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Deliverable Phase 1 – Climate risk assessment

Multi-Risk Climate Assessment through the CLIMAAX Common Methodology Framework and Toolbox Towards Climate Resilience for the Leiria Region (CLIMAAX4Resilience)

Portugal, Region of Leiria

Version 2 | September 2025

HORIZON-MISS-2021-CLIMA-02-01 - Development of climate change risk assessments in European regions and communities based on a transparent and harmonised Climate Risk Assessment approach

Funded by
the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101093864. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Document Information

Deliverable Title	Phase 1 – Climate risk assessment
Brief Description	This document is Deliverable 1 (D1) of the *CLIMAAX4Resilience* project, titled "*Multi-Risk Climate Assessment through the CLIMAAX Common Methodology Framework and Toolbox Towards Climate Resilience for the Leiria Region*". It establishes the baseline multi-risk climate assessment for the Leiria Region. Applying the CLIMAAX methodological framework, it quantifies the current and future impacts of four priority hazards: wildfires, droughts, heatwaves, and coastal floods.
Project name	Multi-Risk Climate Assessment through the CLIMAAX Common Methodology Framework and Toolbox Towards Climate Resilience for the Leiria Region (CLIMAAX4Resilience)
Country	Portugal
Region/Municipality	Region of Leiria
Leading Institution	Intermunicipal Community of the Region of Leiria (CIMRL)
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Deliverable submission date	31/08/2025
Final version delivery date	24/09/2025
Nature of the Deliverable	R – Report
Dissemination Level	PU - Public

Version	Date	Change editors	Changes
1	31/08/2025	CIMRL	Deliverable submitted on Zenodo (v1)
2	24/09/2025	CIMRL	Deliverable submitted on CLIMAAX Deliverable Platform and Zenodo (v2); team description updated.

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Abbreviations and acronyms

Abbreviation / acronym	Description
AWC	Soil Available Water Capacity
CIMRL	Intermunicipal Community of the Region of Leiria
CLIMAAX	Climate Risk Assessment Framework/Project
CLIMAAX4Resilience	Multi-Risk Climate Assessment through the CLIMAAX Common Methodology Framework and Toolbox Towards Climate Resilience for the Leiria Region
CORDEX	Coordinated Regional Climate Downscaling Experiment
COS	Land Cover Map (*Carta de Ocupação do Solo*)
CRA	Climate Risk Assessment
CPU/RAM	Central Processing Unit / Random Access Memory
FWI	Fire Weather Index
KPI	Key Performance Indicators
LiDAR	Light Detection and Ranging
LST	Land Surface Temperature
LUISA	Land cover and land use data
NUTS	Nomenclature of Territorial Units for Statistics
PIAAC	Intermunicipal Climate Change Adaptation Plan
PMAC	Municipal Climate Action Plans
PMEPC	Municipal Emergency and Civil Protection Plan
PRGP	Landscape Reorganization and Management Programs
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathways
WASP	Drought Index
WUI	Wildland-Urban Interface

Executive summary

This document presents the multi-risk climate assessment for the Leiria Region, developed under the CLIMAAX4Resilience project. It was prepared in response to the region's high vulnerability to the interconnected impacts of climate change, whose severity and frequency are projected to increase significantly. This assessment establishes a scientific foundation to support strategic decision-making and guide the development of adaptation measures in the subsequent phases of the project.

The main action of Phase 1 was the application of the CLIMAAX methodology to four priority climate hazards in the region: wildfires, droughts, heatwaves, and coastal floods. For each, a preliminary risk assessment (scoping, exploration, and analysis) was conducted. An initial technical challenge related to computational capacity was successfully overcome, ensuring the necessary capacity for high-resolution data analysis in the next phase.

The key findings reveal a territory facing significant and interconnected climate risks:

- **Wildfires pose a severe and worsening threat:** they are the most significant climate hazard in the region. Projections indicate a substantial increase in days with high fire danger (FWI>30) in all future scenarios. Critical "hotspots" were identified where high hazard intersects with vulnerable populations, valuable ecosystems, and high restoration costs, constituting a systemic risk.
- **Droughts threaten water security and economic viability:** the region has a high susceptibility to droughts. The agricultural drought assessment highlighted a considerable financial risk for maize cultivation, with projections indicating significant revenue losses, which threatens a socioeconomic pillar of the region.
- **Heatwaves represent a growing public health risk:** a considerable increase in the frequency, duration, and intensity of heatwaves is projected. The risk is particularly acute due to the presence of vulnerable demographic groups (the elderly and children). Heatwaves also act as a risk multiplier by exacerbating drought conditions and fire danger.
- **Coastal floods present a high-impact and concentrated risk:** the analysis quantified the potential for significant economic damage to buildings and infrastructure on the coast. Projections for 2050 indicate an increase in both the flooded area and the magnitude of financial losses.

This initial phase established a solid and replicable scientific baseline. However, a key finding was the confirmation that pan-European data, while useful, lacks the local specificity required for operational planning. The integration of high-resolution local data was therefore identified as the main priority for Phase 2.

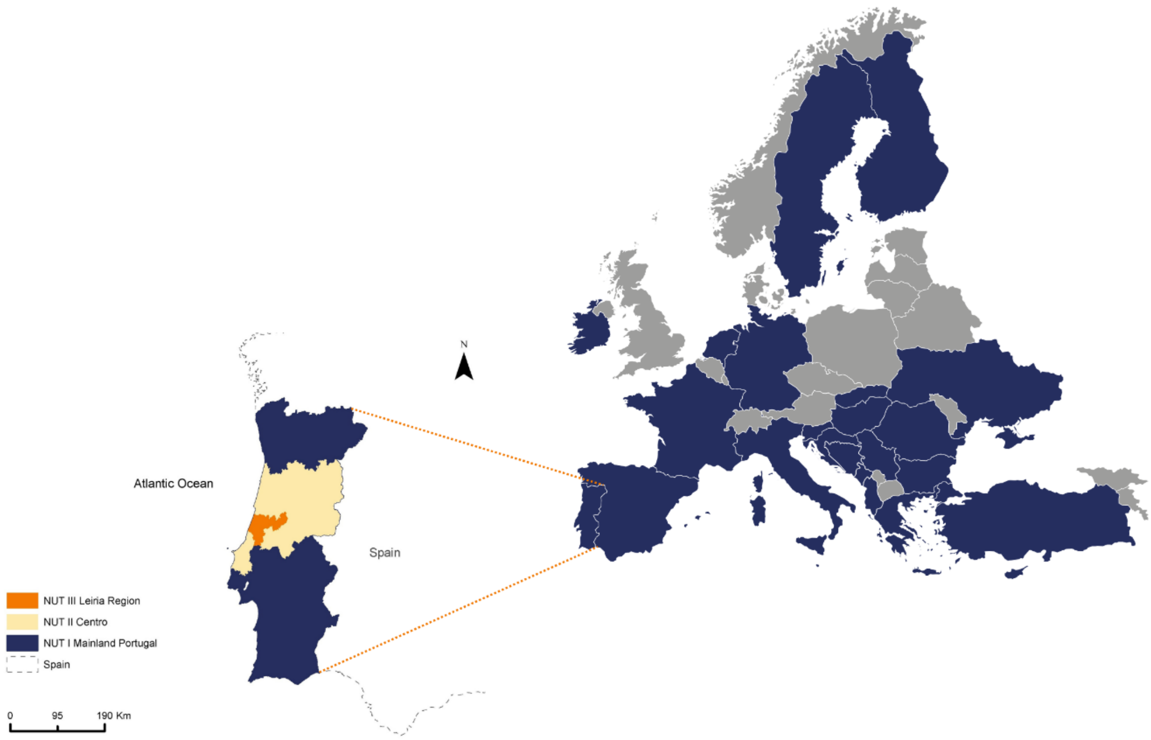
Phase 1 confirms that the Leiria Region faces an urgent and intensifying threat from multiple climate hazards. The primary challenge moving forward is to bridge the gap between this strategic-level assessment and local operational needs by integrating high-resolution data and fostering deep stakeholder collaboration to translate this analysis into effective adaptation actions.

1 Introduction

1.1 Background

Located in the center of mainland Portugal, the Leiria Region has a territorial area of approximately 2,449 km², covering a total of 10 municipalities: Alvaiázere, Ansião, Batalha, Castanheira de Pera, Figueiró dos Vinhos, Leiria, Marinha Grande, Pedrógão Grande, Pombal, and Porto de Mós. According to data from the 2021 Census by the National Institute of Statistics (INE), it had a resident population of 286,752 inhabitants, which corresponds to approximately 17.3% of the population of the Centro region of Portugal.

Figure 1-1 Geographic Location of the Leiria region



The Intermunicipal Community of the Region of Leiria (CIMRL), the beneficiary of the CLIMAAX4Resilience project, operates within the NUT III Region of Leiria.

As established by Portuguese legislation, CIMRL is responsible for pursuing the following public purposes: planning and managing territorial development; coordinating municipal investments; and participating in regional development programs. CIMRL also ensures collaboration between municipalities and the central government in key areas such as spatial planning, nature conservation and natural resources and security and civil protection. Recognizing the region's vulnerability to the impacts of climate change, CIMRL emphasizes the importance of territorial cooperation in seeking good practices and management strategies that can enhance the region's resilience. CIMRL has experience participating in projects co-funded by the European Structural and Investment Funds (ESIF) at both European and national levels.

Various studies indicate that Portugal is among the European countries most vulnerable to the impacts of climate change on society, the economy, and ecosystems. The Leiria Region comprises a vast territory stretching from the mountains to the sea, where urban and rural areas coexist. The landscape is diverse, and consequently, so are the risks to which it is exposed, as well as their geographical distribution and significance.

Considering existing projections at the national level (later regionalized), the main impacts and vulnerabilities of the territory to climate change - which, due to their current expression and future worsening trends, require priority action to reduce or minimize them through climate action measures - are as follows:

- Increased frequency and intensity of rural fires, heatwaves, droughts, and water scarcity; extreme precipitation events; and phenomena that cause coastal overtopping and erosion;
- Increased susceptibility to desertification;
- Increase in maximum temperatures;
- Rising sea levels.

Nevertheless, among the most significant risks in the region - and therefore the main priority - are rural and forest fires. In fact, the Leiria Region has been heavily ravaged by forest fires in its recent past, particularly in 2017, which had extremely serious consequences unprecedented in the region and in Portugal. An unfortunate combination of atypical factors resulted in what is classified as the worst forest fire event recorded in recent years, with an exceptionally large area burned, heavy property losses, and, unfortunately, several lives lost.

1.2 Main objectives of the project

The main goal of the CLIMAAX4Resilience project is empower the Leiria Region to face the challenges of climate change, through the realization of multi-risk assessments, the integration of adaptation measures in planning instruments, and the involvement of local stakeholders, with the goal of increasing resilience and reducing the vulnerability of the territory, in line with the EU Mission.

The specific objectives of CLIMAAX4Resilience include:

- Enhance the identification and spatial analysis of climate risks in the Leiria Region by implementing the CLIMAAX methodological framework and accessing its toolbox;
- Support informed and sustainable decision-making regarding climate action strategies and risk management priorities, utilizing a common and harmonized methodology to facilitate comparison with other European regions;
- Integrate climate risk assessment results into regional and local strategic planning instruments, including Municipal Climate Action Plans (PMAC) and Municipal Emergency and Civil Protection Plans (PMEPC);
- Promote climate resilience in the Leiria Region, aligning with the European Union's Climate Change Adaptation mission through the engagement of stakeholders and the broader community;
- Empower the teams at CIMRL and the municipalities by facilitating the exchange of experiences and best practices through CLIMAAX, covering risk identification, analysis, evaluation, as well as monitoring and assessment;
- Increase knowledge and awareness of climate risks and support local policies through adaptation strategies or risk management plans.

The CLIMAAX approach can help the region improve local knowledge and awareness of climate risks in several ways: by providing a framework for understanding the specific vulnerabilities and challenges the region faces; promoting capacity building; collecting and sharing data and models; demonstrating best practices and case studies; encouraging participatory processes; and establishing systems for monitoring climate risks and adaptation efforts. The Leiria Region will be able to leverage CLIMAAX's common methodological framework and toolbox to develop a regional climate risk assessment that accounts for changing climate risk profiles and is harmonized and comparable at the European level. This climate risk assessment will, in turn, support the improvement and updating of the regional adaptation strategy, as well as the municipal climate action plans, enabling the implementation of more realistic and effective measures.

1.3 Project team

The internal team of CLIMAAX4Resilience project is composed of:

- Paulo Batista dos Santos has a background in Accounting and Administration (Business Management) and serves as the 1st Executive Secretary of CIMRL.
- Valério António has a degree in Geography and Regional Planning and a postgraduate degree in Geographic Information Systems. He is a senior technician at CIMRL, working in the areas of Planning, Geographic Information Systems, Environment, Transport, and Forests.

The supporting team (subcontracted – external support) of CLIMAAX4Resilience is composed of:

- Ricardo Almendra has a degree in Geography and Planning, and a master's degree in Geography, with a specialization in Spatial Planning and Management.
- Liliana Sousa has a degree in Biology-Geology and a master's degree in Geological Heritage and Geoconservation;
- Ana Rita Caldas has a degree in Biology-Geology and a master's in Biophysics and Bionanosystems.
- Andreia Mota has a degree in Geography and Planning, a master's in Geography with a specialization in Spatial Planning and Management, and an executive postgraduate degree in Geographic Information Systems.
- Helena Corrêa has a degree in Agronomic Engineering and a master's in Environmental Science and Technology, specializing in Environmental Monitoring and Remediation.
- Manuel Miranda has a degree in Civil Engineering (Spatial Planning Option) and a postgraduate degree in Spatial Planning, Urbanism, and Environmental Law, with a specialization in Municipal Engineering.
- Rosa Silva has a degree in Education and a master's in Management Studies.

