CLIMAAX
climate ready regions

Deliverable Phase 2 – Climate risk assessment

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

Portugal, Alto Tâmega e Barroso

Version 0.1 | June 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	This deliverable presents the refined and regionalized Climate Risk Assessment (CRA) for the Alto Tâmega e Barroso region, marking the conclusion of Phase 2 of the CLIMAAX_AT project. It integrates high-resolution local data to provide operational mapping and quantitative impact analysis for four prioritized hazards: wildfires, droughts, heatwaves, and river floods.
Project name	Multi-risk Climate Assessment of the Alto Tâmega region to support decision-making on actions to adapt to climate change (CLIMAAX_AT)
Country	Portugal
Region/Municipality	Alto Tâmega e Barroso
Leading Institution	Intermunicipal Community of Alto Tâmega e Barroso (CIMAT)
Author(s)	• Carla Varandas (CIM Alto Tâmega e Barroso) • José Barros (CIM Alto Tâmega e Barroso) • César Baltazar (CIM Alto Tâmega e Barroso) • Ricardo Almendra (GeoAtributo – C.I.P.O.T., Lda) • Liliana Sousa (GeoAtributo – C.I.P.O.T., Lda) • Ana Rita Caldas (GeoAtributo – C.I.P.O.T., Lda) • Andreia Mota (GeoAtributo – C.I.P.O.T., Lda) • Helena Corrêa (GeoAtributo – C.I.P.O.T., Lda) • Manuel Miranda (GeoAtributo – C.I.P.O.T., Lda) • Rosa Silva (GeoAtributo – C.I.P.O.T., Lda)
Deliverable submission date	30/06/2026
Final version delivery date	30/06/2026
Nature of the Deliverable	R – Report
Dissemination Level	PU - Public

Version	Date	Change editors	Changes
0.1	26/06/2026	CIMAT / GeoAtributo	Internal consolidated version (v1.0)
…	…	…	…
…	…	…	…

Table of contents

Document Information ... 1
Table of contents ... 3
List of figures ... 4
List of tables ... 6
Abbreviations and acronyms ... 7
Executive summary ... 9
1 Introduction ... 10
1.1 Background ... 10
1.2 Main objectives of the project ... 10
1.3 Project team ... 11
1.4 Outline of the document's structure ... 11
2 Climate risk assessment – phase 2 ... 13
2.1 Scoping ... 13
2.1.1 Objectives ... 13
2.1.2 Context ... 13
2.1.3 Participation and risk ownership ... 14
2.1.4 Application of principles ... 15
2.1.5 Stakeholder engagement ... 15
2.2 Risk Exploration ... 19
2.2.1 Screen risks (selection of main hazards) ... 19
2.2.2 Choose Scenario ... 20
2.3 Regionalized Risk Analysis ... 21
2.3.1 Hazard #1 – Wildfire fine-tuning to local context ... 21
2.3.2 Hazard #2 – Droughts finetuning to local context ... 29
2.3.3 Hazard #3 – Heatwaves finetuning to local context ... 40
2.3.4 Hazard #4 – River Floods finetuning to local context ... 49
2.3.5 Additional assessments based on local models and data ... 62
2.4 Key Risk Assessment Findings ... 62
2.4.1 Mode of engagement for participation ... 62
2.4.2 Gather output from Risk Analysis step ... 63
2.4.3 Assess Severity ... 64
2.4.4 Assess Urgency ... 64
2.4.5 Understand Resilience Capacity ... 65
2.4.6 Decide on Risk Priority ... 66

2.5 Monitoring and Evaluation ... 67
2.6 Work plan Phase 3 ... 68
3 Conclusions Phase 2 - Climate risk assessment ... 70
4 Progress evaluation ... 71
5 Supporting documentation ... 73

List of figures

Figure 2-1 Stakeholder and risk-ownership organigram of the CLIMAAX_AT project ... 15

Figure 2-2 Panels of the online stakeholder consultative session (videoconference), 5 February 2026. ... 17

Figure 2-3 Climate-literacy awareness session at the Escola Secundária de Vila Pouca de Aguiar, 1 June 2026. ... 17

Figure 2-2 Wildfire structural susceptibility (continuous index, 0–1) across the model's training domain (NUTS II Norte, Centro and Oeste e Vale do Tejo): historical baseline (1991–2010) and four climate projections — RCP 4.5 and RCP 8.5, for 2041–2060 and 2081–2100 (regional climate model MPI-CSC-REMO2009) ... 24

Figure 2-3 Wildfire hazard (discrete classes 1–6) for the Alto Tâmega e Barroso region: historical baseline (1991–2010) and four climate projections — RCP 4.5 and RCP 8.5, for 2041–2060 and 2081–2100 (regional climate model MPI-CSC-REMO2009). ... 25

Figure 2-4 Area-based wildfire risk for the Alto Tâmega e Barroso region across three dimensions — population (BGRI 2021), economic and ecological (JRC) — under the historical baseline and end-of-century RCP 8.5 (2081–2100; MPI-CSC-REMO2009). Left columns: per-pixel risk classes (very low to very high). Right columns: aggregation by parish, expressed as the percentage of each parish's area in high-risk classes (≥4), with municipalities labelled. The economic and ecological components derive from the JRC indices (effective resolution ~12.5 km) and are therefore spatially smoother than the BGRI-based population. ... 27

Figure 2-5 Layer 2 — infrastructure and road exposure to wildfire in the Alto Tâmega e Barroso region. Left: OSM exposure inventory — road network by hierarchy (primary/secondary/tertiary) and point critical assets by type (health, schools, fire/police stations, social facilities, shelters, campsites, fuel stations), with municipalities labelled. Right: road-network risk under the historical baseline and end-of-century RCP 8.5 (2081–2100; MPI-CSC-REMO2009), in five classes (very low to very high). Risk on the road network is obtained by crossing the hazard with the road hierarchy within a 20 m buffer. ... 28

