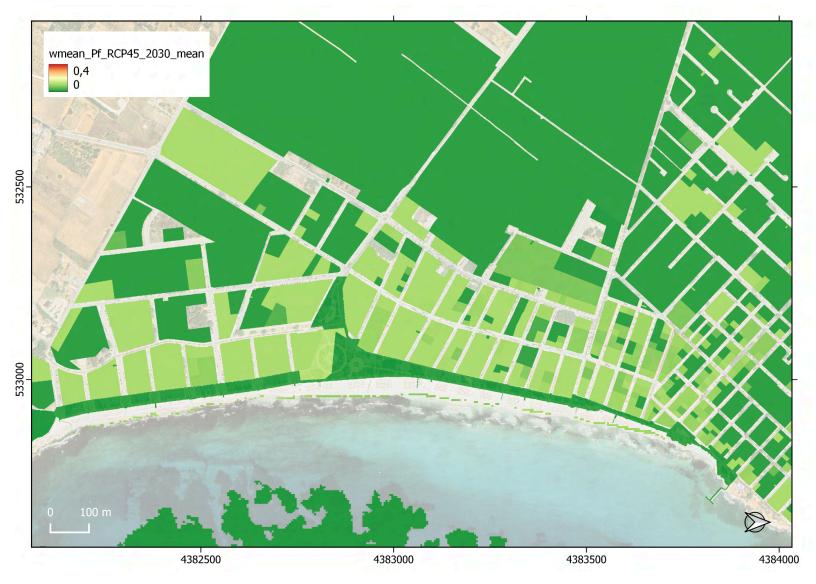
Figure 59. *Weighted MRA mean -per cell map- for Pf RCP-4.5 2030*

Figure 60. *Cumulative MRA values -per cell map- for Pf RCP-4.5 2030*
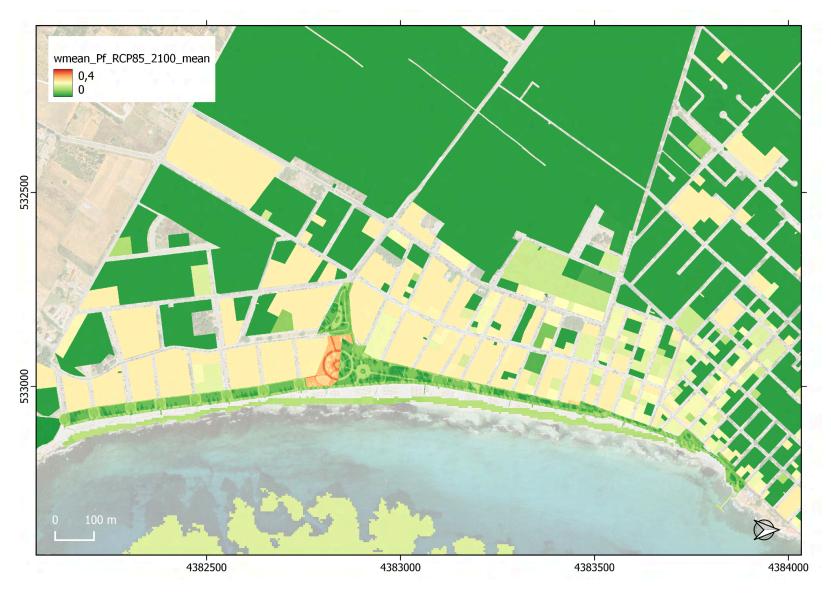
Figure 61. *Weighted MRA mean -per cell map- for Pf RCP-8.5 2100*
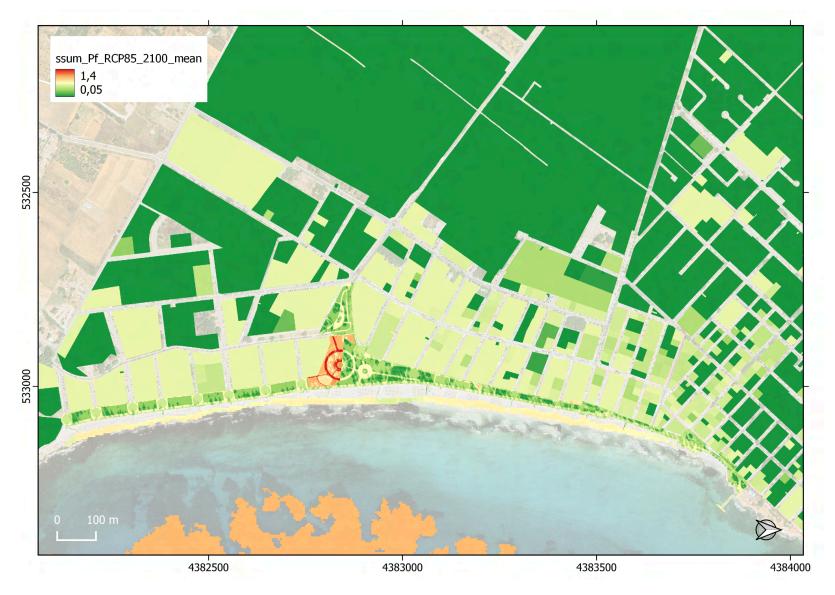
Figure 62. *Cumulative MRA values -per cell map- for Pf- RCP8.5 2100*

