Deliverable Phase 2 – Climate risk assessment

Comunidade Intermunicipal da Região Beiras e Serra da Estrela (CIM-RBSE)

Portugal, Região Beiras e Serra da Estrela

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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

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1. Document Information

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5. Abbreviations and acronyms

Abbreviation / acronym	Description
ADERES	Associação de Desenvolvimento Rural Estrela-Sul (Estrela-Sul Rural Development Association)
ADPM	Associação de Defesa do Património de Mértola (Mértola Heritage Protection 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)
CBPBI	Centro de Biotecnologia de Plantas da Beira Interior (Beira Interior Plant Biotechnology Center)
CCPE	Centro de Competências do Pastoreio Extensivo (Extensive Grazing Competence Center)
CIM RBSE	Comunidade Intermunicipal da Região Beiras and Serra da Estrela
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 Florestas (Institute for Nature Conservation and Forests)
LST	Land Surface Temperature
MACAT	Mapa Anual de Culturas Agrícolas Temporárias (Annual Map of Temporary Agricultural Crops)
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
NDVI	Normalized Difference of Vegetation Index
NGOs	Non-Profit Organizations
PIAAC	Plano Intermunicipal de Adaptação às Alterações Climáticas (Intermunicipal Climate Change Adaptation Plan)

RCM	Regional Climate Model
RCP	Representative Concetration Pathway
SHM	Summer Heat-Moisture Index

6. Executive summary

This deliverable reports the Phase 2 results of the CLIMAAX Climate Risk Assessment (CRA) for the Comunidade Intermunicipal da Região Beiras and Serra da Estrela (CIM RBSE), focusing exclusively on wildfires and heatwaves. Building on the Phase 1 deliverable and stakeholder input, Phase 2 strengthens local relevance and decision usefulness by refining hazard modelling and by expanding the assessment towards operational and urban-scale interpretations of risk.

For wildfires, the hazard component was recalibrated to Portuguese conditions through an updated modelling approach (XGBoost trained on a national domain) and by introducing climate-alignment mechanisms that support a coherent evolution of hazard across future periods and emission pathways. Risk interpretation was extended beyond hazard-only mapping by intersecting hazard with critical exposed assets and by incorporating response-capacity layers (water-point coverage and network-based accessibility to response resources), enabling clearer identification of areas where high hazard may translate into high impacts or constrained suppression capacity.

For heatwaves, methodological continuity was maintained through the EuroHEAT-based indicator and parish-level aggregation, while decision relevance was increased by adding an urban lens. The analysis shows that risk to people concentrates in the main urban parishes where vulnerable population is highest, and that within towns the warmest exposure aligns with dense residential and industrial/commercial fabrics. Vegetation consistently reduces land surface temperatures and cools adjacent built-up areas, providing a practical evidence base for targeted urban cooling interventions. A key limitation remains the inability to establish robust local heat–health relationships due to data access and harmonisation constraints, highlighting an important monitoring gap.

Overall, Phase 2 confirms wildfires and heatwaves as high-priority risks for CIM RBSE, and provides a stronger basis to prioritise prevention, preparedness and urban cooling actions. Phase 3 will translate these prioritised risks into a portfolio of feasible adaptation measures, validated with stakeholders and integrated into existing municipal and intermunicipal planning instruments.

1 Introduction

1.1 Background

The Intermunicipal Community of Região Beiras and Serra da Estrela (CIM RBSE) is a regional public authority located in central Portugal, encompassing 15 municipalities within the NUTS3Beiras and Serra da Estrela sub-region. This area spans over 6,300 square kilometers and includes a diverse mountainous landscape marked by the Serra da Estrela Natural Park, the largest protected area in mainland Portugal. Characterized by significant ecological and socio-economic value, the region is home to approximately 210,000 residents, many of whom rely on climate-sensitive sectors such as agriculture, forestry, pastoralism, and tourism.

The region's vulnerabilities to climate change have been well documented, including increasing exposure to extreme weather events such as heatwaves, droughts, wildfires, intense precipitation, and cold spells. In recent years, the area has experienced some of the most severe forest fires in Portuguese history, notably the 2022 event that consumed nearly 25% of the Serra da Estrela Natural Park and most recently in 2025, that consumed about 107000 ha of Beiras and Serra da Estrela region. These events have underscored the urgent need for an integrated and multi-risk climate adaptation strategy tailored to the unique vulnerabilities of this predominantly rural and mountainous territory.

1.2 Main objectives of the project

The primary objective of this project is to conduct a high-resolution climate risk assessment for Beiras and Serra da Estrela, focusing on wildfire and extreme heat risks. Through the application of the CLIMAAX framework, the project aims to:

- Improve the understanding of climate-related hazards in the region.
- Enhance data integration for more informed decision-making.
- Develop tailored adaptation strategies to mitigate risks and increase resilience.
- Foster regional collaboration among stakeholders to ensure sustainable climate governance.

By utilizing the CLIMAAX Handbook, the project will provide a structured and harmonized approach to climate risk assessment. This methodology will facilitate the identification of vulnerable sectors, enhance risk monitoring, and support the implementation of adaptation measures, such as contingency plans for extreme temperatures. The findings from this study will contribute to broader national and European climate adaptation efforts, positioning Beira Baixa as a model for other vulnerable regions.

1.3 Project team

The project is jointly implemented by CIM RBSE and greenmetrics.ai. CIM RBSE possesses both the legal mandate and institutional capacity to coordinate climate change adaptation efforts across the NUTS3 territory. Greenmetrics.ai contributes specialized technical expertise in environmental data analysis, geospatial modelling, and the application of advanced risk assessment methodologies.

The combination of CIM RBSE's territorial knowledge and institutional authority with greenmetrics.ai's technical expertise ensures a comprehensive and technically sound approach to climate risk assessment in the region.

1.4 Outline of the document's structure

This deliverable is structured in accordance with the CLIMAAX Phase 2 reporting template:

- **Section 2** details the climate risk assessment process, including scoping, risk exploration, hazard and risk analysis, and preliminary findings.
- **Section 3** presents the key conclusions derived from the Phase 2 assessment.
- **Section 4** discusses progress evaluation and outlines contributions to future project phases.
- **Section 5** provides an inventory of supporting documentation produced during this phase.
- **Section 6** contains all references used throughout the report.

Each section follows the CLIMAAX Handbook's guidance to ensure methodological consistency and facilitate knowledge transfer across participating regions.

2 Climate risk assessment – phase 2

2.1 Scoping

2.1.1 Objectives

The objective of the Phase 2 climate risk assessment (CRA) for Beiras and Serra da Estrela is to refine and regionalize the foundational analysis produced in Phase 1, strengthening the understanding of the region's exposure and vulnerability to heatwaves and wildfires. Building on the CLIMAAX framework, Phase 2 emphasizes the integration of higher-resolution and locally validated datasets and methods where feasible, with the expected outcome of more locally representative hazard and risk outputs and clearer evidence to support risk prioritization and subsequent adaptation planning.

The CRA is intended to contribute directly to regional policy and decision-making by improving the usability of risk information for municipal and intermunicipal planning, civil protection preparedness, and sector-specific adaptation actions (notably for climate-sensitive rural systems and vulnerable population groups). In Phase 2, the CLIMAAX workflows were fine-tuned using local land use/land cover information and complemented with additional indicators derived from remote sensing and region-specific modelling choices, so that the resulting maps and metrics can better inform the design, targeting, and justification of adaptation measures, in alignment with national guidance and relevant EU policy directions.

The assessment is bounded by a defined scope (wildfires and heatwaves) and by practical constraints related to data availability, harmonization, and stakeholder-accessible decision needs. In Phase 2, key limitations identified in Phase 1 were partially addressed through improved modelling choices and the addition of targeted exposure and vulnerability layers; however, bottlenecks remained, particularly in obtaining and harmonizing some sectoral datasets (most notably health-related information) and in reconciling differences in spatial resolution and definitions across sources. These constraints were managed by prioritizing analyses through stakeholder input, selecting indicators with robust coverage, documenting assumptions and uncertainty clearly, and framing results as decision-support outputs that can be progressively strengthened as additional local datasets and validation evidence become available.

2.1.2 Context

The Beiras and Serra da Estrela region has historically faced recurring climate hazards, with wildfires and extreme heat events emerging as the most damaging and frequent in recent decades. The devastating wildfires in 2022 and 2025 and increasing occurrences of heatwaves have highlighted systemic vulnerabilities in emergency preparedness, ecological resilience, and infrastructure robustness.

Climate risk management in the region is guided by national and regional legal frameworks, notably the Basic Climate Law (Law 98/2021), Decree-Law 82/2021 on rural fire management, and the national strategy for adaptation to climate change. CIM RBSE plays a pivotal role in coordinating the Sub-Regional Commission for Integrated Rural Fire Management (CSRGIFR), developing, together with the entities that make up the CSRGIFR, the Sub-Regional Action Program for Integrated Rural Fire Management in the Beiras and Serra da Estrela Sub-Region and implementing the PIAAC. The region's governance framework is complemented by civil protection authorities, the Institute for Nature Conservation and Forestry, and local municipalities.

Sectors of high relevance include agriculture, forestry, pastoralism, and tourism. These are not only key economic pillars but are also directly affected by shifts in climate patterns and extremes. External influences, such as national fire prevention programs, EU adaptation strategies, and funding mechanisms, further shape the adaptation landscape.

Potential adaptation interventions explored through this CRA include land use reclassification, green infrastructure development, fire-resistant landscape design, early warning systems, and strengthening the regional data infrastructure for climate monitoring.

2.1.3 Participation and risk ownership

The stakeholder engagement process was initiated during the preliminary design of the CRA and included the organization of a participatory workshop involving a wide range of identified stakeholders. The workshop enabled direct dialogue and input from a diverse range of institutional stakeholders, which can be grouped into the following categories:

Municipal authorities and local governance bodies: Câmara Municipal de Trancoso, Município de Almeida, Município de Seia – Serviço Municipal de Proteção Civil, Município da Covilhã, Município de Figueira de Castelo Rodrigo, Município de Manteigas, Município de Sabugal.

Civil protection and emergency services: Autoridade Nacional de Emergência e Proteção Civil, Comando Territorial da Guarda, ANEPC, GNR, AGIF.

Academic and research institutions: Universidade da Beira Interior, Instituto Politécnico de Castelo Branco, Instituto Politécnico da Guarda, Associação CBPBI.

Environmental NGOs and rural development associations: Quercus, ADERES, ADPM (in representation of CCPE), Raia Histórica, Bioeco.

Forestry and agricultural sector organisations: QUEIRÓ, Urze – Associação Florestal da Encosta da Serra da Estrela, Opaflor – Associação de Produtores Florestais da Serra da Opa, Associação Portuguesa de Criadores de Raça Bovina Limousine, Acriguarda.

National and regional agencies for land and biodiversity management: ICNF

Efforts were made to include organizations and entities with responsibilities or interests aligned with vulnerable groups and sectors sensitive to climate change impacts. The participatory workshop served as a platform for these stakeholders to contribute perspectives on climate risks and regional adaptation priorities.

In addition to sharing their views, stakeholders provided valuable feedback and helped define specific analytical needs to be addressed in Phase 2 of the project. They also committed to supporting the provision of local data inputs, which will be instrumental for increasing the resolution and contextual relevance of the next phase of risk analysis. This guidance and collaboration will help ensure that future assessments are aligned with practical priorities and the decision-making context of local actors.

