Deliverable Phase 1 – Climate risk assessment

Multi-risk Climate Assessment of the Alto Tâmega region to support decision-making on actions to adapt to climate change (CLIMAAX_AT)

Portugal, Alto Tâmega e Barroso

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Project name	Multi-risk Climate Assessment of the Alto Tâmega region to support decision-making on actions to adapt to climate change (CLIMAAX_AT)
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Table of contents

List of figures

List of tables

Abbreviations and acronyms

Abbreviation / acronym	Description
AWC	Soil Available Water Capacity
CIMAT	Intermunicipal Community of Alto Tâmega e Barroso
CLIMAAX	Climate Risk Assessment Framework/Project
CLIMAAX_AT	Multi-risk Climate Assessment of the Alto Tâmega region to support decision-making on actions to adapt to climate change
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-AT	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 Alto Tâmega e Barroso region, developed under the CLIMAAX_AT project. It was created 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 provides a scientific foundation to support strategic decision-making and guide the development of targeted adaptation measures in the subsequent phases of the project.

The main action undertaken in Phase 1 was the application of the CLIMAAX framework to the four priority climate hazards in the region: wildfires, droughts, heatwaves, and river floods. A preliminary risk assessment (scoping, exploration, and analysis) was conducted for each. An initial technical challenge related to computational capacity was successfully overcome by migrating the analysis environment to a local server, ensuring the necessary capacity for high-resolution data 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 frequent 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, signifying a systemic risk with potentially irreversible consequences.
- **Droughts threaten water security and economic viability:** the region has a high susceptibility to droughts. The agricultural drought assessment, which analyzed six key crops (maize, wheat, potato, bean, barley, and sorghum), revealed widespread financial risk. This is particularly evident in the results for the emblematic potato crop, with projections showing significant yield and revenue losses, threatening a key socio-economic pillar of the region.
- **Heatwaves represent a significant and 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 high percentage of elderly residents (over 27.61%). Heatwaves also act as a risk multiplier, exacerbating drought conditions and wildfire danger.
- **River floods present a high-impact, concentrated threat**: rhe flood risk analysis quantified the potential for significant economic damage to buildings and critical infrastructure, particularly in the urban area of Chaves. A substantial human impact was identified, with an expected annual displaced population of approximately 386 people.

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

Phase 1 confirms that the Alto Tâmega e Barroso region faces 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 local operational needs. The project's future success will depend on integrating high-resolution local data and fostering deep stakeholder collaboration to translate this analysis into effective adaptation actions.

1 Introduction

1.1 Background

Located in the north of mainland Portugal, the Alto Tâmega e Barroso region has a territorial area of approximately 2,922 km², covering 6 municipalities: Boticas, Chaves, Montalegre, Ribeira de Pena, Valpaços, and Vila Pouca de Aguiar (Figure 1-1). According to data from the 2021 Census by the Portuguese National Institute of Statistics (INE), it had a resident population of 84,248 inhabitants, which corresponds to approximately 2.4% of the population of the North region of Portugal.

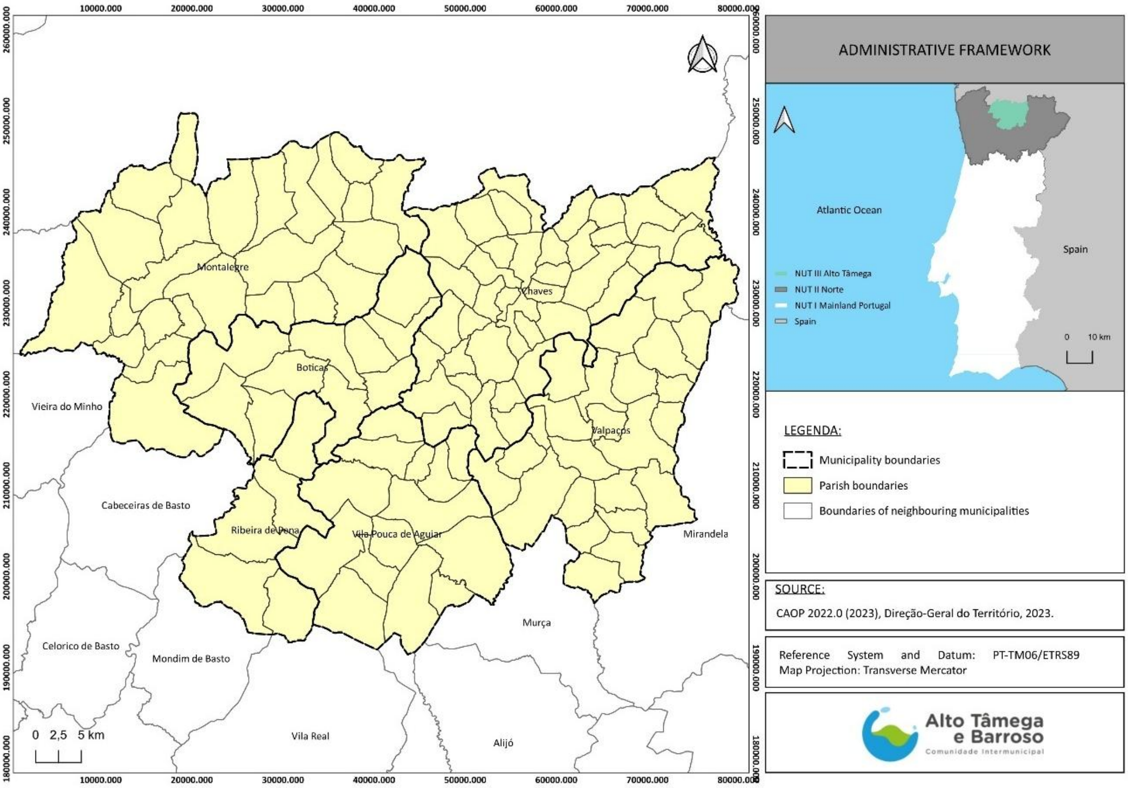


Figure 1-1 Geographic Location of the Alto Tâmega e Barroso region

The Intermunicipal Community of Alto Tâmega e Barroso (CIMAT), the beneficiary of the CLIMAAX_AT project, operates within the NUT III Alto Tâmega e Barroso region.

The CIMAT's mission is to define, promote, plan, and implement strategies for the economic, social, and environmental development of the territory. It also aims to coordinate actions between municipalities and central administration services in strategic areas with particular needs for preparedness for climate change, such as safety and civil protection, or spatial planning and nature conservation.

The main climate risks in the Alto Tâmega e Barroso region is: an increase in the average annual temperature, especially maximum temperatures; a decrease in average annual precipitation and an increase in extreme precipitation events; and wildfires.

The average annual temperature is expected to rise by 2°C to 4°C by the end of the century. This increase is associated with heatwaves, defined as periods of six consecutive days where the maximum air temperature exceeds the average daily maximum temperature of the reference period by 5°C. Heatwaves in the Alto Tâmega and Barroso region have a significant impact, exacerbating droughts and the risk of wildfires, as well as compromising public health, especially among vulnerable populations. These events also affect agriculture and reduce water availability, putting pressure on water resources.

The decrease in average annual precipitation, coupled with heatwaves, contributes to water scarcity and leads to drought periods. Droughts result from regional climate fluctuations, creating adverse weather conditions and periods of low or no rainfall. Furthermore, the alternation between drought periods and intense rainfall increases the risk of flooding and contributes to soil erosion, placing significant pressure on infrastructure and ecosystems.

The Alto Tâmega region has one of the largest continuous stands of maritime pine (*Pinus pinaster*) in Portugal. It is estimated that 23% of the Alto Tâmega territory is covered by maritime pine, which is highly significant due to its ecological and economic value. With 57,000 hectares, it is the predominant species in the region. However, this characteristic makes the Alto Tâmega e Barroso region more susceptible to wildfires, which are predicted to become more severe and extensive in terms of area and duration due to climate change.

1.2 Main objectives of the project

The main goal of the CLIMAAX_AT project is to increase the Alto Tâmega region's resilience to climate change. It aims to achieve this by empowering local communities, strengthening monitoring and research on climate risks, implementing effective adaptation and mitigation strategies, and promoting inter-municipal cooperation for a coordinated and sustainable response.

The specific objectives of CLIMAAX_AT include:

- Improve the identification, spatial analysis, and monitoring of climate risks in the Alto Tâmega e Barroso region by implementing the CLIMAAX methodological framework and accessing its toolbox, thereby developing adaptation strategies based on scientific data;
- Raise awareness and build capacity among the local population and economic agents regarding the impacts of climate change and best adaptation practices, through training actions, workshops, and communication campaigns;
- Integrate the results of climate risk assessment into regional and local strategic planning instruments, adapting them to the region's climate vulnerabilities, including wildfires, water scarcity, and floods, ensuring a rapid and effective response to crises;
- Promote inter-municipal cooperation and co-responsibility among local stakeholders, fostering the exchange of knowledge and experiences to address climate challenges in an integrated manner;
- Develop strategies for the sustainable management of natural resources, especially water and soil, aiming to reduce desertification and erosion, and ensure the region's water security;
- Stimulate the adaptation of the local economy to new climate conditions, encouraging resilient agricultural and livestock practices, promoting economic diversification, and valorizing the region's endogenous resources.

To achieve these objectives, the project can bring several benefits, reducing the region's vulnerability to climate change by increasing knowledge and awareness of associated risks. Key contributions include:

- **Monitoring and Research:** Access to the CLIMAAX methodology (harmonized and comparable at a European scale) and resources will facilitate studies on climate change impacts in the region. This will allow for a better assessment and understanding of risks, and the development of more effective mitigation and adaptation strategies.
- **Increased Local Capacity Building:** Through workshops and participatory processes, CIMAT can empower local communities and economic stakeholders in best practices for risk management and adaptation, enabling them to become more resilient.
- **Awareness and Education:** Conducting awareness campaigns will inform the population about climate change risks, particularly rural fires and droughts, and promote concrete actions that can be taken at individual and community levels.
- **Encouraging Inter-municipal Collaboration:** This project can consolidate cooperation among the six municipalities in the region, allowing for an integrated approach to facing climate challenges through the sharing of experiences and resources.
- **Promoting Co-responsibility Among Local Stakeholders and the Community:** This will be achieved by ensuring participatory processes, as advocated by the CLIMAAX methodology.
- **Improving Risk Management Instruments:** CIMAT will be able to develop and implement management plans for wildfires and other phenomena, ensuring a faster and more effective response in crisis situations, in addition to reviewing, updating, and improving currently active plans.

The additional knowledge promoted by the project will contribute to a greater, more organized, and planned response capacity, minimizing the chances of error.

1.3 Project team

The internal team of CLIMAAX_AT project is composed of:

- Carla Varandas has a degree in Civil Engineering, with a specialization in Environment and Land-Use Planning;
- José Barros has a degree in Forestry Engineering and a postgraduate degree in Forest Resources Engineering;
- César Baltazar has a degree in Geography and Regional Planning and a postgraduate degree in Land Management, with a specialization in Planning and Land-Use Planning

The supporting team (subcontracted – external support) of CLIMAAX_AT 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 and water scarcity, wildfires, heatwaves and river 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

During the scoping phase of the climate risk assessment, objectives (the analysis's desired results) and context (implementation conditions) are established, and stakeholders crucial for project preparation are identified.

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 goal is to ensure that all regional/local climate risk assessments funded under the CLIMAAX project share a common configuration for calculating the expected change in terms of risks and impacts, using a unified methodological approach. This will allow assessment results to be compared at a regional/local scale across Europe.

The Climate Risk Assessment (CRA) for the Alto Tâmega region aims to thoroughly evaluate the threats and risks climate change poses to its environment, economy, and society. This endeavor is central to the CLIMAAX_AT project's core objective: to significantly boost the region's resilience to these changes. To achieve this, the project will focus on empowering local communities, strengthening the monitoring and research of climate-related risks, implementing effective adaptation and mitigation strategies, and fostering inter-municipal cooperation to ensure a cohesive and sustainable response.

The study will help to:

- **Identify the most vulnerable areas and sectors**: By deepening the understanding of specific climate risks, the CIMAT will be able to pinpoint the most vulnerable areas and sectors, such as agricultural zones at higher risk of drought or areas more prone to floods;
- **Develop tailored adaptation strategies**: Understanding vulnerability will allow for the creation of specific action plans for different sectors, such as protecting forest areas from fires or improving water management.

To date, the main difficulties in adapting to and assessing climate risks stem from the lack of a real-time monitoring platform for climate risks and, consequently, a rapid response to them. Challenges in regional coordination also exist, especially when different priorities and resources are available. There is also some resistance to change, particularly in daily practices and habits at the local level.

The CRA's findings are expected to support regional planning, infrastructure investments, emergency preparedness, and long-term sustainability policies. By providing reliable, evidence-based information, the CRA directly contributes to policy formulation and decision-making, enabling both reactive and proactive responses to climate change.

However, the CRA 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 analysis. Additionally, uncertainties inherent in climate models and socio-economic scenarios can impact the predictability of long-term risks. Furthermore, legal and institutional barriers may hinder the implementation of adaptation measures, as existing regulations might not fully align with emerging climate realities.

2.1.2 Context

The Alto Tâmega region is highly vulnerable to the impacts of climate change due to several environmental and socioeconomic factors. Its impact varies significantly across municipalities, which exhibit distinct climatic characteristics due to differences in altitude, topography, and proximity to water bodies. Within the scope of studies already conducted by CIMAT, some challenges associated with climate change will be common to all six municipalities, while others will be specific to a location or municipality, such as water scarcity being more severe in the municipality of Valpaços and floods in the urban area of Chaves.

The main challenges identified in the territory through CIMAT's previous studies include:

- **Rising temperatures**: The region may experience sharper increases than the national average, negatively impacting agriculture, water resources, and public health.
- **Reduced precipitation, especially in summer**: This could intensify desertification, rural fires, and water scarcity, affecting mountainous and rural areas. It also leads to decreased river flows and an increased frequency of droughts, which compromise agriculture and hydroelectric power production – both essential to the local economy.
- **Extreme weather events**: Increased storms, heatwaves, and wildfires directly affect local communities and ecosystems.
- **Desertification and soil degradation**: This is particularly prevalent in mountainous and forested areas, which are especially vulnerable, especially after fires.

The National Territorial Cohesion Program further highlights the economic and social fragility of inland regions, which rely on agriculture and livestock, making them susceptible to climate change. Demographic vulnerability, exacerbated by aging populations and depopulation with losses of 10% between censuses, hinders the adaptation and resilience of communities.