Case Permanent flooding	Risk Beach	Risk Dune	Risk Meadow	Risk LossValue (*)	Risk Seafront Temp.	MRA weighted mean	MRA$_{urban}$[5]	MRA Norm. Sum risks	(*) ~Losses in Thousand Euros
RCP45_2030_min	0.58	0.05	0.06	0.25	0.07	0.20	0.29	0.19	672,280
RCP45_2030_mean	0.57	0.05	0.06	0.29	0.10	0.22	0.31	0.21	765,009
RCP45_2030_max	0.57	0.05	0.06	0.33	0.16	0.24	0.35	0.22	880,919
RCP45_2050_min	0.64	0.05	0.09	0.28	0.15	0.24	0.34	0.23	741,826
RCP45_2050_mean	0.65	0.05	0.46	0.34	0.18	0.32	0.38	0.32	904,101
RCP45_2050_max	0.65	0.05	0.46	0.43	0.22	0.36	0.43	0.35	1,135,922
RCP45_2100_min	0.74	0.05	1.00	0.35	0.14	0.42	0.39	0.44	927,283
RCP45_2100_mean	0.74	0.05	1.00	0.49	0.25	0.49	0.49	0.49	1,321,379
RCP45_2100_max	0.73	0.05	1.00	0.67	0.30	0.55	0.59	0.53	1,785,021
RCP85_2030_min	0.59	0.05	0.06	0.26	0.05	0.21	0.29	0.20	695,462
RCP85_2030_mean	0.58	0.05	0.06	0.29	0.12	0.23	0.32	0.21	765,009
RCP85_2030_max	0.58	0.05	0.06	0.42	0.18	0.28	0.40	0.25	1,112,740
RCP85_2050_min	0.65	0.05	0.48	0.29	0.11	0.30	0.34	0.30	765,009
RCP85_2050_mean	0.66	0.05	0.48	0.35	0.19	0.34	0.39	0.33	927,283
RCP85_2050_max	0.66	0.05	0.93	0.48	0.24	0.46	0.46	0.45	1,275,015
RCP85_2100_min	0.75	0.05	1.00	0.44	0.38	0.49	0.50	0.50	1,182,287
RCP85_2100_mean	0.74	0.05	1.00	0.56	0.44	0.54	0.58	0.54	1,506,836
RCP85_2100_max	0.74	0.05	1.00	0.83	0.48	0.64	0.72	0.60	2,225,481

Table 22. *Averaged R and MRA scores -highlighted- for each scenario (2RCP, 3 time horizons & 3 intervals) related to Pf. The values of the five first columns are those plotted in FIg 58. The "risk loss value" is averaged per cadastral parcel, and its derived economic loss (*) in thousands of euros is shown in last column -explained in Deliverable 3.4-. "MRA Norm. Sum" is normalized with respect to the maximum cumulative risk among all cases (Ef and Pf).*

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[5] Average value considering only the risk from the urbanized and beach areas.

b) Cases of Extreme flooding with _P. oceanica_ dependent (Ef_Pt):

Considering the extreme flooding impacts, the results of the MRA analysis in terms of weighted and cumulative MRA for the mean interval (P50) of RCP4.5 2030 and RCP8.5 2100 scenarios are shown in Figures 64-67. The weighted averages and accumulated (sum of risks) maps have been computed per cell map. Note that graphic scales have truncated values for better visual comparison between maps. The remaining scenarios are available as raster files (18 in total for Ef_Pt) in the links detailed in Annex 2.