The communication of results is targeted at both technical stakeholders and the general public. Outputs will be disseminated via institutional channels, stakeholder workshops, and regional forums, ensuring transparency and inclusivity in the CRA process.

2.1.4 Application of principles

Social justice, equity, inclusivity. Phase 2 was designed to make differences in risk across people and places visible, rather than treating the region as uniform. For heatwaves, vulnerability was represented through demographic sensitivity indicators (notably the spatial distribution of very young and older residents), so that areas with higher concentrations of vulnerable groups can be prioritized even when hazard levels are similar. For wildfires, the analysis was expanded beyond hazard mapping to include factors that influence the ability to prevent, respond and recover (e.g., accessibility constraints, water-point coverage and proximity/travel time to response resources), recognizing that remote and sparsely populated areas may face disproportionate impacts due to slower response and limited local capacity. The selection and refinement of these layers were informed through engagement with municipal and intermunicipal stakeholders (including civil protection and land/forest management actors), ensuring that the assessment reflects locally recognized concerns and decision needs.

Quality, rigor, transparency. Phase 2 followed the CLIMAAX framework and reporting structure to keep the assessment traceable and comparable, while strengthening methodological rigour where Phase 1 limitations were identified. In particular, hazard modelling choices for wildfires were refined to better reflect Portuguese conditions and to ensure that projected patterns remain consistent with physically meaningful climate. Across both hazards, the assessment documents the main data sources, processing steps and assumptions, and explains the intended interpretation of each output layer (including any thresholds or classification rules used in supporting analyses). Remaining limitations such as data gaps for certain vulnerability dimensions and uncertainties associated with climate projections and model sensitivity are stated explicitly to avoid over-claiming and to support appropriate use of results.

Precautionary approach. Given the potential for severe and partly irreversible impacts (e.g., excess mortality during heatwaves and ecosystem degradation and cascading service disruption during wildfires), Phase 2 adopts a precautionary stance in scenario framing and interpretation. Results are considered across multiple future pathways, including more adverse emissions trajectories, and uncertainty is treated as a reason to strengthen preparedness rather than delay action. The assessment therefore supports risk management strategies that are robust across scenarios and deliver benefits even under uncertainty, such as heat-health preparedness and urban cooling measures, improvements in response accessibility and water availability for wildfire suppression, and the protection of critical services and high-value ecosystems where hazard and vulnerability converge.

2.1.5 Stakeholder engagement

Stakeholder engagement in Phase 2 followed the participatory approach established in Phase 1, keeping the same core network involved in the climate risk assessment. Municipal representatives and municipal civil protection services remained central, complemented by sectoral agencies, research partners, utilities, and professional associations with responsibilities in land management, infrastructure, and emergency planning.

At the start of Phase 2, an online survey was used to prioritize the analyses to be developed for wildfires and heatwaves. Participants were invited to indicate which outputs would be most useful in their institutional context (e.g., operational preparedness, long-term spatial planning, asset management) and to propose additional questions or datasets. Inputs from the stakeholder group were used to refine the Phase 2 analytical priorities, including more decision-oriented views of wildfire risk (such as accessibility and operational considerations) and a stronger integration of demographic and health-relevant information in the heatwave assessment.

At the end of Phase 2, an online workshop was held to present the updated outputs and collect feedback for validation and improvement. Project goals and intermediate results were communicated through a structured presentation supported by maps and figures, covering the updated wildfire hazard modelling, revised exposure and vulnerability layers, and the extended heatwave analyses (including land-surface temperature patterns, the role of vegetation in urban cooling, and initial insights from health-related information where available). Overall, participants received the results positively and the discussion focused on practical interpretation and usability: clarifying risk classes, improving the representation of specific assets and services (e.g., key roads, critical facilities, operational resources), and identifying additional indicators that could strengthen the link to planning and response needs. Stakeholders highlighted that the outputs can directly support prioritization of intervention areas, preparedness planning, and communication with local decision-makers, and will be further used as an evidence base for adaptation planning and for targeting future data collection.

The main challenges in Phase 2 were linked to the availability, access conditions, and harmonization of some sectoral datasets (notably in the health domain), as well as the practical effort of aligning schedules to ensure broad participation. In addition, explaining model assumptions and uncertainty in a way that remains technically robust while still operationally clear required careful framing. These lessons will inform future engagement by combining plenary moments with more targeted thematic sessions and focused co-interpretation with specific stakeholder groups.

2.2 Risk Exploration

2.2.1 Screen risks (selection of main hazards)

In Phase 2, the project did not revisit the risk screening step. The hazard selection therefore remains the same as in Deliverable 1, while the work in this phase focused on strengthening the assessment for the prioritized hazards through locally calibrated modelling choices and supporting analyses.

For the Beiras and Serra da Estrela, the screening continues to indicate that **heatwaves** and **wildfires** are the most relevant climate-related hazards for the CLIMAAX climate risk assessment. Heat extremes are already a recurring challenge, with impacts on thermal comfort and health, particularly among more vulnerable groups and in built-up areas with limited cooling capacity. Wildfires remain a structural territorial risk across forested and shrubland areas and the mountainous landscape, with consequences for people, ecosystems (including protected areas), assets, and service continuity.

Information from the Copernicus Climate Atlas is consistent with these priorities, pointing to increasing temperatures and more frequent/intense hot extremes and, in many areas of southern/central Europe, a tendency towards hotter and drier summer conditions that can contribute to elevated fire danger.

The assessment builds on the data base established in Phase 1 (climate projections, land and topographic predictors, and exposure layers) and was complemented in Phase 2 with additional regional datasets and targeted analyses to better characterize exposure and vulnerability patterns. Further work would benefit from more granular local information on heat-related health outcomes and service demand, social vulnerability and adaptive capacity indicators, and operational datasets relevant for wildfire response and critical infrastructure dependencies.

2.2.2 Choose Scenario

To support a comprehensive climate risk assessment, this project adopts the CLIMAAX framework's guidance on scenario development, incorporating both climate and socio-economic pathways. The selected scenarios are grounded in the Representative Concentration Pathways (RCPs) 4.5 and 8.5, which represent moderate and high-emission trajectories, respectively. These pathways enable a comparison of future risk levels under differing mitigation efforts and global climate outcomes.

For the heatwave assessment, two distinct timeframes were considered: a short-term period (2016–2045) and a longer-term horizon (2046–2075), allowing for an evaluation of hazard progression under both emission scenarios.

In Wildfires case the time horizons are considered in the scenario analysis to reflect the gradual evolution of climate hazards and to support planning across short-term, mid-term, and long-term periods, having been used the full future time extent available in ECLIPS2.0 data (2021-2040, 2041-2060, 2061-2080, 2081-2100).

The selected timeframes and emission scenarios were strategically aligned with the most robust and regionally relevant climate projections available for the study. Their application ensures consistency with the modelling approaches embedded in the CLIMAAX workflows and facilitates future comparative analyses across time horizons and hazard types.

2.3 Regionalized Risk Analysis

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

Table 2-1Data 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*
COS-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*

Hazard data	*Vulnerability data*	*Exposure data*
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 developed in Phase 2 builds on the CLIMAAX machine-learning wildfire workflow but is now explicitly calibrated to Portuguese conditions and refined for the Beiras and Serra da Estrela context. The main objective is to produce hazard maps that (i) better reflect projected climate trends and (ii) remain sensitive to local land-use and topographic controls, addressing key limitations identified in Phase 1, where projected climatic change was only weakly expressed in the resulting hazard patterns.

In Phase 2, an XGBoost gradient-boosting model was adopted in place of the Random Forest used in Phase 1. This modelling choice enables more flexible calibration and more explicit control of the model response to climate drivers, while remaining well suited to national-scale training datasets. To improve model robustness and reduce sensitivity to local class imbalance, the susceptibility model was re-trained using a Portugal-wide training domain based on synoptic wildfire events from 1991–2010 and a more focused set of predictors. Training at national scale allows the model to learn from a broader range of climatic and landscape conditions, strengthening the estimated relationships between wildfire occurrence and the predictor space before regional interpretation in Beiras and Serra da Estrela.

Climatic predictors were derived from the ECLIPS2.0 dataset and reduced to three variables that are informative for ignition and spread conditions: a Summer heat–moisture index (SHM), mean annual precipitation (MAP), and mean annual temperature (MAT). These climatic drivers were complemented by higher-resolution geographical predictors that influence fuel availability and fire behavior at regional scale, including land cover (COS-2023 reclassified into fuel-relevant categories), elevation, slope, aspect, terrain roughness, and historical burnt area information used to characterize where fires have effectively occurred under past conditions.

Compared with Phase 1 where land cover and topography tended to dominate and the hazard signal showed limited temporal evolution, the Phase 2 implementation introduces climate-alignment mechanisms (including monotonic constraints) to ensure that, for a given location, hazard evolves consistently with the projected direction of change in temperature, precipitation, and the heat–moisture index. In practice, this reduces spurious decreases in far-future periods observed in some Phase 1 experiments and yields a more coherent progression of hazard intensification over time.

For each GCM–RCM combination available in ECLIPS2.0, the model was run separately to generate a set of hazard maps under alternative climate projections. A mean ensemble of these results was then computed to summarize the temporal evolution of wildfire hazard. The ensemble should be interpreted as an indication of the overall tendency under climate change rather than a precise forecast; uncertainty should be assessed by considering both the ensemble mean and the spread across individual GCM–RCM realizations.

As an additional consistency check, the resulting hazard maps were compared with ICNF structural hazard products, which remain a key operational reference for wildfire risk management in Portugal. The intention is not to replace ICNF products, but to complement them by providing a long-term perspective on hazard evolution under different climate scenarios.

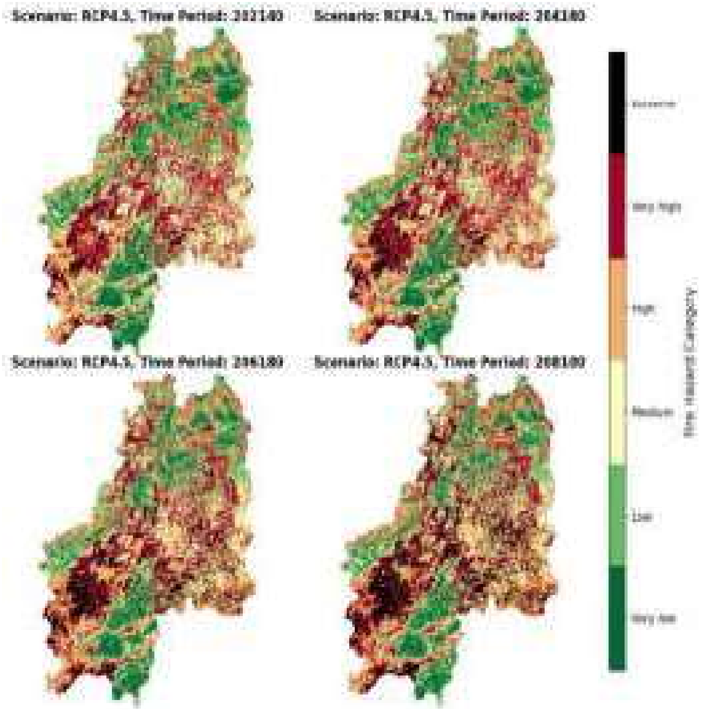

Figure 2-1Wildfire Hazard; Scenario RCP 4.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

