CLIMAAX
climate ready regions

Deliverable Phase 2 – Climate risk assessment

Comunidade Intermunicipal da Beira Baixa (CIM-BB)

Portugal, Beira Baixa

Version 1.0 | Jan 2026

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 2 – Climate risk assessment
Brief Description	
Project name	CLIMAAX-BeiraBaixa
Country	Portugal
Region/Municipality	Beira Baixa
Leading Institution	Comunidade Intermunicipal da Beira Baixa
Author(s)	• João Santos (greenmetrics.ai) • Tiago Marques (greenmetrics.ai) • Pedro Godinho (CIM-BB) • Beatriz Oliveira (greenmetrics.ai)
Deliverable submission date	19/01/2026
Final version delivery date	19/01/2026
Nature of the Deliverable	R – Report
Dissemination Level	PU - Public

Version	Date	Change editors	Changes
1.0	19/01/2026	greenmetrics.ai	Deliverable submitted

Table of contents

List of figures

List of tables

Abbreviations and acronyms

Abbreviation / acronym	Description
ADENE	Agência para a Energia (Energy Agency)
AFLOBEI	Associação de Produtores Florestais da Beira Interior (Beira Interior Forest Owners' Association)
AGIF	Agência para a Gestão Integrada de Fogos Rurais (Agency for Integrated Rural Fire Management)
ANEPC	Autoridade Nacional de Emergência e Proteção Civil (National Authority for Emergency and Civil Protection)
ARBI	Associação de Regantes e Beneficiários de Idanha-a-Nova (Idanha-a-Nova Irrigators and Beneficiaries Association)
CCDR	• Comissão de Coordenação e Desenvolvimento Regional (Regional Coordination and Development Commission)
CIM-BB	Comunidade Intermunicipal da Beira Baixa
CLIMAAX	CLIMAte risk and vulnerability Assessment framework and toolboX
COS	Carta de Ocupação do Solo (Land Use Map)
CRA	Climate Risk Acessment
DEM	Digital Elevation Model
ECLIPS	European CLimate Index ProjectionS
EURO-CORDEX	Europian Coordinated Downscaling Experiment
GCM	General Circulation Model
GNR	Guarda Nacional Republicana (National Republican Guard)
ICNF	Instituto da Conservação da Natureza e das Florestas (Institute for Nature Conservation and Forests)
LST	Land Surface Temperature
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
NDVI	Normalized Difference Vegetation Index
PIAAC	Plano Intermunicipal de Adaptação às Alterações Climáticas (Intermunicipal Climate Change Adaptation Plan)
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
REN	Redes Energéticas Nacionais (National Energy Networks)
SHM	Summer Heat-Moisture index
SMPC	Serviço Municipal de Proteção Civil (Municipal Civil Protection Department)

SSPs	Shared Socioeconomic Pathways

Executive summary

This deliverable presents the Phase 2 Climate Risk Assessment (CRA) for the Comunidade Intermunicipal da Beira Baixa (CIM-BB) under the CLIMAAX framework, focusing on rural wildfires and heatwaves. It builds on the Phase 1 CRA deliverable and on priorities validated with regional stakeholders during Phase 2 engagement, including the in-person workshop held on 14/11/2025. Phase 2 moves from a screening-level picture to more decision-ready evidence by refining hazard, exposure and vulnerability components with higher-resolution national and local datasets and by responding to stakeholder operational questions.

For wildfires, the CLIMAAX workflow was regionalized by retraining the susceptibility model for Continental Portugal and constraining model behavior so hazard evolution remains consistent with projected climatic trends. The resulting hazard maps preserve the main spatial hotspots while providing a clearer intensification signal across scenarios and horizons. Risk analysis combines these hazard outputs with locally validated exposure layers (including critical services and key transport corridors) and integrates response-capacity perspectives through suppression-related indicators, notably aerial/terrestrial water-point coverage and accessibility to response assets. Together, these outputs help identify where high hazard coincides with exposed assets and potential logistical constraints, supporting prevention, preparedness and investment planning.

For heatwaves, Phase 2 retains the EuroHEAT-based hazard indicator (relative change in heatwave days) for continuity with Phase 1, while strengthening exposure and vulnerability assessment at the scales where decisions are taken. Parish-level mapping combines projected intensification with concentrations of vulnerable population and a complementary vulnerability perspective based on cooling energy needs. The analysis is then refined to the main urban areas using high-resolution Land Surface Temperature (LST) and vegetation indicators (NDVI), revealing intra-urban hotspots and quantifying the cooling contribution of green infrastructure.

Overall, Phase 2 confirms wildfires and heatwaves as Tier-1 risks for CIM-BB, with high potential for cascading impacts on ecosystems, critical infrastructure and public health. While wildfire management benefits from established systems and resources, additional action is needed to keep pace with future trends and reduce remaining territorial gaps. For heatwaves, strengthened local impact monitoring (health and social indicators) emerges as a key enabling condition. Phase 3 will use these priority findings to co-develop and prioritize adaptation options with stakeholders, targeting wildfire prevention and operational preparedness where hazard–exposure–response gaps overlap, and targeting urban heat mitigation and protection of vulnerable groups where persistent thermal hotspots coincide with higher vulnerability.

1 Introduction

1.1 Background

The Beira Baixa region, located in central Portugal, encompasses an area of approximately 5 253 km² and comprises eight municipalities: Castelo Branco, Idanha-a-Nova, Oleiros, Penamacor, Proença-a-Nova, Sertã, Vila de Rei, and Vila Velha de Ródão. As of 2024, the region's population stands at approximately 100 733 inhabitants, resulting in a population density of about 19 inhabitants per km². The administrative center and largest municipality is Castelo Branco, which houses 52% of the region's population.

The region's recent administrative expansion to include Sertã and Vila de Rei further reinforces its economic significance in forestry and rural development. The landscape is marked by diverse geographical features, from the Gardunha Mountain range in the north to the expansive plains bordering the Alentejo region in the south. This varied topography contributes to the region's rich natural and cultural heritage.

Beira Baixa has some variability in geomorphological terms (plain and mountain), being composed of some mountain landscapes of the mountains of the central mountain range (Serra da Gardunha – 1227m and Serra da Malcata – 1259m), the unit consisting of the Gardunha Mountains, Alveoli and Moradal and the Serra de Penha Garcia, Serra do Perdigão and Serra do Moradal, as well as lowland landscapes, with elevations in the order of 300-500m, with emphasis on the meadows of Idanha.

The territory has clearly Mediterranean climatic characteristics, with some differences between the more mountainous sectors and the lower elevation zones. Summers are warm and dry to oppose cold winters. The month of July is the month that historically presents the highest values of monthly average temperature, minimum average and maximum average. The month of August is the month with the highest maximum absolute temperature (41.6ºC). The humidity of the air follows the behavior of the temperature, registering the lowest values in the months of July and August. As far as precipitation is concerned, it varies greatly depending on altitude, with values that are between 600 and 1200mm/year.

Land use is also a distinct element in this markedly rural territory, where it is possible to verify the supremacy of forest landscapes, with a greater predominance of Maritime pine forests (Pinus pinaster Ait.), Eucalyptus forests (Eucalyptus globulus L,), and holm oak (Quercus ilex L,) and cork oak (Quercus suber L.) forests, with some constraints in terms of forest management that hinder the exploitation of their resources, aggravated by forest properties that are characterized by a smallholdings structure, mostly without any management, with forest stands disordered and proliferating invasive plants and spontaneous vegetation, which contributes to the risk of high fire in much of the territory, especially west of the Ocreza River.

In recent decades, Beira Baixa has experienced significant demographic shifts, notably a declining and aging population. Many villages now have as few as 70 to 200 residents, predominantly elderly individuals. This demographic trend has led to the closure of schools and the abandonment of agricultural lands, exacerbating the region's vulnerability to environmental challenges.

Beira Baixa is characterized by a rich natural and landscape heritage, which includes several protected areas of significant environmental and cultural value. Among these are the Natural Park of the International Tagus, the Serra da Malcata Nature Reserve, the Natural Monument of the Ródão Gates, the protected landscape of Serra da Gardunha, and sites designated under the Natura 2000 Network (Habitat Directive), specifically Gardunha and Malcata. Also integral to this heritage is the Naturtejo Geopark, which encompasses the municipalities of Vila Velha de Ródão, Castelo Branco, and Idanha-a-Nova. Recognized as part of the UNESCO Global Geoparks Network since 2006 and included in the Biosphere Reserve Network since 2015.

Beira Baixa faces significant climate risks, particularly from wildfires and heatwaves, due to its dry Mediterranean climate, high summer temperatures and low summer precipitation, and extensive forested areas dominated by flammable species such as Maritime pine and Eucalyptus. The prevalence of unmanaged lands, smallholdings, and invasive vegetation further amplifies fire susceptibility, especially west of the Ocreza River. Additionally, recurring heatwaves, with temperatures exceeding 41°C, intensify the region's exposure. These risks are compounded by demographic decline and land abandonment, which weaken local capacity for landscape management and adaptation. As such, Beira Baixa requires focused climate risk mitigation and adaptation strategies addressing both fire and heat stress.

1.2 Main objectives of the project

Phase 2 of the CLIMAAX–Beira Baixa project aims to refine and regionalize the climate risk assessment developed in Phase 1, maintaining the focus on rural wildfires and heatwaves as the two priority climate risks for the region. Building on the CLIMAAX framework and the initial workflows, this phase seeks to deliver a more detailed and locally relevant understanding of how these hazards interact with exposure and vulnerability across the Beira Baixa territory.

More specifically, Phase 2 pursues the following objectives:

- **Refinement of hazard assessments for wildfires and heatwaves**, by adapting the CLIMAAX workflows to Portuguese conditions and the Beira Baixa context, using higher-resolution national and regional datasets and updated modelling approaches. This includes addressing limitations identified in Phase 1 related to the coarse spatial resolution of climate projections and the partial representation of local climatic trends.

- **Integration of local methodologies, data and models** into the CLIMAAX framework, combining the handbook's standard workflows with region-specific analyses (e.g. land use, infrastructure, health and demographic data) to obtain risk outputs that better reflect the local conditions.

- **Development of stakeholder-prioritized risk analyses** for wildfires and heatwaves, such as the identification of areas of maximum hazard, the exposure and accessibility of critical infrastructure, and the vulnerability of population groups to extreme heat, in line with the priorities identified through surveys and workshops held with regional stakeholders.

- **Strengthening of regional decision-support**, by producing risk indicators and maps that can be directly used to inform local and intermunicipal planning instruments, including the

PIAAC-BB, municipal emergency plans and sectoral strategies related to civil protection, health, land-use and infrastructure management.

- **Preparation of the analytical basis for Phase 3**, ensuring that the outputs of Phase 2 can be translated into concrete adaptation options and management measures for wildfires and heatwaves, to be explored and prioritized together with stakeholders in the next phase of the project.

The CLIMAAX Handbook and toolbox remain central to this phase: the standard CRA steps and workflows provide a harmonized methodological backbone, while the inclusion of local datasets, revised model configurations and additional impact metrics allows the assessment to respond to the specific needs and expectations of the Beira Baixa region. In this way, Phase 2 both preserves comparability with other European regions and delivers decision-ready information tailored to the local context.

1.3 Project team

The project team comprises two key entities collaborating to conduct the climate risk assessment and implement the CLIMAAX framework (Phase 1 and Phase 2):

Comunidade Intermunicipal da Beira Baixa (CIM-BB)

CIM-BB is the regional coordinating body responsible for fostering intermunicipal collaboration and implementing strategic initiatives in Beira Baixa. As the lead institution, CIM-BB ensures the alignment of the project with regional climate adaptation policies and facilitates stakeholder engagement across municipalities.

greenmetrics.ai

greenmetrics.ai is a technology-driven organization that provides advanced data analytics for environmental and climate risk assessments. Their expertise in climate modeling and risk prediction supports the project's efforts in quantifying vulnerabilities, identifying high-risk areas, and proposing data-driven adaptation strategies.

1.4 Outline of the document’s structure

The document is structured into the following sections:

Section 1- Introduction

Provides a short summary of the region’s background, main goals for the implementation of the CLIMAAX framework and project team.

Section 2 – Climate Risk Assessment - phase 2

Provides a detailed analysis of climate risks affecting Beira Baixa, including hazard screening, scenario selection and risk analysis methodologies.

Section 3 – Key Findings

Summarizes the preliminary results of the assessment, including identified risks, vulnerabilities, and potential issues requiring future adaptation strategies.

Section 4 – Monitoring and Evaluation

Discusses the mechanisms for tracking progress, refining risk assessments, and integrating stakeholder feedback.

Section 5 – Conclusions

Presents the key conclusions from the preliminary climate risk assessment, reflecting on the main results obtained with this methodology and its limitations.

Section 6 – Supporting Documentation

Includes references, datasets, and supplementary materials used in the assessment.

2 Climate risk assessment – phase 2

2.1 Scoping

2.1.1 Objectives

The main objective of the Phase 2 Climate Risk Assessment (CRA) for Beira Baixa is to refine and deepen the analysis of wildfire and heatwave risks carried out in Phase 1, by integrating higher-resolution local data, regionally calibrated models and stakeholder-prioritized lines of analysis. Building on the initial screening and risk quantification, Phase 2 aims to produce more detailed and policy-ready evidence on where, when and for whom wildfire and heatwave risks are most critical in the region, with a particular focus on critical infrastructure, health systems and vulnerable population groups.

The expected outcome of this phase is a set of regionalized hazard, exposure and vulnerability outputs that can be directly used to support decision-making by CIM-BB and its municipalities.

These outcomes are intended to feed directly into regional and local policy and planning processes. At intermunicipal level, the refined risk information will support the future updating of the PIAAC-BB and other strategic climate adaptation initiatives. At municipal level, the results are expected to inform land-use and urban planning (e.g. location and design of green infrastructure, management of high-risk forest–urban interfaces), emergency and civil protection planning (e.g. evacuation routes, pre-positioning of resources), and sectoral strategies for health, transport and energy. By translating model outputs into interpretable indicators and maps, the CRA is designed to strengthen evidence-based decision-making and facilitate dialogue between technical staff, policymakers and stakeholders.