Figure 2-6 Critical infrastructure at high wildfire risk by asset type (Alto Tâmega e Barroso), historical baseline vs end-of-century RCP 8.5 (2081–2100). Risk is assessed as the fraction of each asset's 250 m buffer in high hazard (classes ≥ 5), binned as low (<25%), medium (25–50%) and high (>50%); bars count elements in the high-risk class. ... 29

Figure 2-7 Elderly population (≥65) at high wildfire risk by parish, historical baseline vs end-of-century RCP 8.5 (2081–2100), expressed as the percentage of each parish's elderly population in high-risk classes (≥4). ... 29

Figure 2-10 Soil Available Water Capacity (AWC), with imputation correction for internal water bodies, representing the physical baseline for agricultural drought ... 31

Figure 2-11 Projections of physical yield loss (%) for chestnut due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 32

Figure 2-12 Projections of physical yield loss (%) for grapevine due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 33

Figure 2-13 Projections of physical yield loss (%) for olive due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 33

Figure 2-12 Spatial distribution of potential revenue losses (€) for chestnut due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 34

Figure 2-13 Spatial distribution of potential revenue losses (€) for grapevine due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 35

Figure 2-14 Spatial distribution of potential revenue losses (€) for olive due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. 35

Figure 2-15 Expected revenue loss (€) per parish for chestnut due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5). 36

Figure 2-16 Expected revenue loss (€) per parish for grapevine due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5). 36

Figure 2-17 Expected revenue loss (€) per parish for olive due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5). 37

Figure 2-18 Aggregated expected revenue loss (€) per parish (chestnut, olive, and grapevine combined) due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5). 38

Figure 2-19 Top 15 parishes with the highest expected economic risk (revenue loss in €) from agricultural drought across all scenarios and time horizons, disaggregated by crop. 39

Figure 2-20 Projected heatwave hazard indices (Occurrence, Frequency, and Total Days) based on IPMA absolute thresholds (Tmax ≥ 35°C for ≥ 6 consecutive days). The panel compares the historical baseline with RCP 4.5 and RCP 8.5 scenarios for Chaves (valley, left column) and Montalegre (plateau, right column). 43

Figure 2-21 Spatial distribution of the relative change in heatwave occurrence across Alto Tâmega e Barroso parishes, comparing future horizons (2016-2045 and 2046-2075) against the historical baseline under RCP 4.5 and RCP 8.5. 44

Figure 2-22 Reclassified magnitude of change (scale 1-10) in heatwave occurrence per parish, highlighting the highest hazard increase in the central-northern valley areas under future climate scenarios. 45

Figure 2-23 Spatial distribution of heatwave vulnerability in the Alto Tâmega e Barroso region, based on the density of the elderly population (≥65 years) (BGRI 2021). The panel presents the vulnerability classified by quantiles at the parish level (top) alongside the high-resolution intra-parish detail at the statistical subsection level (bottom). 46

Figure 2-24 Projected heatwave risk at the parish level for Alto Tâmega e Barroso across future horizons (2016-2045 and 2046-2075) under RCP 4.5 and RCP 8.5 scenarios. The risk index (2-20) highlights the concentration of threat in the central valley axis. 47

Figure 2-25 Top 15 parishes at highest risk of heatwaves under the worst-case scenario (RCP 8.5, 2046-2075) and a synthesized risk heatmap aggregated at the municipal level. 48

Figure 2-26 Comparison between Land Surface Temperature (LST) demonstrating the urban heat island effect and heatwave vulnerability (elderly population density) in the urban area of Chaves. 49

Figure 2-27 High-resolution urban heat risk in Chaves, highlighting the exposure of critical health and elderly care infrastructure over a geographical basemap. 49

Figure 2-28 Complementary exploratory analysis: Exposure of educational facilities (schools) to structural urban heat islands (LST) in the city of Chaves. 49

Figure 2-29 Regional River flood hazard overview for Alto Tâmega e Barroso, illustrating the present-day baseline (JRC) alongside future projections under RCP 4.5 and RCP 8.5 scenarios (Aqueduct Floods). 53

Figure 2-30 High-resolution River flood hazard for the Chaves urban area derived from APA 2D hydraulic models (T=100), alongside the frequency-shift table and log-log chart detailing the acceleration of extreme events under future climate scenarios. 54

Figure 2-33 Hydrological risk context: Catchment area for the Chaves sub-basin (left) and projected shifts in monthly mean river discharge from the historical baseline to future scenarios (right). 55

Figure 2-34 Exceedance probability and extreme discharge values, illustrating the intensification of peak flows and extreme water volumes in future climate scenarios (P2) compared to the historical baseline. 56

Figure 2-33 Regional economic risk assessment for river floods in Alto Tâmega e Barroso, presenting the aggregated damage overview, spatial distribution for the 100-year return period, and damage categorization per land use parcel. 58

Figure 2-34 High-resolution tactical risk assessment for the Chaves ARPSI, highlighting massive economic exposure driven by urban fabric (T=100), alongside categorical damage breakdown and spatial mapping. 59

Figure 2-35 High-resolution structural impact in Chaves. The panel illustrates the spatial distribution of building damage and exposed critical infrastructure for a 1000-year return period, supported by the Expected Annual Damage (EAD) curve. 60

Figure 2-36 Comparative analysis of human displacement across frequent and extreme events. The maps highlight populations in building footprints with inundation depths >1.0m, accompanied by the Expected Annual People Displaced (EAPD) and exposed statistical curves. 61

List of tables

Table 2-1 Stakeholder Engagement Impact 18

Table 2-2 Data overview workflow #1 – Fire (ML approach) 22

Table 2-3 Data overview workflow #2 – Agricultural Drought 31

Table 2-4 Data overview workflow #3 – Heatwaves 41

Table 2-5 Data overview workflow #4 – River Floods 51

Table 2-6 Key Risk Assessment through risk ranking, considering severity, urgency and resilience capacity 67