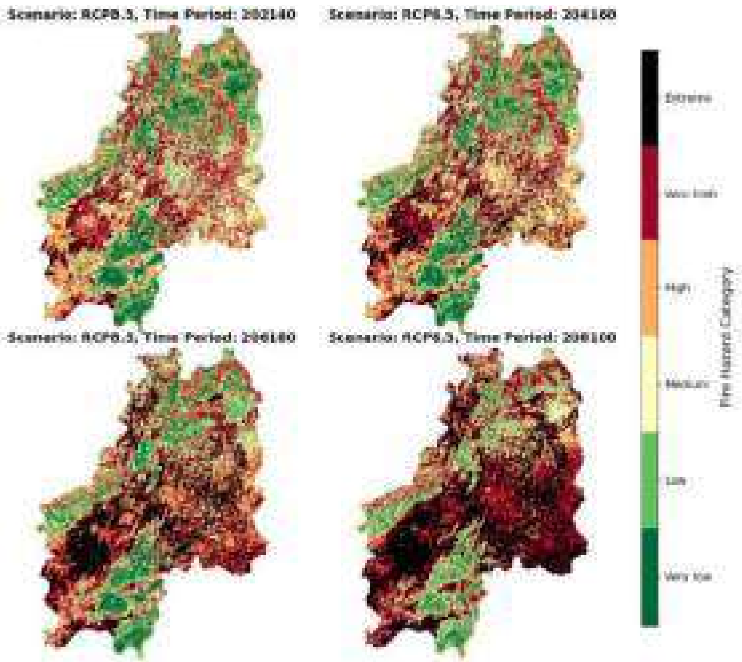

Figure 2-2 Wildfire Hazard; Scenario RCP 8.5; Periods 2021-2040, 2041-2060, 2061-2080, 2081-2100.

Overall, the Phase 2 hazard outputs are more consistent with local expectations and known structural patterns: the areas highlighted as most susceptible align more closely with the spatial logic of Portuguese wildfire hazard, and the RCP 8.5 pathway produces systematically more adverse projections than RCP 4.5. The maps also show clearer temporal evolution, with increasing hazard levels across successive future periods. The strongest increases tend to occur where land cover shifts towards more flammable vegetation types and/or where steep terrain coincides with dense and continuous fuels. Conversely, areas with more fragmented fuels or lower structural hazard tend to retain comparatively lower hazard levels even under more adverse climate trajectories. The main outputs are presented in the wildfire hazard maps (Figure 2-1 and Figure 2-2), which illustrate the spatial distribution of hazard classes and their evolution over time.

One artefact observed in the outputs is the occurrence of very high hazard values at the highest elevations, where wildfire occurrence can be limited. This pattern is interpreted as an extrapolation issue at the edge of the predictor space due to high-elevation conditions are sparsely represented in the training set since Serra da Estrela Mountain is the place with highest elevation in mainland Portugal.

Several limitations should be noted. First, the temporal granularity of training data remains constrained: the model is calibrated using a single historical reference period and then applied to future time slices. Ideally, multiple historical windows with comparable duration would be available to better characterize temporal evolution under observed variability, but this is limited by historical wildfire data availability and quality constraints. Second, some input datasets may contain local artefacts (e.g., land-cover classification issues) that can influence fine-scale model performance and the detailed hazard pattern. Despite these limitations, the datasets are considered broadly representative for regional-scale interpretation. Future work could include more systematic validation of land-cover information and/or the integration of additional local datasets to further strengthen the robustness of the hazard assessment.

2.3.1.2 Risk assessment

The wildfire risk assessment in Phase 2 combines the updated hazard maps described in Section 2.3.1.1 with exposed assets and vulnerability information to identify where wildfires are most likely to generate significant impacts on people, infrastructure, ecosystems, and economic activities. This supports stakeholders in prioritizing prevention and adaptation measures in Beiras and Serra da Estrela.

In line with the CLIMAAX workflow logic, the risk analysis follows the same time slices and emission pathways considered in the hazard assessment. For each period and for both RCP 4.5 and RCP 8.5, the ensemble wildfire hazard index is overlaid with exposure layers to produce risk indicators for the region. Compared with Phase 1, Phase 2 places greater emphasis on fine-resolution, locally validated datasets and incorporates additional exposure layers identified as relevant during stakeholder engagement, including (among others) water points relevant for suppression operations.

The first step is an assessment of the exposure of healthcare services across the region, since these facilities 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 the maps shown in Figure 2-3 where healthcare facilities are shown together with the underlying hazard levels, allowing priority areas to be quickly identified.

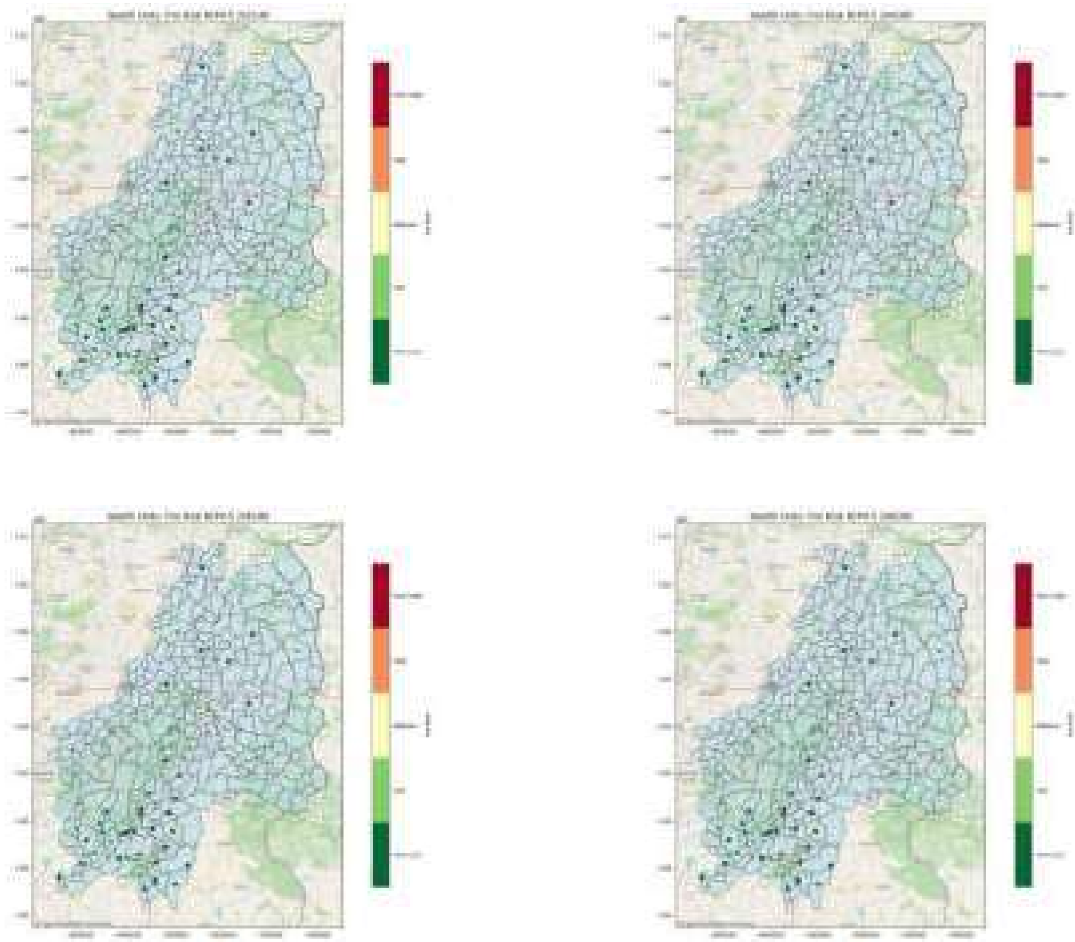

Figure 2-3 Health Care Units Risk.

Infrastructure exposure is assessed by intersecting hazard outputs with key asset layers. For transport infrastructure, the exposure of the primary road network (national roads, motorways, and other major routes) is analyzed in Figure 2-4 to identify segments more likely to be affected by future wildfires, with implications for evacuation, emergency response, and continuity of economic activities.

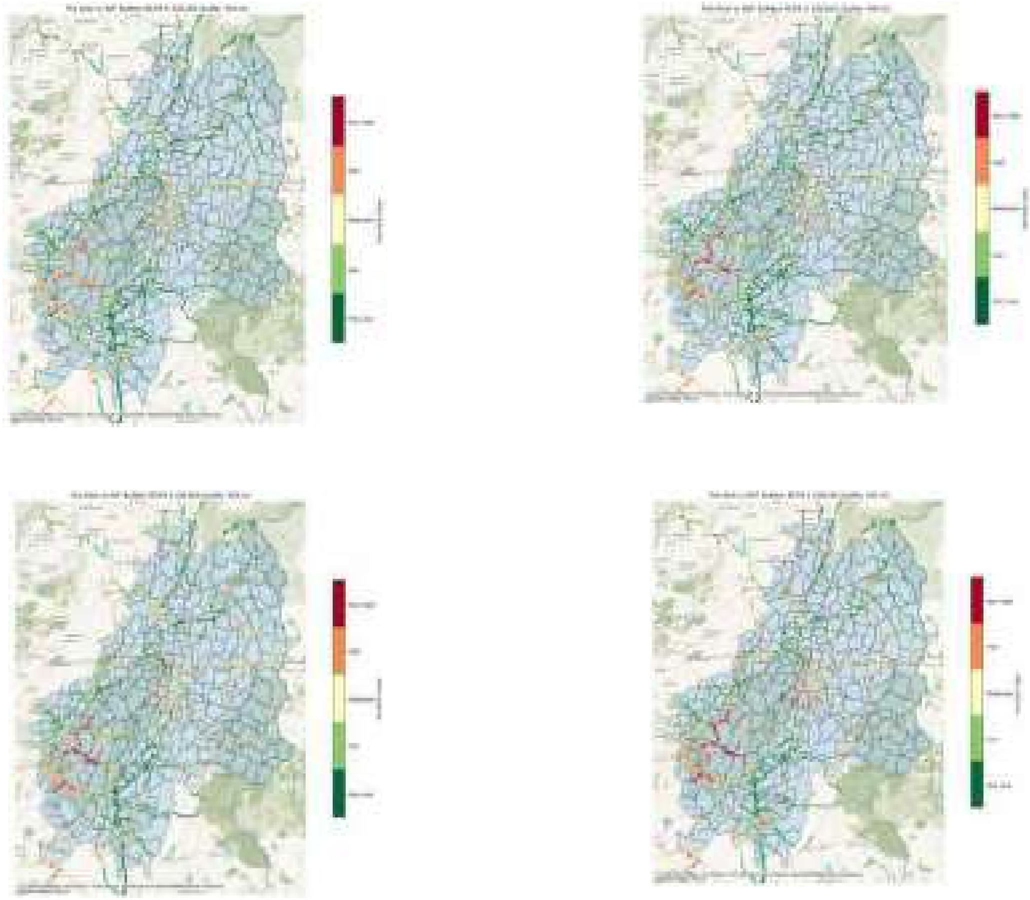

Figure 2-4 Road Network Risk.

Beyond the location of assets, the assessment integrates vulnerability dimensions (population, ecological, and economic) using the available vulnerability indicators. Vulnerability variables are classified into three classes (based on quantiles) and combined with the six hazard classes through the risk matrix (Figure 2-5). The resulting composite risk is presented in Figure 2-6.