Compared to Phase 1, the scope of the objectives has evolved from demonstrating the applicability of the CLIMAAX framework with European datasets towards producing region-specific, decision-support information. Phase 2 explicitly responds to priorities identified by stakeholders in workshops, such as the identification of areas and seasons of maximum wildfire hazard, the analysis of accessibility in high-risk and hard-to-reach zones, the evaluation of coverage by aerial and terrestrial water points, the spatial distribution of urban heat islands, and the resilience of health infrastructure to extreme heat.

The CRA in Phase 2 remains bounded to two main climate hazards—wildfires and heatwaves—within the territory of CIM-BB. Methodologically, the assessment is constrained by the availability, quality and temporal coverage of local and sectoral datasets (e.g. infrastructure inventories, health records, socio-economic indicators) and by the characteristics of the underlying climate projections. For heatwaves, the integration of LST, NDVI and health data is limited by data gaps and by the small number of clearly heat-caused diagnoses, requiring cautious interpretation and further guidance from health stakeholders.

Several challenges identified in Phase 1 continue to influence Phase 2, but are being addressed partially. These include fragmented data ownership, variable spatial resolutions between climate and local datasets, and the need to move from purely climatic indicators towards more operational risk metrics. To mitigate these bottlenecks, Phase 2 makes systematic use of newly available national datasets (such as COS-2023), formalizes data sharing with CIM-BB and partners, and focuses analyses on questions that were jointly prioritized with stakeholders. Remaining limitations—such as incomplete socio-economic scenario detail and restricted access to some sectoral data—are acknowledged in the interpretation of results and will be taken into account when preparing the Phase 3 work on adaptation options and governance.

2.1.2 Context

Climate hazards in Beira Baixa have traditionally been assessed through municipal forest fire defense plans and regional adaptation strategies, such as the Intermunicipal Plan for Adaptation to Climate Change of Beira Baixa (PIAAC-BB). However, these assessments often lack integration, leading to fragmented responses and limited long-term planning.

The primary challenges addressed by this project include the increasing frequency and severity of wildfires and heatwaves, which pose significant threats to the region's economy, environment, and public health. The CLIMAAX project seeks to bridge critical gaps in climate risk assessment by improving data availability, enhancing predictive modeling, and integrating stakeholder-driven adaptation strategies. Additionally, governance frameworks, including regional climate policies and national directives, such as the National Strategy for Integrated Rural Fire Management, play a crucial role in shaping and supporting these adaptation measures.

Furthermore, at both national and local levels, significant efforts are underway to develop heatwave adaptation measures. Portugal's national heatwave contingency plan includes early warning systems, public awareness campaigns, and emergency response protocols, particularly aimed at protecting vulnerable populations. Locally, Beira Baixa municipalities have been working on improving shading in public spaces, increasing access to cooling centers, and integrating heatwave adaptation into urban planning strategies. These measures complement the objectives of the CLIMAAX project by reinforcing community resilience against extreme temperature events.

2.1.3 Participation and risk ownership

At the start of Phase 2, the stakeholder group that participated in Phase 1 was re-activated and invited to an in person workshop (14/11/2025) focused on: (i) presenting the CLIMAAX methodology and the main Phase 1 results; (ii) prioritizing risk analyses for Phase 2; and (iii) identifying additional data sources and contact points for technical validation. This workshop provided the basis for a shared work plan, centered on a shortlist of wildfire and heatwave analyses that stakeholders considered most relevant for their operational needs (e.g. accessibility and exposure in high-risk wildfire areas, influence of green spaces on urban heat, resilience of health infrastructure).

The institutional stakeholders that participated can be grouped into the following categories:

- **Municipal authorities and Municipal Civil Protection Services (SMPC)** of the eight municipalities, responsible for local emergency planning, land-use regulation and implementation of many concrete adaptation measures;

- **Regional and national agencies** such as ICNF, AGIF, ANEPC, CCDR Centro and GNR, which set and enforce policies on nature conservation, rural fire management and civil protection;

- **Sectoral stakeholders** including forestry and agricultural associations (e.g. AFLOBEI, Ovibeira, Acripinhal, ARBI), utility companies (E-Redes, REN) and other infrastructure owners;

- **Research and higher education institutions** (e.g. Instituto Politécnico de Castelo Branco, CEIF-ADAI, other universities) that support the scientific grounding of the assessment;

- **Health-sector actors**, including regional health services and research centres such as the Centro de Investigação em Ciências da Saúde – UBI, who provide and interpret data on health outcomes during heatwaves.

Risk ownership in Beira Baixa is multi-lleveland follows the national governance framework for rural fires and civil protection. For **wildfires**, strategic responsibility for integrated fire management lies with AGIF and ICNF at national level, while ANEPC coordinates civil protection and emergency response. At regional and local level, CIM-BB and the municipal SMPC are responsible for identifying priority areas, preparing and implementing local plans (e.g. municipal emergency plans, fuel-management plans, Integrated Landscape Management Areas and "Condomínio das Aldeias" initiatives), and coordinating suppression resources with national authorities. Forestry and agricultural associations contribute to risk identification and mitigation through land-management practices and communication with landowners.

For **heatwaves**, risk ownership is more strongly anchored in the health and social sectors. National health authorities define alert levels and contingency plans for extreme heat, while regional health services and local health units are responsible for monitoring heat-related morbidity and mortality, managing hospital and primary care capacity and activating targeted interventions (e.g. protection of vulnerable patients). Municipalities assume responsibility for translating heat-risk information into urban planning, public-space design (shade, green infrastructure) and social support measures, often in coordination with civil protection services and social care providers. Phase 2 explicitly reinforced this dimension by integrating anonymized health data from local health units into the analysis and by using the Phase 2 workshop to discuss possible health-sector extensions of the CRA.

2.1.4 Application of principles

In Phase 2, the climate risk assessment for Beira Baixa was explicitly organized around the three core CLIMAAX principles: **social justice, equity and inclusivity; quality, rigor and transparency; and the precautionary approach**. These principles guided the way the work was scoped, which data and methods were prioritized, how stakeholders were involved, and how results and uncertainties are communicated in this report.

Regarding **social justice, equity and inclusivity**, particular attention was given to how climate risks are distributed across different population groups and territories within the CIMBB. The analysis systematically considered groups with reduced adaptive capacity (e.g. elderly people, children, socially isolated residents, populations in remote settlements) and the services they depend on (healthcare, emergency response, critical infrastructure). Vulnerability and exposure indicators were therefore selected in a way that makes these groups and services visible in the maps and statistics, rather than focusing solely on biophysical hazard patterns. Geographical equity was addressed by ensuring coverage of all municipalities and by highlighting situations in smaller or less resourced areas where risk may be high but institutional capacity is more limited. Inclusivity was further pursued through stakeholder engagement: municipal authorities, civil protection, sectoral services and other local institutions were repeatedly involved to comment on priorities, validate emerging results and identify blind spots, including the perspective of territories and groups that are usually less represented in technical processes.

The principle of **quality, rigor and transparency** was applied by using the best available data and methods, documenting choices and limitations, and seeking consistency with the CLIMAAX framework and with the Phase 1 work. Whenever possible, open and well-documented datasets were preferred, and data processing steps were structured so they can be repeated in future updates. Assumptions, thresholds and classification rules are described in the methods sections, and sources of uncertainty are explicitly noted (for example, limitations of specific datasets, model assumptions or gaps in impact information). This aims to make the assessment traceable for other analysts and understandable for decision-makers, while avoiding an appearance of false precision. Furthermore, all the code and results are to be publicly available.

Finally, a **precautionary approach** was adopted throughout the assessment, especially in the interpretation of future climate risks and in dealing with uncertainty. Multiple climate scenarios and time horizons were considered to frame the range of plausible futures, rather than relying on a single "best estimate". Where data or model limitations exist, these were treated as reasons for caution rather than for downplaying risk. In practice, this meant placing emphasis on robust patterns that appear across scenarios and indicators, and on "no-regret" domains for action, such as protecting critical infrastructure, improving emergency access, and reducing exposure of vulnerable populations to wildfires and heatwaves.

Taken together, this application of the CLIMAAX principles in Phase 2 supports a risk assessment that is attentive to distributional and territorial fairness, technically robust and transparent, and oriented towards cautious, forward-looking decision-making for the CIMBB region.

2.1.5 Stakeholder engagement

Stakeholder engagement in Phase 2 built on the network established during Phase 1, maintaining the involvement of municipal authorities, civil protection services, sectoral agencies, research institutions, utility companies and professional associations, and extending it to additional health sector representatives for the heatwave analyses. This ensured continuity in risk ownership while bringing in new expertise relevant to the refined assessment of wildfire and heatwave risks.

At the beginning of Phase 2, an online survey was circulated to the stakeholders engaged in Phase 1. The objective was to identify and prioritize the most relevant analyses to be developed in this phase, both for wildfires and heatwaves. Participants were asked to rank potential lines of analysis, indicate which outputs would be most useful in their institutional context (e.g. operational planning, long-term spatial planning, emergency preparedness), and suggest additional questions or datasets. Responses from municipal civil protection services, forestry and agricultural associations, regional and national agencies, and academic partners were used to select and refine the analytical priorities adopted in Phase 2, such as the focus on accessibility to high-hazard zones, exposure of critical infrastructure, and the integration of demographic and health-related information in the heatwave assessment.

At the end of Phase 2, an in person workshop was organized with the majority of these stakeholders to present the updated results and to validate the new analyses. The workshop combined plenary presentations with detailed maps and figures, followed by open discussion. Project goals and intermediate results were communicated through a structured sequence of slides and cartographic outputs, covering: (i) the updated wildfire hazard model calibrated for mainland Portugal; (ii) revised exposure and vulnerability analyses for key infrastructures and settlements; and (iii) the extended heatwave analyses, including land surface temperature, the influence of green spaces in urban cooling, and preliminary insights from health-related data. This format allowed participants to directly relate the results to their own responsibilities in civil protection, land management, health services and regional planning.

Overall, the results were received positively. Feedback focused on clarifying the interpretation of risk classes, improving the representation of certain infrastructures and services (e.g. specific roads, water points, health facilities), and exploring additional indicators.

During Phase 2, the main difficulties encountered related to the availability and harmonization of some sectoral datasets (particularly in the health domain), as well as coordinating schedules to ensure broad participation in the final workshop. In addition, communicating model uncertainty and technical assumptions in an accessible way required careful balancing between scientific detail and operational relevance. These challenges will inform the design of future engagement activities, including more targeted thematic meetings and dedicated sessions to co-interpret results with specific stakeholder groups.

2.2 Risk Exploration

2.2.2 Screen risks (selection of main hazards)

In Phase 1, a broad risk screening combining historical impact data and stakeholder input identified rural wildfires and extreme heat/heatwaves as the dominant climate-related hazards for the Beira Baixa region. This selection reflected both recent impacts (e.g. large burned areas since 2017 and recurrent extreme temperature events) and the priorities already highlighted in existing strategic documents such as the PIAAC-BB.

No additional risk screening exercise was carried out in Phase 2, and the review of Phase 1 results with regional stakeholders confirmed that wildfires and heatwaves remain the most relevant climate hazards for CIM-BB within the scope of the CLIMAAX project. Other climate-related hazards (such as droughts in the summer or intense precipitation leading to floods in the winter) are recognized in the wider policy context, but were not added as separate workflows in this assessment.

Consequently, the selection of main hazards is unchanged compared to Deliverable 1: the Phase 2 analysis continues to focus on (i) wildfires, particularly in the forested and mountainous areas of the western and northeastern part of the region, and (ii) heatwaves affecting urban and peri-urban areas with high concentrations of vulnerable population and pronounced urban heat island effects. The subsequent sections refine the hazard and risk analyses for these two hazards using updated methods and datasets, but do not alter the underlying hazard selection.

2.2.3 Choose Scenario

In line with Phase 1, the climate scenario design for Phase 2 is based on two Representative Concentration Pathways: RCP 4.5 and RCP 8.5. RCP 4.5 is used as an intermediate pathway and serves as the main reference for decision-making, while RCP 8.5 represents a high-end, worst-case trajectory. Keeping this pair of scenarios allows us to explore a realistic range of future climate conditions for Beira Baixa, to understand how hazards may evolve under moderate mitigation, and to stress-test adaptation options against more severe warming.

For wildfires, future climate conditions are derived from the ECLIPS2.0 dataset, using bias-corrected EURO-CORDEX projections and a retrained machine-learning susceptibility model calibrated for mainland Portugal. The model produces hazard maps for four time horizons: 2021–2040, 2041–2060, 2061–2080 and 2081–2100, for both RCP 4.5 and RCP 8.5. This extends Phase 1, where longer-term outputs were available but less reliable, and reflects a deliberate emphasis on long-term risk to complement the short-term wildfire products already produced by national bodies such as ICNF. The resulting century-scale view is particularly relevant for forestry planning, infrastructure investments and landscape-scale fuel management, where decisions taken today have effects over several decades.

For heatwaves, we retain the Phase 1 time horizons based on the EURO-CORDEX "heat waves and cold spells in Europe" dataset: a first period 2016–2045 and a second period 2046–2075, again for both RCP 4.5 and RCP 8.5, compared against the historical baseline 1986–2015. These horizons are aligned with the planning timescales of local authorities and the health sector: the first period corresponds to the next few decades in which current infrastructure and population will still be highly relevant, while the second period captures medium-term intensification of heat extremes that may require more transformative adaptation. In Phase 2, these projections are combined with high-resolution land surface temperature (LST) maps for summer 2024 and NDVI-based vegetation indicators to characterize urban heat islands and the cooling effect of green spaces at neighborhood scale.

Future socio-economic conditions are treated in a pragmatic way. No formal socio-economic scenario set (e.g. SSPs) is implemented. Instead, the analysis assumes the current spatial distribution of population and infrastructure as a conservative exposure baseline, while recognizing that demographic aging, rural depopulation and concentration of services in urban centers are already ongoing and are likely to continue. For heatwaves, the risk analysis combines projected changes in heatwave frequency with estimates of vulnerable population (under 5 and over 65 years) from WorldPop of year 2020, mapped at parish level. For wildfires, the future hazard maps are overlaid with (socio-economic).