1.4 Outline of the document’s structure

The document begins with an Introduction (project background, main objectives, project team, and document outline). Following this, it describes the Climate Risk Assessment (CRA process, which includes scoping, risk exploration, risk analysis (droughts, wildfires, heatwaves and coastal floods), preliminary key risk assessment findings, and preliminary monitoring and evaluation. Finally, the document presents the conclusions of Phase 1, along with a progress evaluation and contribution to future phases.

2 Climate risk assessment – phase 1

2.1 Scoping

The scoping phase of the climate risk assessment encompasses the establishment of objectives (the intended outcomes of the analysis) and context (the conditions for its implementation), as well as the identification of stakeholders who are essential for the project's preparation.

2.1.1 Objectives

The CLIMAAX methodological approach will be applied as described in the handbook, following the recommended steps for climate risk assessment and utilizing the provided toolbox, which contains specific data and guidelines for regional/local application.

The CLIMAAX4Resilience offers a set of outcomes designed to strengthen the Leiria Region's ability to address the challenges of climate change. Through the implementation of a common methodology and access to specialized tools, the project will improve the identification and analysis of climate risks. This process will result in a more accurate assessment of current and future vulnerabilities in the region, enabling effective comparison with other European regions.

CLIMAAX will support informed and sustainable decision-making regarding climate action strategies and risk management. Simultaneously, the project will empower the teams of CIMRL and the municipalities through the sharing of experiences and good practices in climate risk assessment. One of the most critical aspects of CLIMAAX will be the integration of climate risk assessment results into strategic planning instruments at the regional and local levels. These results will be incorporated into CIMRL's strategic documents and municipal plans.

The project will also promote shared responsibility and active involvement of local stakeholders in climate adaptation efforts. By increasing the resilience of the Leiria Region, CLIMAAX will align with the European Union's Climate Change Adaptation mission.

At the end, CLIMAAX is expected to bring direct benefits to local authorities and communities, enabling authorities to use assessment data for their action plans while communities will benefit from adaptation measures. Additionally, the project will contribute to increasing the adaptation capacity of the region's 10 municipalities by addressing difficulties related to knowledge, information, and limited resources.

Like most of the country, the Leiria region faces some difficulties in adapting to climate change and assessing climate-related risks, despite the efforts that have been made in recent years in this area. Key difficulties include:

- Data gaps (lack of comprehensive, high-resolution data complicates risk assessments);
- Coordination (fragmented responsibilities hinder effective collaboration among stakeholders);
- Financial constraints (limited funding affects the implementation of adaptation and mitigation measures);
- Public awareness (low awareness reduces community engagement in adaptation strategies);
- Sector-Specific challenges (different sectors face unique issues requiring tailored approaches);

- Policy integration (incorporating climate adaptation into existing policies is complex);
- Knowledge transfer (there is a need for better mechanisms to capacity building and share knowledge and best practices). CLIMAAX will help the Leiria Region address these gaps, thereby increasing the resilience and adaptive capacity of the region and local community to confront current and future risks exacerbated by climate change.

In addition to these difficulties, the CRA for the Leiria region faces several limitations, such as challenges with data availability and quality, particularly at the local level. Insufficient stakeholder engagement can also affect the assessment's effectiveness, while resource constraints (including funding and technical expertise) may limit the depth of the analysis.

In turn, uncertainties inherent in climate models and socioeconomic scenarios can impact the predictability of long-term risks. Finally, legal and institutional barriers may hinder the implementation of adaptation measures, as existing regulations may not be fully aligned with emerging climate realities.

2.1.2 Context

The Mediterranean basin, which includes Portugal, is facing significant climate vulnerabilities due to its transitional climate between arid and humid regions. The area experiences distinct weather patterns, characterized by mild, wet winters and dry, hot summers. Recent studies indicate a concerning trend of rising temperatures and declining precipitation across the region throughout the 21st century, with a more pronounced increase in summer temperatures compared to winter.

As temperatures rise, there will be a notable decrease in relative humidity and soil moisture, exacerbating drying conditions. Extreme weather events are expected to become more frequent and intense, including heatwaves and heavy rainfall, despite an overall reduction in rainy days. The frequency of cold spells is projected to decline across the country, while wind speeds are anticipated to increase during the summer months. The geographical diversity of Portugal means that the impacts of climate change will vary across different regions. The "National Roadmap for Adaptation 2100" has classified the Portuguese NUTS III regions into high, medium, and low priority for adaptation, identifying the Leiria Region as high priority for adaptation to rural fires, coastal erosion and coastal overtopping and flooding. It should also be noted that, according to the regional composed Vulnerability Index produced by the JRC Disaster Risk Management Knowledge Centre (DRMKC) at NUTS III level, the Leiria Region has a vulnerability index (5.34) substantially higher than the European average. The same is true for the NUTS II (Centro) index (5.27).

The high vulnerability of the Leiria Region to climate change is evident, particularly due to the diversity and vastness of its territory, which stretches from the mountains to the sea. Recent events, especially the devastating fires of 2017, further highlight this vulnerability.

In compliance with national legislation, the ten municipalities in the NUTS III Region of Leiria are developing their Municipal Climate Action Plans (PMAC), most of which are still in draft form and have not yet been finalized or approved.

The implementation of a methodological framework and access to the CLIMAAX toolbox will enhance the identification and spatial analysis of climate risks. This will strengthen the assessment of current and future vulnerabilities, facilitate comparability with other European regions through a common and harmonized methodology, and ultimately support more informed and sustained decision-making regarding climate action strategies and priorities and risk management. The exchange of experiences and best practices facilitated by CLIMAAX throughout the climate risk assessment framework covering not just risk identification, analysis, and assessment but also monitoring and evaluation will significantly enhance the capacity of CIMRL teams and municipalities in this area.

Additionally, CLIMAAX will play a key role in integrating climate risk assessment results into regional and local strategic planning instruments. It emphasizes participatory processes involving stakeholders at all stages of the methodology. The findings from the climate risk and vulnerability assessments will be incorporated into CIMRL's strategic documents and municipal planning documents, including the Municipal Climate Action Plans (PMAC) and the Municipal Emergency and Civil Protection Plans (PMEPC). To achieve this, participatory processes and active engagement of local stakeholders both public and private as well as the broader community, will be essential in fostering shared responsibility and active involvement in climate adaptation efforts.

All these documents and studies, combined with the team's knowledge of the territory and their expertise, allowed for the identification of the main risks associated with adverse climatic events: **wildfires** and **coastal flooding**.

The vulnerability of sectors in CIMRL to climate change results from their direct or indirect dependence on specific environmental conditions and their exposure to extreme events. In the context of this project, the most vulnerable sectors are Agriculture, Biodiversity, Forests, Human Health, the Safety of People and Property and Tourism:

- **Agriculture** faces soil erosion and water stress due to rising temperatures and decreased precipitation, which makes it more vulnerable to wildfires;
- **Biodiversity and Forests** are threatened by ecosystem degradation and an increase in wildfires; rising sea levels and coastal erosion can lead to the loss of coastal and marine ecosystems;
- **Human Health** is at risk of increased morbidity and mortality caused by heatwaves, as well as vector-borne diseases; there is also a risk of severe health problems and disruption of livelihoods for large urban populations due to flooding;
- **The Safety of People and Property** is endangered by extreme events like floods and fires, as they can cause significant economic damage and endanger lives;
- **Tourism** may face destination obsolescence if destinations become too hot or if the risk of wildfires increases; rising sea levels and coastal overtopping can also lead to the closure of coastal facilities and increased risks to coastal infrastructure and low-lying coastal ecosystems, generating indirect effects on tourism activities.

Outside influences, such as national adaptation initiatives [like the Coastal Zone Management Plan (POOC)] and EU-funded resilience projects, can better frame local strategies to increase the region's resilience.

The Coastal Zone Management Plan (POOC) Ovar-Marinha Grande is fundamental to the CIMRL, serving as both a database and an action framework. This plan provides essential information for identifying and mapping hazards, the exposure of assets, and vulnerabilities in coastal zones. Simultaneously, its measures and objectives already constitute a set of existing adaptation actions, which the Climate Risk Assessment can use as a starting point to analyze their effectiveness against future projections and propose complementary interventions.

Potential adaptation interventions include strengthening wildfire prevention strategies, refining heatwave contingency measures, reinforcing water resource management systems, improving emergency preparedness and early warning systems, and building the capacity of vulnerable groups to enhance their adaptive capabilities. They also encompass targeted policy initiatives, such as integrating climate risk considerations into urban planning and resource allocation.

Regarding the coastal zone, interventions can involve a combination of structural measures (such as the construction of dikes), nature-based solutions (such as dune restoration), and planning measures (such as coastal retreat).

2.1.3 Participation and risk ownership

Initial steps for stakeholder engagement included identifying relevant actors and defining participatory methods to ensure a broad representation of interests and local knowledge. In this first phase, stakeholder involvement was achieved through an online survey.

To maximize the impact of the climate change multi-risk assessment on the region, the involvement of local stakeholders will facilitate both the collection of high-resolution regional/local data to refine the risk assessment and the validation of results by aligning them with the subregion's specific characteristics. This approach will maximize the potential for CLIMAAX results to enhance regional climate and emergency risk management plans and to support informed regional/local decision-making.

The main stakeholders and beneficiaries of the CLIMAAX4Resilience project can be grouped as follows:

- **Municipal Agents:**
  - The 10 member municipalities of CIMRL are the primary direct stakeholders and beneficiaries, as they will use the assessment data to improve their Municipal Climate Action Plans (PMAC) and Municipal Emergency and Civil Protection Plans (PMEPC).
- **Local Sectoral Agents:**
  - Local agricultural producers will receive support for the implementation of sustainable practices. Businesses in the region can adapt to the impacts of climate change, and the tourism sector will benefit from preserving its attractions through risk mitigation.
- **Community and Civil Society:**
  - Local communities residing in the most vulnerable areas of the region are direct beneficiaries, as they will benefit from the implemented adaptation measures. The general population will also benefit from a safer and more resilient environment.
  - Non-Governmental Organizations (NGOs) working in the area of community resilience are also relevant stakeholders.
- **Knowledge:**
  - Academic institutions will benefit from the project data to develop new approaches and methodologies, and to replicate and extend the results.

Interaction with stakeholders will be ensured through:

- Participatory processes, ensuring the involvement of stakeholders in all phases of the methodology, from risk identification and analysis to evaluation and monitoring.

- Awareness-raising actions to raise awareness of climate risks and promote community involvement in adaptation strategies.
- Promoting knowledge sharing, facilitating the integration of climate risk assessment results into regional and local strategic planning instruments.
- Presentation of the results to policy-makers in the Leiria Region, through a final public event.

Priority vulnerable territories include areas prone to wildfires, coastal erosion, and coastal overtopping and flooding, making the Leiria Region a territory with high vulnerability to climate change due to its vast and diverse territorial expanse, which stretches from the mountain areas to the coast. Regarding wildfires, the most vulnerable groups are babies / children, the elderly, and the sick due to heatwaves, along with vulnerable urban populations and people who work outdoors in rural or urban areas. As for coastal overtopping and flooding, priority is given to populations in low-lying coastal areas and large urban populations, as they face health risks, disruption of livelihoods, and the need for relocation due to sea level rise and extreme events. More broadly, disadvantaged people and communities and the poorest populations, in both urban and rural environments, are generally more susceptible to the impacts of climate change.

Managing climate risk in the Leiria region is a collective responsibility, with a well-defined governance framework that outlines distinct roles for CIMRL and its municipalities. The acceptable level of risk will be determined through a collaborative process where technical experts and local stakeholders jointly evaluate the feasibility of measures against community expectations. The primary objective is to minimize risks to an acceptable level, in accordance with public safety standards and regional resilience goals. To maintain transparency, the findings of the Climate Risk Assessment (CRA) will be shared in a clear and accessible manner with local decision-makers, civil society representatives, and the community at large, using workshops, publicly accessible reports, and online platforms.

2.2 Risk Exploration

The risk exploration phase in the Leiria region initiates the climate risk assessment process with a broad screening and identification of climate-related hazards, exposures, and vulnerabilities. This stage involves reviewing existing data and engaging with stakeholders to pinpoint where vulnerabilities and exposures intersect most critically. This approach ensures the assessment focuses on the most significant and apparent risks affecting the region, thereby guiding subsequent detailed analyses and targeted adaptation strategies.

2.2.1 Screen risks (selection of main hazards)

In the territory of the CIMRL, the relevant climate-related hazards and potential risks result from projected climate changes and existing socioeconomic and sectoral vulnerabilities. These are identified by correlating indicators such as exposure to climate risk, the historical record of events, and the population's adaptive capacity.

The main projected climate hazards and priority potential risks include:

- **Increase in average and extreme temperatures:** An increase is expected in the average annual temperature, summer days, and tropical nights, along with a decrease in frost days.

- **More frequent and longer-lasting heatwaves:** The number of heatwave days is projected to increase by the end of the century, with the expectation of them occurring every year.
- **More frequent and intense droughts:** The phenomenon of meteorological drought will worsen, evolving into a moderate drought in the spring and autumn and an extreme drought in the summer.
- **Changes in precipitation patterns:** A widespread reduction in total annual precipitation is expected. However, there will be an increase in the frequency and intensity of extreme precipitation events, especially in winter.
- **Increased risk of wildfires:** The region is classified as a high priority for adaptation to wildfires. An increase in the number of days with a high fire risk is projected for the warmer months (summer and autumn).
- **Coastal overtopping and flooding:** An increase in the frequency and intensity of phenomena causing coastal overtopping and erosion is expected, exacerbated by rising sea levels and storms.
- **Intense winds:** The magnitude of the consequences of intense winds will worsen due to their greater intensity, even if their frequency remains the same.

The selection of workflows for risk assessment in the territory takes into account the main hazards identified.

2.2.2 Workflow selection

The CLIMAAX4Resilience project applies the CLIMAAX framework using 4 targeted workflows to assess the most pressing climate risks in the Leiria region: wildfires, droughts, heatwaves and coastal floods. Additionally, this section details the vulnerable groups and exposed areas, as each workflow includes specific methodologies and datasets.