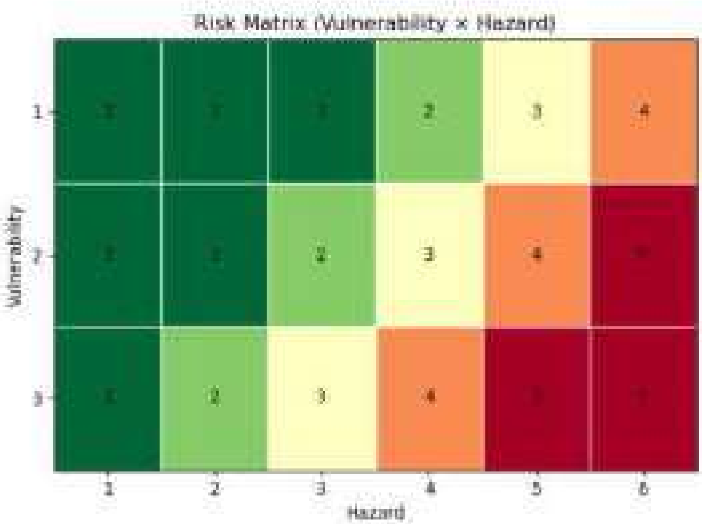

Figure 2-5 Risk Matrix used with population, economic and ecological vulnerability.

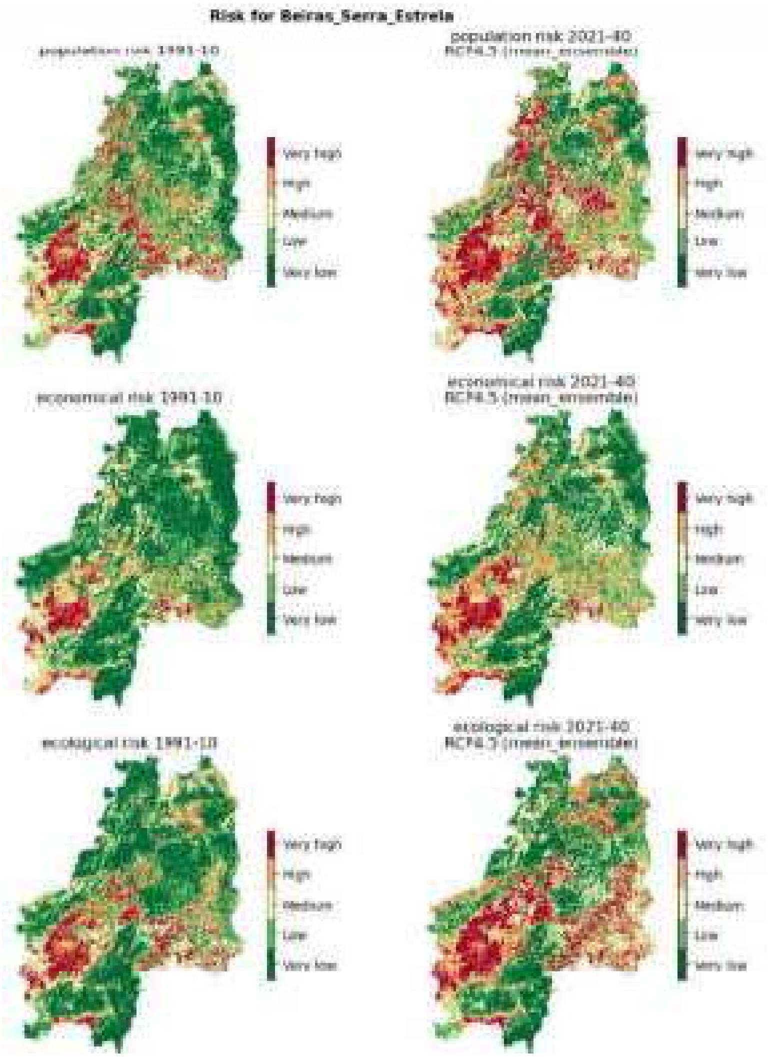

Figure 2-6 Population, economical, ecological Risk for periods 1991-2010 and 2021-2040.

Interpreting the combined outputs shows that high hazard does not automatically translate into high risk for every receptor, because risk depends on the spatial coincidence of hazard with exposure and vulnerability. Areas with limited built assets and lower resident population may still constitute priority zones from an ecological (and, in some cases, economic) perspective, particularly where high hazard overlaps protected areas and high-value ecosystems. The vulnerability results indicate that Beiras and Serra da Estrela presents very high vulnerability to wildfires, especially in the population and ecological dimensions; although economic vulnerability is comparatively less pronounced, it remains high enough to warrant attention in prioritization and planning.

To complement hazard-and-exposure risk, response capacity is assessed to reflect the ability to suppress fires and limit damages. Two main components are considered: (i) coverage and accessibility of water points and (ii) distance (or travel time) to fire stations and strategic parking areas for firefighting resources. Coverage and accessibility metrics are classified into five response-capacity classes (quantiles), where lower classes correspond to better expected response capacity. These response-capacity classes are then combined with wildfire hazard through a risk matrix (Figure 2-7) to identify areas where high hazard coincides with constrained operational response.

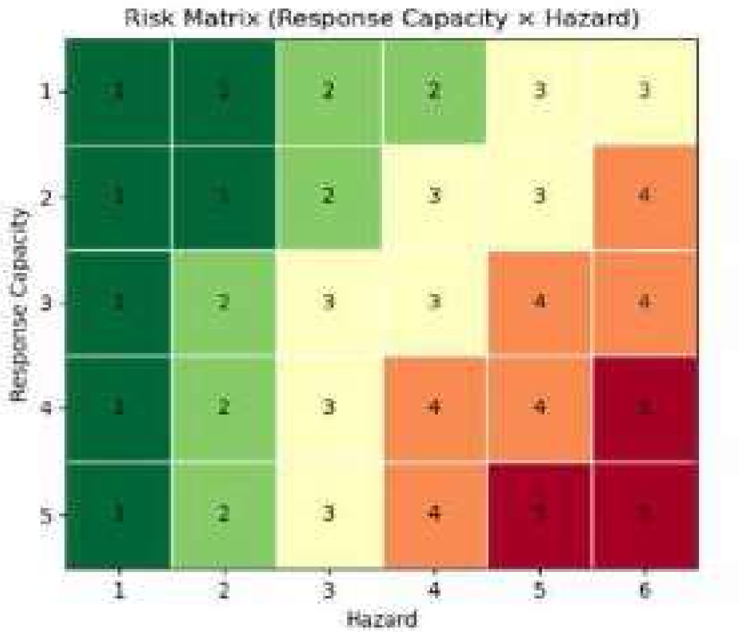

Figure 2-7 Risk Matrix used with response capacity metrics.

For water points, separate analyses are conducted for aerial and terrestrial suppression. For aerial resources, water points are assigned operating radii (e.g., 5 km and 10 km) to represent different operating ranges, and a coverage metric is derived by combining distance and stored volume. To avoid large reservoirs dominating the representation, two complementary variants are used: (i) a capped-volume metric (e.g., limiting effective volume to 10,000 m³) that emphasizes the density of water points rather than points with very big volume of water (Figure 2-8), and (ii) an uncapped metric visualized on a logarithmic scale that preserves the visibility of both low- and high-volume sources while reducing contrast at the lower range (Figure 2-9). This indicator should be treated as a first-order approximation, as local terrain constraints for aerial operations (e.g., orography) are not explicitly modelled.

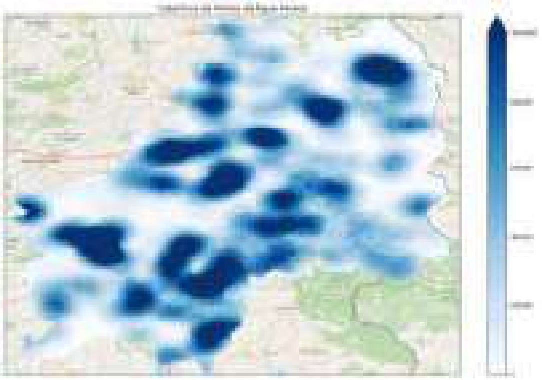

Figure 2-8 Aerial water points capacity with a limit of volume 10000 m3 and a limit of radius of 5 km for each water point.

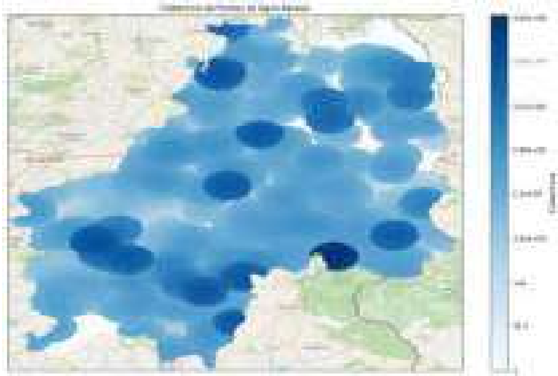

Figure 2-9 Aerial water points capacity with logarithmic scaling and a limit of radius of 5 km.

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-RBSE.

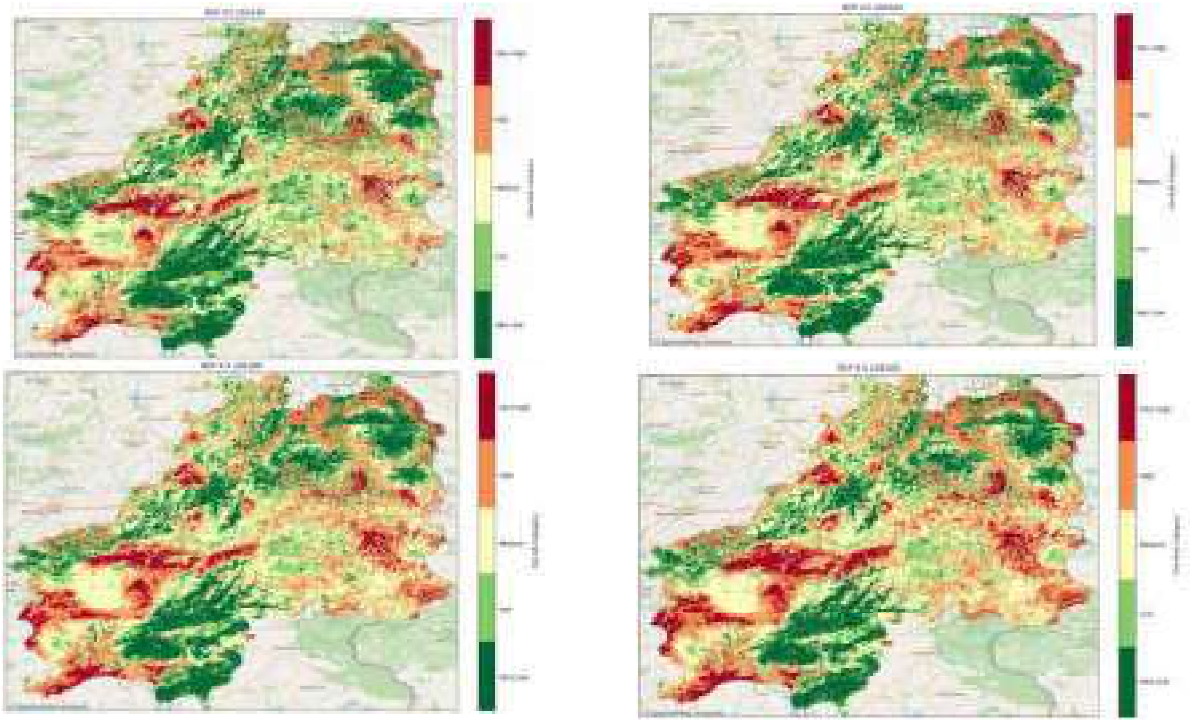

Figure 2-10 Risk of wildfire taking into consideration Aerial Water Points capacity with a limit of 10000 m3.