Table 4-1 Overview key performance indicators 71

Table 4-2 Overview milestones 71

Abbreviations and acronyms

Abbrev. / acronym	Description
ADRAT	Alto Tâmega Regional Development Association
AGIF	Agency for the Integrated Management of Rural Fires
ANEPC	National Authority for Emergency and Civil Protection
APA	Portuguese Environment Agency
ARH	Hydrographic Region Administration
ARPSI	Area of Significant Potential Flood Risk
AST	Adaptation Support Tool
AWC	Available Water Capacity
BGRI	Geographic Information Reference Base
CAOP	Official Administrative Boundary Map
CCDR-N	Northern Regional Coordination and Development Commission (*CCDR Norte*)
CHELSA	Climatologies at High Resolution for the Earth's Land Surface Areas
CIMAT	Intermunicipal Community of Alto Tâmega e Barroso
CINEA	European Climate, Infrastructure and Environment Executive Agency
COS 2023	National Land Use and Land Cover Map, 2023
CPI	Consumer Price Index
CRA	Climate Risk Assessment
D1 / D2 / D3	Deliverable 1 / 2 / 3
DEA	Data Envelopment Analysis
DEM	Digital Elevation Model
DGT	Directorate-General for Territory
EAD	Expected Annual Damage
EAPD	Expected Annual People Displaced
ECLIPS-2.0	High-resolution European climate projection dataset (wildfire forcing)
E-HYPEcatch	European HYPE catchment hydrological model (SMHI/Copernicus)
ENAAC 2030	National Strategy for Adaptation to Climate Change
EURO-CORDEX	Coordinated Regional Climate Downscaling Experiment (European domain)
EUROSTAT	Statistical Office of the European Union
FSTP	Financial Support to Third Parties (CLIMAAX funding mechanism)
FWI	Fire Weather Index
GIAHS	Globally Important Agricultural Heritage Systems (FAO)
GNR	National Republican Guard
HR-DEM	High-Resolution Digital Elevation Model
ICNF	Institute for Nature Conservation and Forests
INE	Statistics Portugal
IPMA	Portuguese Institute for Sea and Atmosphere
IPSS	Private Social Solidarity Institutions
JRC	Joint Research Centre
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LST	Land Surface Temperature

Abbrev. / acronym	Description
LUISA	Land Use-based Integrated Sustainability Assessment (JRC)
MCA	Multi-Criteria Analysis
MIKE 21 FM	Two-dimensional hydrodynamic model (Flexible Mesh)
ML	Machine Learning
NbS	Nature-Based Solutions
NUTS	Nomenclature of Territorial Units for Statistics
OSM	OpenStreetMap
PDM	Municipal Master Plan
PGRI	Flood Risk Management Plan
PIAAC-AT	Alto Tâmega Intermunicipal Climate Change Adaptation Plan
PMAC	Municipal Climate Action Plan
PMDFCI	Municipal Forest Fire Defense Plan
PMEPC	Municipal Civil Protection Emergency Plan
PNGIFR	National Integrated Management Plan for Rural Fires
PNPG	Peneda-Gerês National Park
PRGP	Landscape Reorganization and Management Programme
RCP	Representative Concentration Pathway
RH3	Douro Hydrographic Region
RP	Return Period
SDI	Spatial Data Infrastructure
SMHI	Swedish Meteorological and Hydrological Institute
SSP	Shared Socioeconomic Pathway
WUI	Wildland-Urban Interface
Xclim	Climate-indices computation library
XGBoost	Extreme Gradient Boosting (machine-learning algorithm)

Executive summary

This document presents the results of Phase 2 of the CLIMAAX_AT project, the climate risk assessment for the Intermunicipal Community of Alto Tâmega e Barroso (CIMAT). The central objective of this phase was to overcome the “utility gap” identified in Phase 1, where low-resolution pan-European data proved insufficient for operational planning at the level of parishes, infrastructure and strategic assets. The report describes how the territory's four priority hazards were refined with high-resolution national data and advanced models, turning theoretical climate projections into actionable territorial intelligence.

The analysis moved from generic European datasets to national sources calibrated to the region – COS 2023 land cover, the ICNF fire record, the INE BGRI 2021 census and 2019 Agricultural Census, IPMA climate criteria and APA flood mapping – supported by 2 m LiDAR digital elevation models. Four risk workflows were regionalized: Wildfire, Agricultural Drought, Heatwaves and River Floods, each validated, where possible, against observed records. The achieved results include:

- **Wildfire:** a machine-learning hazard, validated against the 1990–2023 burned area, shows high-hazard classes expanding from 41.1% to 52.4% of the territory by 2081–2100 (RCP 8.5), with the ageing mountain parishes of Montalegre as the adaptation priority.
- **Agricultural drought:** annual revenue losses for the region's identity crops (chestnut, grapevine and olive) of the order of €5 million already in the near term, concentrated in the chestnut-orchard areas of Valpaços.
- **Heatwaves:** an intensification along the Chaves valley axis, where the highest hazard coincides with a markedly elderly population (35.0% of residents), acting as a multiplier of drought and fire.
- **River floods:** highly concentrated in Chaves, with building damage of about €86 million for a 100-year event, an Expected Annual Damage of €3.86 million and up to 1,553 people displaced (EAPD ≈ 69/year).

This phase provides a robust scientific basis for the revision of the municipal civil-protection and emergency planning and for the Municipal Climate Action Plans (PMAC) of the six municipalities.

Beyond the individual figures, the assessment confirms that regionalizing the analysis is what makes climate risk operationally useful here — now a quantifiable, geographically precise threat anchored in the territory's observed record. It also reveals the territory's defining risk signature: the priority hazards converge on the same vulnerable people and places — the ageing mountain interior, where heat compounds drought and fire, and the Chaves valley, where heat overlaps with flood exposure. On this basis, Wildfire, Agricultural Drought and Heatwaves stand as the foremost adaptation priorities (Very High), with River Floods a spatially-concentrated but locally severe fourth (High). The principal residual limitation is the reliance on coarser regional-climate and European vulnerability layers (~12.5 km) and the holding of socioeconomic exposure at present-day conditions.