To simplify the interpretation of spatial results, the average risk values are shown in Table 23 separately for each individual risk considering its particular spatial coverage -thus means average considering the number of pixels affected-. Then, from these averaged values, an overall mean risk value per scenario and a normalized total risk sum are computed in last columns of Table 23.

The main differences compared to previous Pf results lie in the fact that, for these extreme events, four additional risks are now considered alongside the existing ones. These include risks to road infrastructure, the population, the seafront area, and the potential collapse of the urban drainage system. As a result, there is a greater overlap of risks across the entire mapped area which come into play in the calculation of the weighted average and the total sum of the accumulated risk per map cell.

For the results of Ef maps for the RCP4.5 2030 (Figs. 64-65), the following key points are highlighted:

- From a broad perspective, the highest weighted MRA scores are observed in the seafront surface, which are affected by the combined impacts of sea extreme flooding, rainfall flooding ("RiskPonding") and rising temperatures. Also the main coastal roads show slight risk increases. In contrast, the urban area about 400 m away from the coast, and the dune and _P. oceanica_ meadow exhibit minimal risk values.

- For the accumulated case considering the sum of all the risks interacting per map cell, as expected, risk values are higher but concentrated in these same areas. The overall risk, exceeding a sum of 2, is a result of multiple hazards interacting concurrently across susceptible exposed elements. This amplified risk reflects the combined danger of individual risks, each falling between 0 and 1.

- Averaged value for the weighted MRA is ~0.26 which, among other risks, contemplates estimated economic losses of ~830,000 thousand euros (see Table 22 and "socioeconomic hazard assessment section" of Deliverable 3.4). The average results from Table 23 are similar to those of Permanent Flooding in Table 22. This is due to the distribution of weights among a larger number of risks. However, the normalized accumulated sum value shows an approximately 20% increase in risk respect to the Pf case. The MRA maps, which display the total risk sum per cell, also show this increase. Significant differences are found between Ef and Pf cases (Fig. 65 vs Fig. 60, respectively).

For the results of Ef for the RCP8.5 2100 (Figs. 66-67), the following key points are highlighted:

- The highest weighted MRA scores are observed in the same areas (seafront and coastal roads) than in previous scenarios but now doubling the overall mean risk despite the fact that more risks are acting (see accumulated risk values). This indicates that all risks in this area are problematic for this scenario. The seafront stands out with elevated risk levels, likely due to its high usage, structural layout, and exposure to both direct and indirect environmental stressors. In addition to the permanent flooding scenarios, where the beach was already reduced almost entirely to an average width of less than 2 m, extreme flooding events now extend beyond the beach area, impacting the promenade, roads, and even overloading the drainage system when combined with periods of heavy rainfall. This is evident in the accumulated MRA mapped values for these scenarios (compared Fig. 67 vs. Fig. 62).
- For the accumulated case, as expected, risk values are higher across all dimensions reaching a maximum accumulated value of 3.58 at a particular cell. The mean value of 0.74, calculated from all cell values within the map (Fig. 67), indicates a high risk exposure for the area if current urban planning practices persist.

Figure 63 illustrates how, for each scenario, time horizon, and time interval considered, the nine analyzed risks progressively intensify—some gradually, while others escalate more sharply—until they become fully problematic. The average values of each risk, which are stacked in the columns of Fig. 63, correspond to the values found in the first nine columns of Table 23.

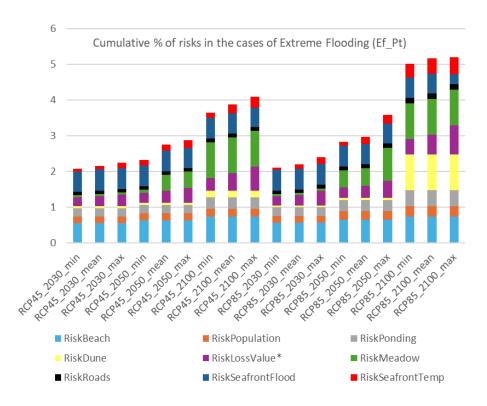**Figure 63.** *Cumulative R scores for the calculation of MRA values in scenarios with Extreme flooding.*