Compared to Phase 1, the scenario design in Phase 2 therefore maintains the same pair of climate pathways to ensure continuity, but (i) extends the wildfire horizon to 2100 with a model explicitly constrained to follow projected climatic trends, and (ii) strengthens the near- and medium-term heatwave analysis by integrating LST, NDVI and health data. This combination of climate and socio-economic assumptions is aimed at supporting both immediate adaptation measures (e.g. health preparedness, fuel management, spatial planning) and longer-term strategic decisions for Beira Baixa.

2.3 Regionalized Risk Analysis

2.3.1 Hazard #1: Wildfires - fine-tuning to local context

Table 2-1 Data overview workflow #1

Hazard data	*Vulnerability data*	*Exposure data*
Climatic variables (Chakraborty, et al. 2020)	Population (Copernicus Emergency Management Service s.d.)	Main Roads - *internal documentation of CIM*
Land types (Direção-Geral do Território 2025)	Ecological (Copernicus Emergency Management Service s.d.)	Healthcare Services - *internal documentation of CIM*
Topography (Gonçalves s.d.)	Economical (Copernicus Emergency Management Service s.d.)	Urban zones - *internal documentation of CIM*
Historic Wildfires (Instituto da Conservação da Natureza e das Florestas 2025)	Water points - *internal documentation of CIM*	Elderly care homes - *internal documentation of CIM*
Susceptibility of land types to wildfires (Instituto da Conservação da Natureza e das Florestas 2020)	Fire stations - *internal documentation of CIM*	Schools - *internal documentation of CIM*
	Strategic Parking Locations - *internal documentation of CIM*	

2.3.1.1 Hazard assessment

The wildfire hazard assessment in Phase 2 builds on the CLIMAAX machine-learning wildfire workflow, but is now explicitly calibrated to Portuguese conditions and refined for the Beira Baixa context. The objective is to obtain hazard maps that are consistent with projected climate trends and sensitive to local land-use and topographic patterns, addressing the limitations identified in Phase 1, where climatic change was only weakly reflected in the hazard maps. In Phase 2, an XGBoost gradient-boosting model was adopted in place of the random forest used in Phase 1, allowing a more flexible calibration and better control of how the model responds to changing climate. This type of model is also well suited to handling large datasets, which was an advantage given that the training was performed for the whole of Continental Portugal.

To achieve this, the wildfire susceptibility model was re-trained on a Portugal-wide training domain, using synoptic wildfire events from 1991–2010 and a more focused set of predictors. Training at the national scale allows the model to learn from a wider range of climatic and landscape conditions and to better capture the relationships between wildfire occurrence and the input variables. Climatic inputs are based on the ECLIPS2.0 dataset and were reduced to three key variables that proved most informative for ignition and spread conditions:

- summer heat–moisture index (SHM);
- mean annual precipitation (MAP);
- mean annual temperature (MAT).

These climatic variables are complemented by high-resolution geographical predictors that control fuel availability and fire behavior at the regional scale:

- land cover from COS-2023, reclassified into fuel-relevant categories;
- elevation, slope, aspect and terrain roughness.
- historical burnt areas from national fire statistics, used to characterize where fires have effectively occurred under past climate.

Compared with Phase 1, where the model tended to be dominated by land cover and topography and showed limited temporal evolution of hazard, the Phase 2 implementation introduces climate-alignment mechanisms and monotonic constraints to ensure that, for a given location, hazard is consistent with the projected evolution of temperature, humidity and precipitation. In practice, this largely suppresses spurious decreases of hazard in far-future periods that were observed in some Phase 1 experiments, and the maps show a more coherent progression of hazard intensification over time.

For each GCM–RCM combination available in ECLIPS2.0, the model was run separately to obtain a set of hazard maps under different climate projections. A mean ensemble of these model results was then computed to analyze the temporal evolution of wildfire hazard. This ensemble should not be interpreted as a precise prediction of the future, but rather as a general indication of the tendency that can be expected under climate change. For a more complete view of uncertainty, the ensemble results should be interpreted together with the individual GCM–RCM realizations.

As an additional consistency check, the wildfire hazard maps produced in this workflow were compared with the structural hazard maps from ICNF (Instituto da Conservação da Natureza e das Florestas), the Portuguese public institution responsible for managing national natural and forest heritage. ICNF’s hazard products are a key reference for short-term and operational wildfire risk management in Portugal. The intention of the present work is not to replace these maps, but to complement them by providing an analysis of the long-term evolution of wildfire hazard under different climate scenarios.

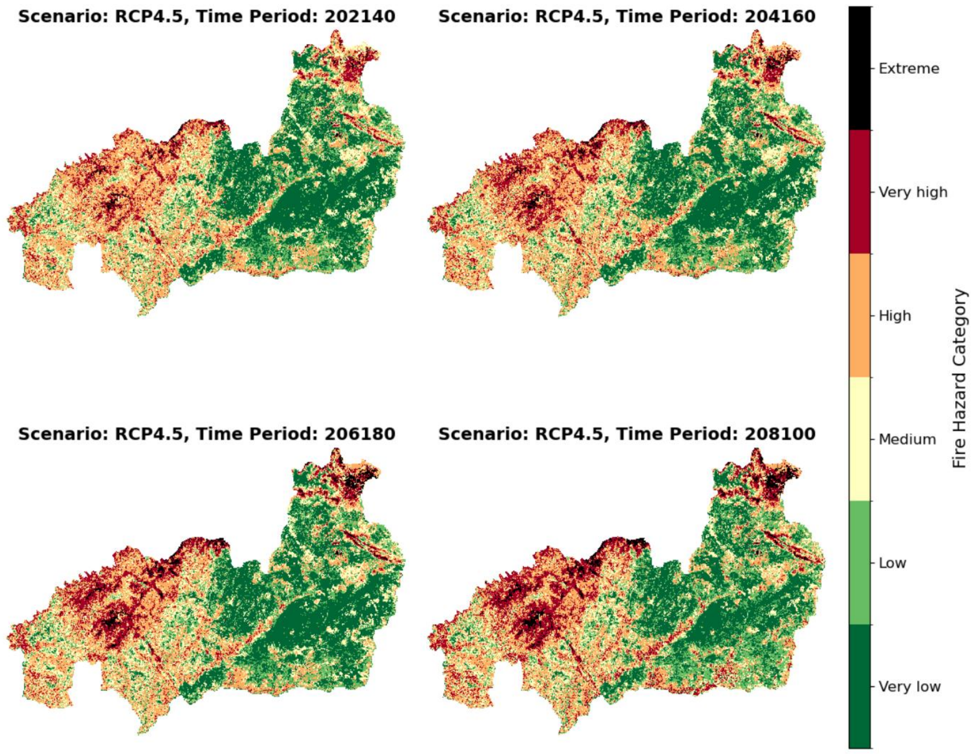

Figure 2-1 Wildfire Hazard; Scenario RCP 4.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

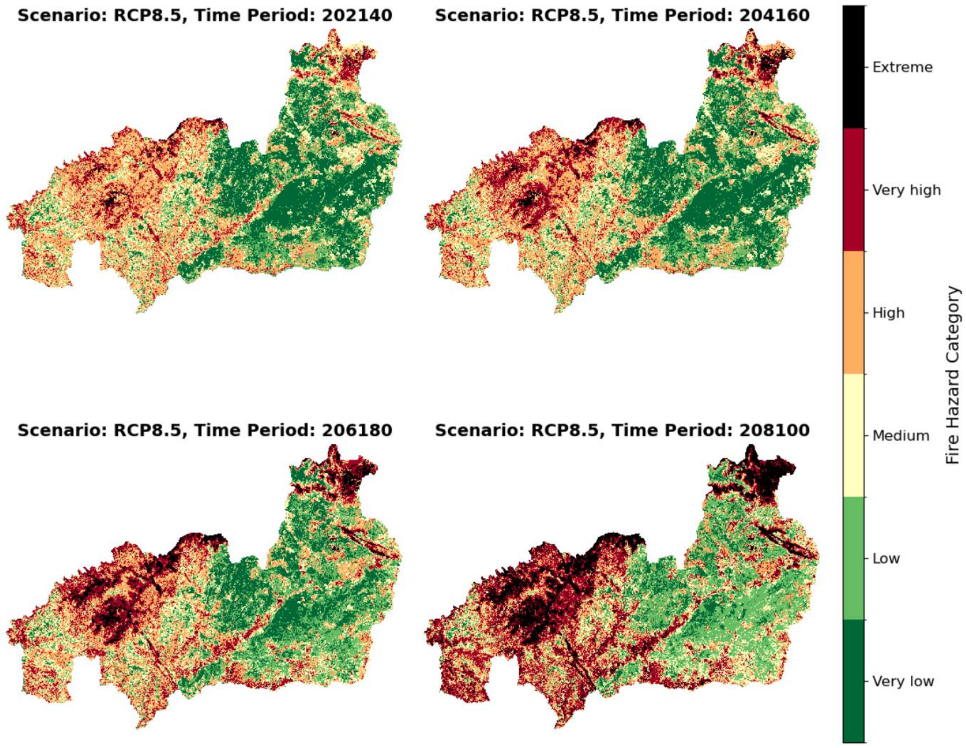

Figure 2-2 Wildfire Hazard; Scenario RCP 8.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

Overall, the Phase 2 hazard patterns confirm the main hotspots already identified in Phase 1 – particularly the mountainous and heavily forested sectors of Beira Baixa – but show a clearer and more gradual intensification of hazard through the century, especially under the high-emission scenario. Areas where land cover transitions towards more flammable vegetation types, or where steep slopes coincide with dense fuel, exhibit the most pronounced increases in hazard class. Conversely, zones with less continuous fuel or lower structural hazard maintain comparatively lower hazard levels, even under adverse climate trajectories. The main outputs are presented in the wildfire hazard maps (Figure 2-1 and Figure 2-2), which show the spatial distribution of hazard classes and their evolution over time.

There are, however, some limitations to this approach. First, the temporal granularity of the training data is limited: the model is calibrated using a single historical period and then applied to future time slices. Ideally, several historical periods with similar duration would be available to better map the temporal evolution of hazard, but this was not possible due to historic wildfire data availability and quality constraints. Second, some of the input datasets present artefacts that may affect local model performance and, consequently, the detailed pattern of hazard. Despite these issues, the datasets were considered broadly representative of the region. Future work could include, for example, a more systematic validation of land-cover information or the integration of additional local datasets to further improve the robustness of the hazard assessment.

2.3.1.2 Risk assessment

For the wildfire risk assessment in Phase 2, the updated hazard maps described in Section 2.3.1.1 were combined with information on exposed assets and their vulnerability. The objective is to identify where wildfires are most likely to lead to significant impacts on people, infrastructure, ecosystems and economic activities, and to provide stakeholders with a clearer basis for prioritizing adaptation and prevention measures in Beira Baixa.

In line with the CLIMAAX workflow, the risk analysis focuses on the same time slices and emission pathways considered in the hazard assessment. For each selected period and for both RCP 4.5 and RCP 8.5, the ensemble wildfire hazard index is overlaid with the exposure layers to obtain a set of risk indicators for the region. As in Phase 1, the climate scenarios and their interpretation are described in Section 2.2.3.

Because risk depends strongly on the spatial distribution of assets, the analysis relies on a combination of local and national datasets made available by CIM-BB, national agencies and other stakeholders. Compared with Phase 1, Phase 2 places greater emphasis on fine-resolution, locally validated information and introduces additional layers requested by stakeholders, including the railway network and water points for fire suppression.

The first step is an assessment of the exposure of healthcare services across the region, since these facilities such as hospitals, health centers and other critical buildings, provide essential services during and after wildfire events. By intersecting their locations with the wildfire hazard classes, it is possible to identify which units are already situated in areas of high or very high hazard and where access routes could be compromised. The results are presented in maps (Figure 2-3) where healthcare facilities are shown together with the hazard levels, allowing priority areas to be quickly identified.

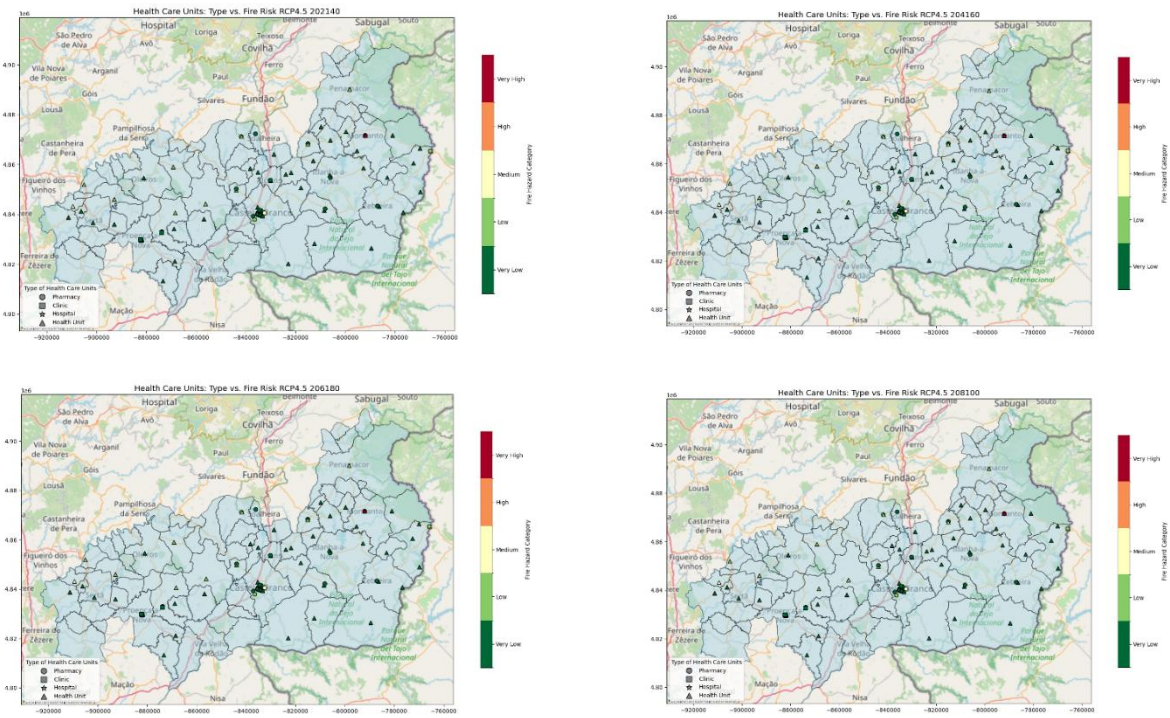

Figure 2-3 Health Care Units Risk.