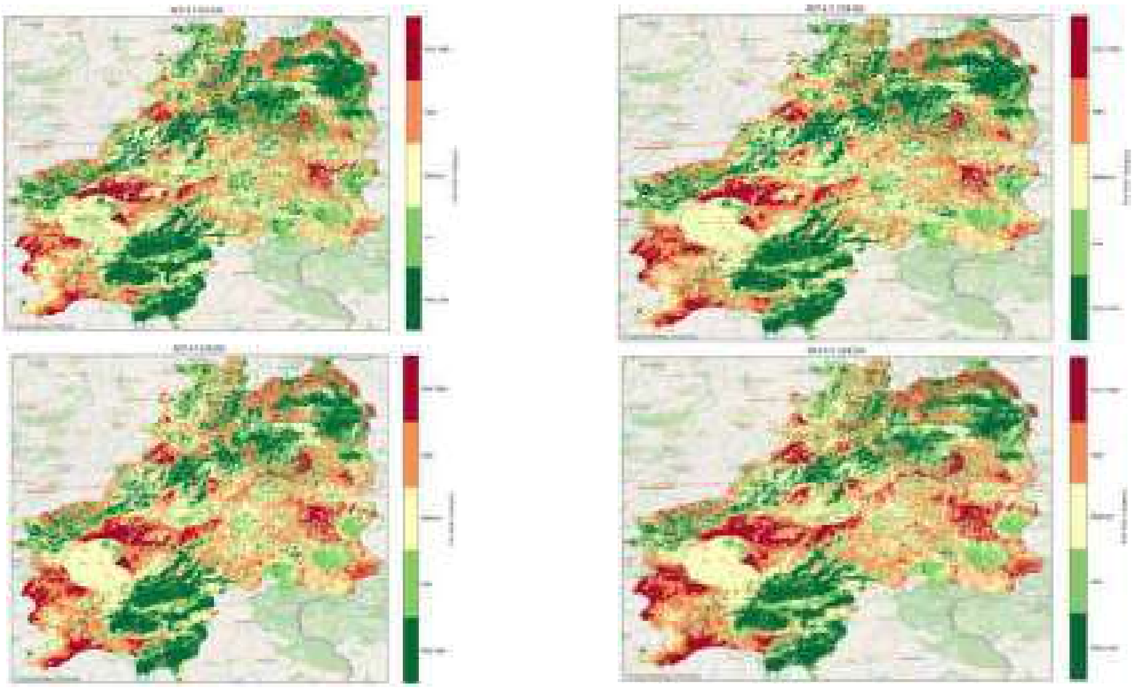

Figure 2-11 Risk of wildfire taking into consideration Aerial Water Points capacity with a logarithmic Scaling.

For terrestrial suppression, coverage is assessed through routing on the road network, producing distance and travel-time indicators 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.

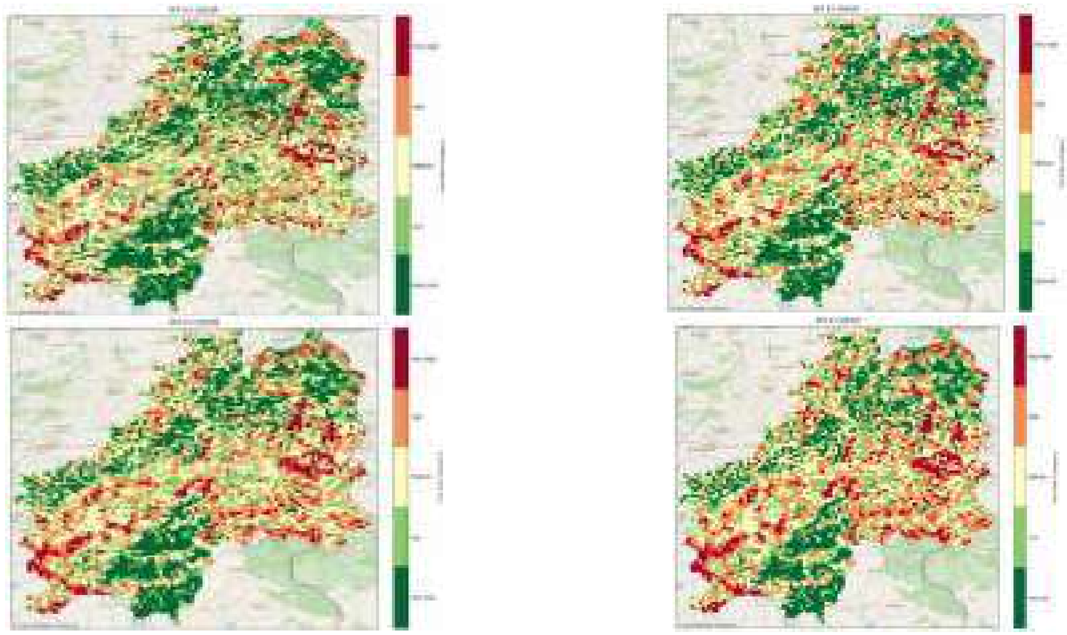

Figure 2-12 Risk of wildfire taking into consideration Terrestrial Water Points capacity.

The same routing approach is applied to fire stations and strategic parking areas, generating spatialized response-time estimates across Beiras and Serra da Estrela.

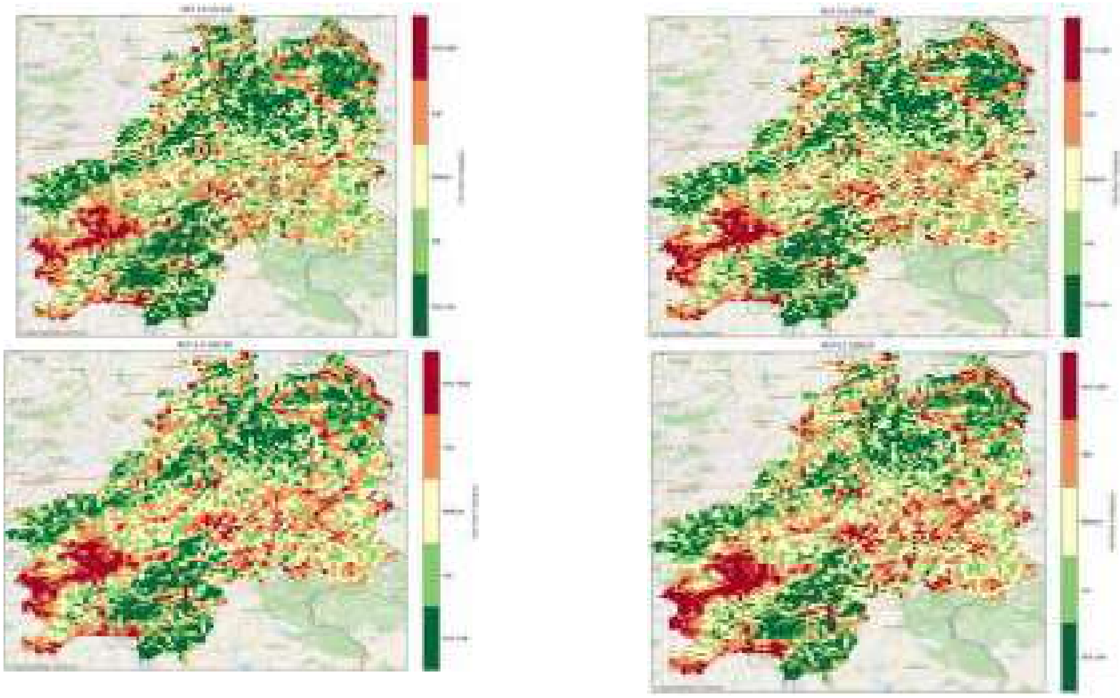

Figure 2-13 Risk of wildfire taking in consideration Fire Stations and Strategic Parking Location.

Taken together, the Phase 2 risk results indicate where projected hazard intensification coincides with exposed infrastructure and vulnerable receptors, and where operational response constraints may further exacerbate impacts. Although results should be interpreted primarily in a relative sense given the dependence on dataset completeness and on the assumptions used to combine the layers, the Phase 2 integration of an improved wildfire hazard model with expanded exposure and response-capacity information provides a more detailed and actionable basis for identifying priority areas for prevention, fuel management, and adaptation planning in Beiras and Serra da Estrela.

2.3.2 Hazard #2: Heatwaves - finetuning 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 maintains the same core climate indicator adopted in Phase 1 to ensure methodological continuity and comparability across project phases: the projected evolution in the frequency of heatwave days, defined using the EuroHEAT criterion as periods of three or more consecutive days in which daily maximum temperature exceeds the 90th percentile of the local historical distribution.

Hazard projections were derived from the Copernicus Climate Data Store dataset "Heat waves and cold spells in Europe derived from climate projections", based on the EURO-CORDEX regional climate model ensemble for RCP 4.5 and RCP 8.5. The analysis evaluates two future horizons relative to the historical baseline 1986–2015: a near-future period (2016–2045) and a mid-century period (2046–2075). For each scenario and horizon, the annual number of heatwave days was calculated and expressed as a relative change (%) against the historical reference period.

To integrate these projections into the CLIMAAX risk framework and align outputs with local decision-making scales, relative changes were spatially aggregated to the level of civil parishes across Beiras and Serra da Estrela. The resulting hazard maps represent the climate-driven tendency for more frequent extreme-heat conditions at parish scale, independently of local exposure and vulnerability.

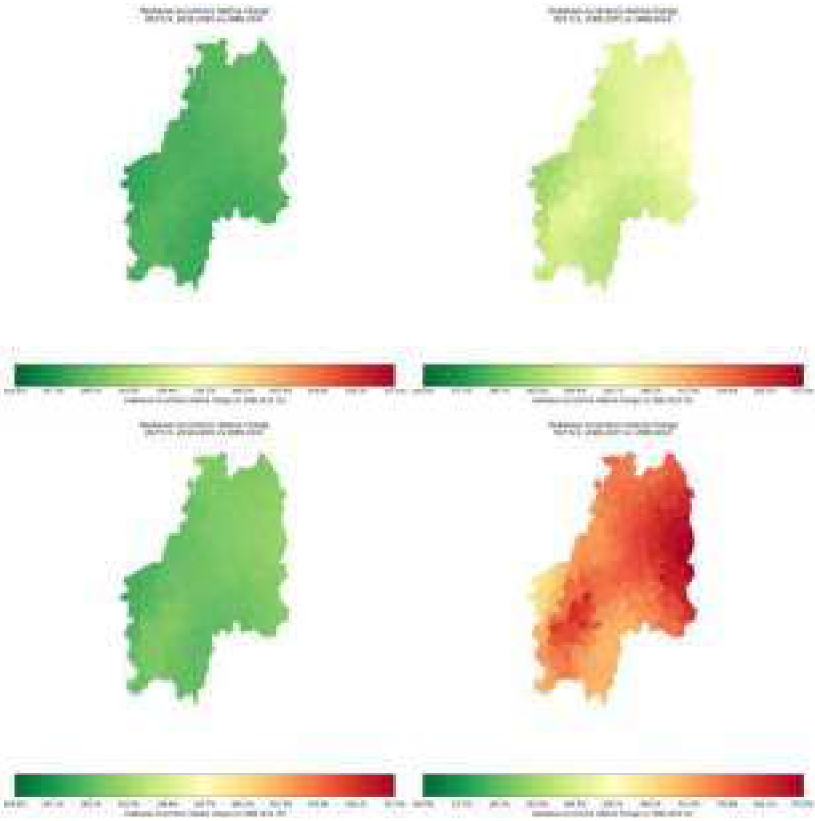

Figure 2-14 Heatwave occurrence relative change to 1986-2015 for scerarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

The eastern part, along with a portion of the southwestern region, is projected to be more severely impacted by extreme heat, with an anticipated increase of approximately 330% under the RCP 4.5 emission scenario and 510% under the RCP 8.5 scenario. The remainder of the region is expected to experience a much lower, though still notable, increase.