Figure 64. *Weighted MRA mean -per cell map- for Pf RCP-4.5 2030 (P50)*

Figure 65. *Cumulative MRA values -per cell map- for Pf RCP4.5 2030 (P50)*

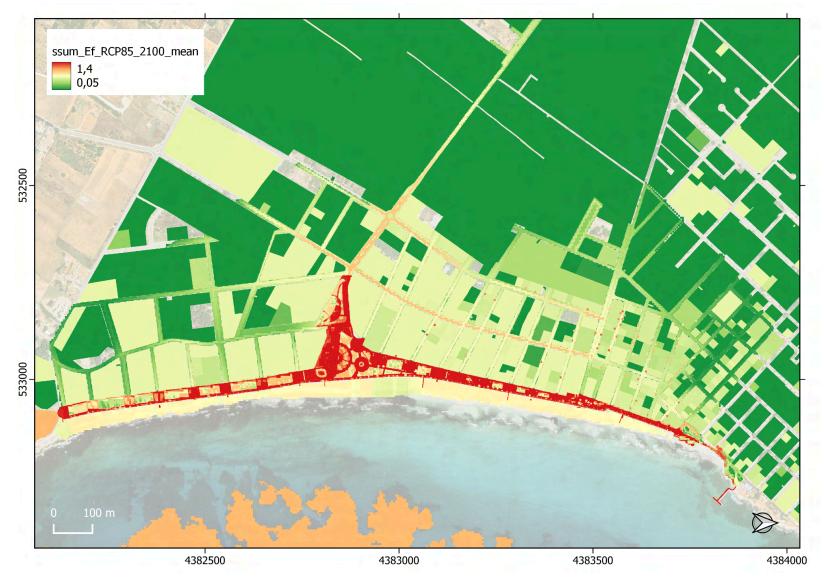**Figure 66.** *Weighted MRA mean -per cell map- for Pf RCP-8.5 2100 (P50)*

Figure 67. *Cumulative MRA values -per cell map- for Pf RCP-8.5 2100 (P50)*

Case_Extreme flooding (*P.Oceanica* dependent)	Risk Beach	Risk Dune	Risk Meadow	Risk Population	Risk LossValue (*)	Risk Roads	Risk Ponding	Risk Seafront Flood	Risk Seafront Temp.	MRA_ weighted mean	MRA_urban[6]	MRA Norm. Sum risks
RCP45_2030_min	0.55	0.05	0.06	0.19	0.25	0.09	0.23	0.58	0.07	0.25	0.28	0.40
RCP45_2030_mean	0.55	0.05	0.06	0.19	0.29	0.09	0.23	0.59	0.10	0.26	0.29	0.42
RCP45_2030_max	0.55	0.05	0.06	0.19	0.33	0.09	0.23	0.58	0.16	0.26	0.30	0.43
RCP45_2050_min	0.63	0.05	0.09	0.19	0.28	0.09	0.24	0.59	0.15	0.27	0.30	0.45
RCP45_2050_mean	0.63	0.05	0.46	0.19	0.34	0.09	0.24	0.58	0.18	0.29	0.31	0.53
RCP45_2050_max	0.63	0.05	0.46	0.19	0.43	0.09	0.24	0.57	0.22	0.31	0.33	0.55
RCP45_2100_min	0.73	0.18	1.00	0.23	0.35	0.11	0.32	0.58	0.14	0.36	0.35	0.70
RCP45_2100_mean	0.73	0.18	1.00	0.23	0.49	0.11	0.32	0.56	0.25	0.38	0.38	0.75
RCP45_2100_max	0.73	0.18	1.00	0.23	0.67	0.11	0.32	0.54	0.30	0.41	0.41	0.79
RCP85_2030_min	0.57	0.05	0.06	0.18	0.26	0.09	0.24	0.59	0.05	0.25	0.29	0.40
RCP85_2030_mean	0.57	0.05	0.06	0.18	0.29	0.09	0.24	0.58	0.12	0.26	0.30	0.42
RCP85_2030_max	0.57	0.05	0.06	0.18	0.42	0.09	0.24	0.59	0.18	0.28	0.32	0.46
RCP85_2050_min	0.65	0.05	0.48	0.24	0.29	0.11	0.32	0.58	0.11	0.31	0.33	0.54
RCP85_2050_mean	0.65	0.05	0.48	0.24	0.35	0.11	0.32	0.58	0.20	0.32	0.35	0.57
RCP85_2050_max	0.65	0.05	0.93	0.24	0.48	0.11	0.32	0.57	0.24	0.36	0.37	0.69
RCP85_2100_min	0.74	1.00	1.00	0.28	0.44	0.15	0.44	0.57	0.38	0.51	0.42	0.96
RCP85_2100_mean	0.74	1.00	1.00	0.28	0.56	0.15	0.44	0.56	0.44	0.53	0.44	1.00
RCP85_2100_max	0.74	1.00	1.00	0.28	0.83	0.15	0.44	0.27	0.48	0.54	0.45	1.00