The exposure of the primary road network (national roads, motorways and other major routes) is then analyzed. This helps to identify sections of road that are most likely to be affected by wildfires in the future and that could become impassable during extreme events, with implications for evacuation, emergency response and the continuity of economic activities. The corresponding maps (Figure 2-4) highlight stretches where high structural hazard and high projected hazard coincide with dense forest fuels, indicating segments that may require particular attention in transport and civil protection planning.

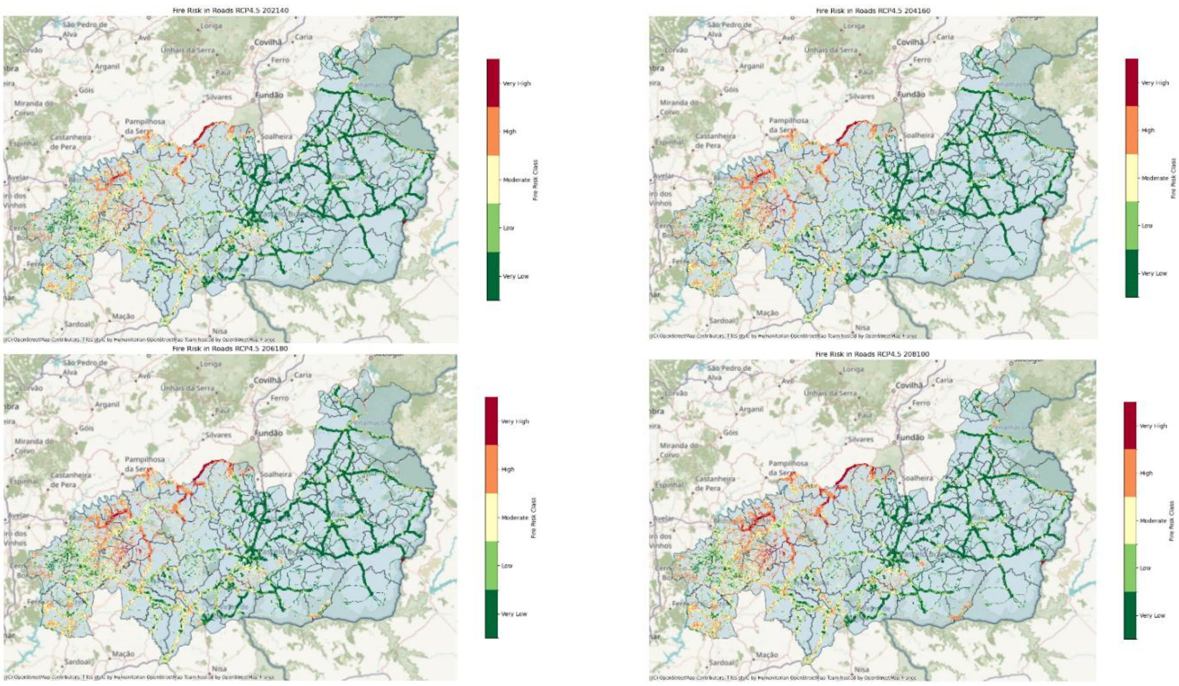

Figure 2-4 Road Network Risk.

Other infrastructures exposure analysis is exposure of urban areas, elderly caring homes and schools.

Beyond infrastructure and settlements, the risk assessment considers populational, ecological and economic vulnerability. Those vulnerabilities were categorized in three based on quantiles and combined with the six hazard categories according to the risk matrix presented in Figure 2-5. The resulting risk is presented in Figure 2-6.

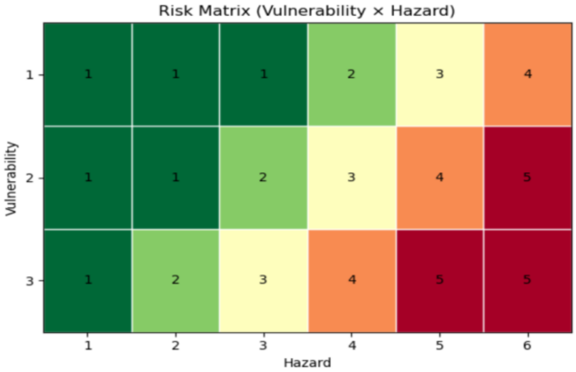

Figure 2-5 Risk Matrix used with population, economical and ecological vulnerability.

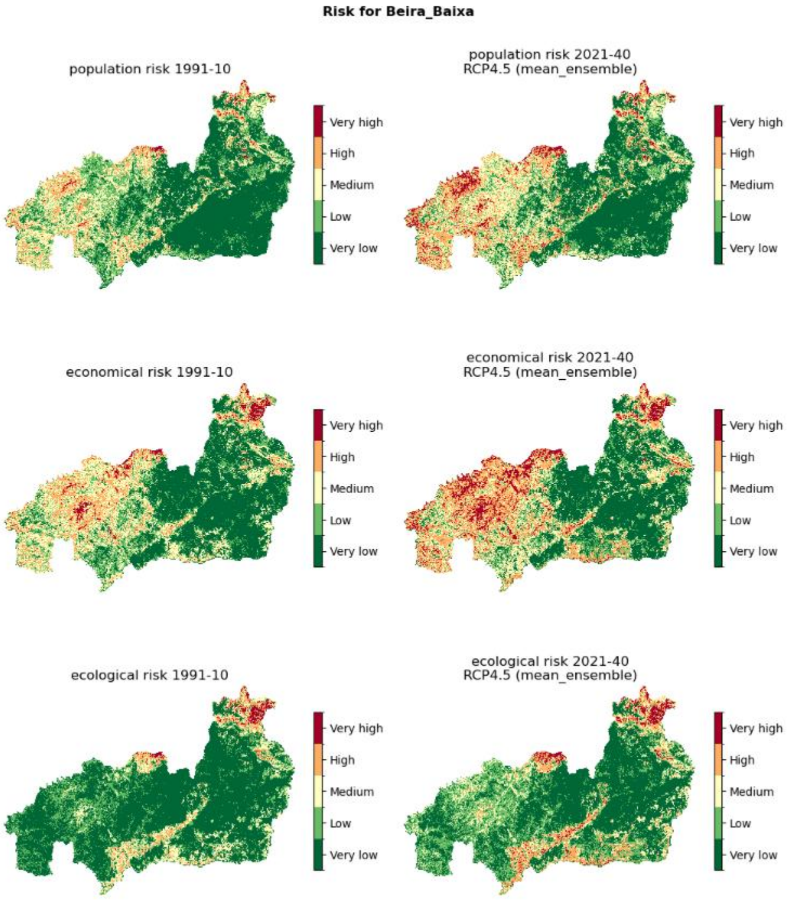

Figure 2-6 Population, economical, ecological Risk for periods 1991-2010 and 2021-2040.

With this we can conclude that even though the northeast area has high hazard, it shows low infrastructure exposure and relatively low population risk due to it being a natural reserve (Malcata) but has high ecological and economical risk. On the other hand the west and central region has high infrastructure exposure risk, population and economical vulnerability risk.

Finally, the analysis includes the response capacity for wildfires, focusing on the availability and accessibility of suppression resources. Two main components are considered: the coverage provided by water points and; the distance to fire stations and strategic parking areas for firefighting means.

The coverage and accessibility metrics derived from these analyses were subsequently classified into five response-capacity classes (using quantiles), with lower classes representing better expected response capacity. These response-capacity classes were then combined with the wildfire hazard classes through a simple risk matrix shown in Figure 2-7.

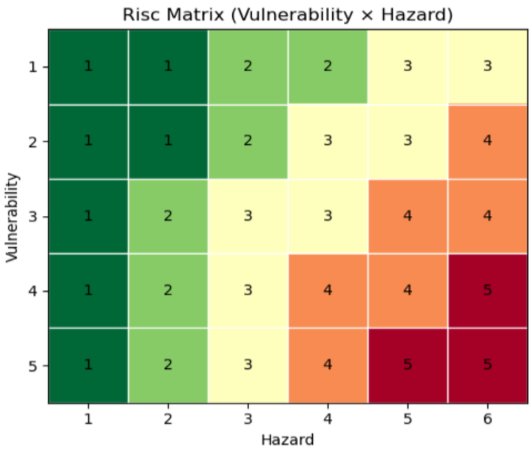

Figure 2-7 Risk Matrix used with response capacity metrics.

For water points, two separate analyses were carried out depending on whether the resources are used by aerial or terrestrial means.

In the case of aerial resources, water points (including reservoirs and selected reaches of the River Tejo, treated as equivalent to a medium-sized dam along its course) were assigned maximum operating radii of 5 km and 10 km, reflecting the different operating ranges of helicopters and fixed-wing aircraft. For each point, a coverage metric was constructed that combines distance and stored volume, and the contributions from all points were aggregated on a raster grid to obtain an overall indicator of aerial water availability. To prevent very large reservoirs from dominating the representation, two complementary approaches were used: (i) a first metric in which the effective volume of each point was limited to 10 000 m^3 (Figure 2-8), giving greater weight to areas with several medium-volume water points; and (ii) a second metric in which no volume limit was applied, but the final raster was visualized using a logarithmic scale (Figure 2-9), allowing both low- and high-volume points to be visible, at the cost of reducing the relative contrast between smaller volumes. The limitation of this analysis is that the elevation of the water points and the surrounding terrain was not explicitly considered, even though orography is an important factor for the safe and effective operation of aerial resources; the indicator should therefore be interpreted as a first-order approximation of aerial water availability.

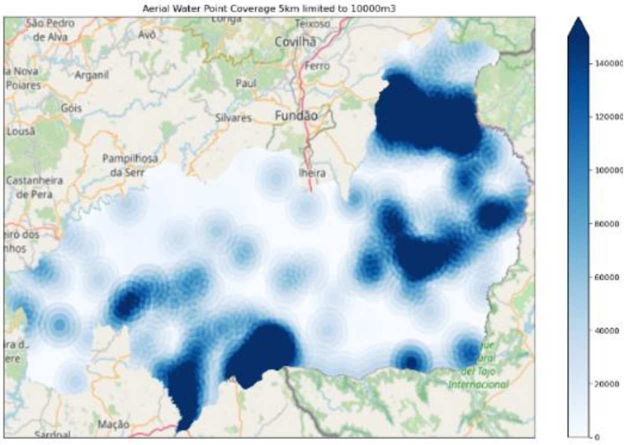

Figure 2-8 Aerial water points capacity with a limit of volume 10000 m3 and a limit of radius of 5 km for each water point.

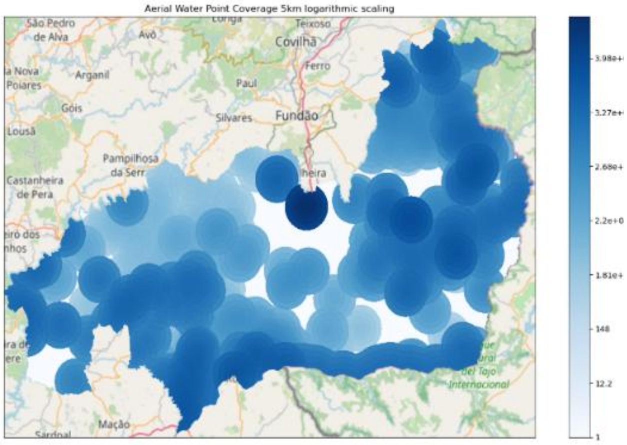

Figure 2-9 Aerial water points capacity with logarithmic scaling and a limit of radius of 5 km.

The resulting risk of the water points capacity for each of the methods (i) and (ii) is then presented in Figure 2-10 and Figure 2-11, respectively. For both methods the risk is situated mostly on the northwest region of CIM-BB.

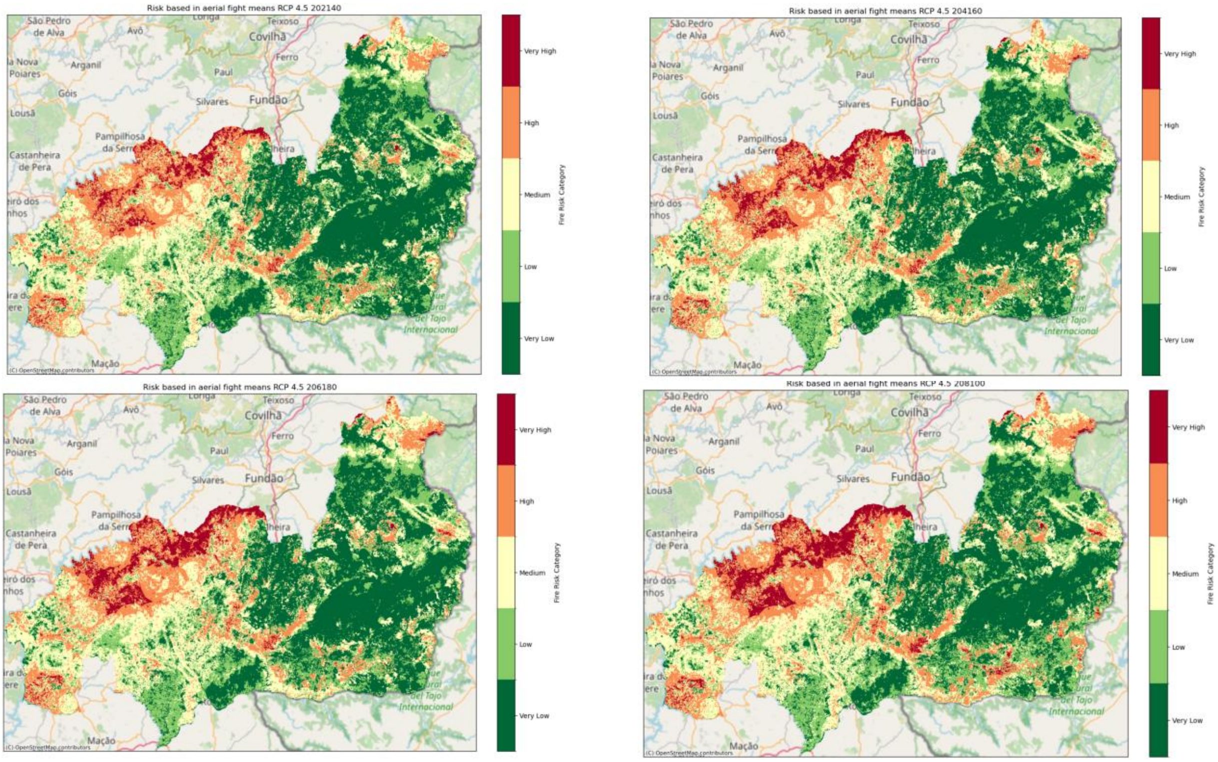

Figure 2-10 Risk of wildfire taking into consideration Aerial Water Points capacity with a limit of 10000 m3 (i).