2.3.2.2 Risk assessment

At parish level, the heatwave 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 consistent with the CLIMAAX methodology.

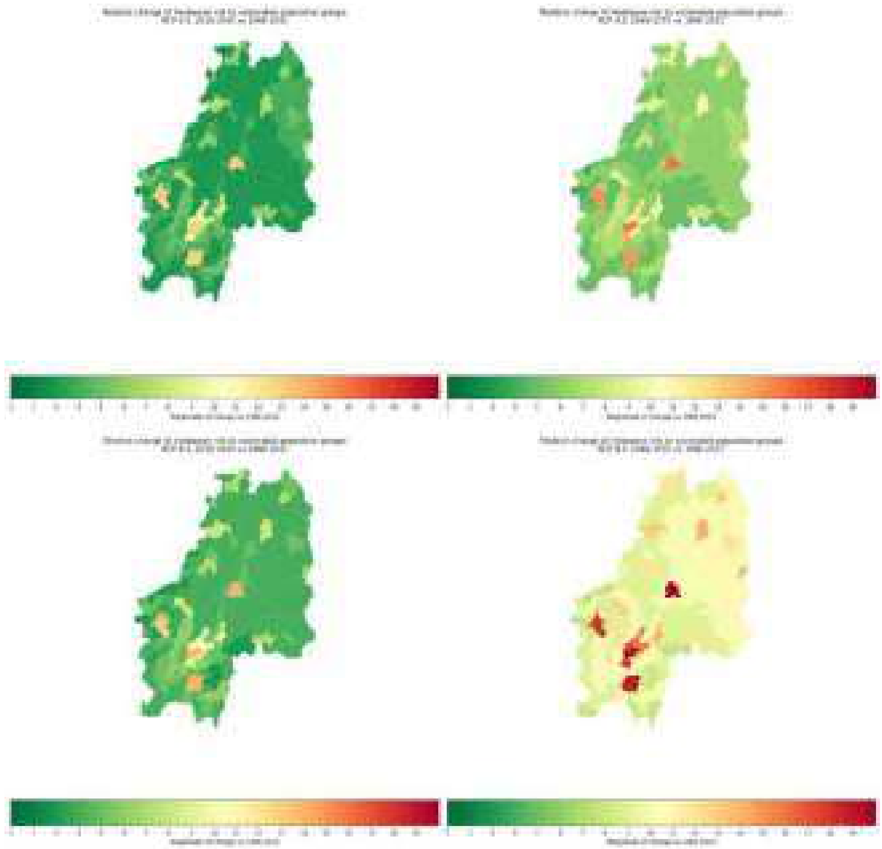

Figure 2-15 Relative change to Heatwave risk to vulnerable population for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075.

In the population vulnerability analysis for heatwaves, we can see that the most at-risk civil parishes are the main ones of the 4 cities of the region: Fundão, Guarda, Seia and Covilhã. While the easternmost part of the region is one associated with a high hazard for the evolution of extreme heat days, the low population in the region mitigates the risk associated with those civil parishes.

The EuroHEAT based hazard indicator was re-analyzed specifically over the region's main built-up polygons, producing an urban-focused hazard metric that enables towns to be ranked according to expected increases in heatwave occurrence as seen in Figure 2-16. This step supports a more decision-relevant framing, since heat-related impacts on people concentrate strongly in compact urban areas rather than across whole parish territories.

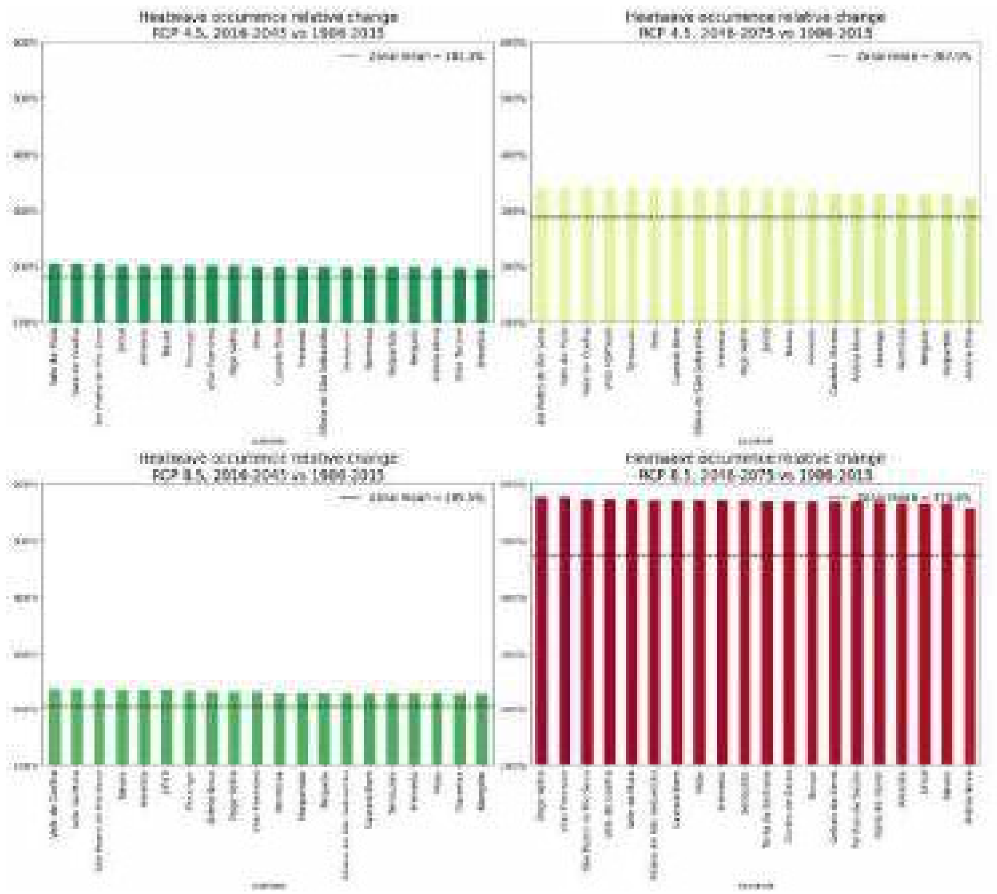

Figure 2-16 Heatwave occurrence relative change to 1986-2015 for scenarios 4.5 and 8.5 and periods 2016-2045 and 2046-2075 for 20 most affected urban areas.

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 2-17) 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.

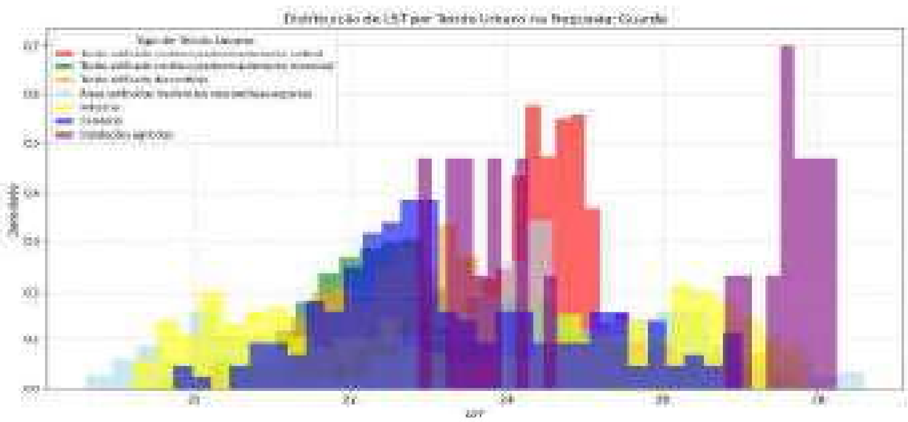

Figure 2-17 Land Surface Temperature distribution for each land type of urban areas.

The moderating influence of vegetation is examined through a joint analysis of LST and NDVI. An automatic classification (k-means) is applied to distinguish "green" pixels (vegetated surfaces such as parks, tree-lined streets, gardens, riparian corridors and agricultural plots) from "grey" pixels (buildings, paved areas and other non-vegetated surfaces). The classification is performed both across the full study area (Figure 2-19) obtaining a NDVI threshold of 0.312 and within urban masks (Figure 2-18) with resulting NDVI threshold of 0.509.

Figure 2-18 Example of classification results for Guarda using only the urban areas for the classification. (threshold: 0.509)

Figure 2-19 Example of classification results for Guarda using all CIM RBSE area for the classification. (threshold: 0.312)

In both cases, temperature distributions show a consistent shift towards lower LST values in green pixels compared with grey ones, with a larger separation when using the stricter NDVI threshold. This separation is quantified using the Wasserstein distance (also known as the Earth Mover's Distance), which measures the minimum "transport cost" required to transform one temperature distribution into the other—here interpretable as the average shift in LST values needed for the green-pixel distribution to resemble the grey-pixel distribution. For Guarda, the EMD is 0.40 for the urban-only classification (NDVI threshold 0.312) and 0.77 for the region-wide classification (NDVI threshold 0.509), confirming a stronger temperature contrast when denser vegetation is isolated.

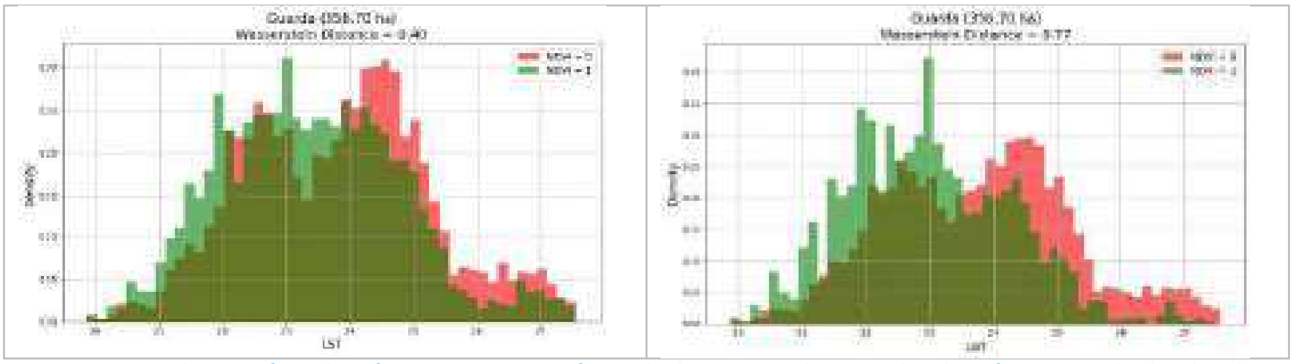

Figure 2-20 Distribution of Land Surface Temperatures for each class in guarda Using the classification method with only urban areas (on the left) and using all the CIM RBSE region (on the right).