Phase 3 (ending July 2026) will focus on translating this high-resolution evidence into concrete, prioritized – and, given the compound nature of the risk, integrated – adaptation measures for the region's planning instruments.

1 Introduction

1.1 Background

Located in the north of mainland Portugal, the Alto Tâmega e Barroso region covers 2,922 km² across 6 municipalities (Boticas, Chaves, Montalegre, Ribeira de Pena, Valpaços, and Vila Pouca de Aguiar) with a population of 84,248 (INE, 2021). The Intermunicipal Community of Alto Tâmega e Barroso (CIMAT) coordinates strategic development across this territory, particularly in areas requiring climate change preparedness, such as civil protection and spatial planning.

The region faces severe climate risks. Average temperatures are projected to rise by 2°C to 4°C by the end of the century, intensifying heatwaves and, together with decreased annual precipitation, exacerbating droughts and water scarcity; at the same time, more intense rainfall events increase flood and soil-erosion risks, placing significant pressure on local infrastructure.

Furthermore, with 23% of the territory (57,000 hectares) covered by continuous stands of maritime pine (Pinus pinaster), the region is exceptionally susceptible to wildfires. Climate change is predicted to make these fires more severe and extensive, threatening both the ecological and economic value of the Alto Tâmega e Barroso region.

1.2 Main objectives of the project

Phase 2 of the CLIMAAX_AT project represents a central methodological evolution in the resilience strategy for the Alto Tâmega e Barroso region, transitioning from a macroscopic and generic hazard analysis to the construction of an operational decision-support capacity. The primary objective remains increasing the region's resilience to climate change by empowering local communities, strengthening risk monitoring, and promoting intermunicipal cooperation for a cohesive and sustainable response.

In Phase 1, the use of European datasets provided a solid foundation for the multi-risk assessment but demonstrated spatial resolution limitations, proving insufficient for detailed planning at the level of local infrastructure and strategic assets. To overcome this gap in operational utility, Phase 2 focuses on the regionalization and physical calibration of the models, ensuring that climate projections are strongly anchored in the empirical, topographic, and historical reality of the territory.

In this regard, the main objectives of this second phase center on transforming raw data into actionable information for risk management and the community, namely through:

- **Operational resolution increase:** Increasing the operational resolution of the analysis — to 100 m and, where supported by local LiDAR, to 10 m – by integrating high-resolution local data such as High-Resolution Digital Elevation Models (HR-DEM), so that hazard maps respect the actual morphology of the terrain.
- **Validation with historical evidence:** Replacing purely theoretical models with approaches validated against the region's actual history of occurrences, allowing for the precise identification of the most critical points (hotspots).
- **Integration into municipal and regional planning:** Incorporating the refined results of the vulnerability and risk assessment into territorial management instruments, with particular emphasis on the revision of Municipal Climate Action Plans (PMAC), Municipal Emergency and Civil Protection Plans (PMEPC), and Municipal Forest Fire Defense Plans (PMDFCI).

The CLIMAAX framework ensures a common, harmonized and transparent approach that makes the region's results comparable at the European scale, while its reproducible workflows will allow the intermunicipal technical team to update the climate database autonomously.

The integration of local data and models, in turn, yields immediate operational benefits: by precisely identifying the areas and sectors most vulnerable to the four priority hazards (wildfires, droughts, heatwaves and river floods), it delivers evidence-based information to guide adaptation strategies tailored to each of the six municipalities, infrastructure investment, emergency preparedness and long-term sustainability policies.

1.3 Project team

The internal team of CLIMAAX_AT project is composed of:

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

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

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

1.4 Outline of the document's structure

This document, the Phase 2 Deliverable – Climate Risk Assessment, is organized to clearly and comprehensively present the work developed and the results achieved during this stage of the project.

- The report begins with an Executive Summary, which provides a complete and self-contained overview of the content, followed by Section 1: Introduction. This Introduction establishes the context of the project, describes the region under study, presents the main objectives, and details the team's composition.

- Section 2 is the core of the document, focusing on the Phase 2 Climate Risk Assessment (CRA). This section is divided into sequential steps from the CLIMAAX Framework:
  - Scoping (2.1), reviewing objectives, governance context, and risk ownership organization.
  - Risk Exploration (2.2), which includes hazard selection and the definition of future scenarios (climate and socio-economic).
  - Regionalized Risk Analysis (2.3), detailing the fine-tuning of CLIMAAX workflows for selected hazards and the integration of local data/models.
  - Key Risk Assessment Findings (2.4), which describe the evaluation of Severity, Urgency, and Resilience Capacity for risk prioritization.
  - The Monitoring and Evaluation module (2.5) and the Work Plan for Phase 3 (2.6).
- The report concludes with the Phase 2 Conclusions (Section 3), the Progress Evaluation (Section 4), which measures performance against key indicators and milestones, and the Supporting Documentation (Section 5), which lists all produced outputs.

2 Climate risk assessment – phase 2

2.1 Scoping

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

2.1.1 Objectives

The CLIMAAX methodological approach is applied following its manual guidelines and using the provided toolbox for regional and local applications. The purpose of this standardization is to ensure that all risk assessments share a common framework, enabling result comparability at the European level.

The Climate Risk Assessment (CRA) for Alto Tâmega e Barroso fundamentally aims to evaluate in detail the threats and risks that climate change poses to the environment, economy, and society, aiming to significantly increase territorial resilience. To achieve this, the project focuses on capacity building within local communities, strengthening monitoring systems, implementing adaptation strategies, and promoting intermunicipal cooperation.

The assessment will enable the region to:

- **Identify the most vulnerable areas and sectors:** Through an in-depth understanding, CIMAT will be able to pinpoint critical hotspots, such as agricultural zones at higher risk of drought or areas more prone to flooding.
- **Develop tailored adaptation strategies:** Insights into local vulnerability will support the design of targeted action plans, such as protecting forest areas against wildfires or improving water management.