It's also worth noting that the region's Vulnerability Index (NUTS III) is higher than the European average, with the same being true for the NUTS II (North) index.

For the Alto Tâmega region, CIMAT has been promoting various studies and projects related to climate change. At the municipal level, key initiatives include the development of Municipal Climate Action Plans, Forest Defense Plans Against Fires, and Emergency and Civil Protection Plans. Meanwhile, at the regional level, notable efforts include the Intermunicipal Climate Change Adaptation Plan, the Climate Change Impacts Investigation study, the implementation of energy communities based on biomass utilization, and the development of a support tool for the cross-border carbon exchange market.

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**, **droughts, heatwaves** and **river floods**.

According to Portugal's Climate Framework Law (Lei n.º 98/2021, of December 31), the climate governance structure for the Alto Tâmega region is based on the governance framework recommended in the Municipal Climate Action Plans (PMACs) of CIMAT's municipalities. This approach fosters synergy, coherence, and complementarity among instruments, and subsequently, operational effectiveness, which is fundamental for defining and ensuring the success of common climate policies.

The most vulnerable sectors to climate change in the region are highlighted by 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, and the Safety of People and Property:

- **Agriculture** faces soil erosion and water stress due to rising temperatures and decreased rainfall.
- **Biodiversity and forests** are threatened by ecosystem degradation and an increase in wildfires.
- **Human health** is at risk of increased morbidity and mortality from heatwaves, as well as vector-borne diseases.
- **The Safety of People and Property** is endangered by extreme events like floods, inundations, and fires.

A key aspect of the region's governance context is the articulation between local needs and national strategic instruments. Of note are the Landscape Reorganization and Management Programs (PRGP), a national policy focused on increasing landscape resilience, particularly to the threat of wildfires.

Although two existing PRGPs partially cover the CIMAT territory (the PRGP of Serra da Cabreira e Serras do Larouco e Barroso; and the PRGP of Terra Fria Transmontana), their limited geographical scope is a significant constraint, failing to address adaptation challenges in an integrated manner at the regional scale. Aware of this gap, the CIMAT has taken on a proactive advocacy role for regional interests. During the consultation process for the 'Plano de Investimento Florestal 2050' (Forest Investment Plan 2050), a national strategic investment plan, CIMAT submitted a formal proposal to the relevant government bodies. The proposal advocates for the creation of a PRGP that covers the entire Tâmega Valley. This strategic vision aims to ensure that a key national policy instrument is applied at a coherent territorial scale, thereby maximizing its effectiveness for climate adaptation and risk management throughout the entire region.

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.

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 multi-hazard climate change assessment in 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 the results, aligning them with the specific characteristics of the sub-region.

This approach will maximize the potential of CLIMAAX results to improve regional climate and emergency risk management plans and to support informed decision-making.

Key stakeholders identified are:

- CIMAT, as the coordinating entity responsible for the management and implementation of the project;
- The 6 municipalities, which play a crucial role due to their direct involvement with communities and their ability to implement local policies that promote risk mitigation, climate resilience and sustainability. These will be the main stakeholders and direct beneficiaries, as they will use the climate risk assessment data to improve their Municipal Climate Action Plans (PMAC) and Municipal Emergency and Civil Protection Plans (PMEPC);
- The local community, which will be directly affected by the increased awareness of climate risks and the empowerment for individual and collective action, with increased security and resilience to climate change, improving quality of life;
- Municipal technicians, with access to learning and knowledge tools that allow them to better plan;
- Emergency and civil protection services, whose teams will benefit from more robust plans adjusted to the specificities of the territory to respond to emerging situations.

Interaction with stakeholders will be ensured through:

- Participatory processes, ensuring stakeholder involvement at all stages of the methodology, from risk identification and analysis to assessment and monitoring;
- Awareness-raising actions to increase 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 sub-region, through a final public event.

Priority vulnerable territories include areas prone to wildfires, water scarcity, and heatwaves, manifesting as zones with a larger thermal discomfort gap or high energy poverty. In terms of population groups, special attention is given to the elderly (aged 65 or over), who represent 27.61% of CIMAT's resident population and are more susceptible to risks like heatwaves and diseases. Equally vulnerable are children, pregnant women, and immunocompromised or chronically ill individuals. Economically disadvantaged communities, such as those with lower incomes or high unemployment rates, and groups with low levels of education or who are renters, also demonstrate a lower adaptive capacity.

Risk ownership in the Alto Tâmega region is a shared responsibility, regulated by inter-municipal and local governance frameworks with clearly defined roles between CIMAT and its municipalities. The acceptable level of risk will be determined through a consensus-building approach that involves technical experts and local stakeholders, weighing the feasibility of measures against community expectations. The goal is to reduce risks to an acceptable minimum, in alignment with public safety standards and regional resilience goals. To ensure transparency, the results of the Climate Risk Assessment (CRA) will be communicated clearly and accessibly to local decision-makers, civil society representatives, and the general public through workshops, publicly accessible reports, and online platforms.

2.2 Risk Exploration

The risk exploration phase in the Alto Tâmega 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 CIMAT, 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 include: increase in average annual temperature; increased frequency and intensity of heatwaves; decrease in average annual precipitation; increase in extreme precipitation events, which can lead to more intense floods and flash floods; increased meteorological risk of wildfires and an extended critical season; and sharp decrease in the number of frost days.

These hazards translate into priority potential risks for the territory:

- **Wildfires:** these are the most prevalent climate event in the region, corresponding to about 61% of the occurrences recorded between 2005 and 2022. The increased risk of fires leads to biodiversity loss, promotes more flammable shrub formations, causes soil water erosion, and contaminates water with ash.
- **Droughts:** a large part of the territory shows high susceptibility, especially in the northern and eastern sectors where precipitation is significantly lower. Historical records show a very significant increase in these occurrences, accounting for about 37% of the climate events recorded between 2005 and 2022.
- **Desertification and Soil Erosion:** the susceptibility to soil water erosion is high in 66.5% of the CIMAT area, particularly in areas with steep slopes. Wildfires followed by drought can prevent vegetation from regenerating and worsen erosion.
- **Plant and Animal Health:** the emergence and different evolution of new pests and diseases, or the proliferation of existing ones, is expected. Climate change can lead to an increase in the population and distribution of insect vectors carrying diseases in major game species, and affect livestock, a source of wealth for the region.
- **Vectors Transmitting Human Diseases:** climate change can increase the incidence of infectious diseases transmitted by vectors. At-risk groups include children (11.35% of the population aged 0-14) and the elderly (27.61% of the population aged 65+).
- **Heatwaves:** the projections for the region point to a considerable increase in the frequency and duration of these events. The number of summer days (with a maximum temperature ≥

25°C) may increase, as well as very hot days (maximum temperature ≥ 35°C) and tropical nights (minimum temperature ≥ 20°C). These occurrences exacerbate droughts and the risk of rural fires (wildfires), and compromise public health, especially among vulnerable populations, leading to increased morbidity and mortality during periods of intense heat.

- **River Floods:** occurrences of "flooding from heavy rainfall" accounted for 536 of the total events recorded in the region between 2005 and 2022. The municipality of Chaves, particularly its urban area, is prone to flooding, accounting for 64% of flooding from heavy rainfall events and 50% of river flood events. Future projections indicate an increase in extreme precipitation events, particularly intense or very intense rainfall, and more severe winter storms, which will lead to a higher number of flooding episodes during the winter.

2.2.2 Workflow selection

The CLIMAAX_AT project applies the CLIMAAX framework using 4 targeted workflows to assess the most pressing climate risks in the Alto Tâmega region: wildfires, droughts, heatwaves and river 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 region has generally been heavily affected by incidents related to wildfires. Forest areas are particularly sensitive to fires, with the main forest types in the region being maritime pine forests, other oak forests, and other broadleaf forests. In rural areas, forest entrepreneurs and people who rely on agricultural practices are also particularly 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 and water scarcity. As a result, agricultural areas and the agricultural sector are highly 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 is particularly vulnerable to the risk of heatwaves, which have been increasing in frequency and intensity. 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: River Floods

The region is susceptible to river floods and intense rainfall inundations, with these occurrences being recorded. The municipality of Chaves, particularly its urban area, is the most affected by these events, which primarily impact urban areas and areas adjacent to rivers. Impacts damage to infrastructures such as energy networks, transport, and communications, also affecting built heritage, economic and social activities, and the safety of people and property. Vulnerability is concentrated on the inhabitants and socioeconomic activities of urban and riverside areas.

2.2.3 Choose Scenario

For the CLIMAAX_AT 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).
- **River 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 10 years, 1 in 50 years, 1 in 100 years, 1 in 200 years, 1 in 500 years (considering 2030, 2050, 2080).

2.3 Risk Analysis

This chapter presents how the selected CLIMAAX risk workflows were applied in the Alto Tâmega e Barroso region. For each workflow, the methodology and datasets used for the assessment of hazards, exposure, and vulnerability were summarized, resulting in spatial risk outputs.

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 socioeconomic 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.

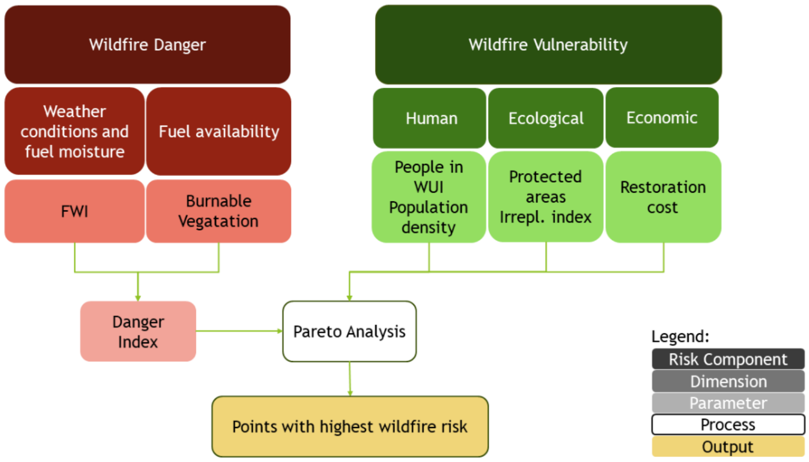


Figure 2-1 Representation of the risk assessment methodology and lists the parameters used to define each risk component. Figure source: CLIMAAX

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.*

Hazard assessment

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.

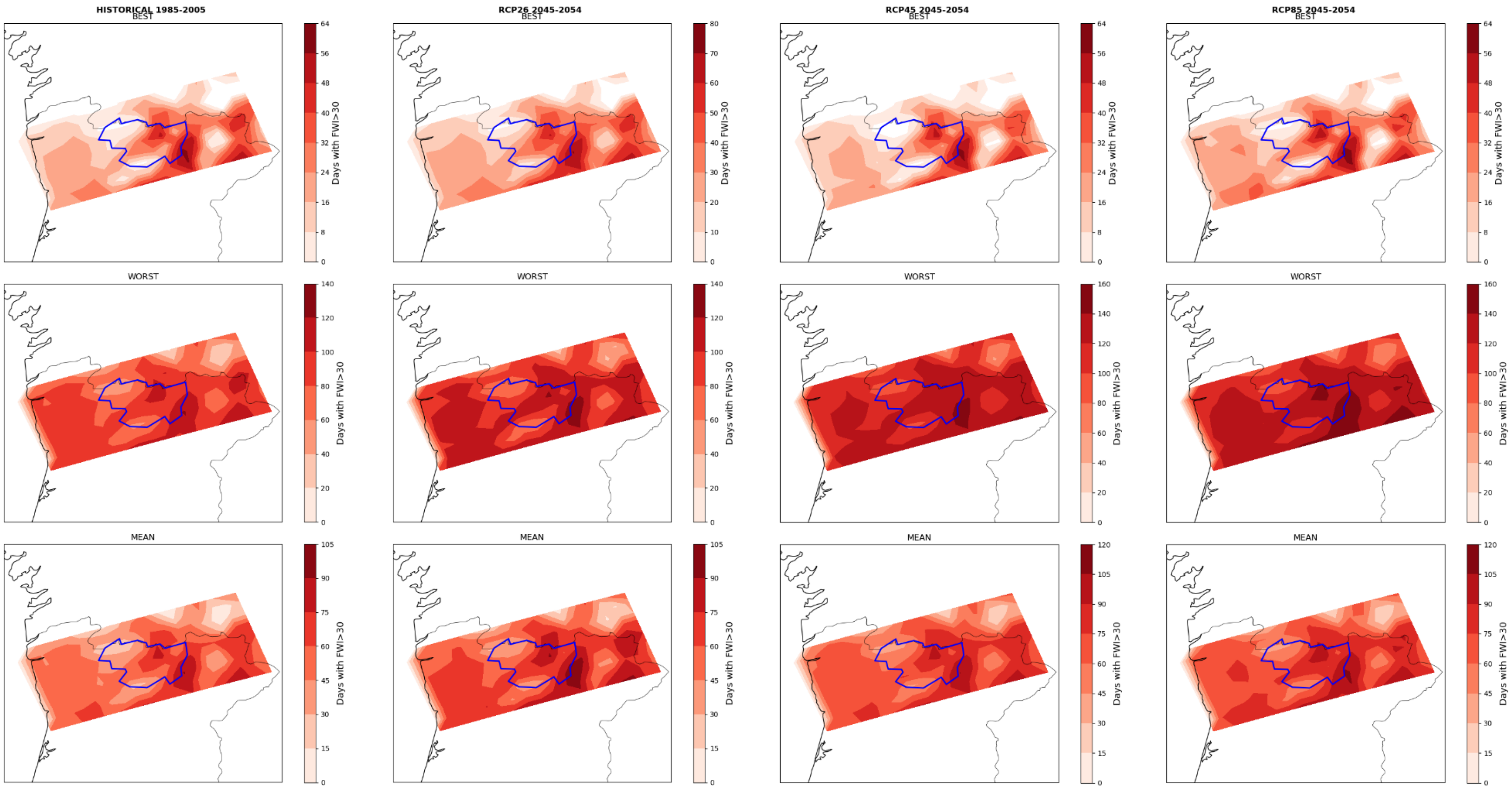


Figure 2-2 Annual number of days with FWI > 30 in the Alto Tâmega e Barroso region, comparing the historical baseline (1985-2005) with future scenarios (RCP 2.6, 4.5, and 8.5) for best, worst, and average cases.

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.