2.2.2.1 Workflow #1 Applied to: Wildfire

The Leiria Region has generally been heavily affected by incidents related to wildfires (particularly the devastating fires of 2017). Forest areas are especially sensitive to fires, as are vulnerable urban populations and people who work outdoors in urban or rural areas. In rural areas, forest entrepreneurs and those who rely on agricultural practices are also especially exposed to this climate risk. Regarding vulnerable groups, it is important to highlight the resident population, namely children, the elderly, and immunocompromised or chronically ill individuals, as well as all the biodiversity present in areas exposed to wildfires.

2.2.2.2 Workflow #2 Applied to: Droughts

The region has generally recorded a significant increase in occurrences related to droughts. As a result, agricultural areas and the agricultural sector are sensitive to this climate risk. Biodiversity and ecosystems are also exposed, facing the modification, degradation, and loss of ecosystems; increased evapotranspiration; high species mortality due to prolonged and severe droughts; and a reduction in the quantity and quality of water in permanent water bodies. Children, the elderly, and immunocompromised or chronically ill people are also considered vulnerable groups.

2.2.2.3 Workflow #3 Applied to: Heatwaves

The region shows an increasing vulnerability to the risk of heatwaves, which are becoming more frequent and intense, particularly affecting its inland municipalities, further from the thermoregulatory influence of the ocean. This climate hazard directly exacerbates the region's susceptibility to wildfires and to the intensification of droughts and water scarcity. The impacts are significant across various sectors: biodiversity and ecosystems are exposed to water stress and habitat degradation, while the agricultural sector and livestock farming face productivity losses. Regarding vulnerable groups, the resident population is the most affected, particularly children, the elderly, and immunocompromised or chronically ill individuals, who are at increased risk of health problems during these extreme events.

2.2.2.4 Workflow #4 Applied to: Coastal flooding

The region is susceptible to coastal erosion and coastal overtopping and flooding, with these occurrences being recorded. As a result, populations in low-lying coastal areas, coastal urban populations, as well as disadvantaged people, communities, and the poorest populations represent vulnerable groups and areas, being very sensitive to this climate risk. Biodiversity and marine habitats are also severely exposed to this risk, facing the modification, degradation, and loss of ecosystems.

2.2.3 Choose Scenario

For the CLIMAAX4Resilience project, the following scenario assumptions were considered relevant:

- **Wildfire (hazard and risk):** RCP 2.6 (low scenario), RCP 4.5 (intermediate scenario) and RCP 8.5 (high scenario) as future scenarios. All the period available for historical FWI data and 2045-2054 as future period.
- **Droughts:**
  - **Relative drought (hazard and risk):** SSP1-RCP2.6 (low scenario), SSP3-RCP7.0 (intermediate scenario) and SSP5-RCP8.5 (high scenario) as future scenarios. All the period available for historical data and 2050 and 2080 as future period.
  - **Agricultural drought (hazard and risk):** RCP2.6 (low scenario), RCP4.5 (intermediate scenario) and RCP8.5 5 (high scenario) as future scenarios. All the period available for historical data and 3 future periods: 2026-2046 (near future), 2036-2065 (mid-century), or 2071-2090 (end-of-century).
- **Heatwaves (hazard and risk):** RCP4.5 (intermediate scenario) and RCP8.5 (high scenario). All the period available for historical data (1971-2000) and 3 future periods: 2011-2040 (near future), 2041-2070 (mid-century) and 2071-2100 (end-of-century).
- **Coastal Floods (hazard and risk):** RCP4.5 (intermediate scenario) and RCP8.5 (high scenario). All the period available for historical data and all return period available: 1 in 2 years, 1 in 10 years, 1 in 100 years, 1 in 250 years (considering 2050).

2.3 Risk Analysis

This chapter presents how the selected CLIMAAX risk workflows were applied in the Leiria Region. For each workflow, the methodology and datasets used for the assessment of hazards, exposure, and vulnerability were summarized, culminating in the presentation of spatial risk maps.

2.3.1 Workflow #1 – Wildfire

2.3.1.1 Wildfire (FWI)

The methodology for assessing wildfire risk combines two main components: wildfire danger and vulnerability (Figure 2-1). Danger is evaluated based on the Fire Weather Index (FWI), which measures climatic conditions favorable to fire and the availability of vegetation. Vulnerability is calculated using a set of indicators that measure the sensitivity of human, ecological, and socio-economic systems (population, biodiversity, etc.). The final phase of the process combines danger and vulnerability using a Pareto analysis algorithm to identify the areas of highest risk.

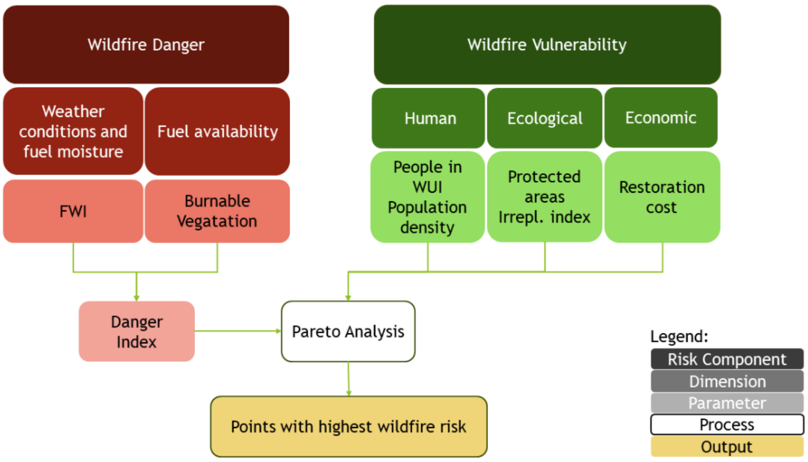


Figure 2-1 Representation of the risk assessment methodology and lists the parameters used to define each risk component. Figure source: CLIMAAX

The main datasets used and produced from the Wildfire (FWI) workflow are identified in the table below, namely the hazard, exposure, and vulnerability datasets.

Table 2-1 Data overview workflow #1 – Wildfire (FWI)

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
· *Fire Weather Index (FWI), based on meteorological data (historical and future).*	· *Ecosystem Irreplaceability Index* · *Ecosystem Restoration Cost Index* · *Population Density (especially in vulnerable groups)*	· *Burnable Vegetation Area (e.g., Corine Land Cover)* · *Population in the Wildland-Urban Interface* · *Protected Areas Distribution.*	· *Wildfire Risk Maps that identify areas with the highest combined risk (hotspots)* · *Analysis of priority areas for intervention.*

<u>Hazard assessment</u>

Using the Fire Hazard workflow, we generated seasonal Fire Weather Index (FWI) scenarios to assess wildfire hazard. The assessment covers a historical reference period and future projections based on three Representative Concentration Pathways: RCP 2.6, RCP 4.5, and RCP 8.5. For each pathway, climate model ensembles were used to produce best, average, and worst-case scenarios. The figures below (Figure 2-2) exemplify the outputs from this analysis.

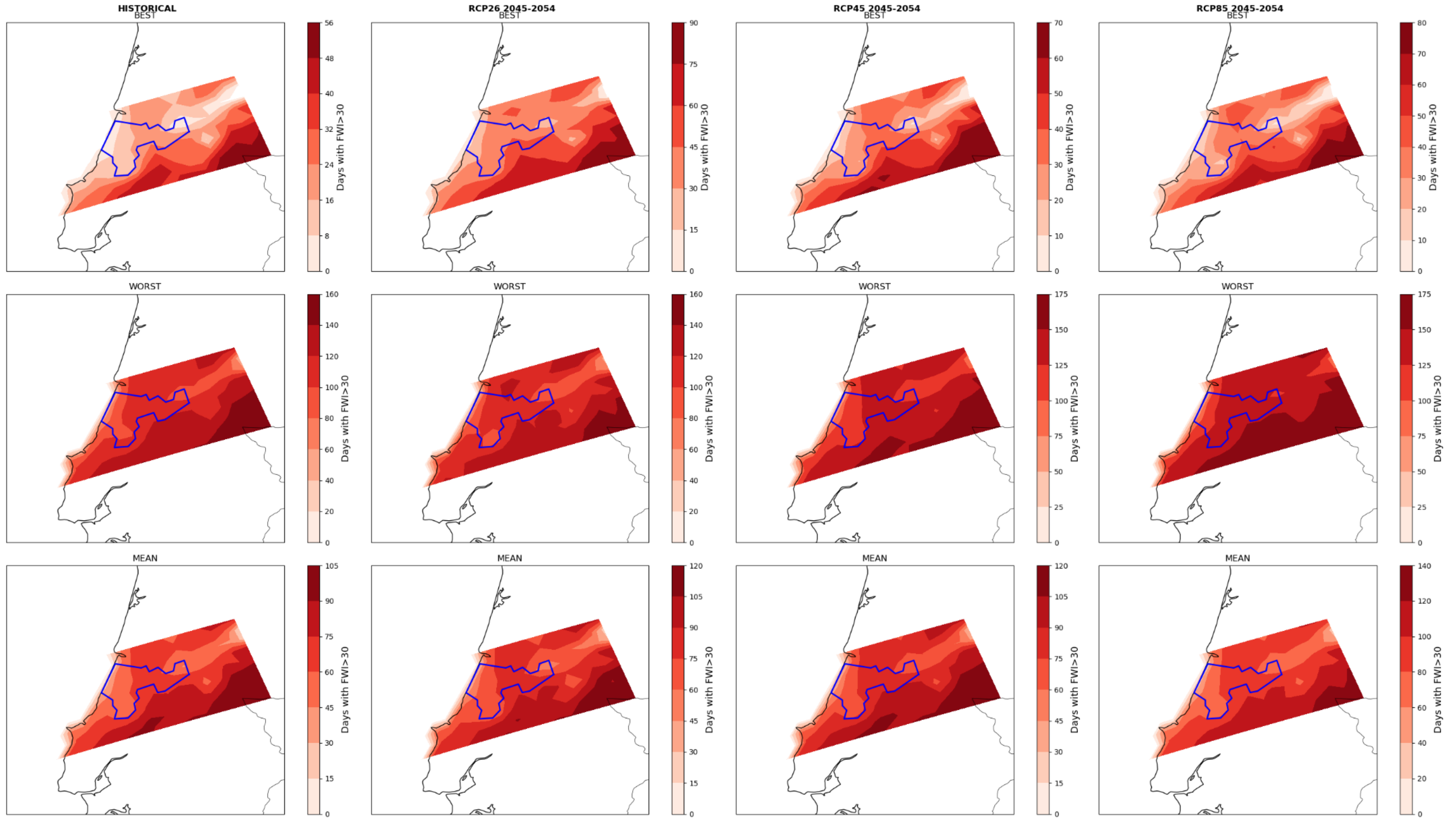


Figure 2-2 Annual number of days with FWI > 30 in the Leiria Region, comparing the historical baseline (1985-2005) with future scenarios (RCP 2.6, 4.5, and 8.5) for best, worst, and average cases.

Risk assessment

The wildfire risk maps, produced by the CLIMAAX workflow, classify areas into different risk levels by combining three essential components: hazard (from FWI projections), exposure (population and infrastructure), and socioeconomic vulnerability. The projections focus on three key indicators: the number of high-danger days, the average seasonal FWI intensity, and the percentage of burnable vegetation.

The maps below (Figure 2-3) focus on the projection of three key indicators: the number of high-danger days (Fire Danger Index), the average seasonal FWI intensity, and the percentage of burnable vegetation, for the RCP 4.5 and 8.5 scenarios for the 2045-2054 period, using a high-danger threshold of FWI > 20.

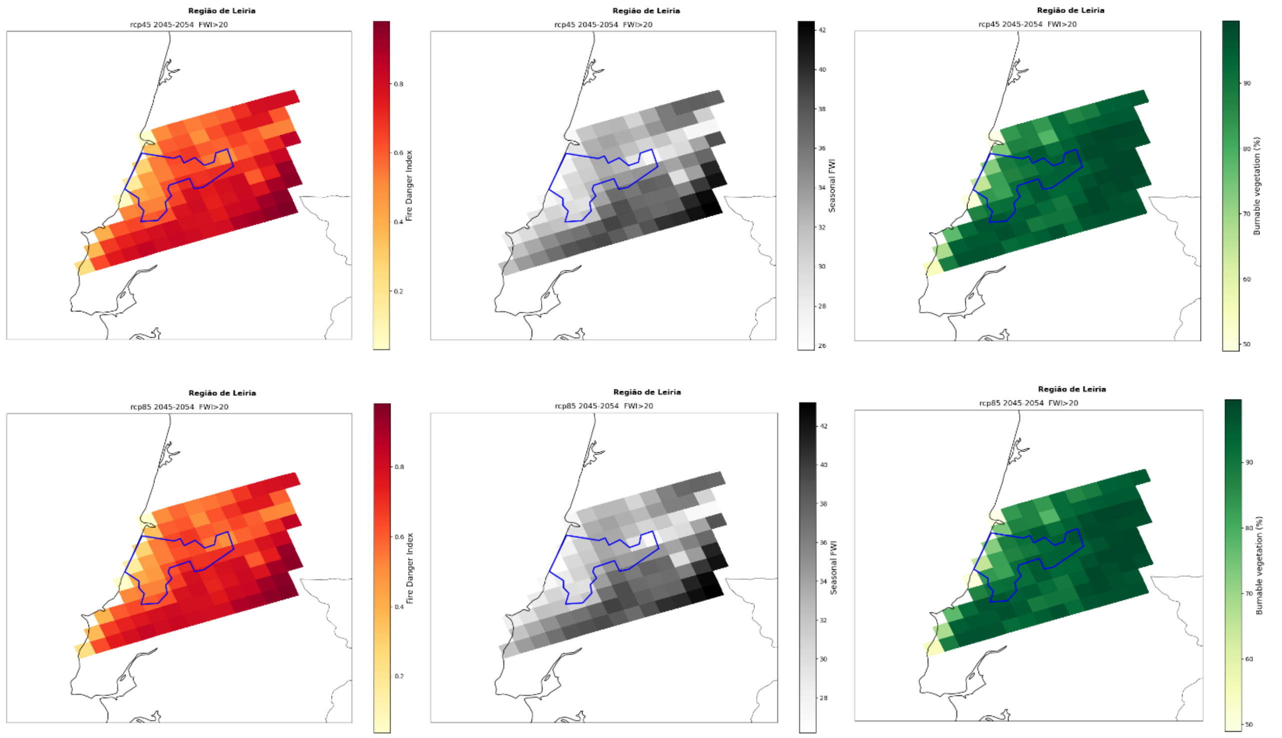


Figure 2-3 Fire Danger Index (days with FWI > 20), Seasonal FWI, and Burnable Vegetation (%) in the Leiria Region, projected for the 2045-2054 period under RCP 4.5 and 8.5 scenarios.