Table 23. *Averaged R and MRA scores -highlighted- for each scenario (2RCP, 3 time horizons & 3 intervals) related to Ef. The "risk loss value" is averaged per cadastral parcel, and the derived estimated losses (climate change indirect socioeconomic effect) in thousands of euros are estimated as in Table 22 (*). The values of the nine first columns are those plotted in Flg 63.*

[6] Average value considering only the risk from the urbanized and beach areas.

4.4. Multi-Risk summary

While MRA or risk values provide insight into the temporal evolution of average risk, they are highly dependent on the spatial extent of each exposed element, the assigned weighting factors, and the vulnerability components considered. However, this analysis incorporates a **strong spatial component**, allowing for the identification of the **most susceptible areas and prioritization of conservation and adaptation efforts**. All results, generated within a GIS framework, are designed as a **tool** to support the **conceptualization, design, and selection of potential climate change adaptation measures** for Cala Millor across the entire affected area.

Additionally, the integration of different spatial layers within this analysis enables a **dimension-specific assessment**, facilitating the development of **targeted adaptation measures for individual dimensions**. These can later be integrated with adaptation strategies from other dimensions if necessary, ensuring a more comprehensive and synergistic approach.

As a final summary, Table 24 presents an **overview of MRA evolution** across different exposed elements simplified to 5 main concepts (beach, meadow, dune, cadastral value and roads) under both RCP scenarios and various time horizons, providing a **visualization of risk progression and aiding in future decision-making.**

Scenario	Time-Horizon	Compound hazards type	PHYSICAL	ENVIRONMENTAL		SOCIO-ECONOMIC	URBAN
			Beach	Meadow	Dune	Land value	Roads and pedestrian paths
RCP 4.5	2030	Permanent	Very low	Very low	Very low	Low	Very low
		Extreme	Intermediate	Very low	Very low	Low	Intermediate
	2050	Permanent	Low	Intermediate	Very low	Low	Low
		Extreme	Moderate	Intermediate	Very low	Low	Moderate
	2100	Permanent	Intermediate	High	Low	Moderate	Intermediate
		Extreme	Moderate	High	Low	Moderate	Moderate
RCP 8.5	2030	Permanent	Very low	Very low	Very low	Low	Very low
		Extreme	Intermediate	Very low	Very low	Low	Intermediate
	2050	Permanent	Intermediate	Intermediate	Very low	Low	Intermediate
		Extreme	Moderate	Intermediate	Very low	Intermediate	Moderate
	2100	Permanent	High	High	Low	High	Moderate
		Extreme	High	High	High	High	High

Legend: ■ Very low ■ Low ■ Intermediate ■ Moderate ■ High

Table 24. *Fuzzy multi risk assessment for the main action areas.*

Concluding remarks

In this section, we summarize the most relevant remarks regarding the Multi-Risk Assessment Approach developed in WP3, and particularly embracing the results of D3.4 and D3.5 and its application in Cala Millor.

HAZARD, VULNERABILITY AND RISK ASSESSMENT

- **Key drivers and interaction:** The developed approach incorporates four key drivers of coastal hazards: **sea-level rise (SLR), extreme waves and surges, and increases in both sea and atmospheric temperatures.** The methodology, particularly within the physical dimension, integrates the combined effects of SLR, extreme events, and the direct impact of rising sea temperatures on *Posidonia oceanica* meadows to simulate coastal flooding across various scenarios. By accounting for these compound events, the analysis addresses the cascading effects that they have on infrastructures, ecosystems as well as in human systems. This integrated approach provides a more accurate picture of hazards, as it reveals the **amplified consequences of multiple interacting hazards**. Such compounded impacts are often more severe than what would be anticipated by considering each hazard individually. For instance, coastal flooding together with the increase of atmospheric temperature and the indirect results of coastal retreat, revealed potential loss of value in the socio-economic dimension, that in the case of only SLR effects would be negligible (no exposed elements)