Beyond the direct green–grey contrast, the analysis quantifies how far vegetation cooling 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. Results indicate that grey pixels located near green areas are noticeably cooler than grey pixels that are more isolated, with a progressive weakening of the cooling effect as distance increases. When considering only areas with denser vegetation (i.e., applying a more restrictive NDVI threshold), the influence of vegetation on temperature is observed at greater distances into grey areas: the region's average temperature can be reached with sparser vegetation up to ~30 m away, and with denser vegetation up to ~100 m. Overall, vegetation-related cooling remains detectable up to approximately 140 m.

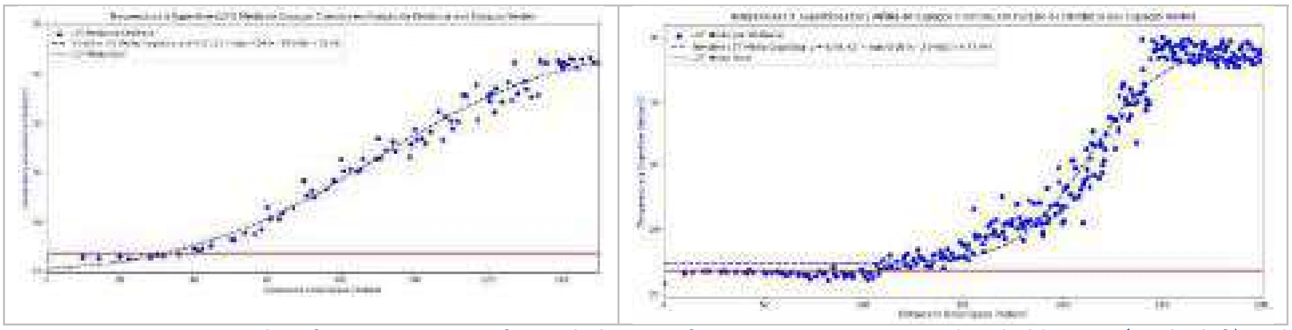

Figure 2-21 Average Land Surface Temperature for each distance for CIMBSE region *using threshold 0.312 (on the left) and threshold 0.509 (on the right).*

Given that the central concern of heatwave risk is its impact on human health it was important to analyze hospital admissions during hot days. 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. 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 Beiras and Serra da Estrela 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 2025, 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 increases 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%). (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 for this age group. (Associação Nacional dos Médicos de Saúde Pública (ANMSP) 2024)

2.4 Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

Risk evaluation in Phase 2 followed the participatory approach established in Phase 1 and focused specifically on the interpretation and usability of the updated outputs. Engagement combined (i) targeted collection of priorities and data needs (survey and bilateral exchanges where relevant) and (ii) a structured online workshop to present the Phase 2 results and gather feedback on interpretation, usability, and priority-setting.

Participants included municipal representatives and municipal civil protection services, regional and national agencies linked to rural fire management and civil protection, research and academic institutions, and sectoral and civil-society organisations. Feedback emphasised the need for decision-scale outputs (urban heat, critical infrastructure, response logistics), the importance of interpreting risk by receptor (population, ecosystems, services), and practical improvements to exposure and operational datasets (e.g., completeness and attributes of water points and critical network segments).

2.4.2 Gather output from Risk Analysis step

Risk evaluation drew on the full set of Phase 2 outputs produced in the Risk Analysis step (Section 2.3) for both hazards. For wildfires, this includes ensemble hazard projections under RCP 4.5/8.5 across future periods, exposure overlays for critical assets and networks, vulnerability-based composite risk (population, ecological and economic), and the response-capacity indicators and associated hazard–capacity risk matrices (water-point coverage and network-based travel time to response resources). For heatwaves, it includes parish-scale hazard and risk to vulnerable population for both scenarios and horizons, the ranking of built-up areas, and the urban exposure assessments based on LST, land-use/urban fabric classes and NDVI-derived vegetation cooling (including distance-to-green analyses). National heat–health evidence was used only to contextualise severity where robust local heat–health linkages could not be established.

2.4.3 Assess Severity

Severity was assessed for both current and future risk using the four categories defined in the Key Risk Assessment Protocol: limited, moderate, substantial, and critical. The assessment considered historical impacts, likely magnitude of consequences, potential irreversibility, and cascading effects across sectors and services.

Wildfires – severity: critical (current) and critical (future). Wildfire impacts in CIM RBSE are already severe, with recent extreme events affecting large areas and generating major ecological damage, including impacts on protected ecosystems. Wildfires can produce irreversible consequences (loss of habitats, biodiversity impacts, long-term soil degradation) and cascading effects (service disruption, access constraints, economic losses in tourism and agroforestry systems). Under future climate pathways, the refined hazard projections show an intensification tendency over time and more adverse outcomes under higher emissions, indicating that the potential for high-impact events remains high and may worsen. Stakeholder interpretation reinforced that wildfire severity should be judged not only through built-asset exposure, but also through ecological value and operational constraints in mountainous terrain.

Heatwaves – severity: substantial (current) and critical (future). Heatwaves already generate measurable health impacts at national level, including increased mortality during heat alerts and increased pressure on health services during hot periods. In CIM RBSE, Phase 2 results indicate strong increases in heatwave hazard in parts of the territory, while risk to vulnerable population concentrates in the main urban parishes due to demographic distribution. Within towns, exposure is heterogeneous and systematically higher in dense residential and industrial/commercial fabrics, while vegetation demonstrably moderates exposure. Given the projected hazard increase and the direct link to health outcomes, future severity is assessed as critical, particularly for vulnerable groups and for urban areas with limited cooling capacity.

2.4.4 Assess Urgency

Urgency was assessed using the four categories defined in the Protocol: no action needed, watching brief, more action needed, and immediate action needed. The assessment considered expected near-term worsening, timing of impacts, event dynamics (sudden vs slow-onset), and persistence.
Wildfires – urgency: immediate action needed. *Wildfires are characterized by sudden onset and fast escalation under adverse weather conditions, with strong seasonality and limited response windows once ignitions occur. The Phase 2 projections suggest hazard intensification over future periods, while the response-capacity analyses identify areas where operational constraints can compound impacts. This supports immediate action on prevention (fuel management and landscape interventions), preparedness (access, water availability, logistics), and protection of critical infrastructure and high-value ecosystems.*
Heatwaves – urgency: immediate action needed. *Heatwave hazard is expected to worsen substantially and is already associated with measurable health impacts at national scale. Heatwave impacts are partly predictable, but their effects accumulate quickly during multi-day events and can persist through prolonged hot spells. Urgency is therefore assessed as immediate, prioritizing near-term measures that reduce exposure in urban hotspots, protect vulnerable groups, and strengthen heat-health preparedness and monitoring.*

2.4.5 Understand Resilience Capacity

Resilience capacity was assessed using four categories—low, medium, substantial, and high—considering financial, human, physical, social, and natural capacity, as well as existing measures and known weak spots.

Wildfires – resilience capacity: substantial. CIM RBSE benefits from established governance and operational structures for rural fire management and civil protection, and from ongoing planning instruments that support prevention and preparedness. However, Phase 2 results highlight weak spots linked to territorial complexity and logistics: remote mountainous areas can experience longer travel times to response resources, and water-point coverage is spatially uneven. These constraints reduce effective capacity in the locations where hazard can be highest and where ecological value is significant. Capacity is therefore assessed as substantial overall, but not uniformly distributed across the territory.

Heatwaves – resilience capacity: medium. While adaptation initiatives exist, heatwave risk management is constrained by gaps in local monitoring and evaluation of health impacts and by uneven readiness at urban scale (availability of cooling spaces, targeted outreach to vulnerable groups, and operational protocols). The inability to robustly use local hospital admissions data in Phase 2 illustrates a monitoring limitation that directly affects preparedness evaluation. Capacity is assessed as medium, with clear opportunities for improvement through stronger heat–health data pipelines, operational heat action plans, and targeted urban cooling interventions.

2.4.6 Decide on Risk Priority

Risk priorities were assigned by combining severity, urgency, and resilience capacity within the evaluation dashboard, and by validating the resulting prioritization logic with stakeholder feedback during Phase 2 engagement. The evaluation also considered that “priority” differs by receptor (population health, ecosystems, critical services, operational constraints).

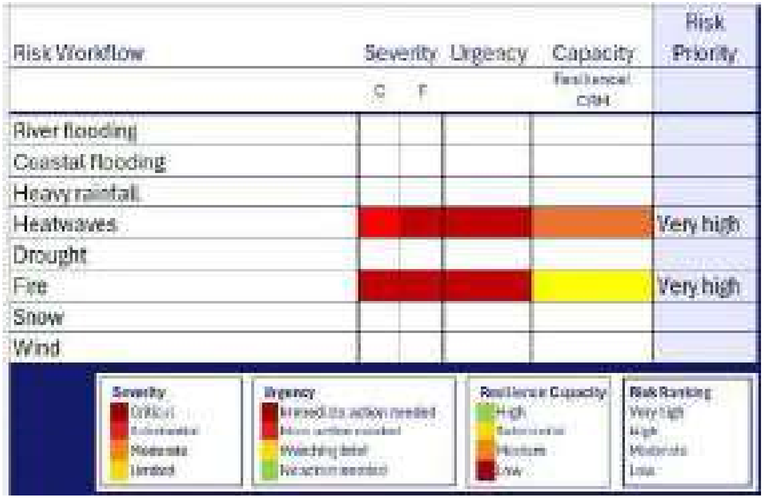

Figure 2-22 Key Risk Assessment.

Based on this combined evaluation:

- **Wildfires are prioritised as a top regional risk** due to critical severity, immediate urgency, and known operational weak spots in parts of the territory. Priority attention is warranted where high hazard converges with (i) high ecological value/protected areas, (ii) exposed critical networks and services, and (iii) constrained response capacity (water-point coverage and travel-time patterns).
- **Heatwaves are also prioritised as a high regional risk** due to substantial-to-critical severity (especially for vulnerable groups), immediate urgency, and medium resilience capacity. Priority attention is warranted in the main urban parishes where vulnerable population concentrates and where urban fabrics amplify exposure, as well as in locations where targeted green infrastructure can measurably reduce LST and adjacent exposure.

These priorities will guide Phase 3, which will focus on translating the prioritised risks into feasible adaptation measures aligned with existing municipal and intermunicipal planning instruments and civil protection routines.

2.5 Monitoring and Evaluation

Phase 2 generated three main learning outcomes for the Beiras and Serra da Estrela climate risk assessment: (i) the value of calibrating modelling choices to Portuguese conditions rather than relying only on generic defaults; (ii) the importance of reframing results to a “decision scale” that matches where impacts and responsibilities concentrate; and (iii) the practical usefulness of complementing risk mapping with response-capacity metrics that connect directly to operational planning.

For **wildfires**, the second-phase refinements improved the coherence of hazard patterns over time and strengthened alignment with the expected direction of climate change, producing more interpretable projections across successive future periods and clearly differentiating more adverse scenarios from less adverse ones. For **heatwaves**, complementing parish-scale indicators with an urban-focused analysis (Land Surface Temperature, land-use/urban fabric classes, and vegetation indices) increased interpretability for municipal decision-making by showing which urban fabrics concentrate the highest thermal exposure and how green infrastructure moderates local temperatures.