Beyond the meteorological hazard, a critical component of risk assessment is understanding the territory's vulnerability. The maps below break down this concept into key indicators that spatially define where the impacts of a wildfire would be most severe. The assessment covers two main dimensions: socio-economic vulnerability, represented by Population Density (people/km²), People living in the WUI (%), and the Restoration Cost Index; and ecological vulnerability, measured by Protected Land Area (%) and the Irreplaceability Index (Figure 2-4).

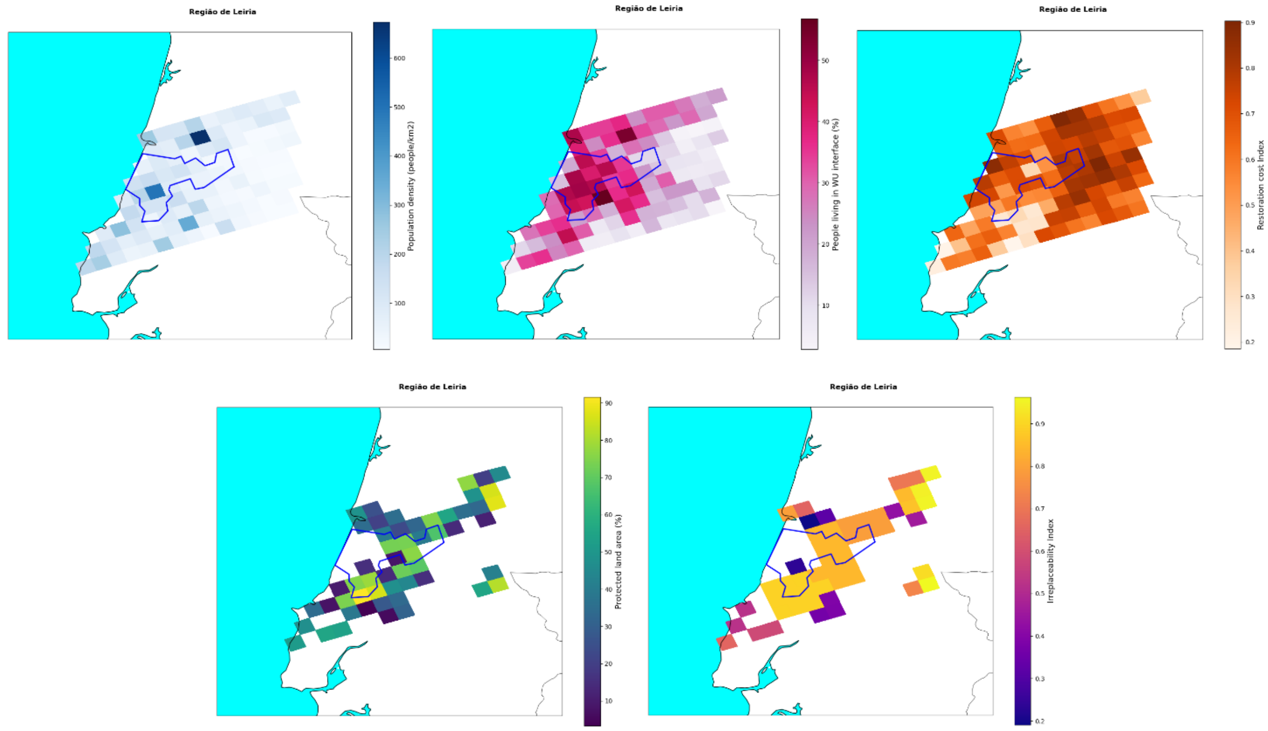


Figure 2-4 Key socio-economic and ecological vulnerability indicators for wildfire risk assessment: Population Density, People living in the WUI (%), Restoration Cost Index, Protected Land Area (%), and the Irreplaceability Index.

The final map synthesizes the wildfire risk for the region (Figure 2-5). The primary indicator for the hazard level is the Seasonal FWI, represented by the greyscale grid where darker shades correspond to higher and more persistent fire danger. Overlaid on this hazard map, we have identified the specific locations with the Highest Risk (red dots) and Lowest Risk (green dots). These points highlight where the combination of hazard, exposure, and vulnerability reaches its extremes, allowing for a quick identification of critical hotspots for regional planning and management.

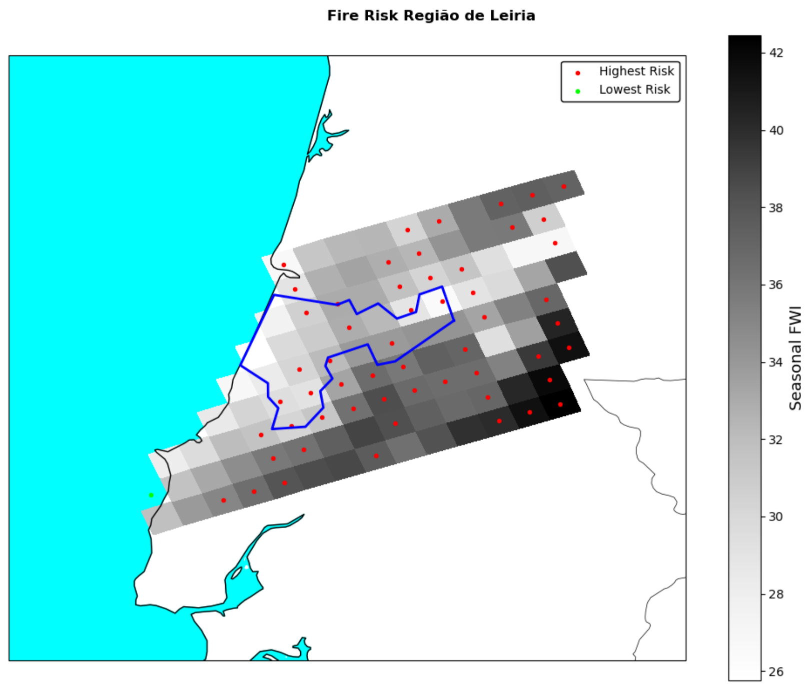


Figure 2-5 Fire risk (Seasonal FWI) in the Leiria Region.

2.3.2 Workflow #2 – Droughts

2.3.2.1 Relative Drought

The methodology of the relative drought workflow calculates drought risk as the product of three main components: hazard, exposure, and vulnerability. Hazard is assessed as the probability of a severe precipitation deficit. Exposure identifies and quantifies the physical elements at risk, such as infrastructure and population. Vulnerability is determined by a composite model that aggregates economic, social, and infrastructure indicators. The combination of these factors results in a relative drought risk map at the NUTS3 level, with scores ranging from 0 to 1.

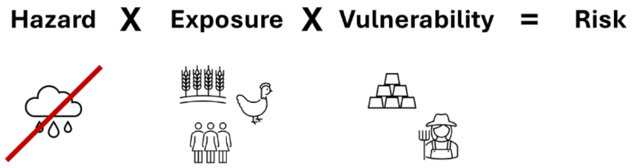


Figure 2-6 Methodology of the relative drought workflow. Figure source: CLIMAAX

The table below details the primary datasets for the relative drought workflow, which include hazard, exposure, and vulnerability data.

Table 2-2 Data overview workflow #2 – Relative drought

Hazard data	Vulnerability data	Exposure data	Risk output
· Drought Index (e.g., SPEI), measuring severe precipitation deficit. · Monthly precipitation data (NUTS3). · Data Sources: Pre-calculated data (e.g., ISIMIP 3b) or base data (e.g., ERA5-Land, CMIP6).	· Proxy indicators: GDP per capita; Percentage of Rural Population. · Data Sources: Global CWatM, Wang and Fubao (2022).	· Cropland area. · Livestock density. · Population (direct human need). · Competition for water (water stress indicator). · Data Sources: SPAM, GCAM, GLW, EUROSTAT, Aqueduct v.4.	· Risk map showing the relative drought risk at the NUTS3 level, with a score from 0 (lowest risk) to 1 (highest risk).

Hazard assessment

The relative drought hazard assessment focuses on the probability of a severe precipitation deficit occurring. To contextualize the region's situation in the historical scenario, the following graph presents the statistical distribution of the drought index (WASP) for Leiria Region, comparing it with the other NUTS3 regions in Centro Region of Portugal (Figure 2-7). This analysis allows for the positioning of the region's hazard severity within the broader territorial context.

Risk assessment

The relative drought risk is calculated as a composite index that integrates the hazard (precipitation deficit) with socioeconomic exposure and vulnerability factors. The result is a relative risk score between 0 and 1, which allows for the comparison of criticality between different regions. The following graph (Figure 2-8) illustrates this risk index for Leiria Region, showing its evolution for different future socioeconomic and climate scenarios (SSP-RCPs) and comparing it with neighboring subregions.

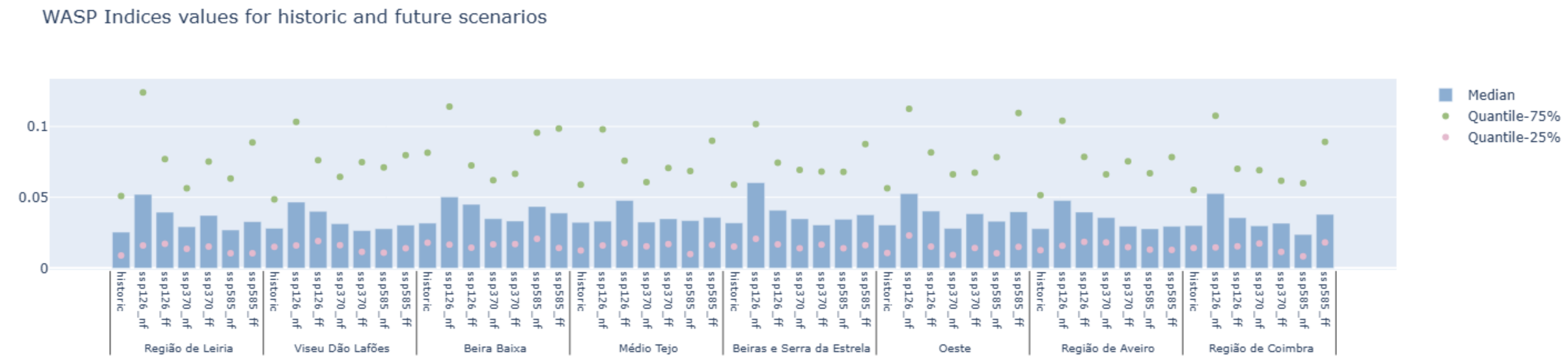


Figure 2-7 Statistical distribution of the drought hazard index (WASP) for the NUTS3 regions in the historical period.

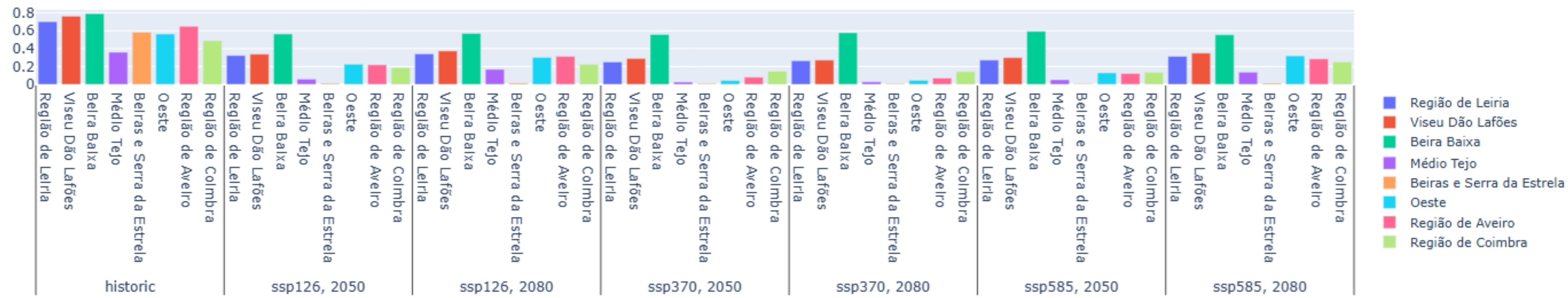


Figure 2-8 Relative drought risk index for the NUTS3 regions, comparing the historical period with future projections for different scenarios (SSP-RCPs).

2.3.2.2 Agricultural Drought

The methodology of the agricultural drought workflow aims to quantify potential agricultural revenue losses caused by precipitation deficits. To do this, it uses climatic data from regional models (CORDEX) and soil data to assess the hazard. Exposure is quantified in economic terms, based on crop production and revenue. Finally, vulnerability is mapped based on the distribution of irrigation systems. The result is a map that shows potential revenue losses as the "lost opportunity cost" if crops are not irrigated.

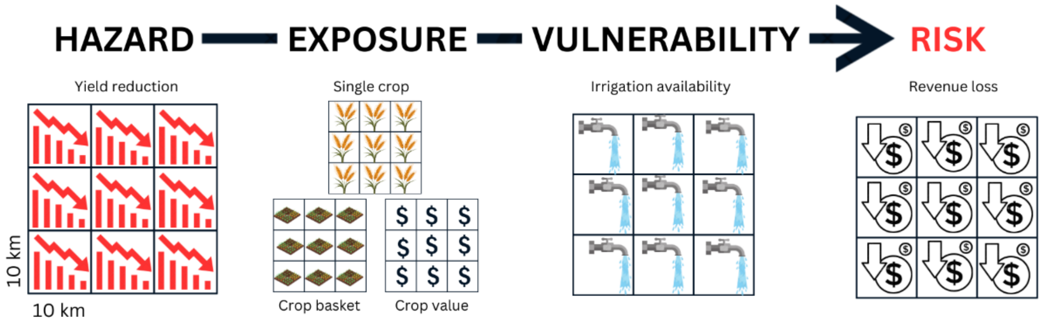


Figure 2-9 Methodology of the agricultural drought workflow. Figure source: CLIMAAX

The table below details the primary datasets for the agricultural drought workflow, which include hazard, exposure, and vulnerability data.