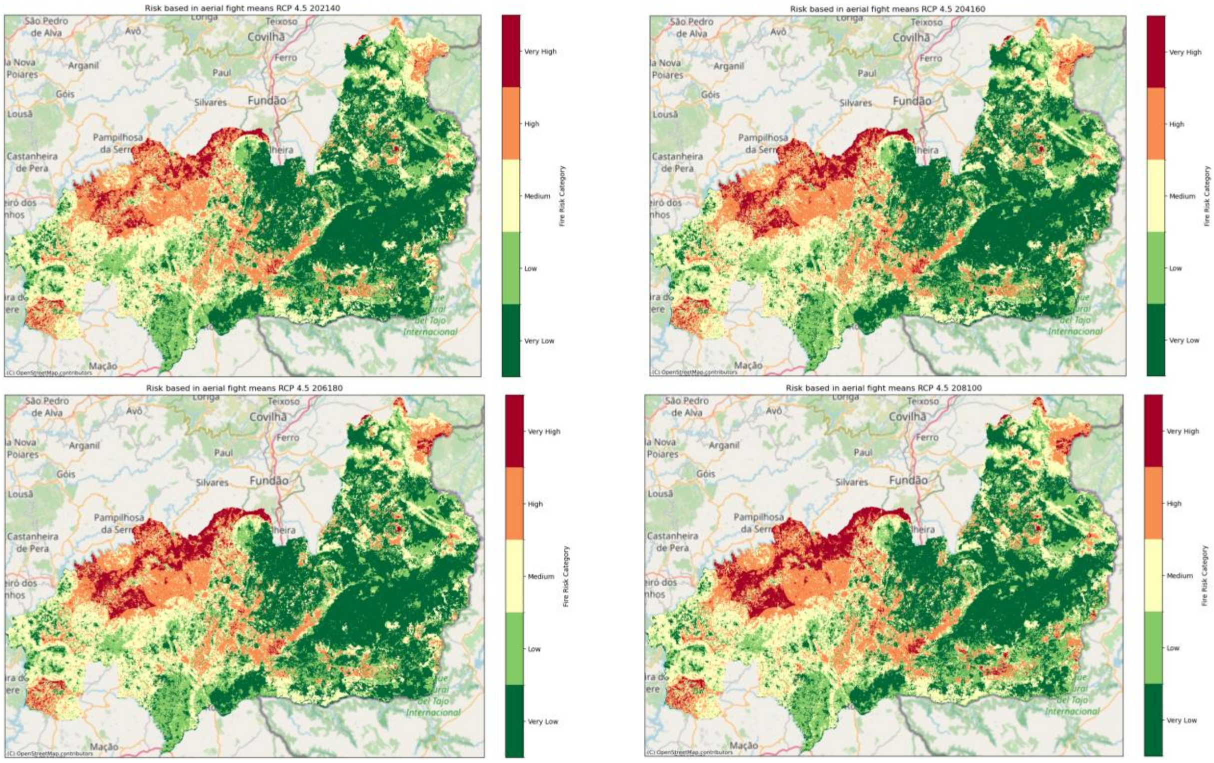

Figure 2-11 Risk of wildfire taking into consideration Aerial Water Points capacity with a logarithmic Scaling (ii).

For terrestrial suppression means, coverage was assessed using a routing algorithm based on the existing road network. The analysis computes, for each pixel in the study area, the distance and travel time to the nearest terrestrial or mixed-use water point, without considering stored volume. Subsequently, this distance was categorized and then matched with the hazard data resulting in Figure 2-12.

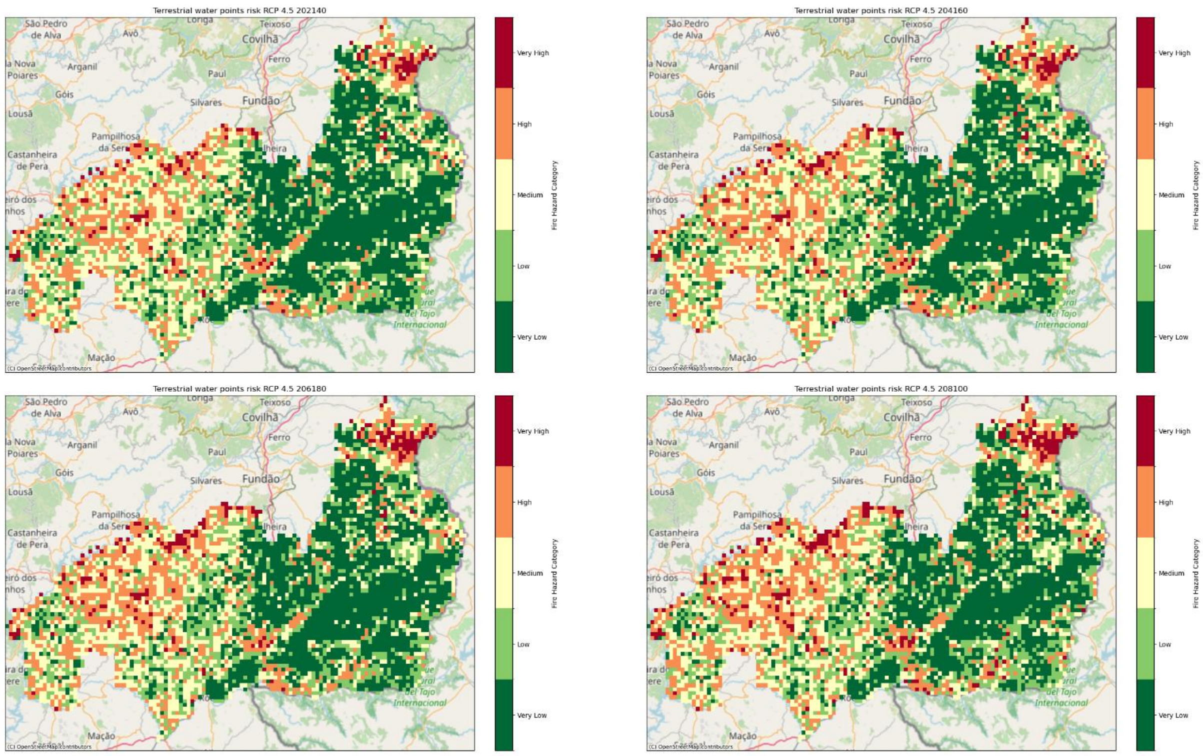

Figure 2-12 Risk of wildfire taking into consideration Terrestrial Water Points capacity.

The same routing approach was applied to fire stations and strategic parking areas for firefighting means, producing maps of the expected response time from the closest unit to each location in Beira Baixa and the respective risk maps (Figure 2-13).

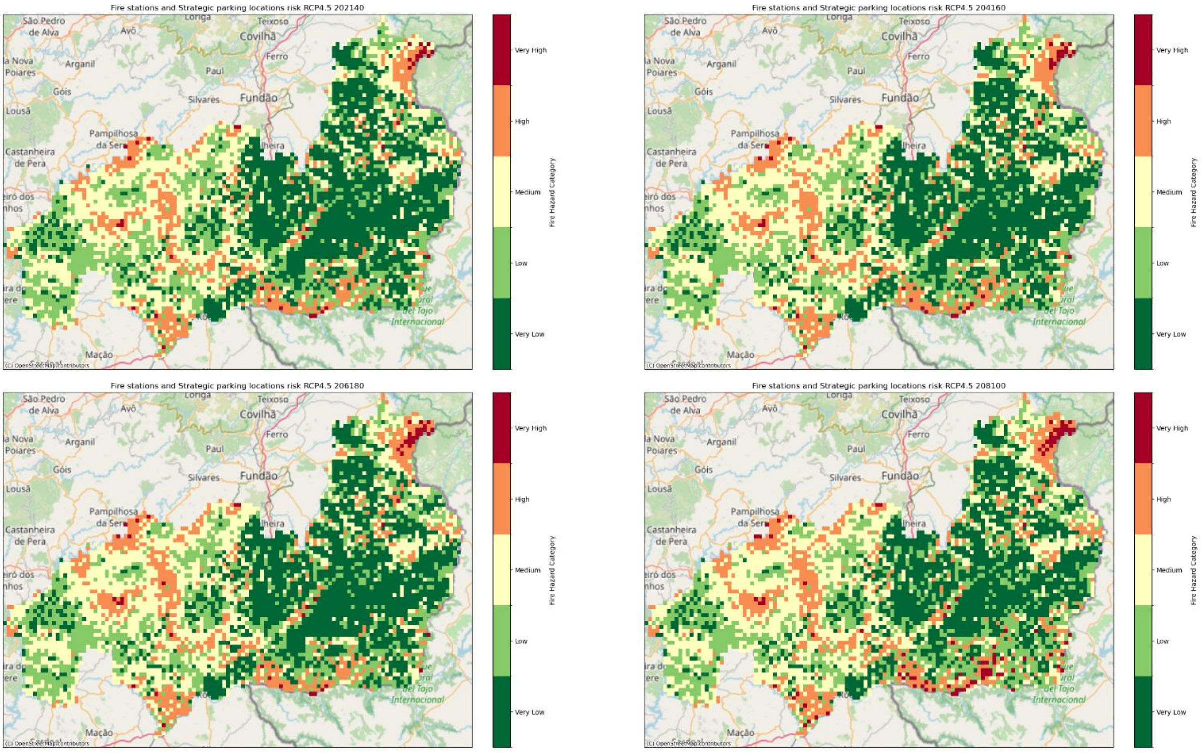

Figure 2-13 Risk of wildfire taking into consideration the location of Fire station and strategic parking location.

Taken together, the Phase 2 risk results confirm that the western and more mountainous parts of Beira Baixa, where structural hazard is highest, also concentrate a large share of exposed assets and vulnerable ecosystems. Healthcare facilities, primary roads, railway segments and power lines located in these zones are particularly relevant from a civil protection perspective, while productive forests and conservation areas in high-hazard classes emerge as priorities for fuel management and prevention measures.

As in the hazard assessment, these risk results should be interpreted primarily in a relative sense, as they depend on the completeness and accuracy of the exposure and vulnerability datasets and on the assumptions used to combine them with the hazard maps. Nevertheless, by integrating the updated wildfire hazard assessment with a broad set of local and national exposure layers, the Phase 2 risk analysis provides a more detailed and actionable picture of where wildfire risk is expected to be highest in Beira Baixa and supports the identification of priority areas for adaptation planning and investment.

2.3.2 Hazard #2: Heatwaves - fine-tuning to local context

Table 2-2 Data overview workflow #2

Hazard data	*Vulnerability data*	*Exposure data*
Heat waves and cold spells in Europe (Hooyberghs, et al. 2019)	Vulnerable Population (WorldPop and Center for International Earth Sc 2018)	Land Types (Direção-Geral do Território 2025)
Parishes - internal documentation of CIM	Urban areas - *internal documentation of CIM*	LST - (Landsat 9 Collection 2 Level-2 data 2024)
	Lugares 2021 (Instituto Nacional de Estatística, I.P. 2024)	NDVI - (Sentinel-2 MSI Level-2A data 2024)

2.3.2.1 Hazard assessment

The heatwave hazard assessment in Phase 2 retains the same core climate indicator used in Phase 1: the projected evolution of the frequency of heatwaves, defined according to the EuroHEAT criterion as three or more consecutive days with daily maximum temperature above the 90th percentile of the local historical distribution. Hazard projections were obtained from the Copernicus Climate Data Store dataset "Heat waves and cold spells in Europe derived from climate projections", based on EURO-CORDEX simulations for the RCP 4.5 and RCP 8.5 emission pathways. The analysis considers two time horizons relative to the historical baseline 1986–2015: a near-future period (2016–2045) and a more distant future period (2046–2075).

For each scenario and time horizon, the number of heatwave days per year was computed and expressed as a relative change compared to the historical reference period. These relative changes were then spatially aggregated to the level of the civil parishes of the Beira Baixa region, ensuring consistency with local administrative boundaries and with the risk assessment framework applied in the rest of the project.