- **Relevance of considering RCP4.5 and 8.5 scenarios and different time-horizons:** In the current analysis, we have analyzed the effects of different hazards in terms of RCP4.5 and RCP8.5 scenarios at multiple time horizons. This approach allows for a more robust identification of **risk-prone areas**, as it considers a range of possible evolutions, from optimistic to more extreme projections. Evaluating risk at multiple time horizons (2030, 2050, and 2100) ensures that **short, medium, and long-term** vulnerabilities are modelled, enabling more proactive planning and adaptation measures. This comprehensive temporal and scenario-based analysis provides a clearer understanding of where and when risks are likely to intensify, allowing for more targeted interventions and better allocation of resources to areas most at risk.

- **Compound risk:** Risk analysis underscores the importance of evaluating coastal risks across different RCPs and time horizons, taking into account **various dimensions and the complexity of compound hazard**s. This approach allows for a better understanding of how different risk drivers interact over time, helping to identify a **broader range of exposed elements.** By considering a variety of future scenarios and potential hazard combinations, the analysis not only highlights the immediate and long-term impacts of climate change but also promotes the **inclusion of additional dimensions, such as the urban dimension.** This has facilitated the integration of further exposed elements within the socio-economic dimension, such as transportation infrastructure (e.g., roads) and vulnerable populations. These additions are critical for ensuring that the risk assessment fully captures the interconnectedness of natural and human systems, reflecting the reality that **climate change impacts are not isolated but rather affect multiple sectors in complex ways.** In doing so, the methodology not only broadens the scope of exposure but also provides a more comprehensive foundation for

decision-making, prioritizing adaptation measures and resource allocation where they are most needed.

- **Addition of urban dimension and drainage system analysis:** Including the urban dimension in the multi-risk assessment provides a more holistic view of risk by considering the vulnerabilities of built environments, infrastructure, and socio-economic systems in addition to natural hazards. The urban dimension addresses the **interconnections between environmental risks and human settlements**, helping to identify high-risk areas that may be susceptible to both direct impacts (e.g., flooding) and secondary effects (e.g., economic losses). The analysis of the drainage system within the urban dimension is crucial for understanding how well the infrastructure can handle heavy rainfall together with sea-level rise and extreme coastal flooding. A well-functioning drainage system can mitigate some of the impacts of flooding, but vulnerabilities in the system can exacerbate risks. Accounting for the **climatic perspective in the design** of these systems is clearly necessary. The effects of SLR and extreme flooding at the outlets of the drainage nets affects upstream tributary areas, resulting in potential ponding of depressed areas. The addition of this dimension enables the **identification of critical exposed elements and vulnerabilities in urban areas** and thus further risks.

- **Awareness of How Vulnerability is Computed and Selection of Sensitivity (S) and Adaptive Capacity (AC)**: It is crucial to raise awareness about the methodology used to compute vulnerability, particularly how the components of **sensitivity and adaptive capacity** are selected and assessed. Understanding how these factors are quantified helps stakeholders and decision-makers interpret risk assessment results more accurately and ensures that the identified vulnerabilities are representative of real-world conditions.

  The involvement of local stakeholders and authorities during the first workshop provided an invaluable opportunity not only in presenting the progress of the analysis but also gathering feedback on the vulnerability of the various exposed elements. This participatory approach allowed us **to incorporate insights from both experts and the local community**—those who live, work, and manage Cala Millor—ensuring a more comprehensive and grounded understanding of vulnerability. By integrating the perspectives of the people directly impacted, the analysis becomes more relevant and **aligned with local realities**.

MULTI-RISK ASSESSMENT

- **Risks integration:** The multi-risk analysis has provided valuable insights into the complex interactions of various hazards across different dimensions of exposure. By **integrating physical, environmental, urban, and socio-economic risks**, the assessment highlighted the most vulnerable areas in front of climate change impacts, particularly in urban zones and coastal areas. The results underscore the need for **targeted adaptation strategies** that address **both the immediate and long-term risks posed by compound hazards**, as well as the necessity of prioritizing interventions in the highest-risk areas. This approach not only helps the understanding of the spatial distribution of risks but also provides a foundation for informed decision-making in climate change adaptation and resilience planning.