Currently, the main adaptation challenges stem from the lack of a real-time risk monitoring platform and ongoing difficulties in regional coordination. Financial constraints, high-resolution data gaps, uncertainties in climate models, and a natural resistance to changing local practices stand as barriers that this project aims to help overcome.

Phase 2 addressed these constraints directly: the data gap through national datasets – the COS 2023 land cover, the BGRI 2021 census, the ICNF burned-area record and IPMA heatwave criteria – and 2 m LiDAR, reaching operational scales of 100 m (hazard) and 10 m (exposure); model uncertainty through multi-scenario exploration and validation against observed records (burned area, APA mapping); and coordination/monitoring limits through the CIMAT intermunicipal structure and stakeholder workshops, with the continuous monitoring network carried forward as a future need.

2.1.2 Context

Alto Tâmega e Barroso is a region highly vulnerable to the impacts of climate change, driven by both environmental and socioeconomic factors. The most climate-exposed sectors in the region are agriculture and agro-forestry (vulnerable to drought and wildfire), water resources and hydroelectric production (to declining precipitation), public health (to heatwaves, given the ageing population), and civil protection (to wildfire and floods).

While challenges vary across the 6 municipalities due to differences in altitude, topography, and proximity to water resources, the following stand out as cross-cutting threats:

- **Rising Temperatures:** Causing severe impacts on agriculture, water resources, and public health.
- **Reduced Precipitation:** Intensifying desertification, rural wildfires, and water scarcity, while negatively affecting ecological flows and hydroelectric production – both of which are critical to the local economy.
- **Extreme Weather Events:** The worsening of heatwaves, droughts, and floods directly impacts local communities and ecosystem stability.

This climate vulnerability is further exacerbated by demographic fragility – characterized by a 10% population loss between censuses and significant aging – which pushes the NUTS III Vulnerability Index well above the European average.

Within the local climate governance structure, the Municipal Climate Action Plans (PMAC), the Municipal Forest Fire Defense Plans, and the Municipal Emergency and Civil Protection Plans (PMEPC) play a central role. At the macro level, the assessment also aligns with larger initiatives – the national landscape-planning reform (Landscape Reorganization and Management Programs – PRGP), the NORTE 2030 programme, and the national adaptation framework (ENAAC / P-3AC).

Because the PRGPs currently in force only provide fragmented coverage of the region, CIMAT has taken a proactive advocacy role with the central government. The intermunicipal community formally submitted a proposal for the creation of a single, comprehensive PRGP covering the entirety of the Tâmega Valley, thereby maximizing the effectiveness of regional-scale forestry adaptation.

2.1.3 Participation and risk ownership

In Phase 2, stakeholder engagement in the CLIMAAX_AT project evolved from an initial exploratory consultation (conducted via online surveys in Phase 1) to a model of active co-creation and technical validation. This intensive participatory process is essential to ensure that the transition to a high-resolution analysis reflects the operational needs and empirical knowledge of the territory.

The key stakeholders who agreed to participate in the CLIMAAX_AT meetings and activities span multiple levels of governance and activity sectors:

- **Regional Coordination:** CIMAT acts as the coordinating entity and strategic management body of the project.
- **Public Administration and Civil Protection:** The 6 municipalities of Alto Tâmega e Barroso (Boticas, Chaves, Montalegre, Ribeira de Pena, Valpaços, and Vila Pouca de Aguiar), focusing on their Environment departments and Municipal Civil Protection Services.
- **Sectoral Agents and Civil Society:** Municipal technicians, agroforestry associations, local communities, and emergency services (fire brigades and security forces), who play a critical role in validating risk maps and sharing historical records of occurrences.

Risk ownership is shared across the region: CIMAT coordinates macro-regional planning, while the 6 municipalities oversee direct mitigation through their PMAC (Municipal Climate Action Plans) and PMEPC (Municipal Emergency and Civil Protection Plans). At the operational level, response efforts for wildfires and floods are managed by the Municipal Civil Protection Commissions and local fire brigades.