Table 2-3 Data overview workflow #2 – Agricultural drought

Hazard data	Vulnerability data	Exposure data	Risk output
· *Indicator: Soil moisture deficit (agricultural drought).* · *Input Data: Climate data (e.g., CORDEX), available soil water capacity, elevation.* · *Method: The indicator is calculated using simulation models (e.g., EPIC-IIASA).*	· *Intrinsic Sensitivity: The sensitivity of each crop type to drought (defined within the crop model).* · *Adaptive Capacity: The presence or absence of irrigation systems in the territory.*	· *Physical Exposure: Crop distribution and area (e.g., SPAM data).* · *Economic Exposure: Total crop production and aggregated crop revenue.*	· *Physical Impact: Maps of relative yield loss (%).* · *Economic Impact: Maps of potential revenue losses (€) due to water deficit.*

For the application of the agricultural drought workflow to the NUTS III - Leiria Region, several agriculturally significant crops were considered, namely: maize, wheat, potato, beans, barley, sunflower, and sweet potato. From among these, maize was selected as the representative crop for the demonstration of results in this report. This choice is justified by its status as the dominant crop in terms of cultivated area in the region, with a particular concentration in crucial agricultural zones like the Lis Valley. Furthermore, as a summer crop with high water requirements, maize is significantly vulnerable to drought, which makes it an ideal case study to illustrate the application and relevance of the results generated by this agricultural drought risk assessment.

<u>Hazard assessment</u>

The agricultural drought hazard assessment analyzes how changes in climatic patterns impact crop productivity. The analysis begins by characterizing a baseline condition of the territory – the Soil Available Water Capacity (Figure 2-10), a fundamental factor for crop resilience.

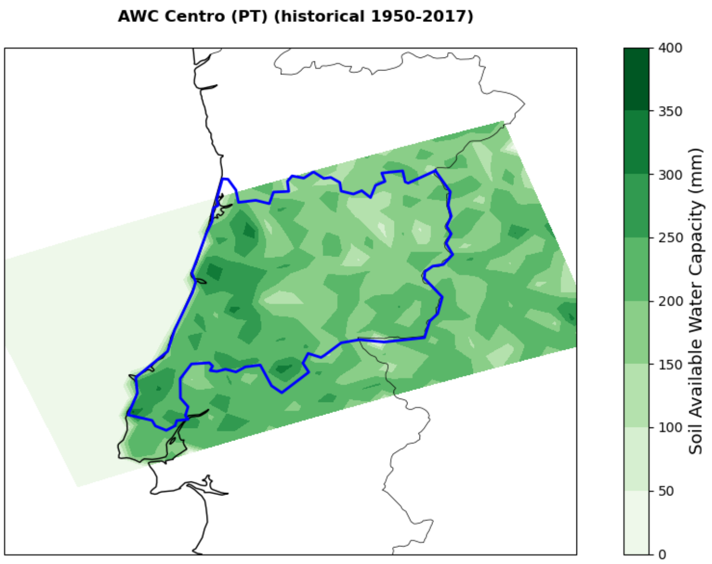


Figure 2-10 Soil Available Water Capacity (AWC), representing the baseline condition for the agricultural drought analysis.

The workflow then projects the evolution of key climatic variables, such as precipitation and evapotranspiration, for future scenarios. The combination of these factors results in the final hazard indicator: the relative yield loss (%) for the maize crop, as illustrated in Figure 2-11.

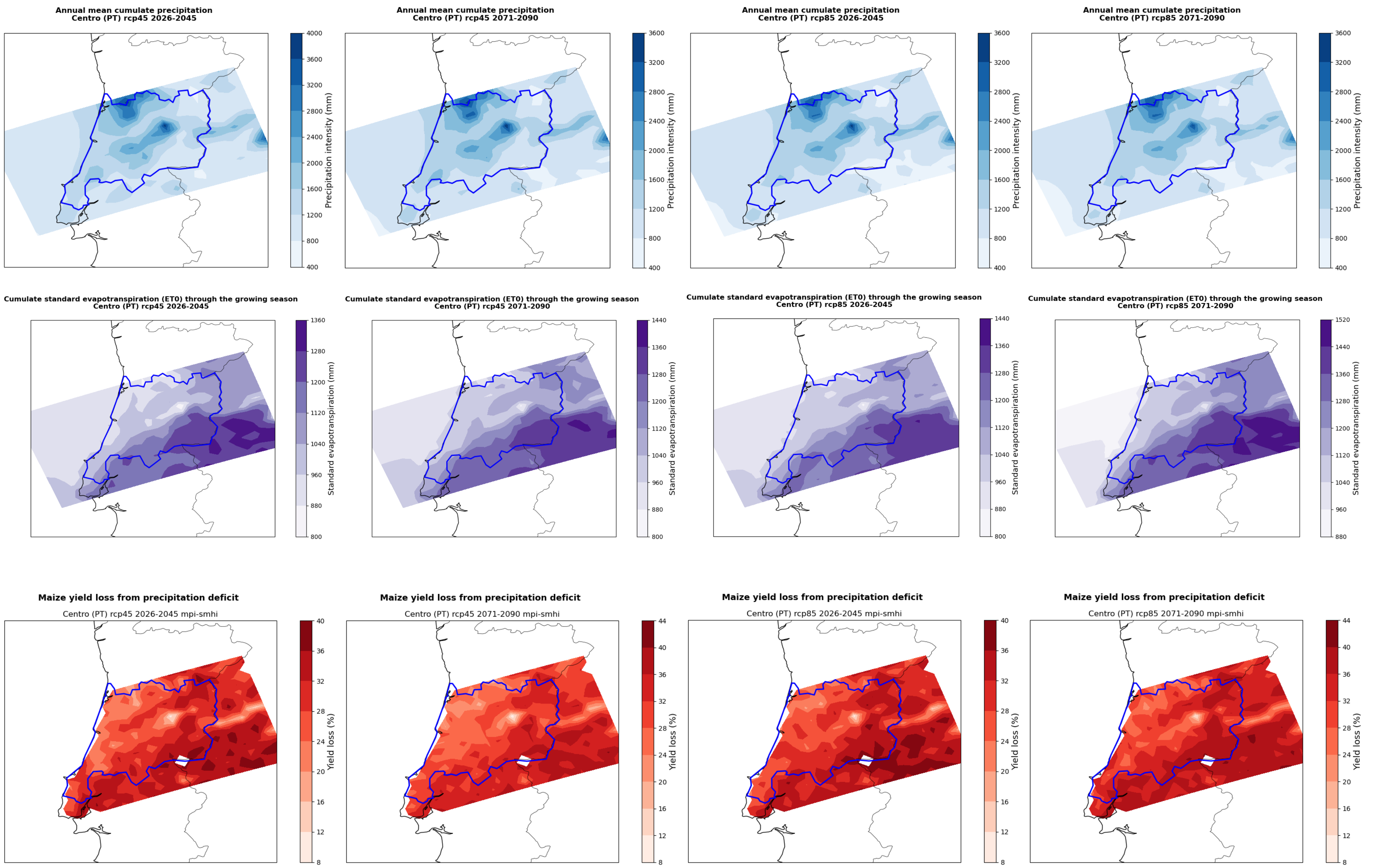


Figure 2-11 Projections of climatic variables and their impact on maize productivity for future scenarios (RCP 4.5 and 8.5).

Risk assessment

Based on the physical yield loss, the risk assessment translates this impact into direct economic consequences. This analysis quantifies the potential revenue losses (in €) for maize production, providing a clear indicator of the financial risk for the region's farmers. The following maps compare the magnitude of this economic risk between the RCP 4.5 and RCP 8.5 scenarios for both the near future (2026-2045) and the end of the century (2071-2090), illustrating the sensitivity of the risk to different climate pathways (Figure 2-12).

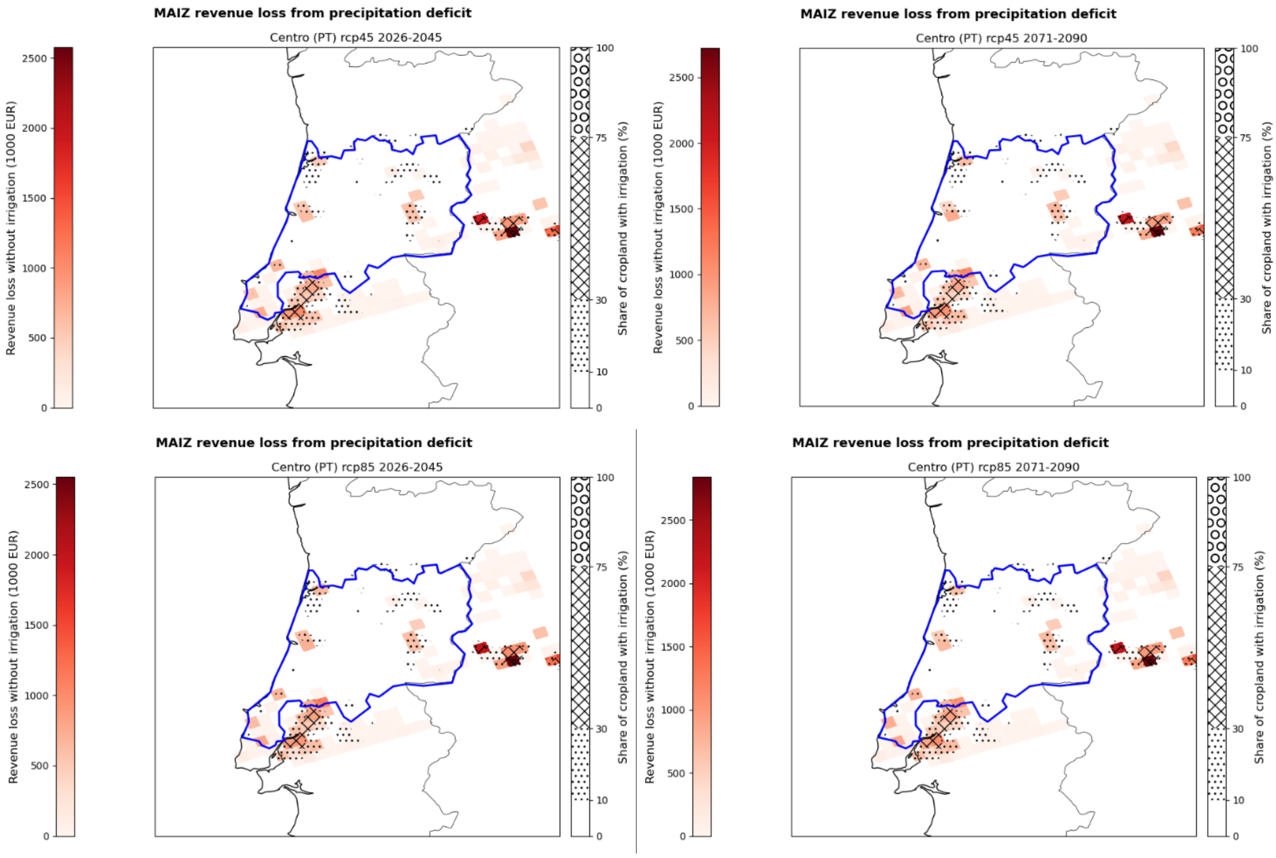


Figure 2-12 Potential revenue losses (€) in maize production, comparing the RCP 4.5 and 8.5 scenarios for the near future and the end of the century.

2.3.3 Workflow #3 – Heatwaves

The methodology of the urban heatwave's workflow explores the risks of heatwaves in urban and regional contexts, focusing on the health impacts on vulnerable populations. The hazard of a heatwave is assessed using two approaches: EuroHEAT (based on apparent temperature percentiles) and Xclim (based on user-defined absolute temperature thresholds).

Both methodologies use climatic projection data from EURO-CORDEX. Risk is evaluated by combining the hazard with population exposure and vulnerability data. This is done using a risk matrix that cross-references land surface temperature (from Landsat8 satellite imagery) with data on vulnerable population groups (people over 65 and under 5) from WorldPop. The output consists of risk maps that show the most critical areas under future climate scenarios (RCP4.5 and RCP8.5).

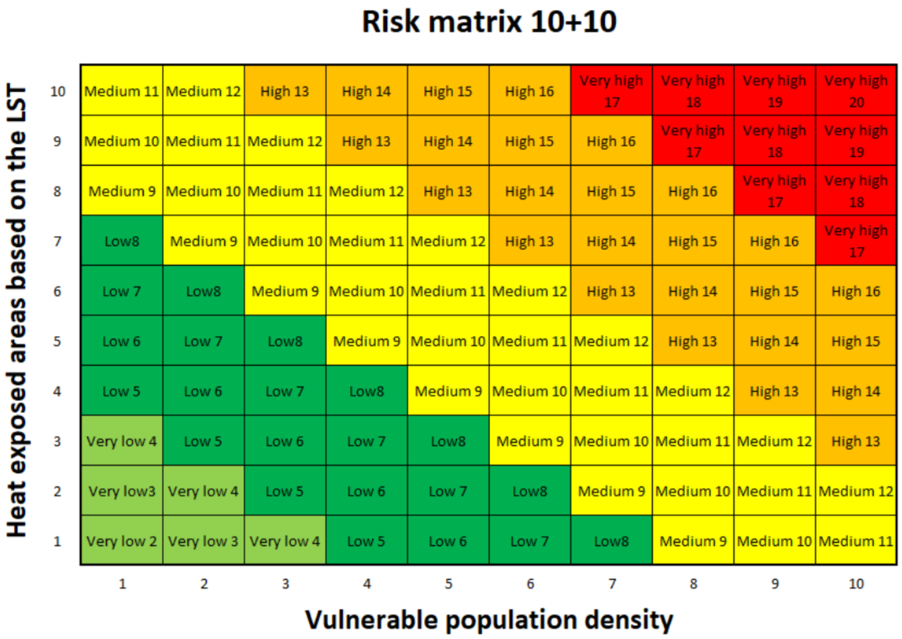


Figure 2-13 Risk matrix of the heatwaves workflow. Figure source: CLIMAAX

The heatwaves workflow uses and produces essential datasets for hazard, exposure, and vulnerability, all of which are listed in the table below.