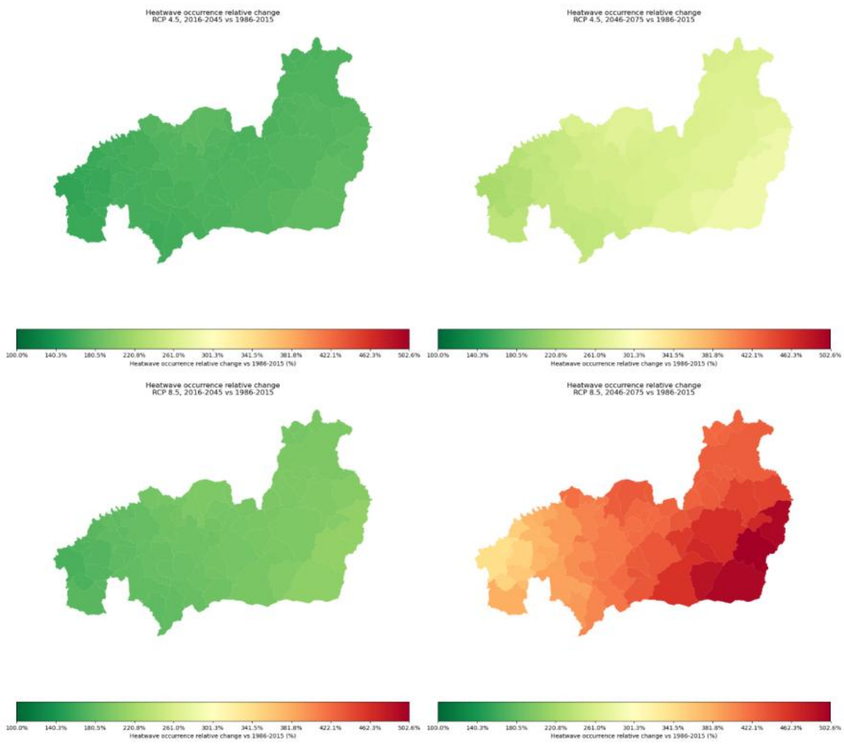

Figure 2-14 Heatwave occurrence relative change to 1986-2015 for scerarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

The spatial patterns obtained (Figure 2-14) confirm and reinforce the tendencies already identified in Phase 1. The southeastern part of the region is projected to experience the strongest increase in heatwave occurrence, with relative changes reaching approximately +300% under RCP 4.5 and +500% under RCP 8.5 in the long-term horizon. The eastern parishes also show a marked increase, although with lower amplitudes than in the southeast. From a climatic perspective, this pattern is consistent with the intensification of summer heat and aridity towards the interior and south of the region. From a risk perspective, however, these high hazard levels intersect with areas where small settlements and ageing populations are present, which is addressed in the risk assessment section.

In the context of Phase 2, these hazard maps are used strictly as the climate-hazard component of the heatwave risk assessment. They represent the underlying tendency for more frequent extreme heat events at the parish scale and are independent of local exposure and vulnerability conditions. High-resolution indicators derived from land surface temperature and vegetation cover are therefore not incorporated into the hazard definition but are instead used in subsequent sections to characterize micro-climatic amplification and the exposure of specific urban areas to this projected increase in heatwave frequency.

2.3.2.2 Risk assessment

At parish level, the hazard indicator from Section 2.3.2.1 (relative change in heatwave days) is combined with a vulnerability layer derived from population data. In line with the CLIMAAX urban heatwaves workflow, vulnerability is represented by the density of vulnerable population (people younger than 5 years or older than 65 years) in each parish, aggregated from gridded demographic data. The hazard and vulnerability layers are normalized and combined into composite indices, producing parish-scale risk maps (Figure 2-15) consistent with the CLIMAAX methodology.

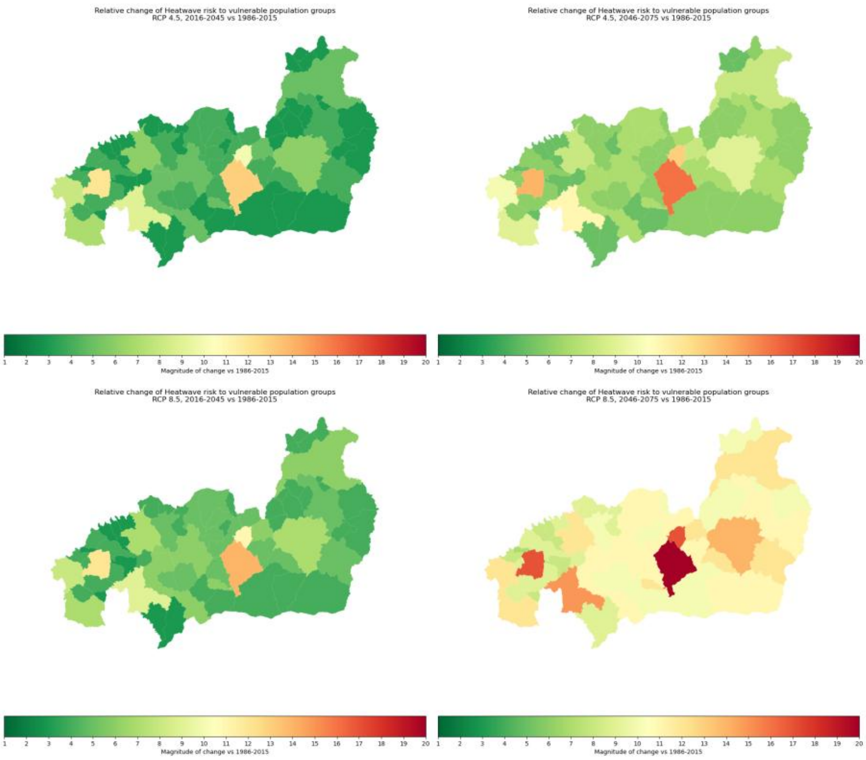

Figure 2-15 Relative change to Heatwave risk to vulnerable population for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

The parish-level results confirm that the highest heatwave risk occurs in the parish of Castelo Branco, where strong increases in heatwave frequency coincide with high densities of vulnerable population and ageing demographic profiles (larger shares of people younger than 5 years or older than 65 years).

In addition, a vulnerability analysis was conducted at the parish level based on cooling energy needs, using energy certification data provided through ADENE. A representative indicator of cooling energy requirements was calculated using Equation 1, where *N* represents the number of energy certificates, *C* corresponds to the average cooling energy needs associated with each energy performance class and e represents the energy performance.

$$\bar{C} = \frac{\sum N_e \times C_e}{\sum N_e} \quad (1)$$

Subsequently, the vulnerability indicator was classified into three categories and combined with ten hazard classes using the risk matrix presented in Figure 2-16.

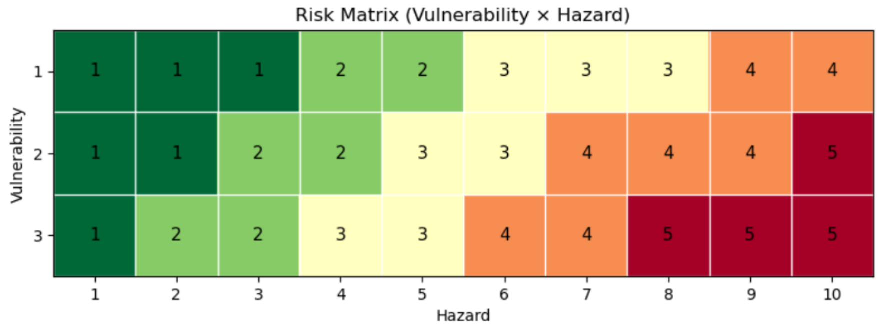

Figure 2-16 Risk Matrix Heatwave Hazard vs Cooling Needs Vulnerability.

The resulting heatwave risk is shown in Figure 2-17, where higher risk levels are observed predominantly in the eastern part of the region. Nevertheless, the results should be interpreted with caution, as uncertainties related to data completeness and spatial representativeness may influence the outcomes.

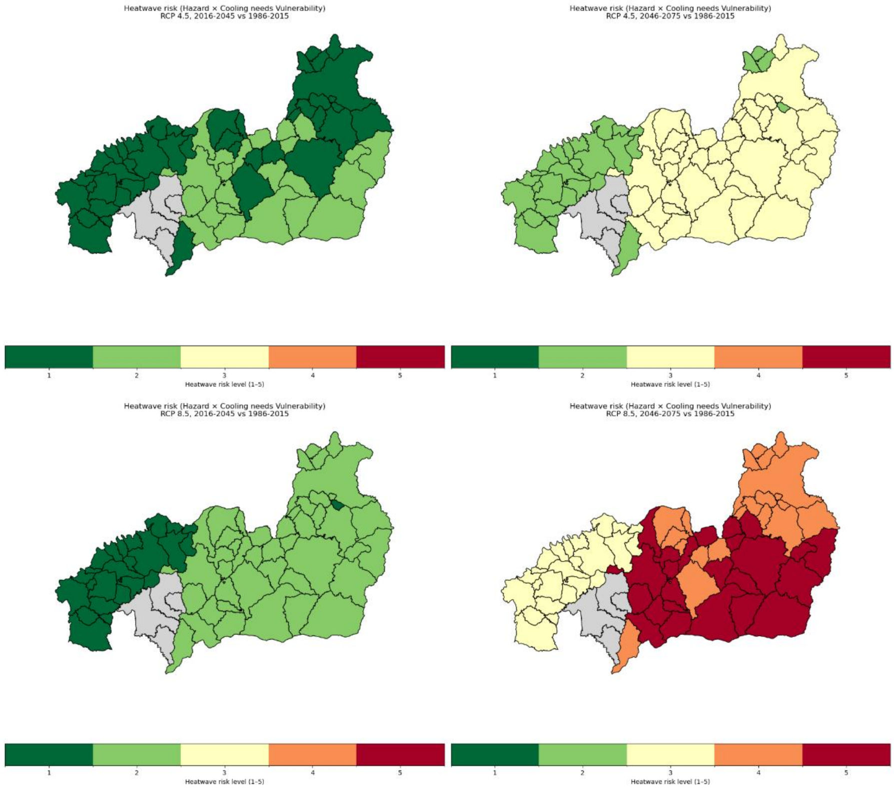

Figure 2-17 Heatwave Risk using Cooling Needs Vulnerability scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

These vulnerability patterns provide a first screening of where climatically driven heat stress is more likely to generate impacts, but they are still too coarse to distinguish the internal structure of risk within each municipality.

To address this limitation, the same EuroHEAT-based hazard indicator used at parish level is re-analyzed for urban areas by computing the projected change in heatwave occurrence specifically over the main built-up polygons of the region. This produces an urban-scale hazard metric that allows the ranking of towns according to the expected increase in heatwave days (Figure 2-18). The rationale is that focusing on urban hazards makes it possible to identify which towns are likely to face the strongest intensification of heatwaves and therefore deserve more detailed analysis.

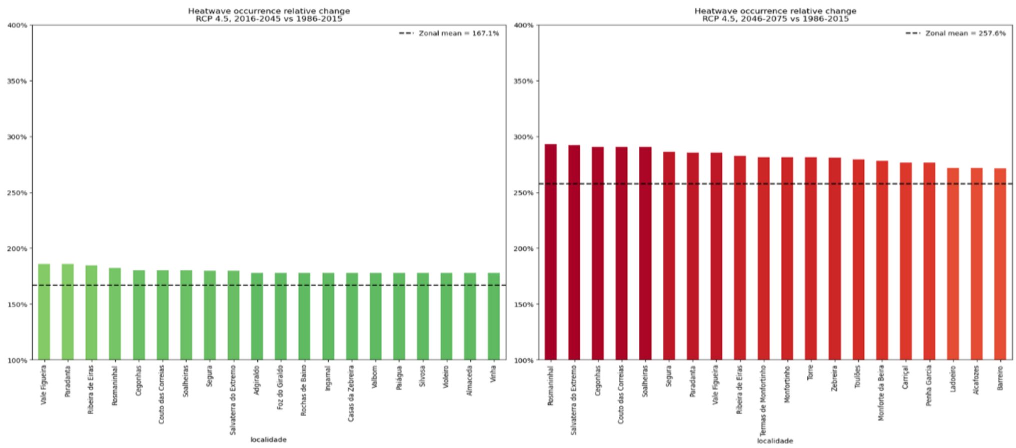

Figure 2-18 Heatwave occurrence relative change to 1986-2015 for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075 for 20 most affected urban areas.

Within selected urban areas, the climatic hazard signal is complemented by a high-resolution assessment of exposure using Land Surface Temperature (LST) and land-use information. Using Landsat-9 summer imagery, an LST raster is derived and intersected with detailed land-cover/land-use classes (e.g., compact residential fabric, more open residential areas, industrial and commercial zones). This makes it possible to compare temperature distributions across urban land types (Figure 2-19) and shows that dense residential blocks and industrial areas systematically occupy the warmest part of the LST distribution. These results refine the urban heat patterns identified in Phase 1 and indicate that, within each town, a relatively limited set of “grey” urban fabrics concentrates the highest potential exposure.

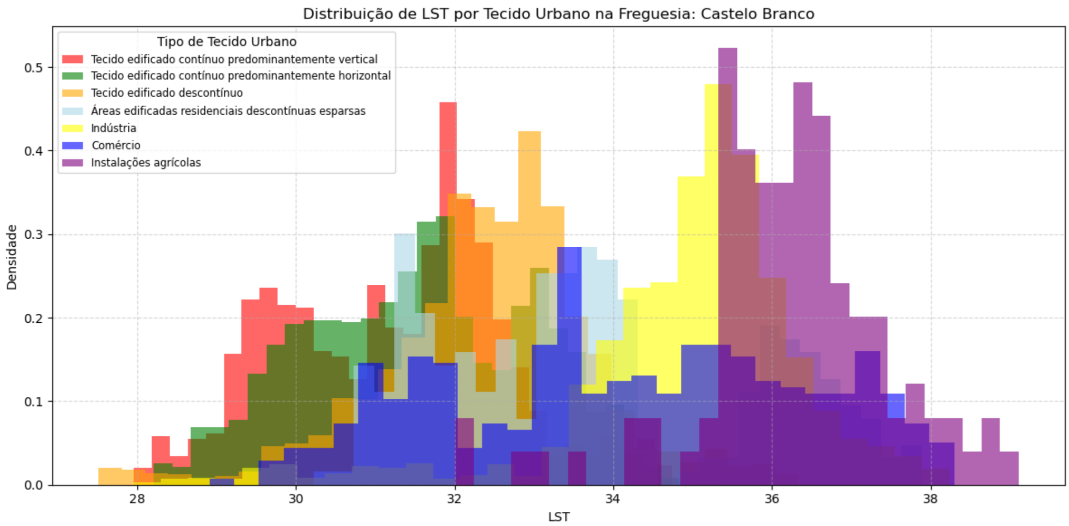

Figure 2-19 Land Surface Temperature distribution for each land type of urban areas, example Castelo Branco.

The influence of vegetation on temperature is examined explicitly through a joint analysis of LST and NDVI. An automatic classification (k-means) based on NDVI thresholds is used to distinguish “green” pixels (vegetated surfaces such as parks, tree-covered streets, gardens, riparian corridors and agricultural plots) from “grey” pixels (buildings, paved areas and other non-vegetated surfaces). This classification is applied in two complementary ways: first over the whole study area to obtain a general picture of how green and grey surfaces differ in temperature (resulting threshold: 0.473), and then restricted to urban masks to focus specifically on green infrastructure inside and around the main towns (resulting threshold: 0.311). The examples of the resulting classification on the urban area of Castelo Branco are presented in Figure 2-20 and Figure 2-21.