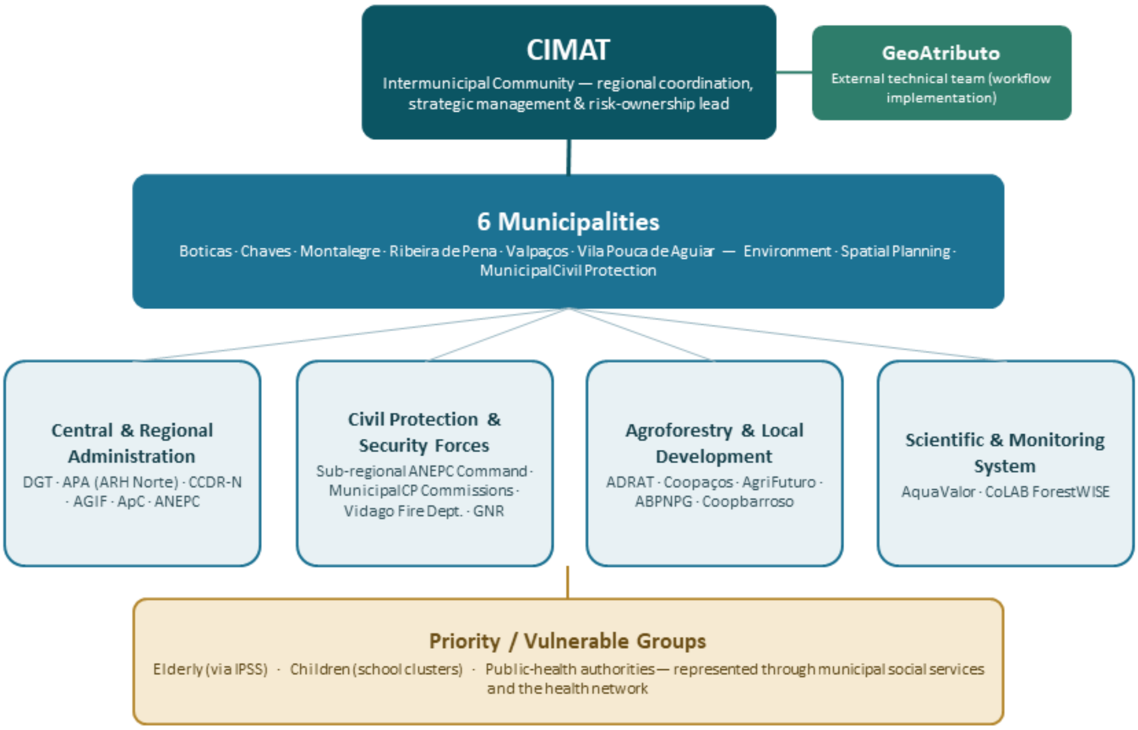


Figure 2-1 Stakeholder and risk-ownership organigram of the CLIMAAX_AT project

The demographic matrix dictates clear priorities: the most vulnerable groups encompass the elderly and children. Their protection is coordinated indirectly through IPSS (Private Institutions of Social Solidarity), school clusters, and public health authorities. The acceptable level of risk is determined by building technical consensus among these local stakeholders.

2.1.4 Application of principles

The CLIMAAX_AT project actively integrates the fundamental principles of the CLIMAAX Framework throughout all stages of the Climate Risk Assessment (CRA), ensuring the analysis is technically robust, ethically informed, and socially responsible.

1. **Social Justice, Equity, and Inclusivity:** The process flagged marginalized and highly exposed groups, ensuring that the climate risk assessment quantifies not only economic losses, but gives absolute priority to the protection and vulnerability of the most fragile social fabric.
2. **Quality, Rigour, and Transparency:** The adoption of CLIMAAX workflows ensures a reproducible methodology. The systematic documentation of data calibration using local datasets, combined with the full sharing of files in the Zenodo repository, confirms the total traceability of the results.
3. **Precautionary Approach:** Applied to address the inherent uncertainty of climate modeling, translating into the exploration of multiple future scenarios (both climate and socioeconomic) and ensuring that prioritized actions are capable of responding to increasingly severe, yet plausible, futures.

2.1.5 Stakeholder engagement

Stakeholder engagement in the CLIMAAX_AT project strategically evolved from an informative and preliminary consultation in Phase 1 to an active model of co-creation, co-production, and technical validation in Phase 2. This participatory process was designed to bridge the "utility gap" associated with macro-regional scale analyses by integrating local empirical knowledge and high-resolution operational datasets into the calibration and refinement of hazard and risk models. The Intermunicipal Community of Alto Tâmega e Barroso (CIMAT) and the GeoAtributo technical team adopted a multi-channel approach to ensure the mobilization and shared ownership of strategic regional actors:

- **Online Consultative Session (05/02/2026):** A key phase-transition workshop held online via videoconference, mobilizing 48 participants representing central and regional administration bodies, municipal technical teams, civil protection agents, security forces, and local agricultural and forestry cooperatives.
- **Direct Contacts for Data Integration:** Direct bilateral technical contacts were established with partner entities to collect local information and high-resolution datasets (such as municipal mapping and historical occurrence records), ensuring the robust calibration of the priority risk workflows.
- **News Publication and Dissemination:** News and updates regarding the progress of the CLIMAAX_AT project were periodically disseminated through CIMAT's institutional channels (website and social media) and its close partner network, promoting transparency and public awareness of climate change.
- **Awareness and Climate Literacy Session (01/06/2026):** An awareness-raising and information session on climate action was conducted at the Escola Secundária de Vila Pouca de Aguiar. This session was inspired by the proactive interest of a student who, while searching online for a school project, came across references to the CLIMAAX project and contacted the team, highlighting the real-world impact of the project's dissemination on the local and school community.
- **Stakeholder Consultation Survey (05/02/2026 to 16/02/2026):** Implementation of a structured online questionnaire that gathered 15 validated responses from highly representative entities within CIMAT's territorial management ecosystem. The survey validated risk severity perceptions and mapped primary datasets held by partners.
- **Dissemination and Dedicated Point of Contact:** Broad sharing of the Phase 1 Report (D1) and *Newsletter #1* to establish a common baseline of technical knowledge, paired with dedicated data-sharing channels for integrating operational GIS datasets.

The full design, agenda, participant list, survey instrument and consolidated outcomes of the consultative session are compiled in a dedicated public Results Report (CLIMAAX_AT – Stakeholder Consultative Session, 05/02/2026: Results Report), provided as an annex.

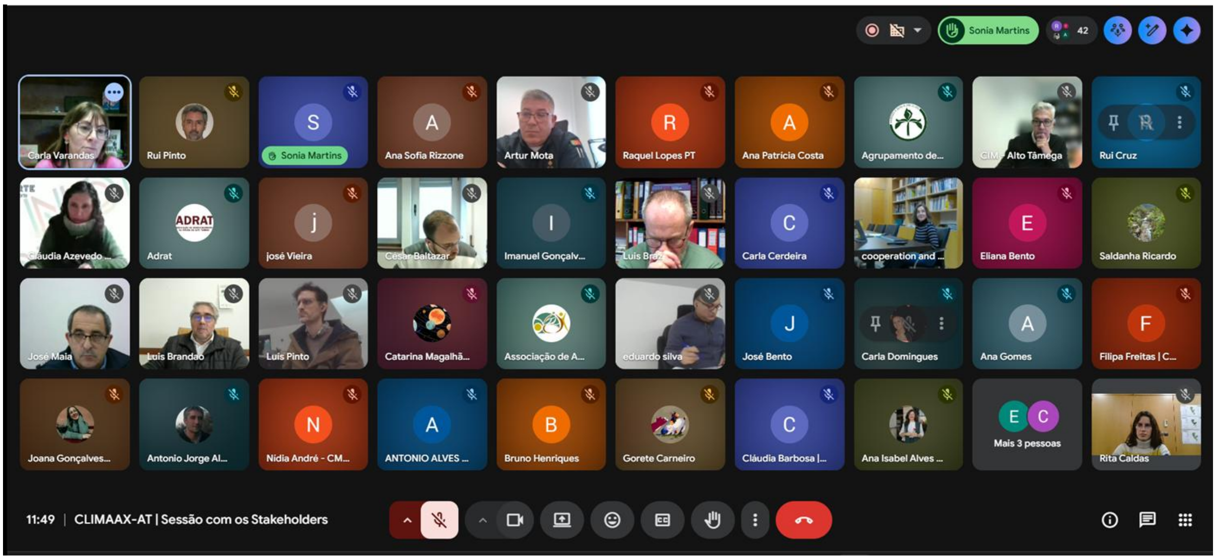


Figure 2-2 Panels of the online stakeholder consultative session (videoconference), 5 February 2026.