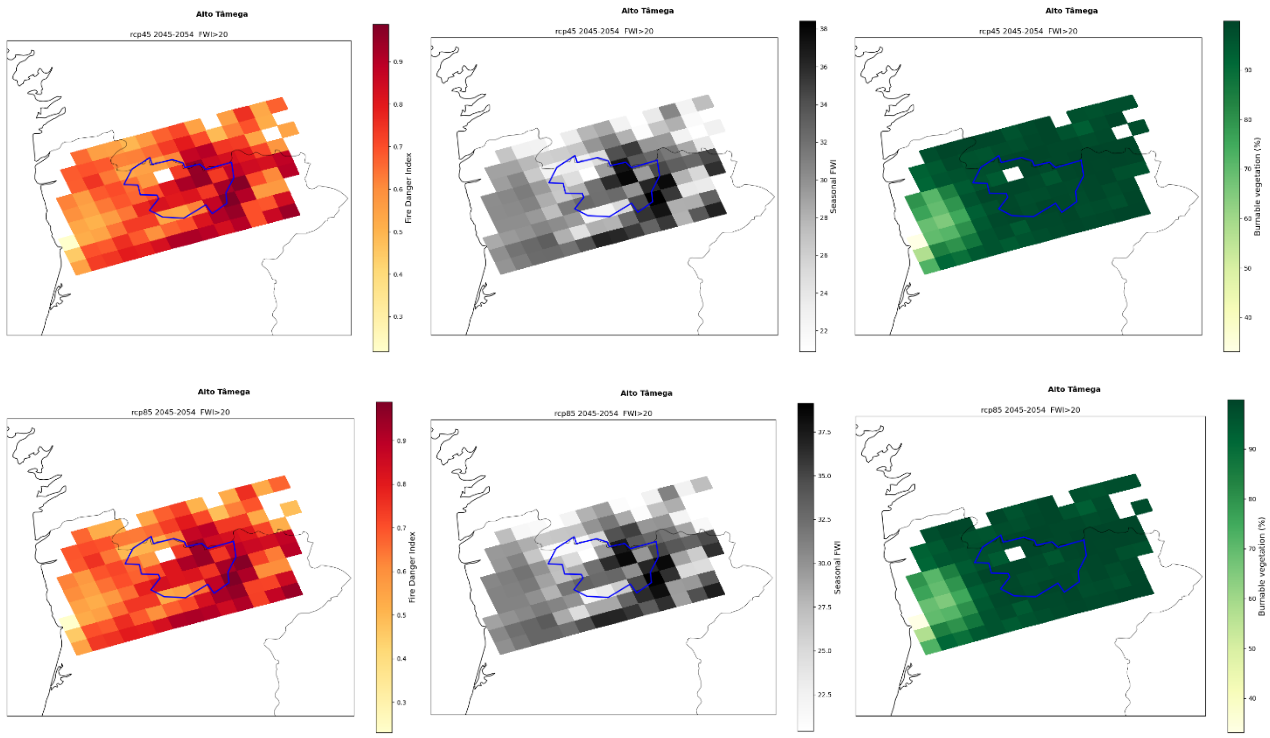


Figure 2-3 Fire Danger Index (days with FWI > 20), Seasonal FWI, and Burnable Vegetation (%) in the Alto Tâmega e Barroso region, projected for the 2045-2054 period under RCP 4.5 and 8.5 scenarios. [1]

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).

[1] The data gap pixel corresponds to the location of the Alto Rabagão reservoir. In the land cover data resampling process, this area was classified as a 'Water Body'. Consequently, it was automatically excluded from the analysis, as the wildfire risk model does not consider areas with no burnable vegetation.

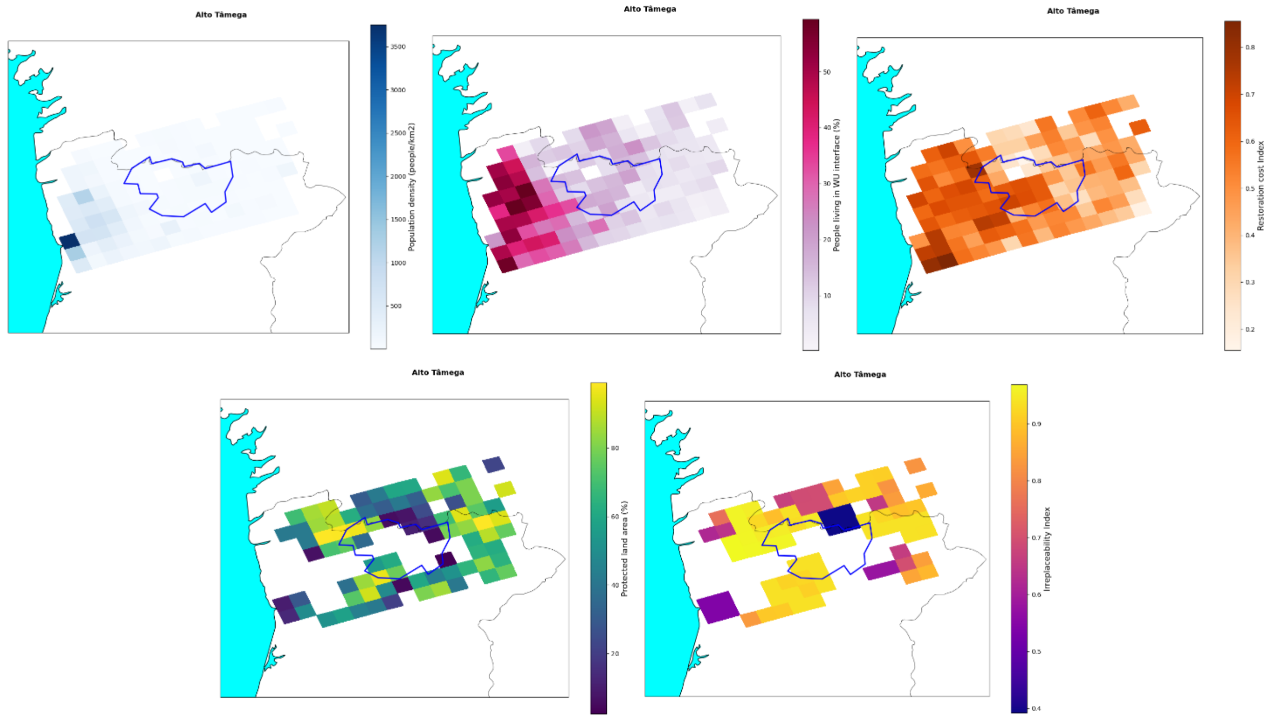


Figure 2-4 Key socio-economic and ecological vulnerability indicators for wildfire risk assessment: Population Density, People living in the WUI (%), Restoration Cost Index, Protected Land Area (%), and the Irreplaceability Index.

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.

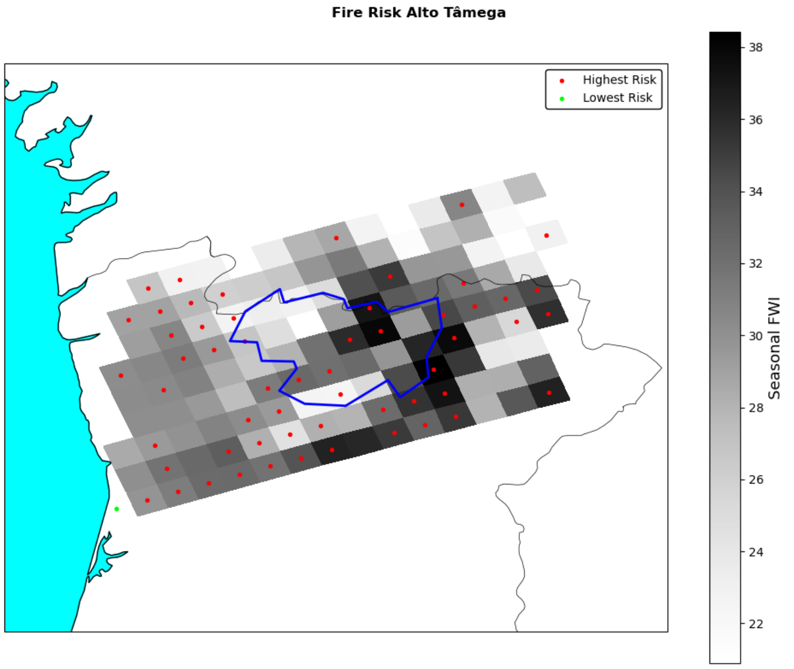


Figure 2-5 Fire risk (Seasonal FWI) in the Alto Tâmega e Barroso region.

The results clearly indicate a significant worsening of wildfire danger, with a projected increase in the frequency of days with high fire danger (FWI>30) across all future scenarios. The final risk map (Figure 2-5) synthesizes this threat, identifying several critical hotspots (red dots). These hotspots are predominantly located in the central and eastern parts of the region, where high meteorological danger coincides with areas of significant socio-economic and ecological vulnerability, such as the Wildland-Urban Interface (WUI) and protected areas.

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.

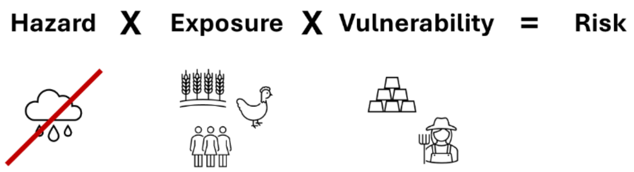


Figure 2-6 Methodology of the relative drought workflow. Figure source: CLIMAAX

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).*

<u>Hazard assessment</u>

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 Alto Tâmega e Barroso, comparing it with the other NUTS3 regions in Northern Portugal (Figure 2-7). This analysis allows for the positioning of the region's hazard severity within the broader territorial context.

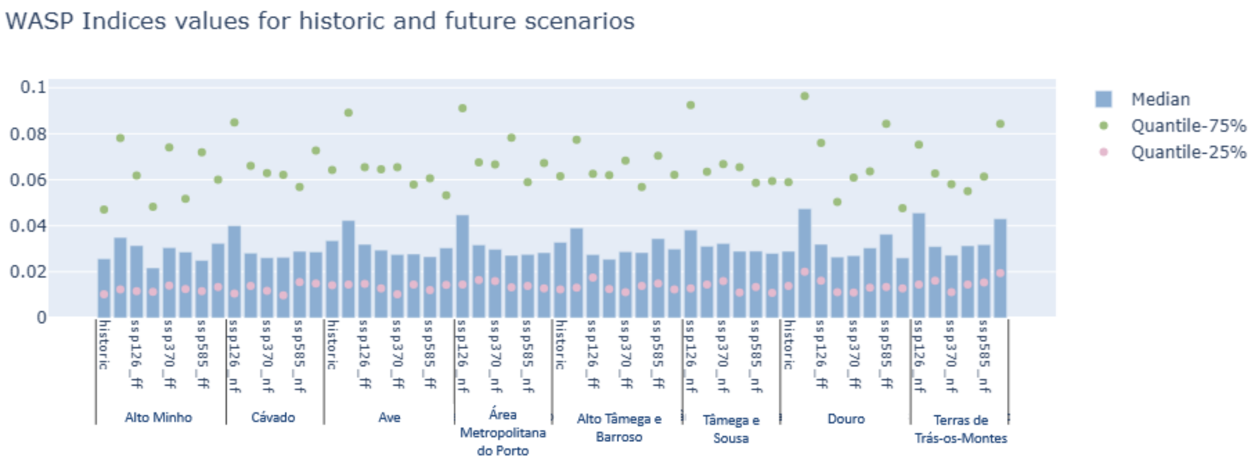


Figure 2-7 Statistical distribution of the drought hazard index (WASP) for the NUTS3 regions in the historical period.

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 Alto Tâmega e Barroso, showing its evolution for different future socioeconomic and climate scenarios (SSP-RCPs) and comparing it with neighboring regions.

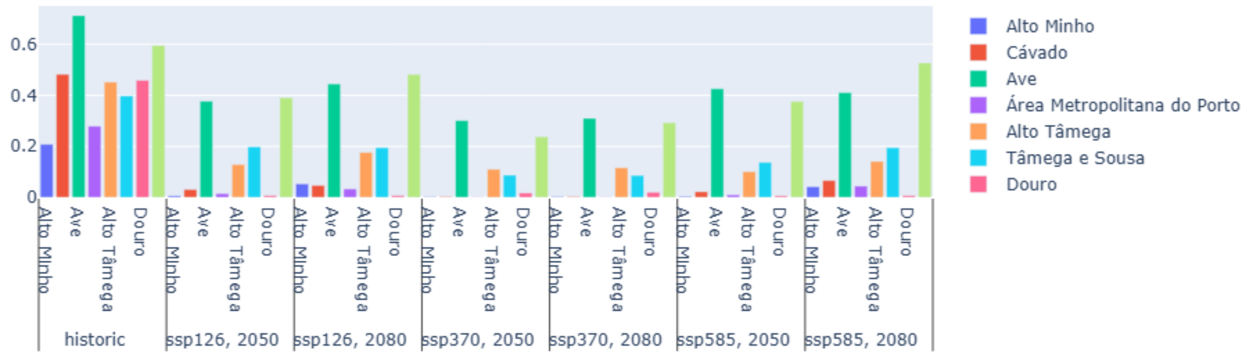


Figure 2-8 Relative drought risk index for the NUTS3 regions, comparing the historical period with future projections for different scenarios (SSP-RCPs).

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.

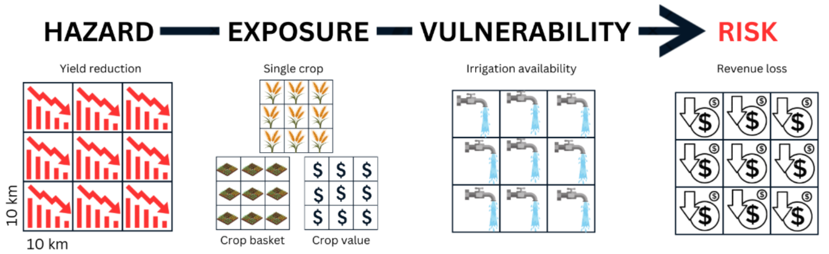


Figure 2-9 Methodology of the agricultural drought workflow. Figure source: CLIMAAX

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.*

Hazard assessment

The agricultural drought hazard assessment analyzes how climatic changes impact crop productivity. The analysis was conducted for six crops available within the CLIMAAX workflow: maize, wheat, potato, bean, barley, and sorghum. For the purpose of this report and in the interest of synthesis, the results for the potato crop are presented in detail, as it is considered emblematic and of high socio-economic importance to the region. It should be noted that other critical regional crops, such as chestnut, olive, and vineyard, could not be assessed as they are not currently available in the CLIMAAX workflow. The complete results for all six analyzed crops are available in the project's supporting documentation repository.