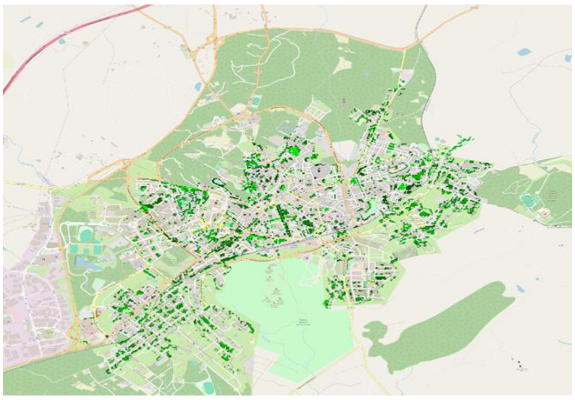

Figure 2-20 Example of classification results for 0.311 using only the urban areas for the classification.

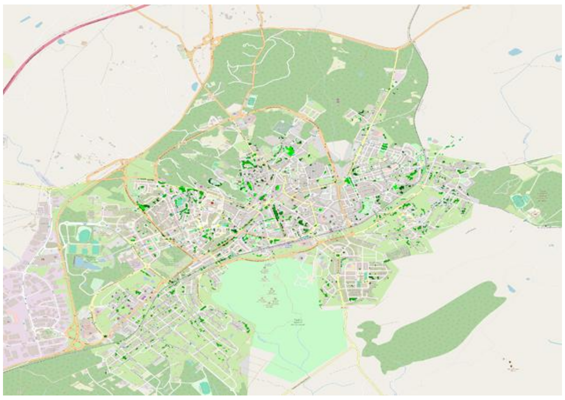

Figure 2-21 Example of classification results for 0.473 using all CIMBB area for the classification.

In both cases, the comparison of temperature distributions (Figure 2-22) shows a clear shift towards lower LST values in green pixels compared with grey ones with the biggest difference using the threshold 0.473. The difference between the distributions was also quantifies using Earth Moving Distance that represents *on average, how far does a single unit of LST value need to move for one distribution to resemble the other* resulting on a value of 1.1471 for the case of using the classification method with only urban areas (threshold: 0.311) and a value of 1.8499 for the case of using all the CIMBB region (threshold: 0.473).

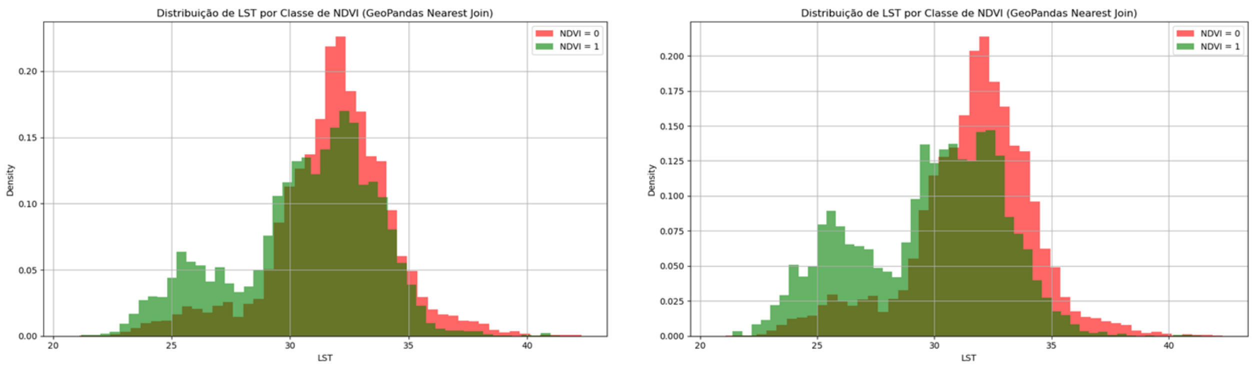

Figure 2-22 Distribution of Land Surface Temperatures for each class. Using the classification method with only urban areas (on the left) and using all the CIMBB region (on the right).

Beyond this direct comparison between green and grey surfaces, the classification is also used to quantify how far the cooling effect of vegetation extends into surrounding built-up areas. For each grey pixel, the distance to the nearest green pixel is calculated, and LST values are grouped into distance classes to evaluate how temperature changes with increasing separation from vegetated areas. Although grey pixels are more numerous close to green areas, this difference in density is not directly reflected in the distance-based averages, since mean LST is computed per distance class. Analyzing the results we can see that grey pixels located next to green areas are noticeably cooler than grey pixels that are more isolated, and that the influence of vegetation can be detected up to ~90–100 m, with a gradual weakening of the cooling effect as distance increases. Moreover, when focusing only on denser vegetation (using a more restrictive NDVI threshold), the cooling signal persists to larger distances into grey areas. In practical terms, the mean LST for the region is reached within ~20 m when considering sparser vegetation, whereas with denser vegetation this “return to the regional mean” extends to ~30 m.

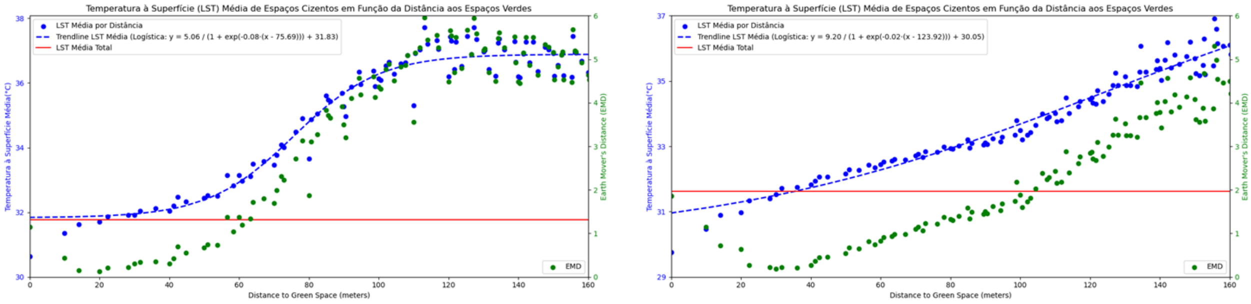

Figure 2-23 Average Land Surface Temperature for each distance for CIMBB region, using threshold 0.311 (on the left) and threshold 0.473 (on the right).

Given that the central concern of heatwave risk is its impact on human health, an attempt was made in Phase 2 to complement these spatial analyses with local health data, in particular hospital diagnoses and admissions potentially associated with heat stress or with cardiovascular, respiratory and renal conditions that tend to worsen during heatwaves. However, data access constraints and limitations in the temporal coverage and consistency of diagnostic coding meant that robust statistical relationships between local temperature anomalies and health outcomes could not be derived during the Phase 2 period. This difficulty is itself an important finding, as it reveals a gap in the monitoring and evaluation of heatwave impacts that would be valuable to address in future work.

Although it was not possible to directly link the Beira Baixa analysis with local hospital data, national evidence shows that heatwaves already have a measurable impact on mortality in Portugal. During a recent heatwave episode between 26 and 30 July, an excess of approximately 264 deaths was estimated for mainland Portugal. Overall mortality at national level was around 21.2% higher than expected, with the largest relative increase observed in the population aged 75 years and over. (SIC Notícias 2025).

Recent studies for Portugal further show that hospital admissions increase by around 18.9% on heatwave days. The largest relative increase is observed for admissions due to burns (34.3%), highlighting the risks associated with prolonged sun exposure and direct contact with hot surfaces. (Associação Nacional dos Médicos de Saúde Pública (ANMSP) 2024)

Although heatwaves lead to statistically significant increases in hospital admissions across both sexes and all age groups, children are the most affected group, with an estimated 21.7% increase in admissions. Adults aged 18–64 years also show a substantial increase (19.7%). Among older people, admissions rise by around 17.2%; considered together with the higher heat-related mortality in this age group, this emphasizes the need to raise awareness of early signs of dehydration and decompensation, to provide climate-controlled spaces, to strengthen social support networks and to ensure easy access to transport for medical care. (Associação Nacional dos Médicos de Saúde Pública (ANMSP) 2024)

2.4 Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

Feedback gathered during the risk evaluation (building on the engagement already described in Section 2.1.5) confirmed that wildfires and heatwaves remain the two most critical climate risks for CIM-BB and that Phase 2 outputs are most useful when they can be interpreted in operational terms. Stakeholders emphasized the need for clear explanations of risk classes and thresholds, and requested refinements to the representation and completeness of key exposed assets (notably specific infrastructure elements and service locations). For wildfires, discussion highlighted the practical relevance of accessibility constraints and suppression-resource coverage (water points and response-asset proximity) alongside hazard mapping. For heatwaves, stakeholders valued the move from parish-scale indicators to neighbourhood-scale evidence (LST/NDVI), and identified local impact monitoring—especially health and social indicators—as a key gap to address to better validate and track heat-related risk over time.

2.4.2 Gather output from Risk Analysis step

Risk evaluation considered the full set of outputs produced in the Phase 2 Risk Analysis step (Section 2.3) for both hazards and across the analyzed scenarios and time horizons, including hazard maps, exposure overlays, vulnerability indicators, composite risk layers and the additional operational metrics developed in Phase 2 (e.g., wildfire response-capacity indicators and urban-scale heat exposure analyses).

2.4.3 Assess Severity

Wildfires represent a recurrent high-impact hazard in Beira Baixa, with potential for loss of life, large burned areas, ecosystem degradation and disruption of critical infrastructure. Phase 2 risk overlays indicate that high hazard areas coincide with exposed assets (including healthcare and key transport corridors) and with ecosystems of high value, creating conditions for cascading impacts (service disruption, evacuation constraints, economic losses). Future hazard evolution further increases the likelihood of severe seasons and reinforces the **critical** severity classification for both current and future trends.

Heatwaves already create material public-health impacts, particularly for older adults and other vulnerable groups. Phase 2 shows strong projected increases in heatwave frequency at parish scale and identifies intra-urban hotspots where thermal exposure is systematically higher. While heat impacts are sometimes less visible than wildfire impacts in infrastructure-loss terms, the combination of demographic vulnerability and persistent multi-day exposure supports a **substantial** current severity classification. Under future intensification (especially in the later horizon and higher-emission pathway), the potential for excess mortality/morbidity and sustained pressure on health and social services justifies a future **critical** severity classification.

2.4.4 Assess Urgency

Wildfires already generate recurring impacts in Beira Baixa, but the region also benefits from an established and continuously improving risk-management system (prevention measures, surveillance and suppression resources). In this context, urgency is best characterised as **more action needed**: sustained and incremental strengthening is required to keep pace with projected worsening of fire-weather conditions and to close the remaining gaps identified in Phase 2 (notably in accessibility constraints, protection of critical corridors, and territorial imbalances in suppression-resource coverage). The priority is therefore to maintain and scale prevention and preparedness measures ahead of each fire season and to progressively adapt capacity and planning to the future trend, rather than to treat wildfire risk as a one-off emergency intervention.

Heatwaves are intensifying and persist over multiple consecutive days, producing cumulative health impacts and operational stress on services. Urban-scale exposure evidence indicates that targeted measures are needed in specific neighbourhood types and locations. Many effective interventions (risk communication, identification and support of vulnerable groups, cooling strategies, and urban greening planning) also require advance preparation and coordination, supporting an **immediate action needed** urgency classification.

2.4.5 Understand Resilience Capacity

Beira Baixa benefits from established wildfire risk management structures and measures (fuel-management networks, landscape-management initiatives, surveillance and detection). Phase 2 adds value by identifying where operational capacity may be weaker relative to hazard (e.g., locations with lower water-point coverage or longer response accessibility). The overall capacity is assessed as **substantial**, but uneven across the territory due to terrain, dispersed settlements, fragmentation of land management and the variable accessibility of high-hazard areas.

Heatwave management is distributed across health services, social services, municipal planning and civil protection, but monitoring and impact evaluation at local scale are less mature. Phase 2 demonstrates strong spatial evidence of intra-urban exposure differences and the mitigating role of vegetation, but also highlights limitations in linking local outcomes (health impacts) to hazard and exposure due to data constraints. This combination suggests **medium** capacity: relevant structures exist, but stronger local monitoring, targeted protocols and clearer operational thresholds are needed to systematically reduce health impacts.

2.4.6 Decide on Risk Priority

Risk prioritizations was derived by jointly considering severity, urgency and resilience capacity, and by reviewing how risk concentrates spatially around critical assets and vulnerable groups.

Rural wildfires — Very high risk priority due to critical severity, immediate urgency, and identifiable territorial hotspots where hazard overlaps with exposed assets and response-capacity constraints.

Heatwaves — Very high risk priority due to substantial-to-critical severity (increasing over time), immediate urgency, and clear evidence of concentrated exposure and vulnerable populations in specific urban contexts.

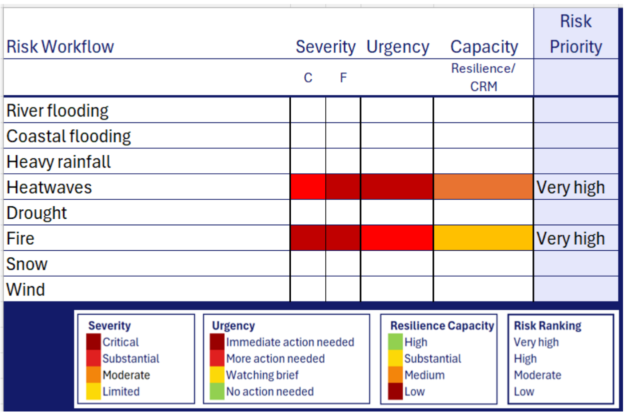

Figure 2-24 Key Risk Assessment Findings

2.5 Monitoring and Evaluation

The second phase strengthened the climate risk assessment for Beira Baixa by moving from a mainly screening-level picture toward a more locally grounded and spatially explicit understanding of wildfire and heatwave risk. The main learning was that, even when the overall regional narrative is well established (recurring severe wildfires and intensifying heat), decision support improves markedly when hazard, exposure and vulnerability information are refined to the scales at which decisions are taken (municipality/parish and the main urban areas). A second key learning was the importance of explicitly linking risk mapping to operational questions that matter locally—such as where access constraints are likely to delay response, where critical infrastructure is exposed, and where vulnerable populations and urban heat hotspots overlap.