Stakeholders are central to Monitoring and Evaluation in two ways:

1. **Validation of relevance and plausibility:** confirming whether the mapped patterns match local experience and operational realities.
2. **Co-ownership of the policy pathway:** ensuring CRA outputs translate into actionable steps within municipal and intermunicipal planning and civil protection routines.

Engagement through workshops was used to prioritize analyses and identify data needs. Stakeholder feedback highlighted the importance of: (i) exploring heat–wildfire interactions; (ii) strengthening the evidence base on heat-related health outcomes; (iii) improving socio-economic vulnerability layers; (iv) assessing how green spaces reduce thermal exposure; and (v) clarifying resilience of services during compound events.

Learning is ensured through an iterative cycle:

- stakeholder feedback informs refinements and prioritization;
- assumptions, limitations, and artefacts are documented transparently;
- results are cross-compared against operational references where appropriate.

Phase 2 already incorporated higher-resolution and more locally meaningful datasets (including remote sensing products supporting urban heat exposure mapping). Still, priority needs to strengthen understanding and monitoring include:

- **Heat–health impact datasets:** consistent and accessible local health outcomes (stable coding practices and adequate temporal coverage) to enable evaluation of heat impacts.
- **Exposure and vulnerability layers:** richer socio-economic vulnerability indicators and infrastructure attributes that support targeted planning.
- **Operational constraint data:** improved, quality-controlled information on usability/seasonal availability of water points and practical accessibility constraints in complex terrain.
- **Skills and resources:** continued capacity for geospatial analytics, remote sensing, model interpretation, and stakeholder facilitation to convert outputs into implementable measures.

Resources were used efficiently by focusing on two priority hazards and by leveraging existing workflows, while directing Phase 2 effort toward the refinements with the highest decision value (local calibration, urban-scale heat analysis, expanded exposure layers, and response-capacity overlays).

The efficiency trade-off is that some extensions remain partially addressed (e.g., deeper local impact validation, richer vulnerability modelling, and broader sensitivity testing), which should be treated as priorities for Phase 3 follow-up.

Phase 2 improved the region's understanding of where wildfire and heatwave risks concentrate, why these patterns emerge (hazard versus exposure/vulnerability), and which monitoring gaps constrain evidence-based evaluation of impacts—particularly for heat-related health outcomes. This strengthens institutional capacity to prioritize adaptation measures, supports clearer communication to the public, and provides a more robust basis for planning, funding, and investment decisions.

2.6 Work plan Phase 3

Building on the refined climate risk assessment developed in Phases 1 and 2, Phase 3 focuses on translating the analytical results into actionable adaptation strategies and concrete improvements to existing risk management instruments at intermunicipal and municipal levels. This phase represents a shift from diagnostic and analytical work towards strategic planning and decision-support, ensuring that climate risk knowledge is effectively operationalized within territorial governance frameworks.

The work plan for Phase 3 is structured to ensure continuity with previous phases, methodological coherence with the CLIMAAX framework, and strong alignment with existing planning instruments, particularly the Intermunicipal Climate Change Adaptation Plan (PIAAC), Municipal Climate Action Plans, and Municipal Emergency and Civil Protection Plans. The activities are designed to progressively move from the interpretation of refined risk outputs to the co-definition, prioritization, and consolidation of adaptation measures with territorial relevance and institutional feasibility.

The first step of Phase 3 consists of a systematic review and interpretation of the refined risk assessments produced in Phase 2. This analysis will focus on the most critical climate risks identified for the territory, taking into account their severity, urgency, spatial distribution, and potential cascading effects. Particular attention will be given to risks already prioritized in earlier phases, such as heatwaves and rural fires, while also considering how refined local data may alter or nuance previously identified vulnerability patterns. This step ensures that adaptation planning is firmly grounded in robust, high-resolution risk evidence.

Based on this consolidated understanding of vulnerabilities and priority risks, the second step involves the identification of a portfolio of potential adaptation measures. These measures will cover a broad range of intervention types, including structural solutions, nature-based solutions, governance and planning measures, and institutional or capacity-building actions. The identification process will draw on European and national good practices, relevant adaptation frameworks, and the methodological guidance provided by the CLIMAAX Adaptation Support Tool, ensuring consistency with recognized adaptation planning approaches.

A core component of Phase 3 is the active involvement of regional and local stakeholders. Dedicated participatory activities will be organized to discuss the refined risk results, validate identified vulnerabilities, and gather inputs on adaptation needs, priorities, and implementation constraints. These interactions aim to incorporate local knowledge, sectoral perspectives, and institutional responsibilities into the adaptation planning process, while also fostering ownership and legitimacy of the proposed measures. Stakeholder engagement will therefore play a central role in shaping and refining the adaptation options considered.

Following the identification phase, adaptation measures will be assessed and prioritized using a set of qualitative criteria, such as relevance to the identified risks, expected effectiveness, feasibility of implementation, potential co-benefits, and alignment with existing planning instruments. This prioritization step supports informed decision-making by distinguishing short-term, no-regret measures from medium- to long-term strategic interventions, and by clarifying potential synergies and trade-offs between different adaptation options.

The final step of Phase 3 focuses on consolidating the selected adaptation measures into a coherent strategic output. This includes the formulation of recommendations for updating or reinforcing existing risk management and adaptation plans, as well as the definition of implementation-oriented elements such as indicative timelines, responsible entities, and monitoring considerations. The results of this work will be synthesized in the Phase 3 deliverable, which will articulate how refined climate risk knowledge can be effectively embedded into territorial planning and governance processes, strengthening the region's adaptive capacity and resilience to climate change.

Through this structured and participatory work plan, Phase 3 ensures that the analytical advances achieved in the earlier phases are translated into practical, policy-relevant outcomes, fully aligned with the objectives of the CLIMAAX project and the strategic priorities of the Beiras and Serra da Estrela territory.

3 Conclusions Phase 2- Climate risk assessment

Phase 2 significantly strengthened theBeiras and Serra da Estrela climate risk assessment by moving from a primarily toolbox-driven application (Phase 1) to a more locally calibrated and decision-relevant analysis for the two prioritized hazards: **wildfires** and **heatwaves**. The main progress was achieved through (i) improved hazard modelling choices and constraints, (ii) expanded exposure and operational-capacity layers, and (iii) targeted “extra analyses” that clarify why risk concentrates, where it does and what that implies for adaptation planning.

Phase 2 produced wildfire hazard outputs that better reflect the expected direction of climate change and Portuguese wildfire logic by adopting an XGBoost-based susceptibility model, training on a national domain (1991–2010), reducing and focusing climate predictors, and introducing climate-alignment mechanisms (e.g., monotonic constraints). This resolved an important Phase 1 limitation where temporal evolution could be weak or counterintuitive. The resulting projections show a clearer intensification pattern across successive future periods and a systematically more adverse signal under RCP 8.5 than under RCP 4.5.

Risk interpretation in Phase 2 also moved beyond hazard-only mapping. By intersecting hazard with expanded exposure layers (including critical infrastructure such as healthcare services, roads and other assets) and by adding operational response-capacity indicators (water-point coverage and travel-time to response units), the assessment becomes more actionable for prevention and preparedness planning. Importantly, the analysis confirmed that high hazard does not automatically translate into high risk for every receptor: areas with low built exposure may remain high priority for ecological (and sometimes economic) reasons when high hazard overlaps protected or high-value ecosystems.

Phase 2 maintained methodological continuity with Phase 1 by keeping the EuroHEAT-based heatwave indicator and parish-level aggregation, while improving decision relevance by adding an urban-focused framing. The work shows that heatwave risk to people is strongly shaped by where vulnerable populations concentrate (notably in the main urban parishes), and that within towns, exposure is further amplified by urban fabrics that consistently occupy the warmest part of the Land Surface Temperature (LST) distribution (dense residential and industrial/commercial zones).

A key added value of Phase 2 was the explicit quantification of the cooling role of vegetation, using NDVI-based “green vs grey” classification and distance-to-green analyses. Results support a practical planning message: vegetation acts as a local cooling asset and its influence extends into neighboring built-up fabric, with an observable decay as distance increases—evidence that can directly guide where to prioritize small green interventions, shade corridors and park upgrades.

Several challenges were addressed during this second phase including:

- Increased realism and interpretability of wildfire hazard evolution through national-scale training and climate-alignment mechanisms, reducing spurious temporal behavior observed in Phase 1 experiments.
- Expanded the risk concept from “hazard footprint” to “priority for action” by integrating exposure, vulnerability dimensions, and operational response constraints (water points and response times).

- Improved the heatwave narrative from parish-scale hazard to urban-scale exposure, clarifying where impacts on people are most likely to concentrate and what urban form/land use contributes to those hotspots.

There is still, however, work for improvement that could be addressed in a future analysis, such as:

- A robust, local statistical linkage between heat exposure and health outcomes could not be established due to constraints in accessing/using local hospital and diagnostic data with sufficient consistency. This is itself a critical finding for monitoring and evaluation: strengthening health-impact data pipelines would materially improve future heat risk management.
- Some wildfire modelling artefacts remain possible at the edge of the predictor space (e.g., very high hazard at the highest elevations), interpreted as extrapolation where training samples are sparse rather than an operationally realistic signal.

Main key findings

- Wildfire hazard shows clearer temporal evolution and a consistent worsening under higher emissions, with strongest increases where flammable land cover and steep terrain combine.
- Wildfire risk priorities depend on the receptor: ecological priorities may be high even where population/build assets are lower, while infrastructure priorities emerge where hazard intersects critical networks and services.
- Response capacity matters: areas where high hazard coincides with lower water-point coverage and longer travel times to response units represent compounding risk and should be central in prioritizing operational improvements.
- Heatwave hazard increases substantially across the region, but risk to vulnerable people concentrates in the main urban parishes due to demographic distribution; therefore, adaptation needs an explicitly urban operational lens.
- Urban exposure is heterogeneous within towns: dense residential and industrial/commercial fabrics are persistently warmer, while green elements reduce LST and cool adjacent grey areas, supporting targeted green/grey interventions rather than uniform measures.

Overall, Phase 2 provides a stronger evidence base for prioritizing where to intervene and what levers are most relevant for each hazard. Phase 3 should therefore concentrate on (i) formalizing risk priorities with stakeholders and (ii) translating the mapped drivers into a feasible and funded package of adaptation measures integrated into existing regional and municipal instruments.

4 Progress evaluation

Table 4-1 Overview key performance indicators.

Key performance indicators	Progress
Delivery of all 5 deliverables	2/5 (40%)
At least 2 workflows ran correctly during Phase 1	2/2 (100%)
At least 2 workflows ran correctly during Phase 2	2/2 (100%)
At least 15 plans of climate action and resilience updated	0/15 (0%)
At least 15 plans of emergency and risk management updated	0/15 (0%)
At least 25 stakeholders involved in the project	28/15 (100%+)
At least 2 public dissemination events regarding the project organized	0/2 (0%)
At least 3 notes given to local governments and administrations	0/3 (0%)

Table 4-2 Overview milestones

Milestones	Progress
Publication of an article when the project is finished	Not done

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 Beiras and Serra da Estrela:

Zenodo Repository Link: https://doi.org/10.5281/zenodo.18283474

DOI: 10.5281/zenodo.18283474

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