- **The spatial component:** The spatial component is fundamental in multi-risk analysis, as it allows for a precise assessment of how hazards, exposure, and vulnerabilities vary across different areas. **Coastal risks are highly location-dependent,** with certain zones experiencing

higher susceptibility due to factors such as elevation, land use, infrastructure density, and ecological characteristics. By incorporating **spatial analysis**, it is possible to identify higher risk zones, understand the **distribution of compounding hazards**, and to evaluate how risks evolve over time. This approach also enhances the prioritization of adaptation measures by pinpointing the **most vulnerable areas** that require urgent intervention. Furthermore, integrating spatial data enables a more accurate representation of **cascading and cross-sectoral impacts**, ensuring that risk assessments capture the complex interconnections between natural and human systems. Ultimately, considering the spatial dimension in multi-risk analysis leads to **more informed decision-making**, improving resilience planning and resource allocation.

- **Permanent flooding and extreme flooding** represent two distinct but highly interconnected risks that need to be assessed together in a multi-risk framework. **Permanent flooding** often reflects **long-term changes** (sea-level rise), while **extreme flooding** is driven by **episodic events** (extreme waves and storm surges). **Accounting for both** in the assessment allows for a more complete and realistic understanding of **coastal cities risks.** The results from the MRA show that accounting for **extreme flooding**, even in the most optimistic scenario, is essential to better address MRA as well as to **integrate exposed elements and dimensions**. Ignoring extreme flooding could underestimate the vulnerability of areas that may not be permanently flooded (exposed elements) but that are still exposed to significant short-term risks that could cause damage, disrupt livelihoods, and trigger economic losses.

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ANNEX 1. Adaptive Capacity indexes

The Vulnerability Social Awareness Map is one of the indexes of adaptive capacity needed to create the beach vulnerability map. It is calculated by averaging the social awareness values of the three specific groups detailed as follow:

1.   Citizens' associations involved

Civil society: Implication Yes (1) or No (0)	Sant Llorenç	Son Servera
Asociación de Jubilados y Pensionistas de Cala Millor	1	1
Asociación de 3ª Edad Cala Millor	0	0
Asociación de Vecinos de Sa Coma (Sant Llorenç des Cadassar)	1	-
Associació de Gent Gran Punta de n'Amer	1	-
Associació de la Tercera Edat de Son Carrió	1	-
Associació de Veïnats de Son Carrió (Sant Llorenç des Cadassar)	1	-
Asociación de la Tercera Edad de Son Servera	-	1
Associació de pensionistes, jubilats, 3a edat i consorts de Sant Llorenç des Cardassar	0	-
Associació de Mares i Pares d'Alumnes del Col·legi d'Educació Infantil i Primaria Jaume Fornaris i Taltavull	-	1
Associació de Families d'IES Puig de Sa Font de Son Servera	-	1
AMIPA CEIP Punta de n'Amer de Sa Coma	0	-
Associació de Mares i Pares d'Alumnes de CP Mestre Guillem Galmés	0.5	-
Associació de Pares i Mares d'Alumnes del CEIP Sant Miquel de Son Carrió	1	-
	0.65	**0.8**

2.   Students (from 6 education centers) properly aware of Climate Change and Good Practices

	Sant Llorenç	Son Servera
%students with a correct perception about climate change		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	32	-
CEIP PUNTA DE N'AMER (Sa Coma)	40.4	-
CEIP SANT MIQUEL (SON CARRIÓ)	41.2	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	32.6
CEIP NA PENYAL (CALA MILLOR)	-	36.1