The analysis begins by characterizing the baseline soil condition (Figure 2-10), and then combines it with climate projections (such as precipitation and evapotranspiration) to calculate the final hazard indicator: the relative yield loss (%), as illustrated in Figure 2-11 for the potato crop.

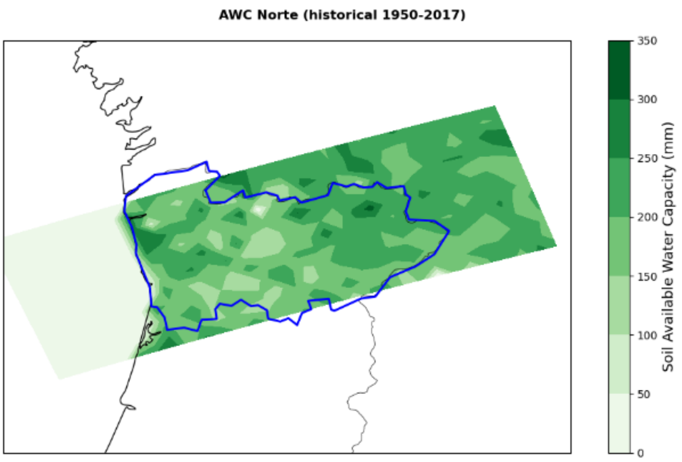


Figure 2-10 Soil Available Water Capacity (AWC), representing the baseline condition for the agricultural drought analysis.

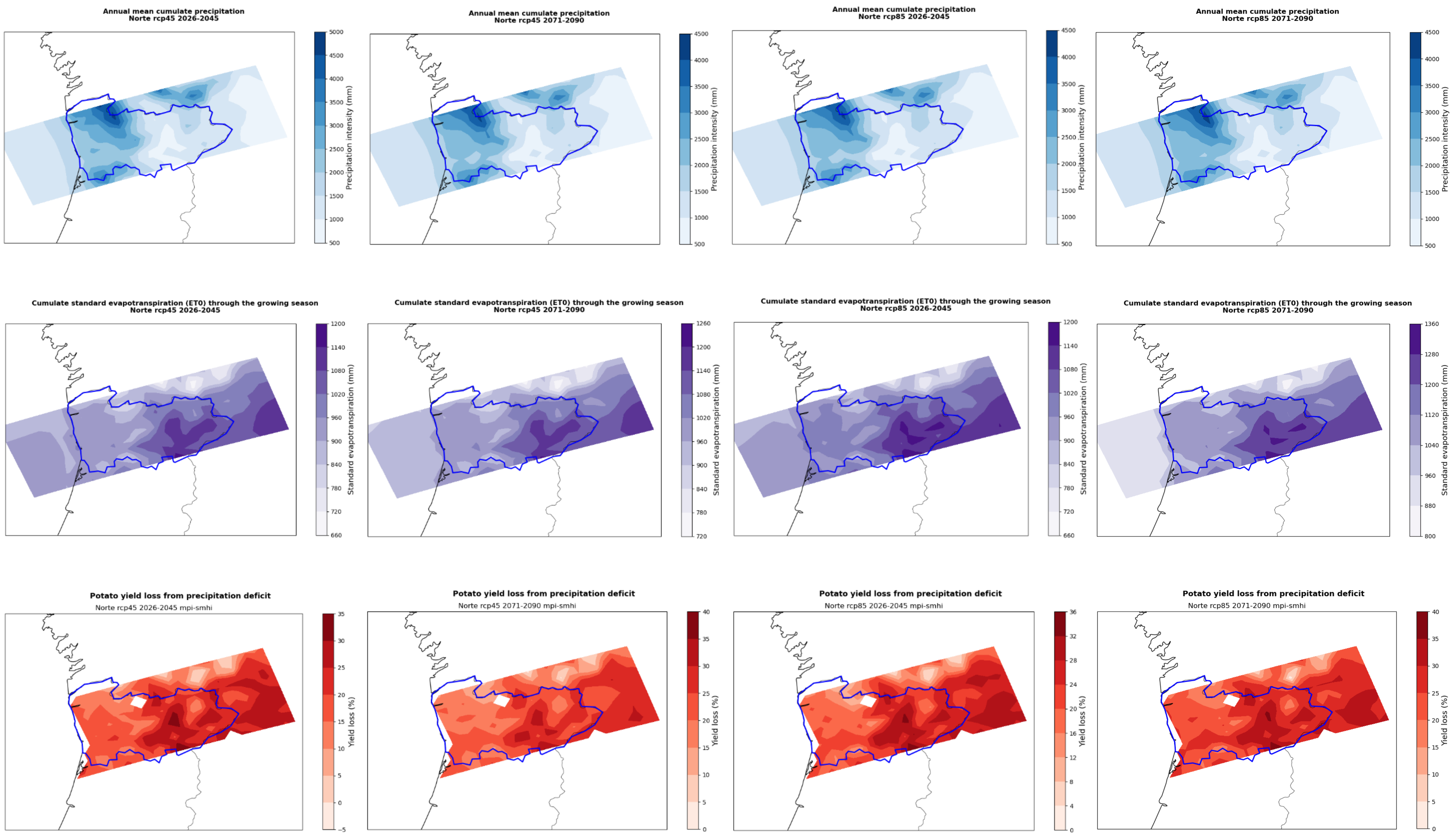


Figure 2-11 Projections of climatic variables and their impact on potato productivity for future scenarios (RCP 4.5 and 8.5). [2]

[2] The data gap pixel corresponds to the location of the Alto Rabagão reservoir. Due to the base data resampling process, this area was classified as having 'zero available water capacity'. As such, it was excluded from the agricultural drought model's calculations, which only analyzes areas with productive potential.

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 potato 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).

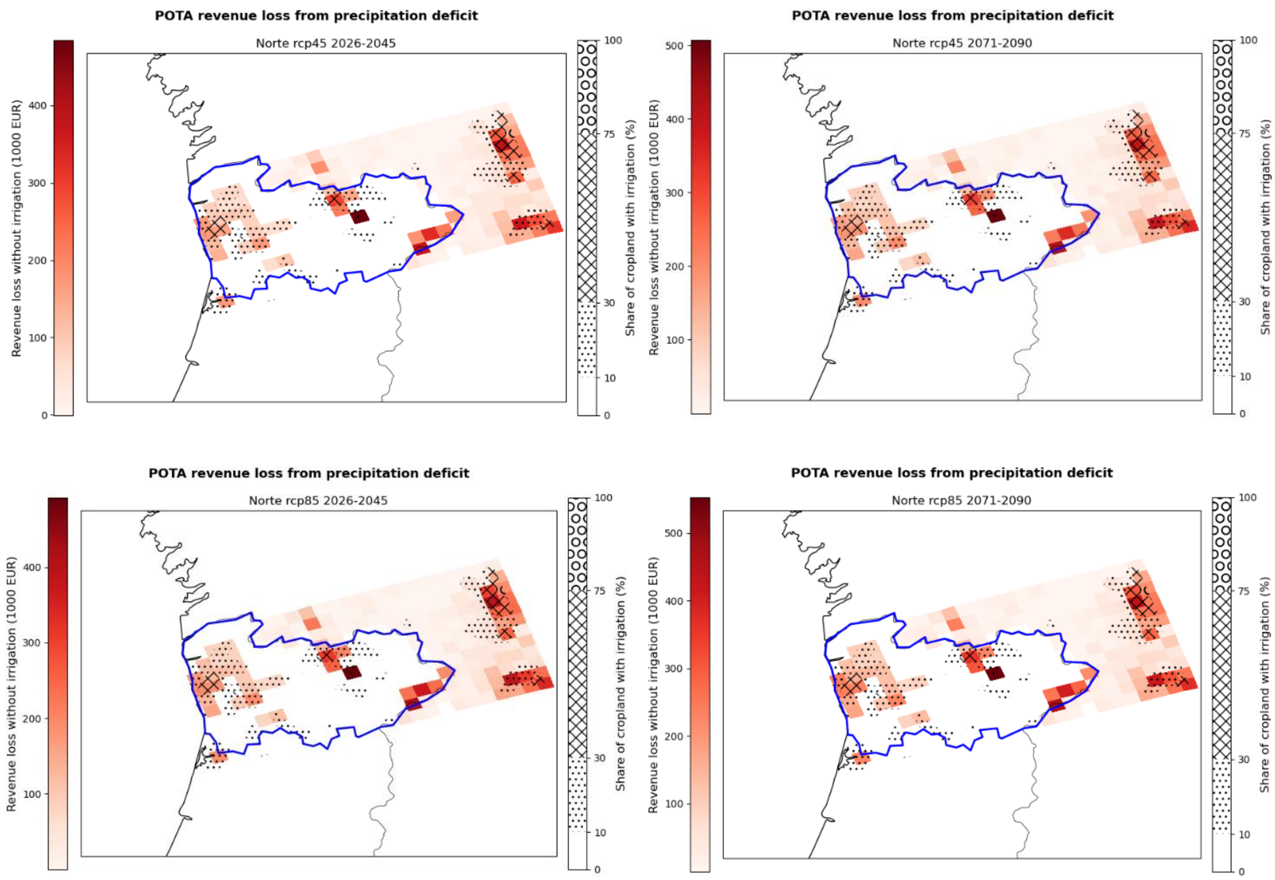


Figure 2-12 Potential revenue losses (€) in potato production, comparing the RCP 4.5 and 8.5 scenarios for the near future and the end of the century.

The analysis of relative drought indicates that while the region's current risk is moderate in the national context, it is projected to increase under more severe future scenarios. The assessment of agricultural drought, however, reveals a more direct economic threat. For the emblematic potato crop, projections show a clear trend of increasing yield losses, leading to substantial potential revenue losses. This financial risk is shown to intensify significantly towards the end of the century, particularly under the high-emissions RCP 8.5 scenario, highlighting a major vulnerability for the regional agricultural economy.

A cross-cutting analysis reveals a critical distinction between biophysical and economic vulnerability. While crops like sorghum and beans show the highest percentage yield losses, the greatest economic risk in absolute terms is concentrated in maize and potato, with maize showing the highest potential for revenue loss across all scenarios. Conversely, wheat and barley appear comparatively more resilient. This highlights a systemic risk to the regional agricultural economy, with specific crops facing critical financial vulnerabilities.

2.3.3 Workflow #3 – Heatwaves

The methodology of the urban heatwaves 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).

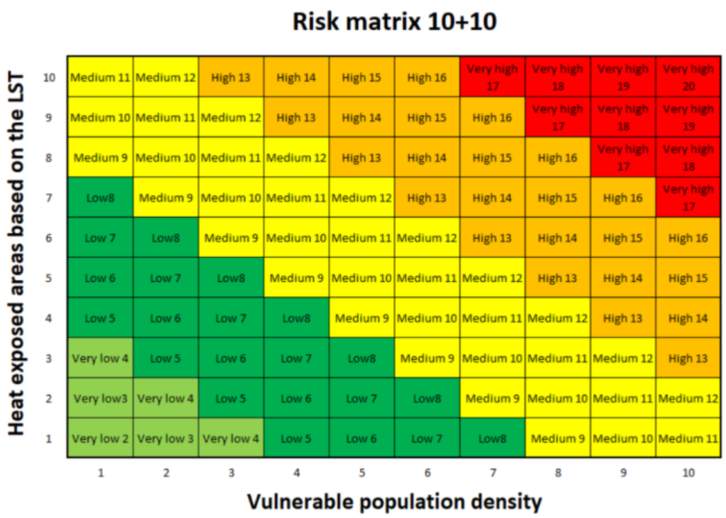


Figure 2-13 Risk matrix of the heatwaves workflow. Figure source: CLIMAAX

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).

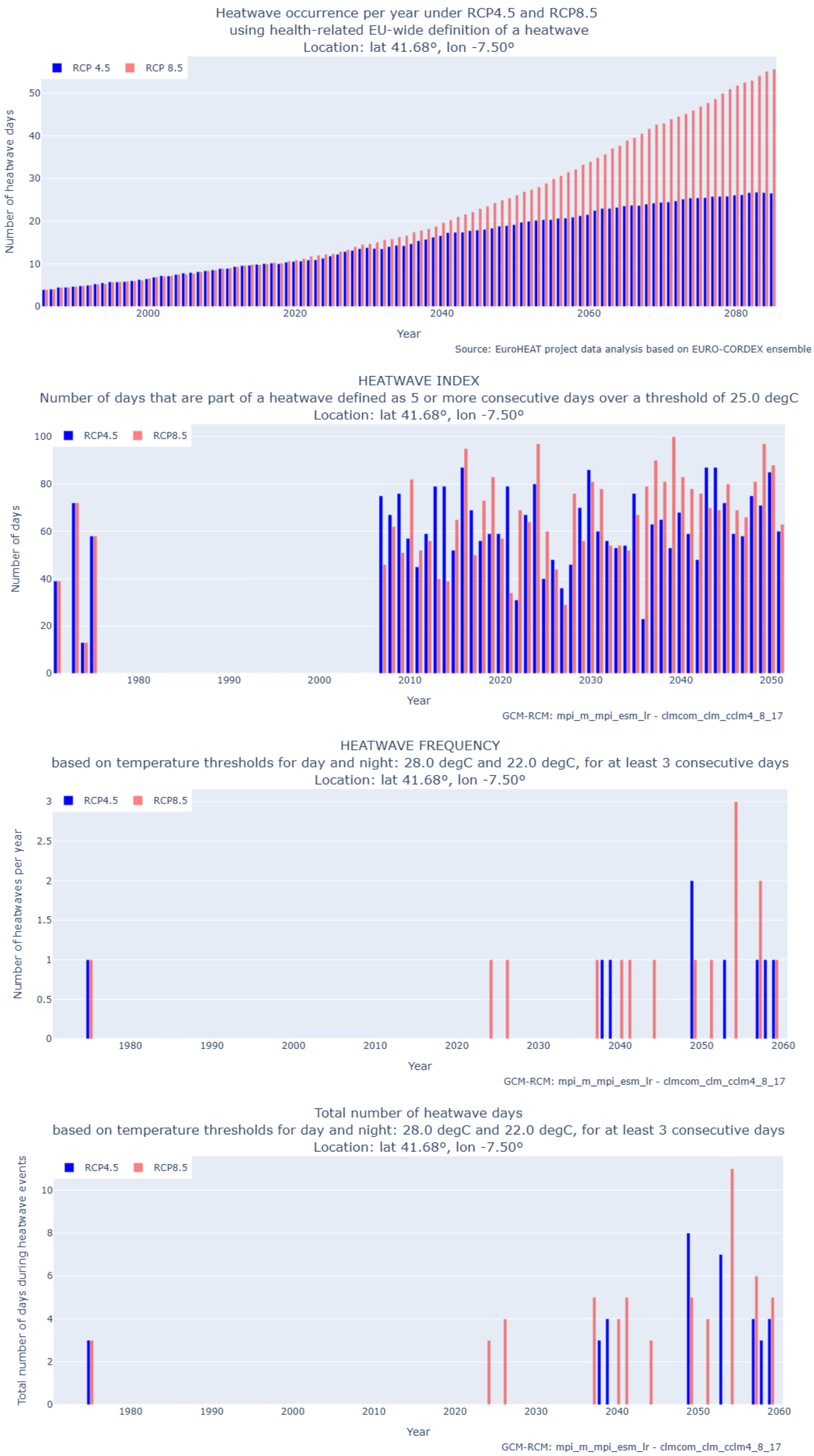


Figure 2-14 Heatwave hazard indicators for future scenarios RCP 4.5 and 8.5. in the Alto Tâmega e Barroso region (using Chaves as a geographical reference point).