Table 2-2 Data overview workflow #3 – Heatwaves

Hazard data	Vulnerability data	Exposure data	Risk output
· *Land Surface Temperature (LST) (e.g., Landsat satellite).* · *Air temperatures (maximum and minimum).* · *Climate projections for heatwave frequency/duration (e.g., EURO-CORDEX).*	· *Demographic data on vulnerable groups: Elderly population (>65 years); Young children (<5 years).* · *Data Sources: WorldPop, EUROSTAT*	· *Population distribution and density.* · *Data Sources: WorldPop, GHSL.* · *Urban fabric and land use (e.g., Corine Land Cover) to identify impervious vs. green areas.*	· *Urban Heat Risk Map resulting from the combination of hazard, exposure, and vulnerability* · *Identification of "hotspots" where vulnerable populations are exposed to intense heat.*

2.3.3.1 Hazard assessment

The hazard assessment for heatwaves was conducted using two complementary methodologies proposed within the CLIMAAX framework to characterize the future evolution of these extreme events. The first approach, EuroHEAT, uses a relative definition based on health perspectives at the European level. The second, Xclim, is based on user-defined absolute temperature thresholds, allowing for an analysis adapted to local specificities. The following graphs present the results of both approaches for the RCP 4.5 and 8.5 scenarios (Figure 2-14).

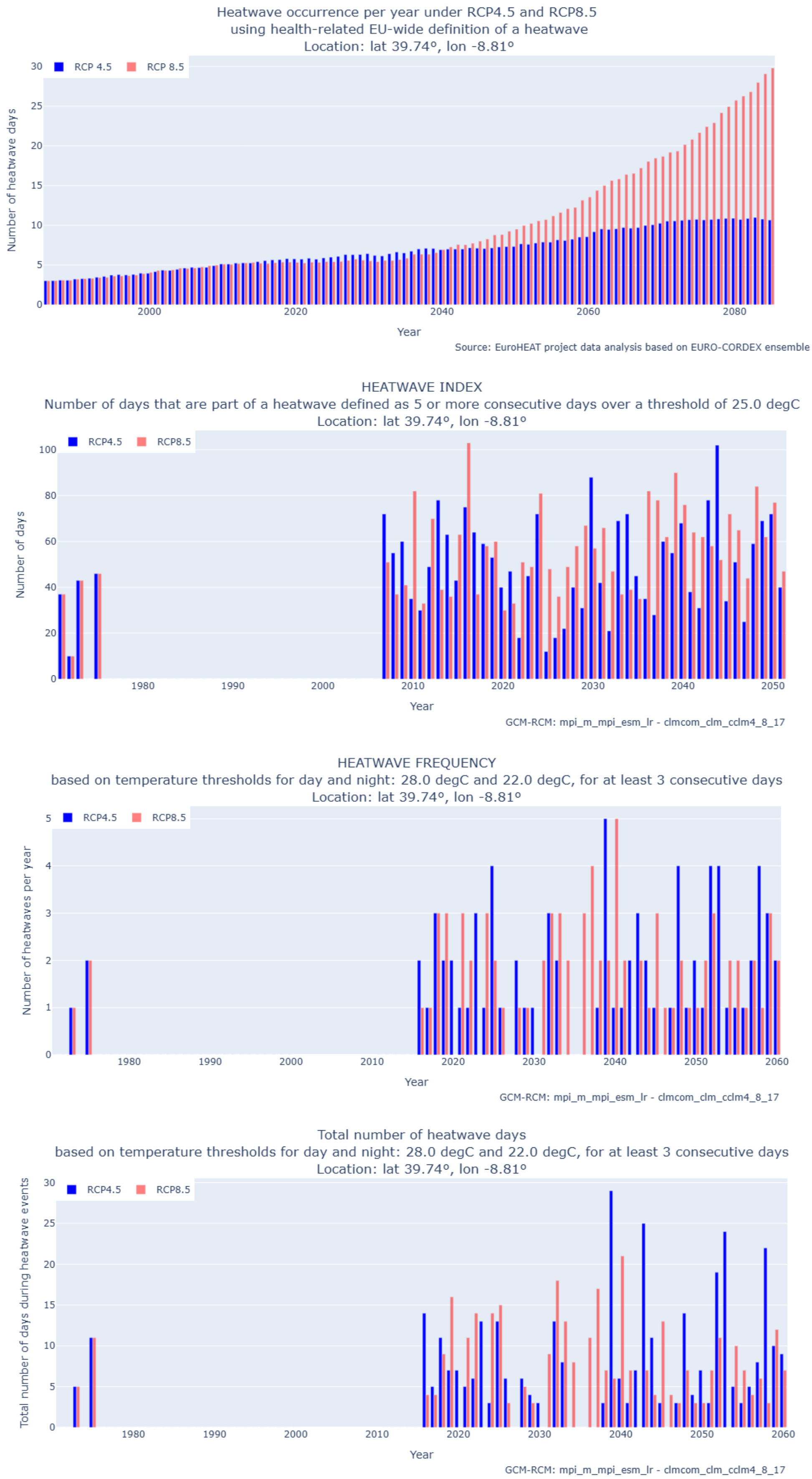


Figure 2-14 Heatwave hazard indicators for future scenarios RCP 4.5 and 8.5. in the Leiria Region (using Leiria as a geographical reference point).

2.3.3.2 Risk assessment

The risk assessment for heatwaves focuses on the intersection of the event's hazard and the population's vulnerability. To analyze this component, the first step is to map the base demographic indicators that define the territory's sensitivity, such as total population density and the distribution of vulnerable age groups (children and the elderly), as detailed in Figure 2-15. These indicators are then integrated to produce the final vulnerability classification map (Figure 2-16), which synthesizes the analysis and identifies the most critical areas in the territory.

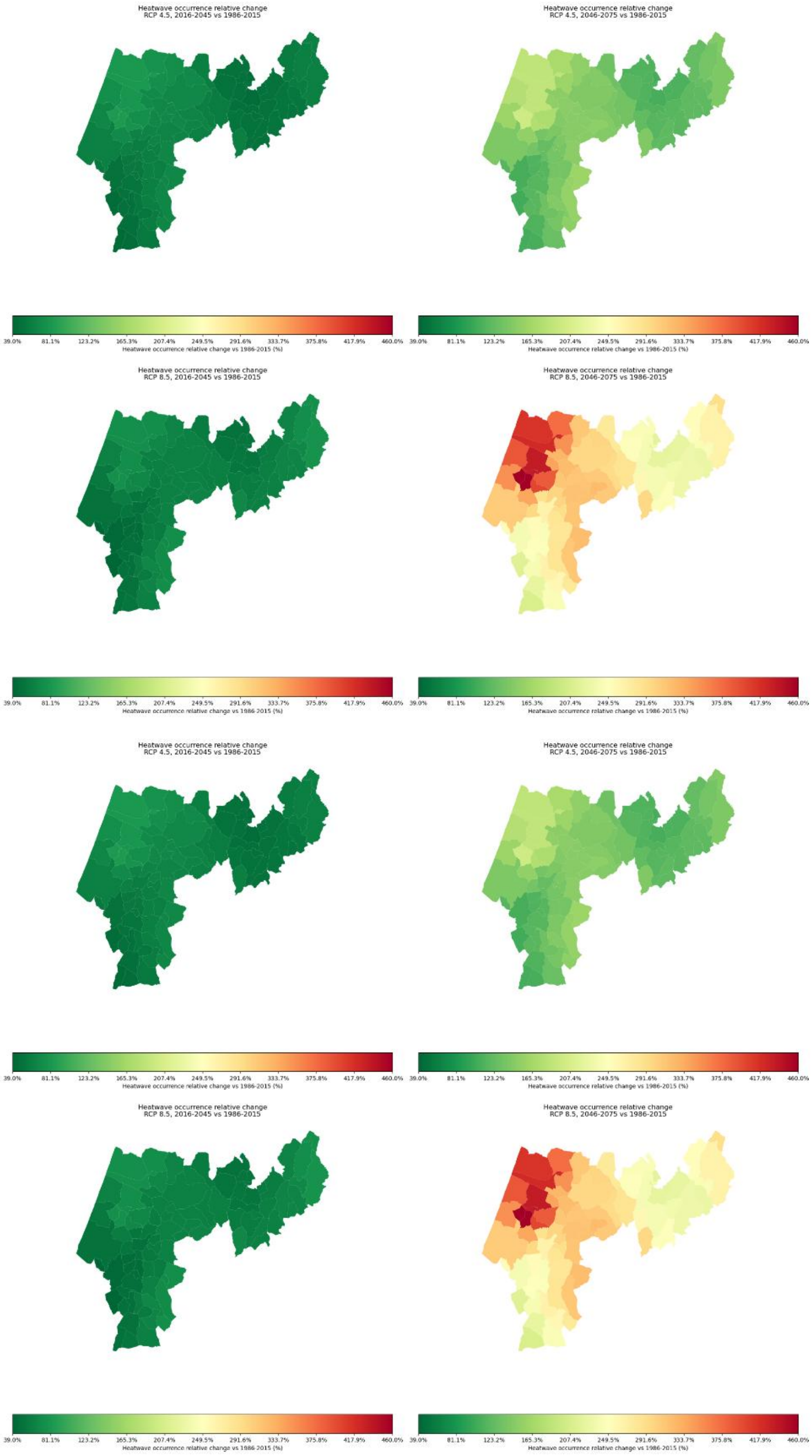


Figure 2-15 Maps of the base demographic indicators used in the heatwave vulnerability assessment for Leiria Region

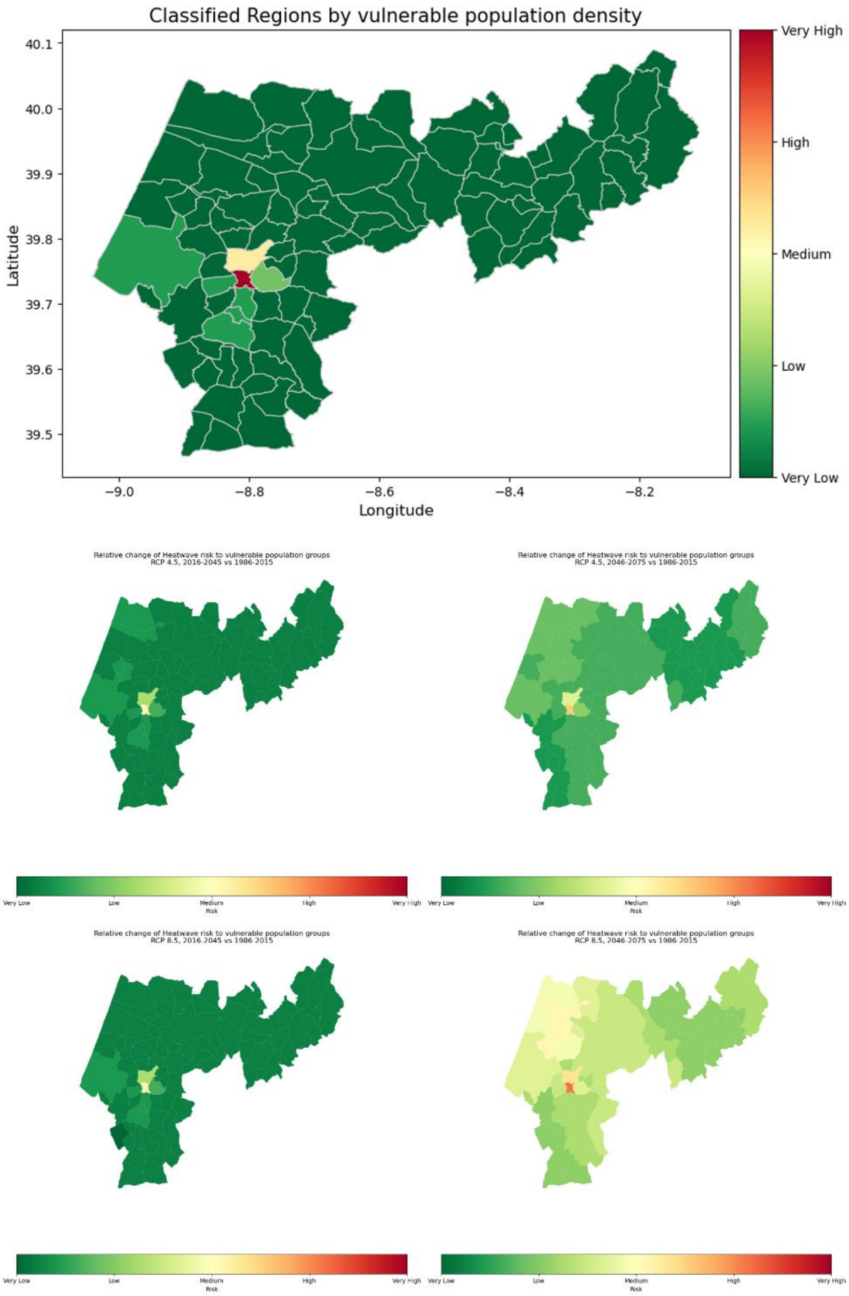


Figure 2-16 Final classification map of the territory's vulnerability to heatwaves, based on vulnerable population density.