IES PUIG DE SA FONT (SON SERVERA)	-	33.3
%Positive actions/behavious on urban beaches		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	24.1	-
CEIP PUNTA DE N'AMER (Sa Coma)	11.15	-
CEIP SANT MIQUEL (SON CARRIÓ)	15.25	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	15.5
CEIP NA PENYAL (CALA MILLOR)	-	12.55
IES PUIG DE SA FONT (SON SERVERA)	-	21.45
%Positive attitude towards the ecosystem on urban beaches		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	10.8	-
CEIP PUNTA DE N'AMER (Sa Coma)	16.3	-
CEIP SANT MIQUEL (SON CARRIÓ)	23.6	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	19.3
CEIP NA PENYAL (CALA MILLOR)	-	15.4
IES PUIG DE SA FONT (SON SERVERA)	-	14.7
% Awareness that climate change is a serious problem		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	17.4	-
CEIP PUNTA DE N'AMER (Sa Coma)	14.2	-
CEIP SANT MIQUEL (SON CARRIÓ)	20.5	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	16
CEIP NA PENYAL (CALA MILLOR)	-	12.7
IES PUIG DE SA FONT (SON SERVERA)	-	19.2
% Interested in hearing about climate change		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	18.6	-
CEIP PUNTA DE N'AMER (Sa Coma)	15.4	-
CEIP SANT MIQUEL (SON CARRIÓ)	18.4	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	15.4
CEIP NA PENYAL (CALA MILLOR)	-	16.4
IES PUIG DE SA FONT (SON SERVERA)	-	15.9
% who know that a storm can have consequences on the beach		
CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	19.8	-
CEIP PUNTA DE N'AMER (Sa Coma)	15.3	-
CEIP SANT MIQUEL (SON CARRIÓ)	16.8	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	19.7
CEIP NA PENYAL (CALA MILLOR)	-	16.7
IES PUIG DE SA FONT (SON SERVERA)	-	11.6
% who knows that a boardwalk is not necessary		

CEIP MESTRE GUILLEM GALMÉS (Sant Llorenç des Cardassar)	33.2	-
CEIP PUNTA DE N'AMER (Sa Coma)	8.6	-
CEIP SANT MIQUEL (SON CARRIÓ)	36.2	-
CEIP JAUME FORNARIS I TALTAVULL (Son servera)	-	7
CEIP NA PENYAL (CALA MILLOR)	-	4.5
IES PUIG DE SA FONT (SON SERVERA)	-	10.4
Average % aware students	21.39	17.44
Average (0-1) aware students	**0.21**	**0.17**

3. **Students (from 4 summer schools) Properly Aware of Climate Change and Good Practices**

%Students Concerned About Cimate Change	Sant Llorenç	Son Servera
Escuela de verano de Son Servera;	-	0.42
Escuela de verano de Sant Llorenç des Cardassar	0.63	-
Escuela de verano de Cala Millor	-	0.5
Escuela de verano de Sa Coma	0.2	-
	0.42	**0.46**

ANNEX 2. Available data: maps of Vulnerability, Risk, and Multi-Risk

The GIS datasets (Raster ".tif" and vectorial ".shp" layers) and PNG figure maps produced during WP3 and referenced in this document are available upon request from the project coordinators at lifeadaptcalamillor@gmail.com. This Annex lists these repositories:

- 📁 MAPS Risk Vulnerability:

  Data related to each of the vulnerability indexes (section 2) used for the computation of the final vulnerability maps (section 3.2). All files are organized by exposed element: Beach; Dunes; *P. oceanica*; Roads; Population; Seafront; Urban drainage system.

- 📁 MAPS Risk:

  Organized in 9 subfolders, each of them containing maps corresponding to the Risks identified and explained in Section 3. Maps resulting from the intersection of vulnerability and impact maps. The nearest neighbor approach was used to resample the risk raster maps to the highest resolution maps (up to 0.25 m). This maintained the highest level of detail from the vulnerability and indexes data.

  - Risk beach; 36 risk maps (.tif) - 18 for Pf and 18 for Ef_Pt-.
  - Risk Dune; 12 risk maps (.tif) - 6 for Pf and 6 for Ef_Pt (P50 interval)-.
  - Risk *P. Oceanica*; 18 risk maps (.tif).
  - Risk Population; 7 risk maps (.tif).
  - Risk Loss of Land value; 18 risk maps (.tif) related with Pf maps of P50.
  - Risk Roads; 7 risk maps (.tif).
  - Risk Urban Drainage system; 7 risk maps (.tif).
  - Risk Seafront Flooding; 36 risk maps (.tif) - 18 for Pf and 18 for Ef_Pt-.
  - Risk Seafront Temperature; 18 risk maps (.tif).

- 📁 MAPS Multi-Risk:

  The multi-risk raster maps were calculated using either a weighted mean (wmean) or a simple sum (ssum) of the intersecting individual risk maps. These results are organized in two subfolders based on flooding temporality:

  - "MRA_Pf" contains the "wmean" and "ssum" results of the 18th different scenarios where 5 risks have intervened as explains Section 4.3a.
  - "MRA_Ef" contains the "wmean" and "ssum" results of the 18th different scenarios where 9 risks have intervened as explains Section 4.3.

  A third subfolder, "png_figs_doc" contains only the figure maps that have been extracted in png format for display within the document.