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.

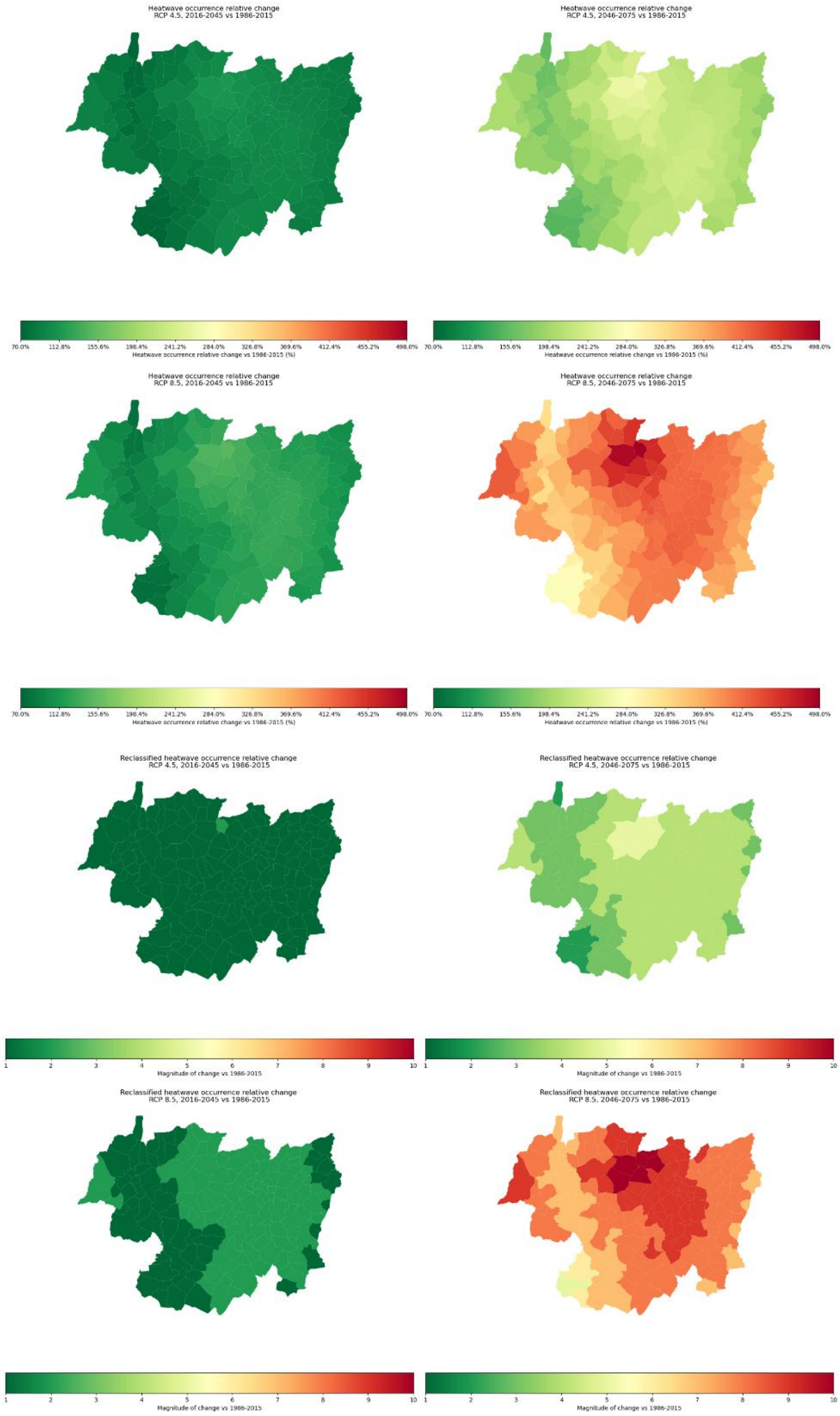


Figure 2-15 Maps of the base demographic indicators used in the heatwave vulnerability assessment for Alto Tâmega e Barroso region.

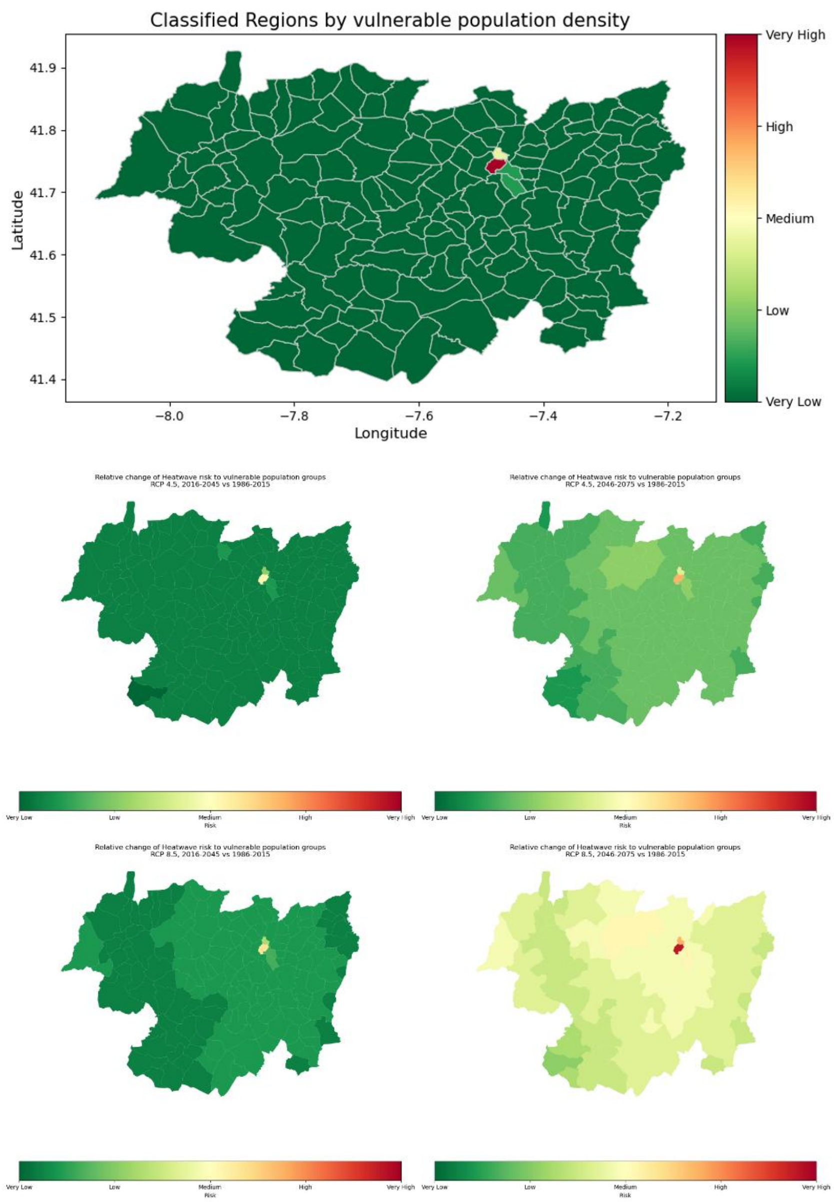


Figure 2-16 Final classification map of the territory's vulnerability to heatwaves, based on vulnerable population density.

The hazard analysis consistently projects a significant increase in the frequency, duration, and intensity of heatwaves, especially under the RCP 8.5 scenario. When this growing hazard is cross-referenced with demographic data, the final vulnerability map (Figure 2-16) reveals that the highest risk is concentrated in the region's main urban centers. Although these areas are geographically small, they represent critical hotspots where a large number of vulnerable people (particularly the elderly) are exposed, demanding targeted public health interventions.

2.3.4 Workflow #4 – River Floods

2.3.4.1 River flooding

The workflow methodology for River Floods aims to assess the regional risks associated with fluvial flooding and, crucially, to understand how climate change will impact and exacerbate these risks in the future. The process calculates potential damages by combining three essential sources of information: detailed maps showing the inundation depth at each location, depth-damage curves that estimate economic losses based on that depth, and data on land use and the local economy to determine the exposed value.

The analysis is conducted in two distinct phases. In the first phase, the methodology focuses on the historical climate, using high-resolution European data to generate detailed inundation maps. These maps illustrate the extent of extreme floods for different return periods, such as those that occur, on average, every 100 years, offering a precise view of the current risk.

The second phase addresses future climate impact. Using a lower-resolution dataset, the methodology compares the flood maps from the historical scenario with those of two future climate scenarios (RCP4.5 and RCP8.5). The result of this comparison is a qualitative assessment that demonstrates how the severity and extent of flooding could worsen. This provides not only a detailed assessment of the flood risk in the region for the present day, but also a clear projection of future trends, which is essential for effective planning and adaptation.

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

Table 2-4 Data overview workflow #4 – River Floods

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
· *European high-resolution dataset (for historical analysis)* · *Aqueduct Flood Hazard Maps dataset (for future scenarios).*	· *Depth-damage curves that relate water depth to the percentage of expected damage.*	· *Land use maps (e.g., Corine Land Cover)* · *Country-specific economic parameters (to assess the value of assets).*	· *Inundation maps for different return periods* · *Estimated economic damage maps* · *Qualitative assessment of the increase in future risk.*

2.3.4.2 Hazard assessment

The workflow successfully produced Hazard maps for river flooding. The following maps from the river flood hazard assessment illustrate the potential inundation depth [m]. The analysis first covers the present-day scenario (ca. 2018) for 10, 50, and 100-year return periods in the Alto Tâmega e Barroso region and the Chaves municipality. Subsequently, it projects the impacts of climate change through maps for an extreme 250-year event, considering the RCP 4.5 and 8.5 scenarios.

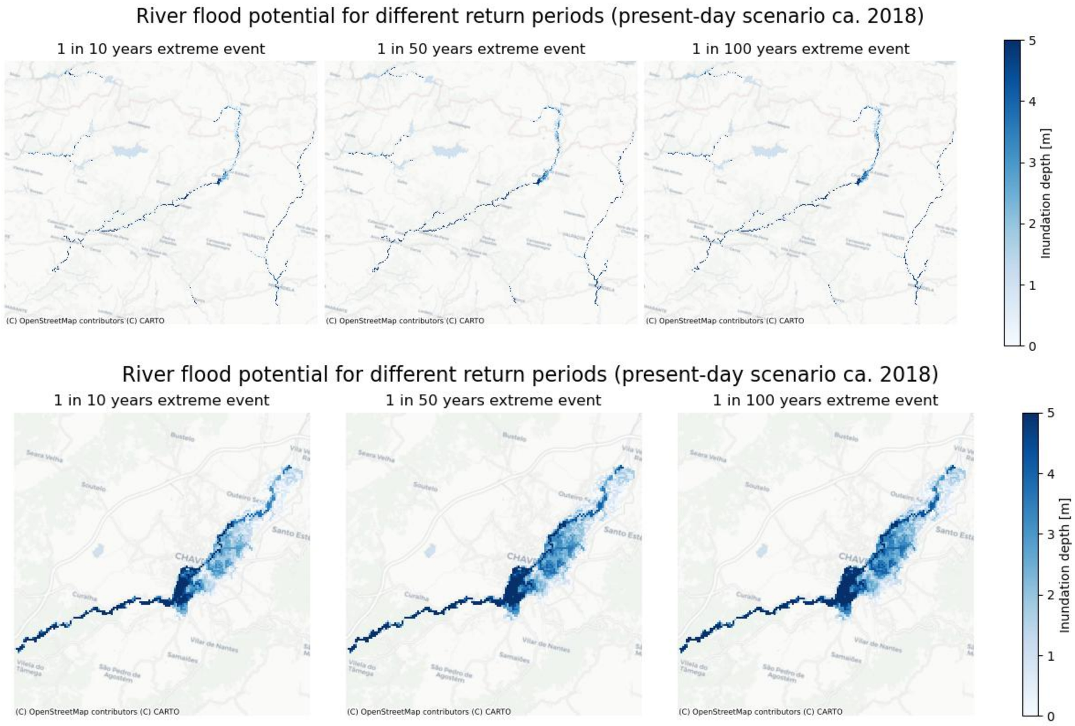


Figure 2-17 River flood potential (inundation depth [m]) for different return periods: 10, 50 and 100 years in the Alto Tâmega e Barroso region (above) and Chaves municipality (below) (present-day scenario ca. 2018).