Figure 2-3 Climate-literacy awareness session at the Escola Secundária de Vila Pouca de Aguiar, 1 June 2026.

The composition of the participant panel reflected the multi-sectoral and institutional diversity required by the CLIMAAX methodology, linking national and regional strategic visions with local tactical expertise. The following actor groups were represented:

- **Local Administration and Intermunicipal Cohesion:** CIMAT and municipal technical teams (environment, spatial planning, and civil protection) from the six constituent municipalities.
- **Civil Protection Authorities and Security Forces:** Alto Tâmega e Barroso Sub-regional Emergency and Civil Protection Command of the National Emergency and Civil Protection Authority (ANEPC), Vidago Volunteer Fire Department, and the National Republican Guard (GNR).
- **Central and Regional Administration:** Directorate-General for Territory (DGT), Portuguese Environment Agency (APA - ARH Norte), Northern Regional Coordination and Development Commission (CCDR-N), Agency for the Integrated Management of Rural Fires (AGIF), and the Climate Action Agency (ApC, I.P.).
- **Agricultural, Forestry, and Local Development Sectors:** Alto Tâmega Region Development Association (ADRAT), Valpaços Agricultural Cooperative (Coopaços), AgriFuturo Farmers' Association, Peneda Gerês National Park Common Land Association (ABPNPG), and the Barroso Agricultural Cooperative (Coopbarroso).

- **Scientific, Monitoring, and Research System:** AquaValor (Water Valuation and Technology Transfer Centre) and CoLAB ForestWISE (Collaborative Laboratory for Integrated Forest and Fire Management).

The online debate and survey analysis generated critical insights that redirected the technical and methodological planning of Phase 2:

1. **Duality in Risk Priorities:** A duality in risk perceptions based on the entities' operational scale was confirmed. Local actors and the scientific system unanimously identified Rural Wildfires as the region's most severe and urgent threat, with Valpaços highlighting Droughts as its priority. Conversely, regional and national bodies (CCDR-N, DGT, APA) flagged River Floods and Flooding as the structural risk of highest relevance for regional spatial planning.
2. **Agricultural Gaps and Reorientation (Droughts):** Stakeholders identified a critical "blind spot" in the Phase 1 European drought workflow, which focused on generic staple crops (such as maize and potatoes). A formal decision was made to replace these with high-value permanent and regional identity crops: **chestnut** (requested by ~73% of respondents, driven by extensive groves in Valpaços, Chaves, and Vila Pouca de Aguiar), vineyards, and olive groves.
3. **Integration into Local Territorial Planning (PDMs/PMACs):** Guided by DGT and CCDR-N, it was established that Phase 2 refined risk maps must not remain theoretical exercises but must directly support the ongoing revisions of Municipal Master Plans (PDMs), Municipal Emergency and Civil Protection Plans (PMEPCs), and Municipal Climate Action Plans (PMACs) to ensure legally binding local effectiveness.
4. **Commitments to Share Local Data:** The workshop successfully mobilized partners to provide high-resolution datasets: LiDAR surveys and Land Use/Occupation Maps (COS 2023) from the DGT; detailed historical fire perimeters from the ICNF and flood incident logs from the ANEPC; hydrological monitoring from the APA; and local agricultural sensor data (GIAHS Project) from AquaValor.
5. **National strategic alignment:** The Climate Action Agency (ApC, I.P.) confirmed the project's alignment with the revision of the National Strategy for Adaptation to Climate Change (ENAAC 2030) and registered its interest in the Alto Tâmega results as a pilot case for the forthcoming National Climate Risk Platform.

The following table systematizes how the contributions and concerns raised by local actors were incorporated into the operational refinements executed in Phase 2 of the CLIMAAX_AT project:

Table 2-1 Stakeholder Engagement Impact

Phase 1 Limitation	Stakeholder Feedback	Phase 2 Improvement
Coarse hazard models (~12 km to 100 m) lacking representation of real orography.	Need for fine-scale tactical resolutions to support local Civil Protection planning.	Integration of high-resolution LiDAR Digital Elevation Models (DGT) downscaled to 10 m for flood modeling and fire slope derivatives.
Drought workflow based on generic crops (maize, potatoes) of low regional relevance.	Requirement to integrate high-value, regional identity crops (chestnuts, vineyards, olive groves).	Transition to the *non-staple* workflow, integrating real agricultural areas at the parish level (INE RA2019) and real market prices from EUROSTAT (2019–2024).
Pan-European land cover (CORINE Land Cover, 100m) unsuitable for local spatial planning and PDM reviews.	Demand to integrate official national cartography (COS 2023) and align risk outputs with ongoing Municipal Master Plan (PDM) reviews.	Mapping of the COS 2023 thematic classes (DGT) translated into a national classification of four Fuel Types (1-4) validated by Portuguese literature.

Phase 1 Limitation	Stakeholder Feedback	Phase 2 Improvement
Uniform demographic vulnerability based on coarse global rasters (WorldPop).	Need to accurately locate isolated elderly populations and low-density residential pockets.	Replacement of WorldPop with official national census data at the statistical subsection level from the BGRI 2021 Censuses (INE).
Absence of physical vulnerability assessment at individual asset scales.	Request to evaluate direct risks along transportation networks and critical infrastructure inside forests.	Creation of an infrastructure exposure layer (Layer 2) evaluating buffers of 250 m around 342 critical assets and 20 m along the road network (OSM/LiDAR).