The most persistent difficulties were related to data availability, comparability and validation. For wildfires, the challenge is less about recognizing the hazard and more about obtaining complete, up-to-date and spatially consistent information on assets, prevention measures and operational resources that determine impacts and response effectiveness (e.g., infrastructure attributes, the real condition and accessibility of water points, and the status of fuel management actions). For heatwaves, the difficulty is often the limited availability of local outcome data and indicators that translate exposure into impact (e.g., health and social service signals at an appropriate spatial and temporal resolution), as well as the need to connect thermal indicators to actionable urban and public-health measures.

Stakeholders are central to monitoring and evaluation because they provide the operational and policy context that determines whether the assessment is usable. Their role includes validating assumptions, confirming priority impact pathways (e.g., which infrastructures or services are most critical), interpreting results in light of local experience, and translating outputs into concrete planning and investment decisions. Stakeholder feedback also supports policy outcomes by helping align the risk assessment with municipal and intermunicipal instruments (civil protection planning, land management, public health preparedness and urban planning).

Learning is ensured by documenting methods and data sources, maintaining reproducible workflows for indicators and maps, and creating a clear trace between questions raised by stakeholders and the analytical refinements implemented. This enables iterative improvement as new information becomes available (e.g., updated land cover, fire occurrence datasets, infrastructure inventories, or local monitoring signals).

New or improved data streams that can support monitoring include: updated wildfire occurrence and burned area information; land-cover and vegetation/fuel proxies; meteorological time series and drought indicators; remotely sensed thermal indicators (e.g., land surface temperature) for urban areas; demographic and service location datasets; and, where feasible, local temperature monitoring in the main urban centers. For heatwaves in particular, better integration of health and social service indicators (where data governance allows) would support stronger evaluation of impacts and of the effectiveness of response actions.

Final outcomes should be communicated in formats that match user needs, combining a concise narrative for decision makers with clear maps and indicators that can be reused in planning. This can include the deliverable report, a short policy-facing summary, map annexes (for technical teams), and stakeholder sessions where results and limitations are discussed transparently.

Regarding monitoring systems, wildfire risk management in Beira Baixa already relies on operational monitoring elements (surveillance and detection networks, patrols, and civil protection procedures). The climate risk assessment complements these systems by providing a longer-term perspective on where hazard conditions are expected to worsen and where exposure patterns suggest higher consequences. For heatwaves, monitoring is typically less mature at local scale, and the assessment highlights the value of strengthening local temperature monitoring, urban heat hotspot tracking, and mechanisms to identify and support vulnerable groups during multi-day extreme heat periods.

Overall, what worked well was the ability to refine the spatial representation of risk and to structure the assessment in a way that supports practical use (maps, indicators and clearly defined assumptions). What worked less well relates mainly to gaps in locally validated datasets and the difficulty of connecting some hazard indicators to impact metrics without stakeholder-confirmed thresholds and outcome data. Resource efficiency benefited from reusing established workflows and openly available datasets, but time and staffing constraints can limit the depth of validation, the level of disaggregation for some indicators, and the integration of additional local datasets.

The assessment's impact is reflected in an improved shared understanding of where and why risks are higher within Beira Baixa, which supports more targeted prevention and adaptation actions, strengthens the basis for prioritizing investments, and provides a clearer evidence base for communication with the public and for securing funding.

2.6 Work plan Phase 3

Phase 3 will represent the transition from climate risk assessment to action-oriented planning, capitalizing on the refined, high-resolution risk analyses produced during Phases 1 and 2. Building on the consolidated understanding of priority climate hazards and vulnerabilities, this phase will focus on translating technical evidence into coherent, territorially grounded adaptation responses, while also considering mitigation aspects where relevant, in line with stakeholder feedback gathered throughout the project.

The work plan for Phase 3 will follow the CLIMAAX common methodological framework, ensuring continuity, coherence and traceability with the previous phases. The refined multi-risk assessments will be systematically reviewed to identify critical vulnerabilities, exposure patterns and response gaps at intermunicipal and local levels. This analytical consolidation will provide the basis for the identification and prioritization of adaptation options, taking into account criteria such as effectiveness, feasibility, cost-efficiency, co-benefits, and institutional capacity.

A participatory approach will remain central to the implementation of Phase 3. Structured engagement activities with key regional and local stakeholders will be organized to validate findings, discuss priorities, and co-develop adaptation pathways. These interactions will ensure that proposed measures are realistic, context-specific and aligned with local governance structures, while fostering ownership and long-term uptake. Stakeholder contributions will also be used to refine the balance between adaptation and mitigation considerations, particularly where synergies can enhance overall climate resilience.

Based on the prioritized options, Phase 3 will develop structured adaptation strategies supported by clear implementation logics. These will include the definition of objectives, intervention pathways, indicative timelines, responsible actors and monitoring considerations, allowing the strategies to be operationally robust while remaining flexible to future updates. Particular attention will be given to the integration of these strategies within existing risk management and planning frameworks, ensuring consistency with broader regional and sectoral objectives.

The phase will conclude with the consolidation of results into a comprehensive contribution to improved risk management and adaptation planning. This final output will synthesize the analytical evidence, stakeholder inputs and strategic orientations developed across the project, providing a clear and actionable foundation for enhancing climate resilience in the territory. In this way, Phase 3 will complete the CLIMAAX cycle by effectively bridging scientific risk assessment and practical decision-making, reinforcing the long-term relevance and impact of the project outcomes.

3 Conclusions Phase 2- Climate risk assessment

Phase 2 of the CLIMAAX climate risk assessment confirms wildfires and heatwaves as the priority climate risks for the Intermunicipal Community of Beira Baixa (CIMBB). Building on the screening performed in Phase 1, Phase 2 strengthens methodological robustness, integrates additional regionally relevant datasets, and produces more decision-oriented outputs. In particular, the work advances from identifying broad spatial patterns of risk to clarifying where risk concentrates, which assets are most exposed, and which aspects of response capacity and adaptation should be prioritized.

A key outcome of Phase 2 is the improvement of wildfire hazard coherence through time. Compared with Phase 1, the wildfire workflow was refined to better reflect expected climate-driven evolution, reducing unrealistic temporal behavior and providing a clearer intensification signal—most notably under the high-emission pathway.

The refined hazard patterns broadly confirm the main hotspots previously identified, while sharpening the spatial differentiation of hazard intensity across the region. Areas combining fuel availability, terrain conditions, and climatic drivers continue to show the strongest hazard signal, supporting targeted prevention strategies.

On the risk side, Phase 2 increases operational relevance by expanding and refining exposure layers and by incorporating stakeholder-requested elements (including additional infrastructure assets). The results indicate that mountainous and more forested areas of Beira Baixa tend to combine high hazard with relevant concentrations of exposed assets and vulnerable ecosystems, making them priority zones for prevention, preparedness, and long-term adaptation planning.

A further Phase 2 contribution is the explicit inclusion of response capacity as a complementary lens on wildfire risk. Two suppression-related components were mapped: (i) the coverage and availability of water points (considering distinct operational characteristics for aerial and terrestrial resources), and (ii) accessibility from fire stations and strategic parking areas for firefighting means. These layers add actionable insight by indicating where risk reduction may depend not only on hazard mitigation in fuels but also on resource positioning, accessibility, and logistical constraints.

For heatwaves, Phase 2 confirms that risk tends to be higher in parts of the region where increases in heatwave occurrence coincide with higher concentrations of vulnerable populations (particularly older adults and young children). This reinforces the importance of linking climatic signals to demographic vulnerability when prioritizing adaptation.

The most important advance for heatwaves in Phase 2 is the urban-scale refinement of exposure, using high-resolution Land Surface Temperature (LST) derived from satellite imagery and intersecting it with land-use/land-cover information. This enables identification of intra-urban hotspots: dense residential areas and industrial/commercial fabrics systematically correspond to the warmest parts of the LST distribution, indicating that a relatively limited share of “grey” urban fabric concentrates the highest potential exposure.

Phase 2 also quantifies the mitigation role of vegetation through combined LST–NDVI analyses, distinguishing “green” and “grey” surfaces and assessing neighborhood cooling effects. Results show a consistent temperature shift towards lower LST values in vegetated pixels and indicate that cooling effects extend into adjacent built-up areas over short distances, gradually weakening with distance. This provides spatially explicit evidence in support of adaptation options based on urban greening (parks, riparian corridors, tree-lined streets, and distributed green infrastructure).

Phase 2 attempted to strengthen the evidence base on health impacts by exploring local health outcome data potentially related to heat stress. This component could not be fully operationalized due to constraints in data access, consistency, and/or temporal coverage. This limitation is itself a key finding, highlighting a structural gap in local monitoring of heat-related impacts.

Challenges addressed in Phase 2 include:

- Improved temporal consistency and climate responsiveness in wildfire hazard modelling.
- Expanded and refined exposure datasets for wildfire risk, incorporating additional locally relevant assets.
- Urban-scale characterization of heat exposure and evidence on the cooling value of vegetation, moving beyond parish-level averages.

Challenges not fully addressed (to be carried forward) include:

- Limited ability to validate heat exposure using local health outcomes due to data constraints.
- Remaining uncertainties and potential artefacts in some input datasets, reinforcing the need for continued local validation.
- Simplifications in suppression-resource indicators (e.g., first-order representations of operational reach and accessibility).
- Limited incorporation of socio-economic futures (e.g., population or land-use change scenarios), implying that exposure and vulnerability dynamics over time are only partially represented.

Overall, Phase 2 delivers a more policy- and operations-relevant evidence base by combining CLIMAAX workflows with region-specific modelling and datasets. The assessment supports prioritization of interventions across both risks, including fuel management and protection of critical infrastructure corridors for wildfires, and urban heat mitigation through green infrastructure and preparedness measures for heatwaves.

These Phase 2 results provide a solid analytical foundation for the next project steps, where the priority is to translate identified hotspots, exposed assets, and vulnerability patterns into stakeholder-endorsed adaptation options, supported by a concise set of monitoring indicators that can be updated over time for both wildfires and heatwaves.

4 Progress evaluation

Table 4-1 Overview key performance indicators.

Key performance indicators	*Progress*
Delivery of all 5 deliverables	2/5 (40%)
2 successfully applied workflows in Phase 1	2/2 (100%)
2 successfully applied workflows in Phase 2	2/2 (100%)
At least 5 sources of information consulted in Phase 2	13/5 (+100%)
Involvement of at least 15 Stakeholders in the project's communication activities	29/15 (+100%)
Organization of at least 5 dissemination actions	2/5 (40%)

Table 4-2 Overview milestones.

Milestones	*Progress*
Organization of a public session in the Pinhal Interior region in Phase 3	0/1 (0%)
Updated version of PIAAC-BB, including guidelines for policymakers in Phase 3	0/1 (0%)

5 Supporting documentation

Workflow #1 – Wildfires

Filename: Wildfires.zip

Includes maps, raster images and visualizations related to the wildfire workflow, under RCP 4.5 and 8.5 for four time periods, a short-term, a medium-term and a long-term future periods. Also includes the code related to this workflow.

Workflow #2 – Heatwaves

Filename: Heatwaves.zip

Includes hazard and vulnerability maps produced in the heatwave workflow, under RCP 4.5 and RCP 8.5 for two time periods, one short-term and another long-term future periods. Also includes the code related to this workflow.

All outputs listed above have been uploaded to the Zenodo repository under the CLIMAAX entry for Beira Baixa:

Zenodo Repository Link: https://doi.org/10.5281/zenodo.18280768

DOI: 10.5281/zenodo.18280768

6 References

Associação Nacional dos Médicos de Saúde Pública (ANMSP). *Qual o impacto das ondas de calor nos internamentos em Portugal? Um alerta de Saúde Pública.* August 2024. https://www.anmsp.pt/post/qual-o-impacto-das-ondas-de-calor-nos-internamentos-em-portugal-um-alerta-de-sa%C3%BAde-p%C3%BAblica.

Chakraborty, P., L. Dobor, A. Zolles, T. Hlásny, and S. Schueler. "High-resolution gridded climate data for Europe based on bias-corrected EURO-CORDEX: the ECLIPS-2.0 dataset." 2020.

Copernicus Emergency Management Service. *Vulnerability layers from the Fire Risk Viewer.* n.d. https://forest-fire.emergency.copernicus.eu/apps/fire.risk.viewer/.

Copernicus Sentinel-2. *Sentinel-2 MSI Level-2A data.* European Space Agency, 2024.

Direção-Geral do Território. "Carta de Uso e Ocupação do Solo (COS) - Série 2 (nova)." 2025.

Gonçalves, José Alberto & Pinhal, André. *DEM data for Portugal.* n.d. https://www.fc.up.pt/pessoas/jagoncal/dems/.

Hooyberghs, H., J. Berckmans, F. Lefebre, and K. De Ridder. "Heat waves and cold spells in Europe derived from climate projections." Copernicus Climate Change Service (C3S), Climate Data Store (CDS), 2019.

Instituto da Conservação da Natureza e das Florestas. "Anália da Susceptibilidade de Incêndio Rural em Portugal Continental." 2020.

Instituto da Conservação da Natureza e das Florestas. *Territórios ardidos (Área ardida entre 1975 e 2024).* Instituto da Conservação da Natureza e das Florestas, 2025.

Instituto Nacional de Estatística, I.P. *Lugares 2021 (Population clusters, census 2021).* INSPIRE Geoportal, 2024.

SIC Notícias. *Calor extremo faz disparar nível de mortalidade para o triplo face a 2024.* August 2025. https://sicnoticias.pt/pais/2025-08-22-calor-extremo-faz-disparar-nivel-de-mortalidade-para-o-triplo-face-a-2024-726984a9.

U.S. Geological Survey. *Landsat 9 Collection 2 Level-2 data.* U.S. Geological Survey, 2024.

WorldPop and Center for International Earth Sc. "Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation." 2018.