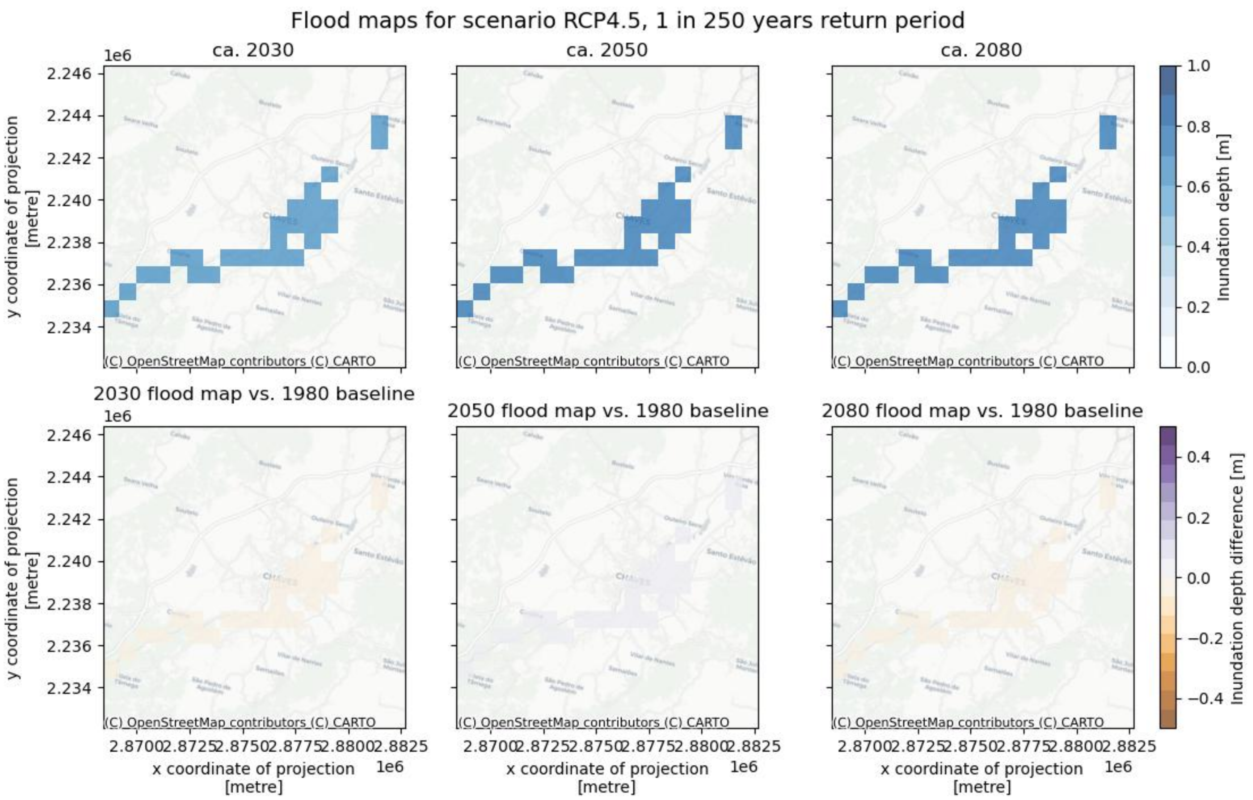


Figure 2-18 Flood maps (inundation depth [m]) for scenario RCP 4.5 (return period: 250 years) in the Alto Tâmega e Barroso region.

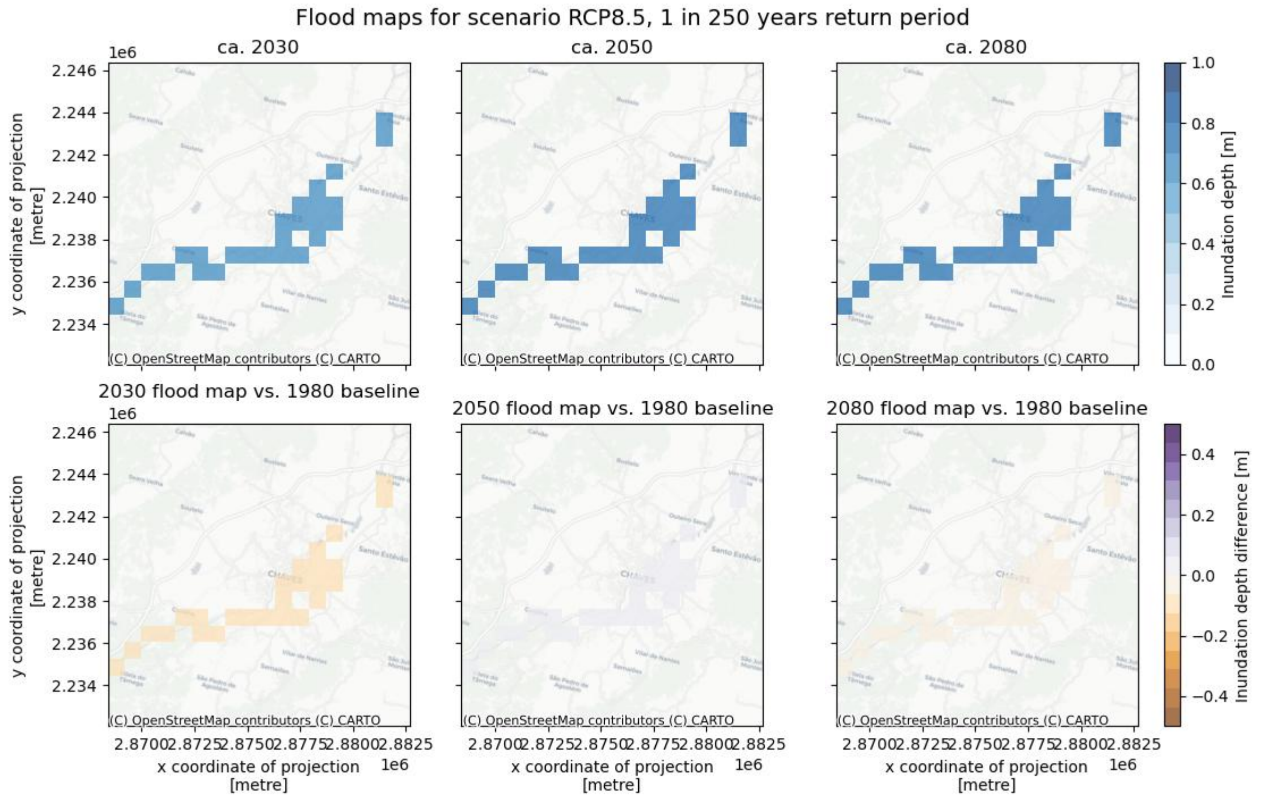
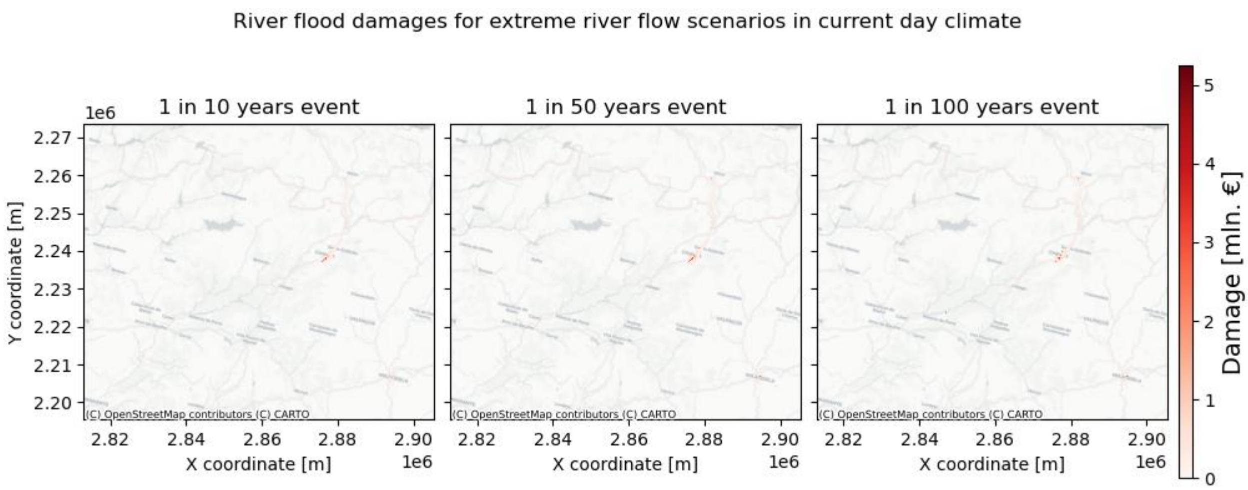


Figure 2-19 Flood maps (inundation depth [m]) for scenario RCP 8.5 (return period: 250 years) in the Alto Tâmega e Barroso region.

2.3.4.3 Risk assessment

Based on the hazard assessment, the flood risk was quantified in terms of direct economic damages for the current climate scenario. The methodology combines the inundation depth maps with land use and land cover data (LUISA 2018) to estimate the value of affected assets. The results are presented in two parts: first, the aggregated estimate of damages (in mln. €) for events with 10, 50, and 100-year return periods. Subsequently, maps are shown that detail the location and magnitude of these damages, allowing for a precise spatial analysis of the most vulnerable areas in the Alto Tâmega e Barroso region and the Chaves municipality.



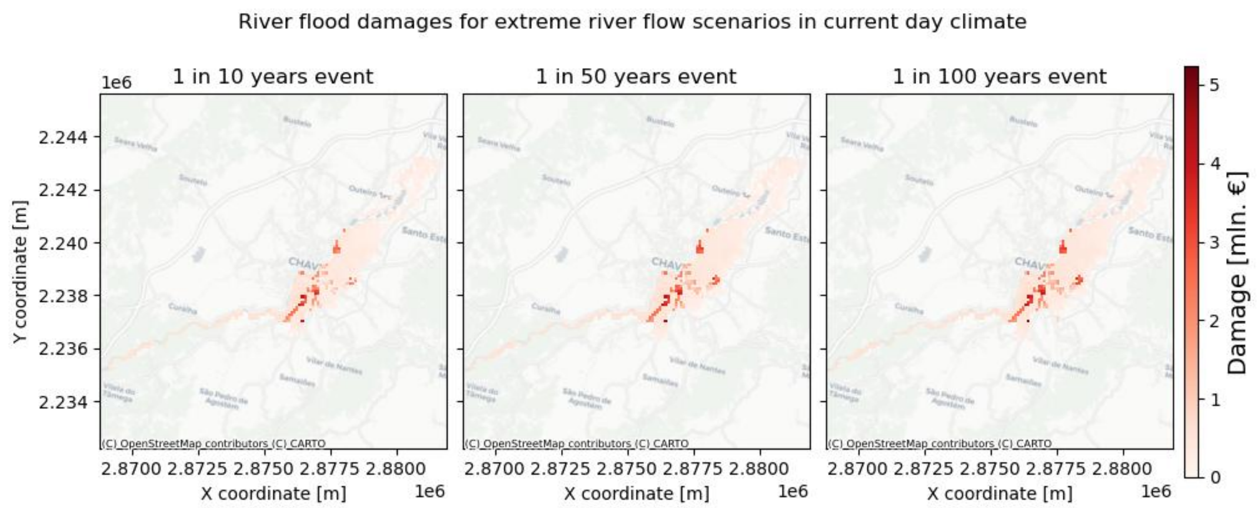


Figure 2-20 River flood damages (mln. €) for extreme river flow scenarios in current day climate (to different return periods: 10, 50 and 100 years) in the Alto Tâmega e Barroso (above) region and Chaves Municipality (below).

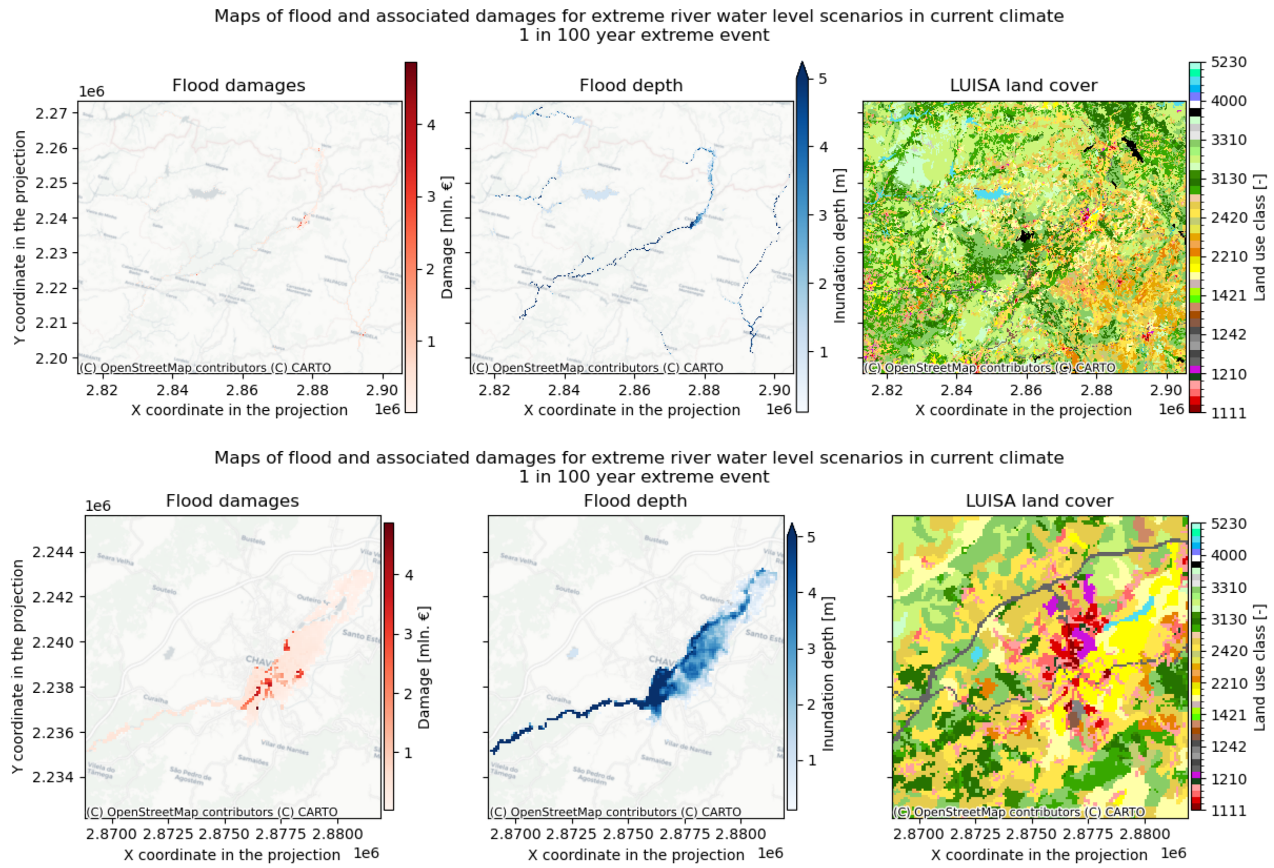


Figure 2-21 Maps of flood (inundation depth [m]) and associated damages (mln. €) for extreme river water level scenarios in current climate (LUISA land cover 2018) in the Alto Tâmega e Barroso (above) region and Chaves Municipality (below).