2.3.4 Workflow #4 – Coastal Floods

2.3.4.1 Coastal flooding

The methodology of the Coastal flooding workflow focuses on calculating potential economic damage to build infrastructure caused by coastal flooding. The process involves three main steps. First, the user can explore extreme water levels and sea level rise projections from global databases. Second, a flood hazard assessment is conducted using the Global Flood Maps dataset to retrieve and compare coastal flood maps for different return periods and scenarios. Finally, the risk assessment is performed by combining the flood maps with data on land use, economic value, and vulnerability curves. This final step estimates the economic damage at each grid point based on flood depth, land use type, damage curves, and country-specific economic values.

The main datasets used and produced from the coastal floods workflow are identified in the table below, namely the hazard, exposure, and vulnerability datasets.

Table 2-4 Data overview workflow #4 – Coastal flooding

Hazard data	Vulnerability data	Exposure data	Risk output
· *Coastal inundation maps: Inundation depth and extent for different return periods (e.g., 10, 50, 100, 500 years).* · *Base data source: Extreme sea levels from Copernicus Marine Service (CMEMS) and bathymetry/topography data from EMODnet Bathymetry.*	· *Land Use/Land Cover: CORINE Land Cover (CLC) for the identification of exposed urban, industrial, agricultural, and natural areas.* · *Population: Population density grids (e.g., Global Human Settlement Layer - GHS-POP).* · *Critical Infrastructure: Transport networks (roads, railways) and buildings (health, education) from OpenStreetMap (OSM).*	· *Depth-damage functions: Models that relate inundation depth (hazard) to damage magnitude (%) for each land use class (exposure).* · *Reference source: Vulnerability functions from the EU's JRC (Joint Research Centre) and scientific literature.*	· *Damage maps (€) for each return period.* · *Expected Annual Damages (EAD), which integrates damages from all events.* · *Population at risk (no. of inhabitants affected annually).* · *Final coastal risk maps (combining hazard, exposure, and vulnerability).*

Hazard assessment

The coastal flood hazard assessment focuses on characterizing the extent and severity of potential coastal overtopping events. This analysis forms the basis for the subsequent risk assessment by delineating the geographically exposed areas. The following maps (Figure 2-17 and Figure 2-18) visualize this hazard, comparing the flood extent for extreme events with different return periods (from 2 to 250 years). The analysis contrasts the baseline scenario (c. 2018) with projections for the future (2050), thereby identifying the coastal areas where hazard exposure is expected to increase.

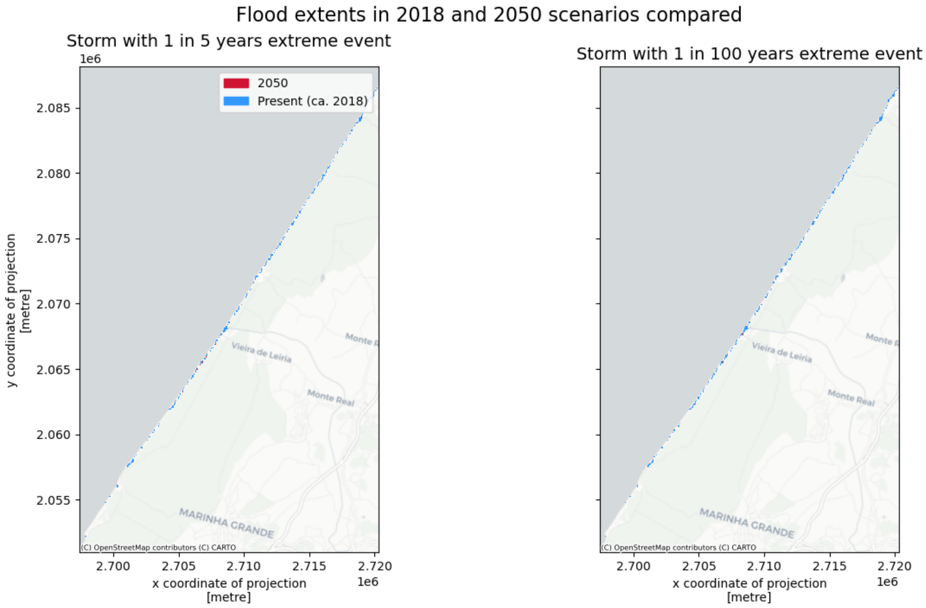


Figure 2-17 Flood extents in present (c.a. 2018) and 2050 scenarios compared for Leiria Region

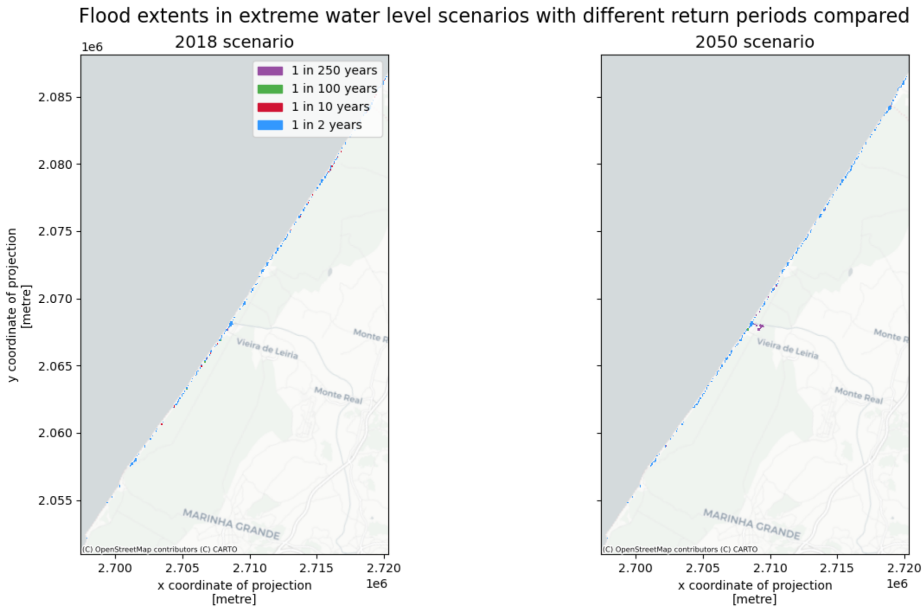


Figure 2-18 Floods extents in extreme water level scenarios with different return periods (2, 10, 100 and 250 years) compared (2018 and 2050) scenarios for Leiria Region

Risk assessment

Building on the hazard analysis, the risk assessment quantifies the direct socioeconomic impacts resulting from a flood event. The methodology combines the hazard maps (inundation depth) with exposure data (land use/land cover, infrastructure) and vulnerability data (functions that estimate damage based on water depth). The following maps (Figure 2-19 and Figure 2-20) illustrate the final output of this analysis, presenting the potential economic damages (in million €) for each flood scenario. This approach not only identifies the areas in danger but also prioritizes the zones where the financial impact of the risk is most severe, providing a crucial evidence base for planning adaptation measures.

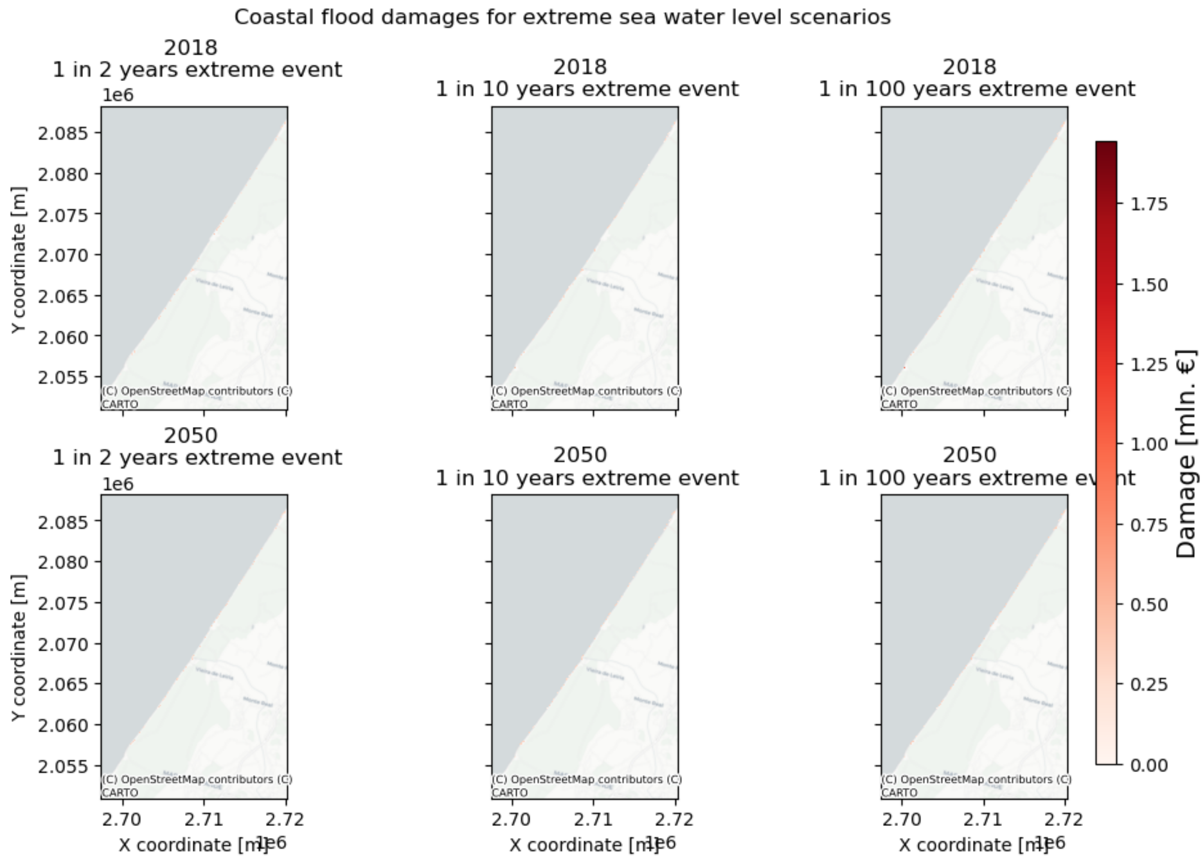


Figure 2-19 Coastal flood damages (mln. €) for extreme sea water level scenarios with different return periods (2, 10 and 100 years) compared (2018 and 2050) scenarios for Leiria Region

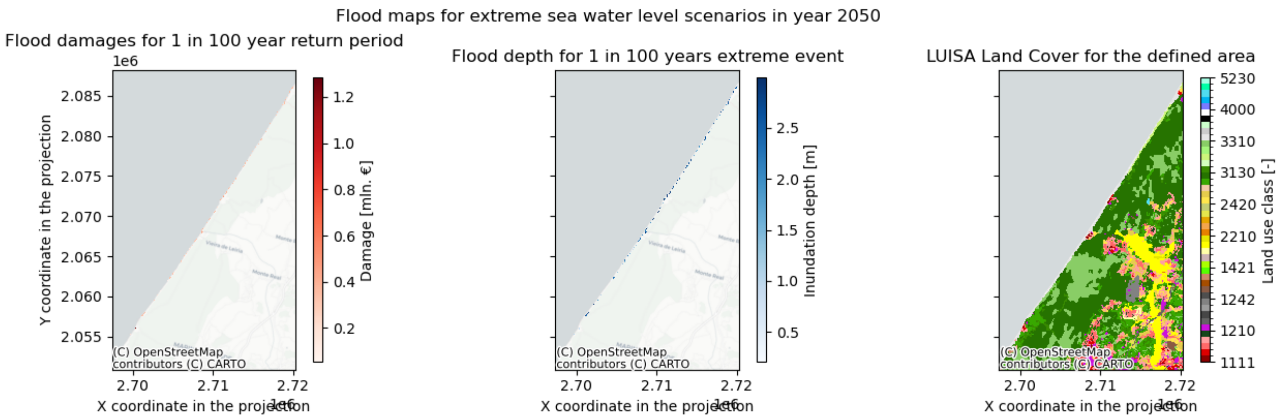


Figure 2-20 Maps of flood (inundation depth [m]) and associated damages (mln. €) for extreme sea water level scenarios in year 2050 for Leiria Region

2.4 Preliminary Key Risk Assessment Findings

2.4.1 Severity

The hazard and risk assessment reveals that the Leiria Region is exposed to multiple climate hazards, the impacts of which can be severe and, in some cases, permanent. Consequently, these hazards exert considerable pressure on forest and rural areas, agricultural activity, biodiversity, the regional economy, and, fundamentally, on the safety and quality of life of the population.

The severity of each of the main climate risks can be detailed as follows

- **Wildfires:** the hazard level is high, making it one of the most significant climate phenomena for the region. Future scenarios point to a substantial increase in days with high fire danger (FWI>30). Its consequences are serious and potentially irreversible, resulting in biodiversity loss, the destruction of forest ecosystems, and socioeconomic damages. The assessment identified critical "hotspots" where high hazard converges with the presence of vulnerable populations in the Wildland-Urban Interface (WUI) and with high ecological restoration costs.
- **Droughts:** the territory shows a high susceptibility to this hazard, with a projected increase in its frequency and intensity. In the agricultural sector, the analysis highlights a considerable financial risk for maize cultivation, as projections indicate worsening revenue losses in future scenarios. This scenario represents a direct threat to one of the pillars of the regional economy.
- **Heatwaves:** a considerable increase in the frequency, duration, and intensity of these extreme phenomena is foreseen. Their impact on human health is significant, especially for the most vulnerable groups, such as the elderly and children. The mapping of their concentration has identified areas requiring priority intervention. Additionally, heatwaves act as a risk multiplier, exacerbating drought conditions and worsening fire danger.
- **Coastal Floods:** the severity of this risk is concentrated in the territory's coastal strip. The detailed risk assessment highlights the potential for significant economic damage to infrastructure and assets resulting from coastal overtopping events. Scenarios projected for 2050 point to an increase in the extent of flood-prone areas and the magnitude of associated financial losses, with direct impacts on coastal communities and economic activities like tourism.

2.4.2 Urgency

The urgency for action is driven by both rapid-onset events and slow-developing processes, whose effects are expected to intensify considerably in the near future.