2.3.4.4 Flood building damage and population exposed

This workflow assesses flood risk at a detailed scale, focusing on the direct impact on buildings and populations. The process integrates hazard maps (indicating inundation depth) with high-resolution exposure data, such as building footprints, typologies, and demographic distribution.

The core of the analysis involves applying specific damage functions that calculate the economic losses for each building based on water depth. In parallel, it quantifies the exposed population by overlaying the inundation extent with population data. The final outputs are detailed building-level damage maps and statistics on the number of affected inhabitants, which are essential for urban planning and emergency management.

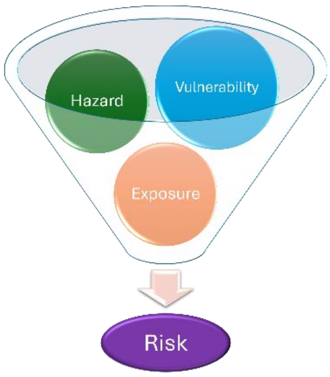


Figure 2-22 Workflow for Flood Damage and Population Exposure Analysis. Figure source: CLIMAAX

The table below details the primary datasets for the flood building damage and population exposed workflow, which include hazard, exposure, and vulnerability data.

Table 2-5 Data overview workflow #4 – River Floods (flood building damage and population exposed)

Hazard data	Vulnerability data	Exposure data	Risk output
· *Inundation maps with water depth (historical and future).*	· *Depth-damage curves (specific to building typology: residential, commercial, etc.)*	· *Building data (e.g., location, typology, height, year of construction).* · *Population distribution data (e.g., census, population grids).*	· *Building-level damage map (€).* · *Number of people exposed (classified by inundation level).* · *Aggregated damage statistics (e.g., by parish, municipality, etc.).*

Hazard assessment

The river flood hazard assessment for the Chaves area defines the potential extent and water depth for events of varying severity. The following maps (Figure 2-23) illustrate this analysis, presenting the inundation footprint for 10, 50, 100, and 500-year return periods. This hazard characterization is the foundational step that underpins the subsequent risk analysis.

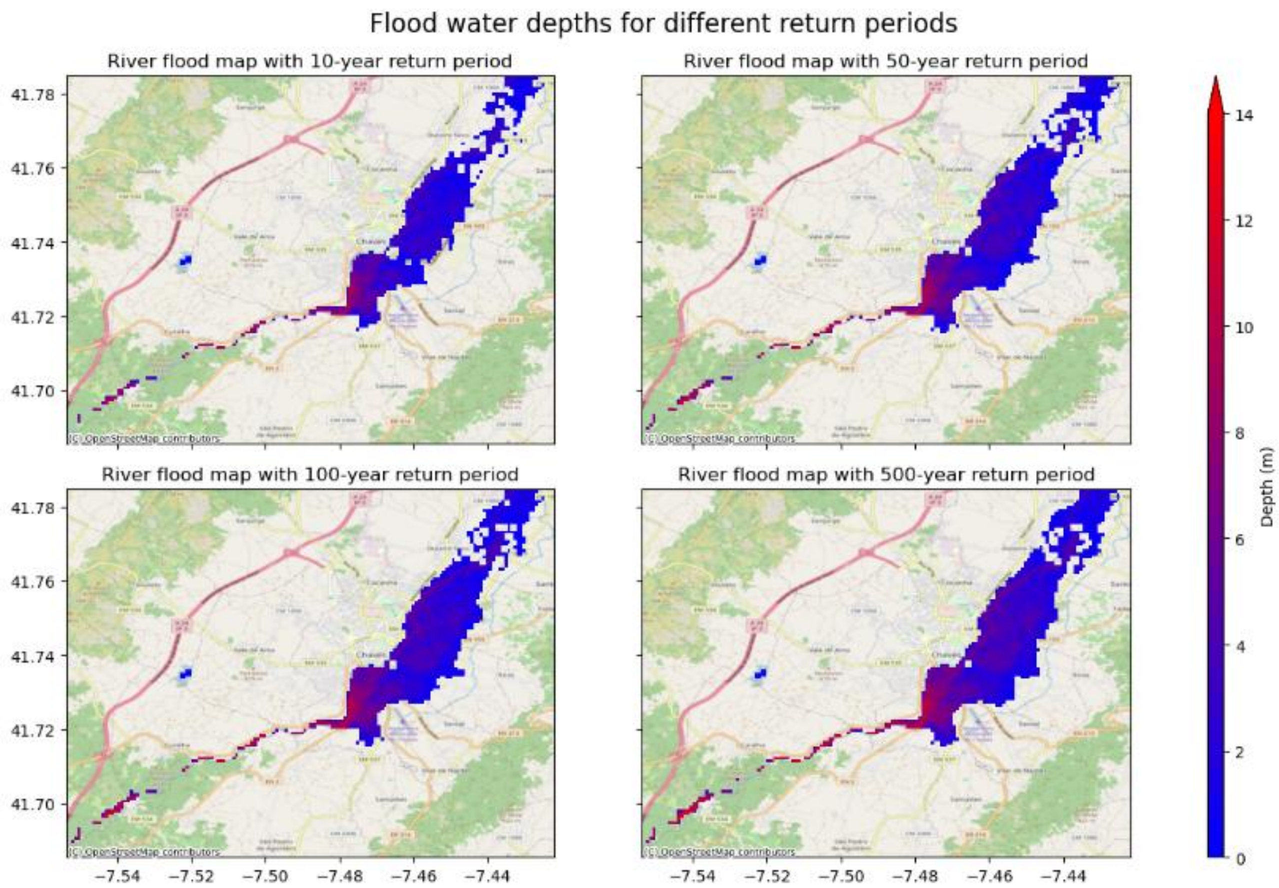


Figure 2-23 Flood hazard maps for the Chaves area, illustrating the water depth [m] for 10, 50, 100, and 500-year return periods.

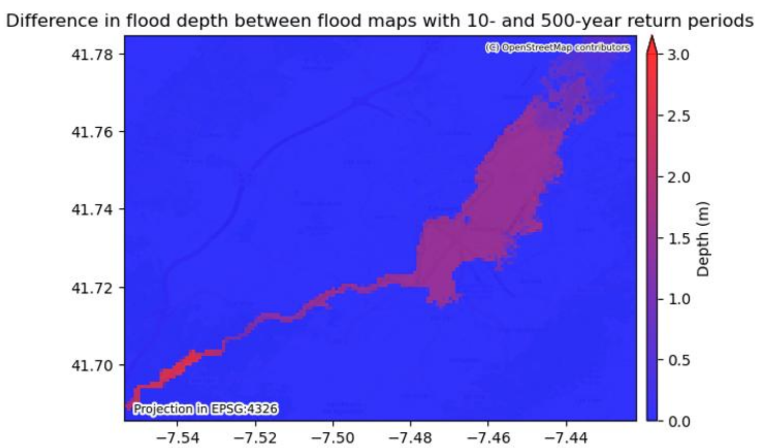


Figure 2-24 Map of the difference in flood depth [m], comparing a frequent event (10-year return period) with an extreme event (500-year).

Risk assessment

Based on the hazard analysis, the risk assessment quantifies the direct socioeconomic impacts of a flood event. The methodology translates water depth into tangible consequences, focusing on the two most critical indicators: the estimated economic damage per building and the number of inhabitants who would be forced to evacuate (>1m depth). The following maps visualize these outcomes, comparing a frequent (10-year) with an extreme (500-year) event to identify the most vulnerable areas.

One of the most significant findings of the assessment is the expected annual displaced population, which reaches approximately 386 people, indicating the average number of inhabitants who may be forced to evacuate annually due to floods.

The results of the flood analysis demonstrate that the risk is highly concentrated geographically, with the urban area of Chaves being the most critical territory. The maps illustrate a significant escalation in both economic damages and the number of displaced people when comparing frequent events (e.g., 10-year return period) with more extreme ones (e.g., 500-year return period). Furthermore, the analysis highlights the exposure of critical infrastructure located within these flood-prone zones, indicating a systemic risk to urban services during severe flood events.

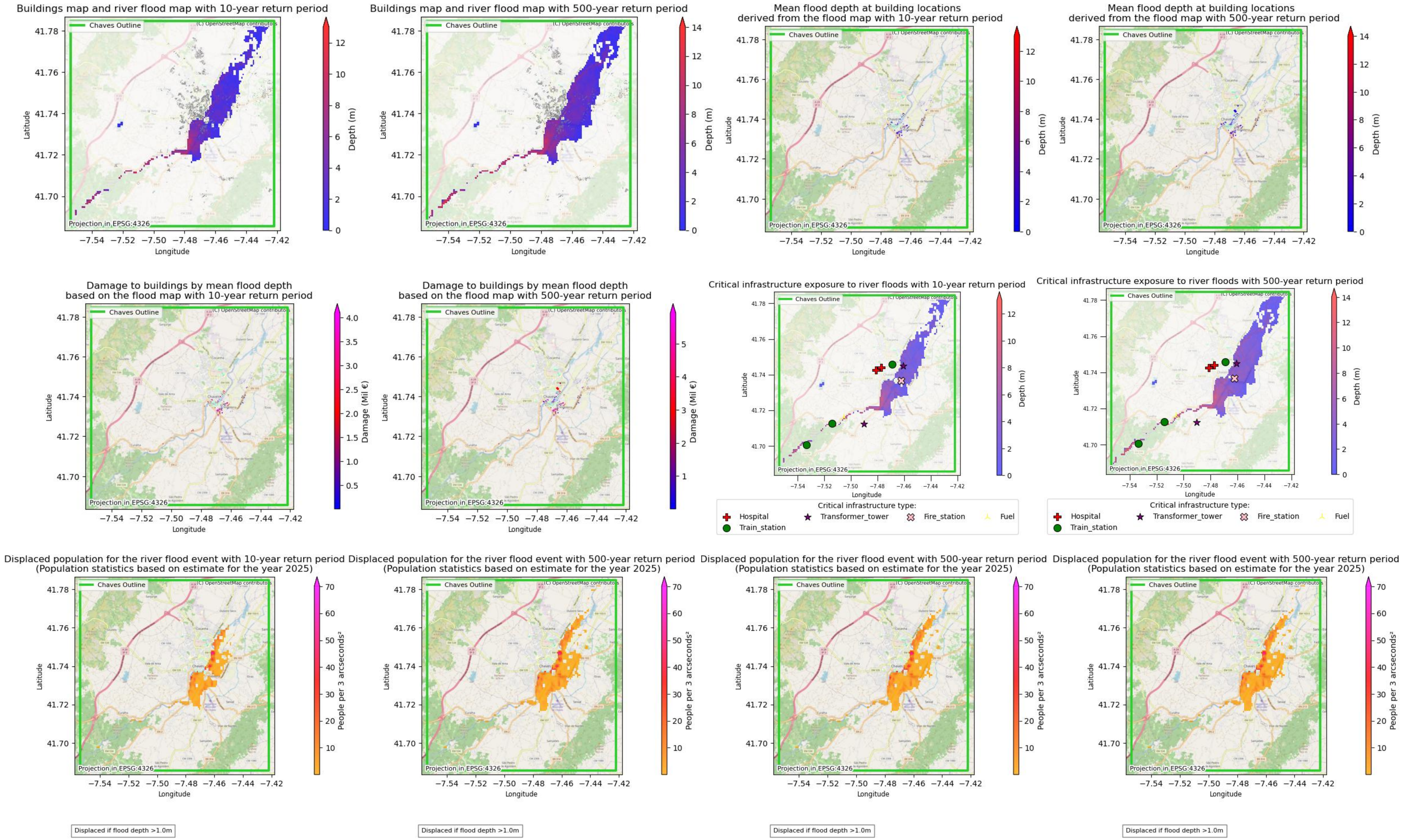


Figure 2-25 Risk analysis comparing the impact of a 10-year (frequent) versus a 500-year (extreme) event for the Chaves area: economic damage to buildings [M€] and displaced population (number of inhabitants in areas with >1m inundation depth).

2.4 Preliminary Key Risk Assessment Findings

2.4.1 Severity

The hazard and risk analysis indicates that the Alto Tâmega e Barroso region is vulnerable to multiple climate-related hazards with severe and sometimes irreversible impacts. As a consequence, these hazards have a significant impact on forest and rural areas, agriculture, biodiversity, the economy, and, above all, on people's quality of life and safety.

Among the various climate risks, the severity of each can be detailed as follows:

- **Wildfires:** the hazard is high, as this is the most frequent climate event in the region. Future projections indicate a significant increase in the number of days with high fire danger (FWI>30). The consequences are severe and potentially irreversible, including biodiversity loss, the destruction of forest ecosystems, water resource contamination, and soil degradation.
- **Droughts:** the region has a high susceptibility, with a significant increase in occurrences. Agricultural drought represents a massive financial risk for the sector. This is clearly demonstrated by the results for the potato crop, with projections indicating an increase in yield and revenue losses in future scenarios. This trend of significant risk is also observed in the other crops analyzed (e.g., maize, wheat), confirming a systemic vulnerability for the region's agriculture.
- **Heatwaves:** the frequency and duration of these events are projected to increase considerably. The impact on human health is high, especially for vulnerable groups like the elderly, who represent 27.61% of the population. Heatwaves trigger cascading effects, exacerbating droughts and the risk of wildfires.
- **River Floods:** severity is particularly high in the municipality of Chaves. The detailed risk analysis demonstrates the potential for significant economic damage to buildings and an expected annual displaced population of about 386 people. The impact affects critical infrastructure, economic activities, and the safety of people and property.

2.4.2 Urgency

The urgency for action is dictated by both sudden-onset events and slow-onset processes whose impacts will worsen significantly in the near future.

- **Wildfires and River Floods:** These are sudden-onset hazards, requiring early warning and rapid response systems. The urgency is high, as projections indicate an increase in the frequency of high-danger fire days and extreme precipitation events.
- **Heatwaves:** Although their onset can be gradual, their impacts are acute and persistent. The urgency is high, as projections indicate the hazard will worsen significantly in the near future (2011-2040) and will continue to increase until the end of the century.
- **Droughts:** This is a slow-onset hazard, but with persistent and cumulative effects. The urgency stems from the clear trend of worsening risk over time, as demonstrated by projections for 2050 and 2080, which indicate the need to plan medium and long-term adaptation measures to ensure water security and agricultural viability.

2.4.3 Capacity

The region has climate risk management instruments in place but faces challenges that limit its response capacity.

- **Existing Measures:** the region has several planning instruments that contribute to risk management, such as Municipal Climate Action Plans (PMACs), Forest Defense Plans Against Fires, and Emergency and Civil Protection Plans. At the regional level, there is an Intermunicipal Climate Change Adaptation Plan and programs like the PRGPs (Landscape Reorganization and Management Programs) to make the territory more resilient to wildfires.
- **Response Capacity:** although these instruments are in place, significant gaps remain. There is a lack of a real-time climate risk monitoring platform and challenges in regional coordination. Human and social capacity are affected by population aging and desertification. Financial capacity to prepare for and respond to risks is a constraint.
- **Planned Interventions:** the CLIMAAX_AT specifically aims to strengthen this capacity by improving monitoring, building the capacity of local technicians and communities, reinforcing inter-municipal cooperation, and integrating the results of this assessment into strategic planning instruments.

2.5 Preliminary Monitoring and Evaluation

This section outlines the main lessons learned from 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, highlighting both the strategic lessons and the technical challenges inherent in a multi-regional climate risk assessment. At a strategic level, participation in the CLIMAAX workshop in Barcelona was a fundamental milestone. The event, which brought together the project's key stakeholders, provided a valuable exchange of knowledge and validated our approach by contextualizing the work developed in Alto Tâmega e Barroso within the scope of a broader European effort. This sharing of experiences was crucial to the success of the initial phase.

At the methodological level, the most significant lesson was the confirmation of the importance of adopting a clear and structured workflow for each risk analyzed—wildfires, droughts, heatwaves, and river floods. The approach advocated by CLIMAAX provided a robust and auditable methodological foundation. This structure not only allowed for the systematic testing of different methods but also ensured that data was processed and analyzed consistently. The result was a standardized assessment that not only enhances the reliability of the findings but also improves their comparability across different risks and regions.

However, the main technical challenge lay in the availability and quality of input data. Although the CLIMAAX workflows were designed to operate with pan-European or global datasets by default, our analysis confirmed that these often lack the spatial resolution and local specificity required for civil protection planning at the local scale. The exclusive use of these datasets limits the applicability of the results for informed on-the-ground decision-making. Consequently, the integration of high-resolution local data is not just an improvement but the main methodological priority to ensure the relevance and success of the project's second phase.

Stakeholders' engagement

The stakeholder engagement strategy for the first phase was intentionally designed to focus on communicating preliminary results and preparing for a deeper collaboration in the next phase. To this end, an online questionnaire was developed to be administered at the end of the phase, targeting key local actors already identified by CIMAT. This instrument serves a dual purpose: on one hand, to present the project and disseminate the findings of the initial assessment; on the other, to gather strategic input on how to refine and improve the risk analysis in the subsequent phase. To complement this action and ensure continuous communication, an informational newsletter will also be developed to communicate the main results of the phase, ensuring that stakeholders remain informed and engaged.

This methodological approach was adopted to allow the project team to first establish a robust technical baseline for the risk assessment. During this more exploratory phase, the challenge was to balance technical rigor with the need to translate the findings into accessible yet assertive information. This foundational work is crucial, as the second phase of the project will transition to a more active and intensive engagement model. In that stage, stakeholders will play a decisive role in refining the assessment, ensuring its full alignment with the territory's specificities and with the strategic and operational needs of civil protection.

Data availability and requirements

The initial assessment phase identified critical gaps in two key areas crucial to the robustness of the findings—baseline data availability and continuous monitoring—while simultaneously overcoming a technical challenge related to processing capacity.

Regarding data gaps, to fully understand the risks at a scale tailored to the needs of civil protection planning and operations, the following baseline datasets are required: a consolidated and georeferenced history of climate-related civil protection incidents, which is essential for validating susceptibility models; high-resolution topographic data (e.g., LiDAR), which is crucial for precise hydrodynamic flood risk modeling, particularly in complex urban areas like the Chaves case study; and updated land use and land cover maps (e.g., *Carta de Ocupação do Solo* - COS) and, ideally, forest fuel models, which are fundamental for calibrating wildfire spread models and ensuring the analysis reflects current hazard conditions.

With respect to processing capacity, handling high-resolution datasets and running complex models presented an initial computational challenge. The infrastructure first explored, the CLIMAAX Jupyter Hub, revealed performance limitations (e.g., data transfer latency, CPU/RAM restrictions) that impacted the agility and timely execution of the analysis workflows. To address this challenge, the team migrated the analysis to a local development environment (Jupyter Lab). This transition, carried out with the support of the CLIMAAX technical team, made it possible to overcome the initial constraints. Currently, the project has a robust and optimized analysis environment with greater control, scalability, and access to dedicated hardware resources, ensuring the necessary capacity for efficient data processing.

Regarding monitoring needs, beyond static data, the assessment would benefit from the expansion of monitoring networks in the Alto Tâmega e Barroso region. This would allow for not only more effective hazard detection but also the continuous validation of risk models. Possible priorities in this area include: the installation of additional weather stations in areas with insufficient climatic representativeness; the implementation of flow and level sensors (i.e., stream gauges) in critical river sections; and a network of soil moisture sensors in strategic areas for monitoring wildfire risk and agricultural drought.

Some of these priorities are already being addressed in standalone projects promoted by CIMAT, with which the CLIMAAX_AT project will establish direct synergies to mutually enhance their results.

2.6 Work plan

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

Phase 2: Refinement of the High-Resolution Regional/Local Analysis and Risk Assessment: This phase will focus on enhancing the multi-risk climate assessment conducted in Phase 1. The initial analysis, by predominantly using pan-European and global data, generated results that lack the spatial resolution and local specificity required for operational civil protection planning and on-the-ground decision-making. Phase 2 aims to address this gap by adapting the models to the territory's reality 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 a history of incidents, risk characterization studies, Municipal Emergency and Civil Protection Plans, Flood Risk Management Plans, Climatological Normals and Municipal Climate Action Plans.
- **Improvement and validation of workflows:** the risk workflows will be improved and validated with the new local data. The results of Phase 1 and Phase 2 will be compared to identify improvements.
- **Co-creation with stakeholders:** intensive participatory processes will be implemented, which is essential for validating the models and aligning them with operational needs.

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, aiming to strengthen regional adaptive capacity and improve current risk management plans and strategies. A vulnerability analysis will be included to identify the most susceptible sectors and population groups.

Using the scientific results from Phases 1 and 2, the goal is to reduce risks and increase the region's resilience by integrating new information and strategies into regional and local strategic planning instruments, such as PMACs and PMEPCs. To this end, the following steps will be taken:

- **Identification and assessment of adaptation options:** the identification and assessment of adaptation options will follow the logic of the Adaptation Support Tool (AST).
- **Stakeholder engagement:** regional/local stakeholders will be actively involved in the discussion, validation, and prioritization of adaptation options through participatory processes.
- **Capacity building and dissemination:** training and capacity-building actions will be carried out for technicians and stakeholders for the implementation of measures and the creation

of a knowledge network. A final publication detailing the project's actions and results will be produced, and a final public event will be held to present the results to policy makers and the general public in the Alto Tâmega region.

3 Conclusions Phase 1- Climate risk assessment

The first phase of the CLIMAAX_AT project established a multi-risk climate assessment baseline for the Alto Tâmega e Barroso region. By applying the CLIMAAX methodological framework and its associated workflows, this assessment quantified the current and future impacts of four priority hazards: wildfires, droughts, heatwaves, and river floods. This initial phase has confirmed that the region is highly vulnerable to a range of interconnected climate risks, whose severity and frequency are projected to increase significantly throughout the 21st century. The findings from this phase provide a robust scientific foundation to support strategic decision-making and guide the development of targeted adaptation measures in the subsequent phases of the project.

The risk analysis conducted in Phase 1 yielded several critical findings that underscore the urgency for climate action in the region:

1. **Wildfires pose a severe and worsening threat:** the analysis confirmed that wildfires are the most frequent and severe climate hazard in the region. Projections based on the Fire Weather Index (FWI) indicate a substantial increase in the number of days with high fire danger (FWI>30) across all future climate scenarios (RCP 2.6, 4.5 and 8.5). The risk is not purely meteorological; the vulnerability analysis identified critical hotspots where high hazard intersects with sensitive populations (in the Wildland-Urban Interface), valuable ecosystems (Protected Areas), and high restoration costs, signifying a systemic risk with potentially irreversible consequences for the territory's biodiversity and economy.
2. **Droughts threaten water security and economic viability:** the region exhibits a high susceptibility to droughts, with both relative and agricultural drought analyses pointing to a clear trend of increasing risk. The agricultural drought assessment, which evaluated six different crops, highlighted a financial risk to the region's agricultural sector. This is exemplified by the results for the emblematic potato crop, which show significant increases in both relative yield loss and potential revenue losses, particularly in the end-of-century scenarios. These findings confirm a significant threat to a key socio-economic pillar of the region. Furthermore, the cross-cutting analysis of the different crops reveals a differentiated vulnerability that is critical for designing targeted adaptation strategies. While crops like sorghum and beans show the highest percentage yield losses, indicating high biophysical sensitivity to water scarcity, the greatest economic risk in absolute terms is concentrated in maize and potato. Conversely, wheat and barley appear comparatively more resilient, with lower projected yield and revenue losses.
3. **Heatwaves represent a significant and 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 region's demographic profile, with a high percentage of elderly residents (>65 years) who are especially vulnerable. The vulnerability mapping identified specific areas where this sensitive population is concentrated, highlighting critical zones for public health intervention. Furthermore, heatwaves act as a risk multiplier, triggering cascading effects by exacerbating drought conditions and increasing wildfire danger.
4. **River floods present a high-impact risk concentrated in urban areas:** the flood risk analysis demonstrated a severe and concentrated threat, particularly in the urban area of the Chaves municipality. The detailed assessment quantified the potential for significant economic

damage to buildings and critical infrastructure. Crucially, it identified a substantial human impact, with an **expected annual displaced population of approximately 386 people**, indicating a high probability of recurring social disruption. Future projections for extreme events (250-year return period) under RCP 4.5 and 8.5 scenarios show an intensification of this hazard.

This initial phase successfully addressed several core methodological and technical challenges while also identifying critical needs that must be tackled in the next project cycle.

Challenges Addressed:

- **Methodological Implementation:** The project successfully tested and applied the CLIMAAX workflows for the four selected hazards, establishing a standardized and replicable baseline for the multi-risk assessment. This provides a solid and comparable foundation for all future work.
- **Technical Capacity:** Initial computational limitations related to processing large datasets were overcome by migrating the analysis environment to a local server, ensuring the project has the necessary capacity for handling high-resolution data in the next phase.
- **Initial Stakeholder Engagement:** A preliminary engagement strategy was implemented through an online questionnaire, which served to communicate the project's objectives and gather initial feedback, preparing the ground for more intensive collaboration.

Priorities for Phase 2:

- **Integration of high-resolution local data:** The most significant challenge identified is the limitation of using pan-European and global datasets, which lack the local specificity required for operational planning. While this phase established a baseline, the results are not yet sufficiently granular for local civil protection and land management. The primary challenge for Phase 2 is to acquire and integrate high-resolution local data (e.g., LiDAR, local incident records, detailed land cover maps) to refine and validate the risk models.
- **Deep stakeholder co-creation:** The initial engagement was primarily informative. The next phase must transition to a model of active co-creation, where local stakeholders (municipal technicians, civil protection agents, etc.) play a decisive role in validating the models, interpreting the results, and ensuring the final outputs are fully aligned with their operational needs.

In conclusion, Phase 1 has successfully produced a comprehensive, albeit preliminary, climate risk assessment for the Alto Tâmega e Barroso 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 high-resolution 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 Alto Tâmega region. Throughout this phase, and with the completion of this deliverable, the following milestones were achieved (Table 4-1): M2: Test CLIMAAX workflows for different hazards; M3: Carrying out participatory processes with stakeholders (phase 1); M4: 2 Workflows for different risks successfully applied and M5: Application of the common CLIMAAX methodology for multi-hazard climate assessment.

Table 4-1 Overview milestones

Milestones	*Progress*
M1: Subcontracting carried out - Phase 1 and 2 of the project	Achieved
M2: Test CLIMAAX workflows for different hazards	Achieved *(4 workflows tested)*
M3: Carrying out participatory processes with stakeholders (phase 1)	Achieved
M4: 2 Workflows for different risks successfully applied	Achieved *(4 workflows applied)*
M5: Application of the common CLIMAAX methodology for multi-hazard climate assessment	Achieved
M6: Carrying out stakeholder participatory processes (phase 2)	Planned for Phase 2
M7: Collection and compilation of high-resolution local data	Planned for Phase 2
M8: 2 Workflows for different hazards improved and enhanced	Planned for Phase 2
M9: Subcontracting carried out - Phase 3 of the project	Planned for Phase 3
M10: Potential regional/local adaptation options identified	Planned for Phase 3
M11: Carrying out stakeholder participatory processes (phase 3)	Planned for Phase 3
M12: Regional/local adaptation options assessed and prioritized	Planned for Phase 3
M13: Recommendations to improve the risk management plans formulated	Planned for Phase 3
M14: Presentation of results to policy makers in the Alto Tâmega region (final public event)	Planned for Phase 3
M15: Participate in the CLIMAAX workshop held in Barcelona	Achieved
M16: Participate in the CLIMAAX workshop held in Brussels	Planned for Phase 3

In addition to these milestones, Phase 1 achieved the three key performance indicators (KPIs) defined for this phase and contributing to the overall success of the project: the completion of risk assessments for three 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] Selection of hazards with a substantial societal impact, known or projected to be affected by climate change in the Alto Tâmega	Achieved
[2] risk workflows will be successful applied in Deliverable 1 (multi-risk climate assessment)	Achieved
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] Selection of indicators for meteorological or hydrological hazards and societal or ecological impacts, suitable for designing and monitoring adaptation and risk management strategies	Planned for Phase 2
Phase 3	
[1] sub-regional climate policy will be explored and improved	Planned for Phase 3
[6] local adaptation strategies (Municipal Climate Action Plans) will be explored and improved	Planned for Phase 3
[6] emergency and risk management plans will be improved based on the results of the risk and vulnerability assessment	Planned for Phase 3
[1] final publication, detailing the project's actions and results, will be produced	Planned for Phase 3
[1] public final event will take place to present the results to policy makers and decision-makers in Alto Tâmega	Planned for Phase 3
KPIs common to all three phases	
[3] policy briefs will be developed for political decision-makers, based on the results of the risk and vulnerability assessment	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)
12 of 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)
  - HEATWAVES (HEATWAVES.zip)
  - FLOODS (FLOODS.zip)
- DOI generated by ZENODO: 10.5281/zenodo.17054374