- **Wildfires and Coastal Floods:** these hazards are characterized by a rapid onset, which demands robust early warning and emergency response mechanisms. A high level of urgency is justified by projections showing a greater frequency of high-danger fire days and more intense coastal overtopping events, which are further aggravated by rising sea levels.
- **Heatwaves:** while their development can be gradual, the effects of heatwaves are acute and long-lasting. There is a high degree of urgency, given that projections show the hazard will significantly worsen in the near term (2011-2040) and will continue on an upward trajectory through the end of the century.
- **Droughts:** as a slow-onset hazard, droughts are defined by their persistent and cumulative impacts. The need for urgent planning arises from a clear trend of escalating risk over time, supported by projections for 2050 and 2080. This underscores the necessity of timely medium and long-term adaptation planning to safeguard water security and the viability of the agricultural sector.

2.4.3 Capacity

The region's response capacity is supported by a set of planning instruments, although it faces specific challenges that limit their effectiveness.

- **Existing measures:** at the regional level, the CIMRL has an Intermunicipal Climate Change Adaptation Plan. For the coastal zone, the Coastal Zone Management Plan (POOC) Ovar-Marinha Grande is a fundamental framework. At the local level, the ten municipalities are developing their Municipal Climate Action Plans (PMAC), which complement the existing Municipal Emergency and Civil Protection Plans (PMEPC).
- **Response capacity:** despite the instruments in place, the report identifies significant gaps that affect response capacity. Key issues include data gaps (lack of comprehensive, high-resolution local data), financial constraints that limit the implementation of measures, and low public awareness, which reduces community engagement. Additionally, difficulties are mentioned in coordination among different entities and in the integration of adaptation policies into existing spatial planning instruments.
- **Planned interventions:** the CLIMAAX4Resilience project aims precisely to address these gaps. Its actions plan to improve the risk analysis with higher-resolution data, build the capacity of local technicians and communities, strengthen inter-municipal cooperation, and, crucially, integrate the results of this assessment into strategic planning instruments, such as the PMACs and PMEPCs.

2.5 Preliminary Monitoring and Evaluation

This section describes the main lessons learned in the initial phase of the climate risk assessment, details the challenges encountered, summarizes stakeholder feedback, and identifies the needs for the next project cycle.

Lessons and most difficulties

The first phase of the project was a period of intensive learning. At a strategic level, participation in the CLIMAAX workshop was a fundamental milestone, as it allowed for the contextualization of the work developed in the Leiria Region within the scope of a broader European effort. At a methodological level, the most significant lesson was the importance of adopting a clear and structured workflow for each risk analyzed—wildfires, droughts, heatwaves, and coastal floods.

The main technical challenge lay in the availability and quality of input data. Although the CLIMAAX workflows operate with pan-European datasets, the analysis confirmed that these lack the spatial resolution and local specificity required for civil protection planning at the municipal scale. Consequently, the integration of high-resolution local data is the main methodological priority for Phase 2.

Stakeholders' engagement

The engagement strategy in Phase 1 focused on communicating preliminary results and preparing for a deeper collaboration in the next phase. To this end, an online questionnaire was developed, aimed at the main local actors identified by CIMRL. This approach allowed for the establishment of a robust technical baseline before moving on to a more active and intensive engagement model in Phase 2, in which stakeholders will play a decisive role in refining the assessment, aligning it with the territory's specificities and the operational needs of civil protection.

Data availability and requirements

The initial assessment identified critical gaps in data essential for the robustness of the results. To adapt the analysis to the needs of civil protection planning, the following baseline datasets are required: a consolidated and georeferenced history of civil protection incidents to validate susceptibility models; high-resolution topographic data (e.g., LiDAR) for the coastal zone, crucial for the precise modeling of coastal overtopping risk; and updated land use and land cover maps (e.g., COS) and forest fuel models, fundamental for calibrating wildfire spread models.

Regarding processing capacity, the initial computational challenge was overcome by migrating the analysis to a local development environment, ensuring the necessary capacity to handle high-resolution data. As for monitoring, the assessment would benefit from the expansion of networks in the Leiria Region, as well as from a careful analysis of the data generated by the current monitoring networks in the territory and other official high-resolution information, to determine how they can contribute to the improvement and refinement of the priority risks assessment.

The CLIMAAX4Resilience project will establish synergies with other projects promoted by CIMRL to mutually enhance their results.

2.6 Work plan

The work plan for the subsequent phases aims to deepen the climate risk assessment and develop adaptation strategies tailored to the territory, building upon the baseline established in Phase 1.

Phase 2: Refined regional/local high-resolution analysis and risk assessment: this phase will focus on enhancing the multi-risk assessment conducted in Phase 1, which, by predominantly using pan-European data, lacks the local specificity required for operational civil protection planning. Phase 2 aims to address this gap through the following main activities:

- **Collection and integration of high-resolution local data:** detailed local data will be compiled to enrich the risk models, including documentary sources such as the history of incidents, Municipal Emergency and Civil Protection Plans (PMEPC), and Municipal Climate Action Plans (PMAC). Additionally, an attempt will be made to integrate high-resolution cartographic data, such as LiDAR data for the coastal zone, the most recent Land Use/Land Cover Map (COS), and forest fuel models.
- **Improvement and validation of workflows:** the risk workflows will be refined and validated with the new local data. The results of Phase 1 and Phase 2 will be compared to assess the improvements achieved.
- **Co-creation with stakeholders:** intensive participatory processes will be implemented, which are essential for validating the models and aligning them with the operational needs of entities on the ground.

This phase will culminate in the delivery of the refined regional/local multi-risk assessment (D2).

Phase 3: Exploration of local adaptation strategies and improved risk management plans: based on the refined risk assessment, this phase will focus on proposing options and strategies for local adaptation to climate change, with the objective of strengthening regional adaptive capacity and improving existing risk management plans. To this end, the following steps will be executed:

- **Identification and assessment of adaptation options:** the identification and assessment of options will follow the logic of the Adaptation Support Tool (AST). A catalogue of relevant options for the Leiria Region will be created, which will then be assessed and prioritized through a multi-criteria analysis (MCA).
- **Stakeholder engagement:** regional and local stakeholders will be actively involved in the discussion, validation, and prioritization of adaptation options through participatory processes.
- **Integration into planning instruments**: the final goal is to reduce risks and increase the region's resilience by integrating the new information and strategies into strategic regional and local planning instruments, such as the PMACs and PMEPCs.
- **Capacity building and dissemination:** the final goal is to reduce risks and increase the region's resilience by integrating the new information and strategies into strategic regional and local planning instruments, such as the PMACs and PMEPCs.
- **Dissemination:** a final publication will be produced with the project's actions and results, and a public event will be held to present the conclusions to policymakers in the Leiria Region.

This phase will culminate in the delivery of the adaptation and improved risk management report (D3).

3 Conclusions Phase 1- Climate risk assessment

The first phase of the CLIMAAX4Resilience project has established a baseline multi-risk assessment for the Leiria Region. Through the application of the CLIMAAX methodology, this assessment has quantified the current and future impacts of four priority hazards: wildfires, droughts, heatwaves, and coastal floods. This initial phase confirms that the region faces high vulnerability to a set of interconnected climate risks, whose severity and frequency are projected to increase significantly throughout the 21st century. The findings presented here provide a robust scientific foundation to support strategic decision-making and guide the development of adaptation measures in the subsequent project phases.

The risk analysis yielded several critical findings that underscore the urgency for climate action in the region:

1. **Wildfires pose a severe and worsening threat:** the analysis confirms that wildfires are one of the most significant climate hazards for the region, a fact highlighted by its recent history, namely the devastating events of 2017. Projections from the Fire Weather Index (FWI) indicate a substantial increase in the number of high-danger days (FWI>30) across all future climate scenarios. The vulnerability assessment identified critical "hotspots" where high meteorological hazard intersects with sensitive populations (in the Wildland-Urban Interface), valuable ecosystems, and high restoration costs, constituting a systemic risk with potentially irreversible consequences.
2. **Droughts threaten water security and economic viability:** the region demonstrates a high susceptibility to droughts, with a clear trend of worsening risk. The agricultural drought assessment highlighted the considerable financial risk for maize cultivation, a local socioeconomic pillar, with projections pointing to a significant increase in revenue losses, especially in end-of-century scenarios.
3. **Heatwaves represent a growing public health risk:** the assessment revealed a considerable projected increase in the frequency, duration, and intensity of heatwaves. The risk is particularly acute due to the presence of vulnerable demographic groups, such as the elderly and children, and the vulnerability mapping has identified specific areas of higher population concentration that require priority intervention. Furthermore, heatwaves act as a risk multiplier, exacerbating drought conditions and wildfire danger.
4. **Coastal floods present a high-impact risk concentrated on the coastline:** the risk analysis demonstrated a severe and concentrated threat along the region's coastal strip. The detailed assessment quantified the potential for significant economic damage to buildings and infrastructure. Projections for 2050 indicate an increase in both the extent of the flooded area and the magnitude of potential financial losses, posing a direct threat to coastal communities and economic activities, such as tourism.

This initial phase successfully overcame several methodological and technical challenges while also identifying critical needs to be addressed in the next project cycle. Among the challenges overcome are the successful application of the CLIMAAX workflows for the four hazards, the establishment of a replicable assessment baseline, and the resolution of initial computational limitations.

The main priority for Phase 2 is the integration of high-resolution local data. The most significant finding of this phase was the realization that pan-European datasets, while useful, lack the local specificity required for operational planning. The central challenge will, therefore, be to acquire and integrate local data (e.g., LiDAR, incident records, COS) to refine and validate the risk models. Additionally, deepening co-creation with local stakeholders will be fundamental to ensure the final results are fully aligned with their operational needs.

In conclusion, Phase 1 has produced a comprehensive, albeit preliminary, climate risk assessment for the Leiria Region. The key findings reveal a territory facing an urgent and intensifying threat from multiple, interconnected climate hazards. The primary challenge moving forward is to bridge the gap between this strategic-level assessment and the operational needs of local decision-makers by enriching the analysis with local data and fostering deep stakeholder collaboration.

4 Progress evaluation and contribution to future phases

Phase 1 focused on the comprehensive application of the CLIMAAX Climate Risk Assessment (CRA) methodology, resulting in a preliminary risk baseline for the Leiria Region. Throughout this phase, and with the completion of this deliverable, the following milestones were achieved (Table 4-1): M2: Test the CLIMAAX workflows for the prioritized risks; M3: Workflows for the prioritized risks successfully applied; and M4: CLIMAAX common methodology for multi-risk climate assessment applied.

Table 4-1 Overview milestones

Milestones	*Progress*
M1: Subcontracting done (contract 1)	Achieved
M2: Test the CLIMAAX workflows for the prioritized risks	Achieved *(4 workflows tested)*
M3: Workflows for the prioritized risks successfully applied	Achieved *(4 workflows applied)*
M4: CLIMAAX common methodology for multi-risk climate assessment applied	Achieved
M5: High-resolution local data collected and compiled	Planned for Phase 2
M6: Workflows for the prioritized risks refined and improved	Planned for Phase 2
M7: Subcontracting done (contract 2)	Planned for Phase 3
M8: Potential regional/local adaptation options identified	Planned for Phase 3
M9: Stakeholders participatory processes carried out	Planned for Phase 3
M10: Regional/local adaptation options evaluated and prioritized	Planned for Phase 3
M11: Recommendations for improve risk management plans formulated	Planned for Phase 3
M12: Presentation of the results to policy and decision makers in Leiria Region (public final event)	Planned for Phase 3
M13: Attend the CLIMAAX workshop held in Barcelona	Achieved
M14: Attend the CLIMAAX workshop held in Brussels	Planned for Phase 3

In addition to these milestones, Phase 1 achieved (fully or partially) some of the key performance indicators (KPIs) defined for this phase, which contributed to the overall success of the project, notably: the completion of risk assessments for four identified hazards (Table 4-2).

Table 4-2 Overview key performance indicators

Key performance indicators	*Progress*
Phase 1	
[1] scoping exercise will be conducted to determine context, objectives and criteria of the regional climate risk assessments (CRAs)	Achieved
[1] set of climate change-affected hazards with substantial societal impact, known or projected in the Leiria sub-region, will be selected	Achieved
[2] risk workflows will be successful applied in Deliverable 1 (multi-risk climate assessment)	Achieved *(4 workflows applied)*
Phase 2	
[1] key risk assessment will be conducted to guide priorization of upcoming climate risk management strategies	Planned for Phase 2
[2] risk assessment will be refined and improved using local data of higher resolution on Deliverable 2 (refined regional/local multi-risk assessment)	Planned for Phase 2
[1] set of indicators for meteorological or hydrological hazards and societal or ecological impacts, suitable for designing and monitoring adaptation and risk management strategies, will be selected	Planned for Phase 2
Phase 3	
[1] regional adaptation strategy (Intermunicipal Climate Change Adaptation Plan) will be explored and improved	Planned for Phase 3
[10] local adaptation strategies (Municipal Climate Action Plans) will be explored and improved	Planned for Phase 3
[10] emergency and risk management plans will be improved based on the results of the risk and vulnerability assessment	Planned for Phase 3
KPIs common to all three phases (at the end of the project)	
	Achieved (partially)
More than 20 stakeholders will be engaged in the project's activities	Achieved (partially)
At least 5 communication actions will be implemented to disseminate the project's launch, the results of each of the 3 phases, and the final outcomes	Achieved (partially)
[1] public final event will take place to present the results to policymakers and decision-makers in the Leiria Region	Planned for the end of the project
[1] final publication, detailing the project's actions and results, will be produced	Planned for the end of the project
[3] policy briefs will be developed for political decision-makers, based on the results of each of the project's 3 phases	Achieved (partially)
[3] articles in regional media mentioning the project	Achieved (partially)

5 Supporting documentation

All outputs produced were shared in the Zenodo repository, following this structure:

- Main Report (PDF)
- Workflows outputs:
  - FIRE (FIRE.zip)
  - DROUGHTS (DROUGHTS.zip)
  - HEATWAVES (HEATWAVES.zip)
  - FLOODS (FLOODS.zip)