The stakeholder engagement process faced three main difficulties:

1. **Methodological Translation:** The technical challenge of translating complex mathematical algorithms and global climate models (such as monotonic XGBoost or MIKE 21 FM) into operational, clear, and interpretable language for policymakers and non-technical actors.
2. **Intermunicipal Coordination:** The logistical complexity of aligning schedules and availability across multiple municipalities and sectoral entities scattered across the sub-region, which prevented additional joint in-person workshops midway through the process, consolidating interaction at key phase-transition milestones.
3. **Climate and Data Literacy Barriers:** Some cultural resistance in adopting probabilistic future climate projections over planning based solely on "historical incident memory" or traditional primary sector practices, requiring increased awareness-raising and capacity-building efforts in adaptive planning.

2.2 Risk Exploration

Risk exploration builds upon the scoping phase to analyze the climate hazards and risks most relevant to the context of Alto Tâmega e Barroso. By integrating stakeholder perspectives with factual and empirical evidence from the region, this phase facilitates the selection of appropriate risk workflows and climate scenarios for the subsequent quantitative analysis.

2.2.1 Screen risks (selection of main hazards)

The Screen Risks stage in Phase 2 focuses on the detailed validation and substantiation of the hazard selection made in the Phase 1 report. In Phase 1, the Alto Tâmega e Barroso region identified four crucial workflows for its assessment: Wildfires, River Floods, Droughts, and Heatwaves.

The primary methodological evolution of this phase is the confirmation and formalization of the technical priority assigned to these four hazards, ensuring a multi-risk approach that covers the most critical spectrum of slow-onset and rapid-onset risks for the territory. To validate and justify the urgency of this selection, the historical record of incidents between 2005 and 2022 was utilized:

- **Wildfires:** Constitute the most severe and persistent threat, accounting for approximately 61% of all recorded climate occurrences in the region.
- **Droughts:** Represent about 37% of historical events, structurally impacting the territory's primary sector.

- **River Floods:** A total of 536 "intense precipitation flooding" events were recorded, with the municipality of Chaves (due to its valley morphology) concentrating 50% of all river floods and 64% of all flash floods across the entire CIMAT.
- **Heatwaves:** Consist of events with a systemic and growing impact on local public health, while also functioning as an indirect driver that worsens droughts and exponentially increases rural wildfire risk.

Additionally, an exploration of data from the Copernicus Interactive Climate Atlas unequivocally validated these priorities. Climate projections for Northern Portugal confirm an increase in the frequency and intensity of heatwaves, more prolonged drought conditions, a worsening wildfire risk index driven by rising mean temperatures, and a documented increase in the intensity of extreme precipitation events.

The major transition from Phase 1 to Phase 2 materializes in the shift from simple hazard "identification" to the rigorous "quantification" of risk.

The Regionalized Risk Analysis will require the integration of high-resolution local data (such as municipal equipment inventories, demographic matrices at the statistical subsection level, and exact land cover data) to ensure the extraction of precise financial and human metrics across all four workflows.

2.2.2 Choose Scenario

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

- **Wildfire (hazard and risk):** RCP 4.5 (intermediate scenario) and RCP 8.5 (high scenario) as future scenarios. Historical baseline 1991–2010 and two future 20-year windows: 2041–2060 (mid-century) and 2081–2100 (end-of-century), based on the regional climate model MPI-CSC-REMO2009 (ECLIPS-2.0 dataset).
- **Agricultural Droughts (hazard and risk):** RCP2.6 (low scenario), RCP4.5 (intermediate scenario) and RCP8.5 (high scenario) as future scenarios. All the period available for historical data and 3 future periods: 2026-2046 (near future), 2036-2065 (mid-century) and 2071-2090 (end-of-century).
- **Heatwaves (hazard and risk):** RCP4.5 (intermediate scenario) and RCP8.5 (high scenario). All the period available for historical data (1971-2000) and 3 future periods: 2011-2040 (near future), 2041-2070 (mid-century) and 2071-2100 (end-of-century).
- **River Floods (hazard and risk):** RCP 4.5 and RCP 8.5. Present-day hazard from two complementary sources — JRC pan-European statistical flood maps (return periods of 10, 50, 100, 200 and 500 years) for regional context, and the APA PGRI hydrodynamic model (MIKE 21 FM; return periods of 20, 100 and 1000 years) for the Chaves ARPSI — with future conditions obtained by a frequency-shift of SMHI E-HYPEcatch discharge projections to the 2050 and 2071–2100 horizons.

RCP 4.5 and RCP 8.5 were selected to bracket an intermediate-mitigation and a high-emission future, in line with CLIMAAX guidance; RCP 2.6 was additionally explored for agricultural drought, where the dataset allows it. Time horizons and return periods follow the data availability of each workflow.

To translate climate threats into quantifiable risks, future hazard projections were combined with socioeconomic data through methodological recalibration and spatial intersection. The resolution of land-use and vulnerability data was aligned with the hazard map resolutions (such as by using high-resolution matrices or HR-DEM), ensuring that impact assessments – such as economic losses in agricultural yields or projected structural damages – accurately reflect the actual exposure of the Alto Tâmega e Barroso territory.

2.3 Regionalized Risk Analysis

Through the CLIMAAX methodological framework, risk analysis is operationalized as a quantitative estimation that intersects climate hazards with exposure and vulnerability data. In the current Phase 2 of the CLIMAAX_AT project, advanced implementation levels were adopted to adapt global and European models to the reality of the Alto Tâmega e Barroso territory, ensuring significantly higher spatial and thematic precision.

To overcome the "utility gap" identified in Phase 1 (which was based on generic ~100m grids), the regionalization strategy rested on three fundamental pillars of methodological refinement:

- **Spatial and Thematic Precision:** The analysis evolved from the global 100-meter scale to an operational 10-meter scale, supported by local High-Resolution Digital Elevation Models (HR-DEM). The thematic precision was reinforced by replacing the European CORINE database with the national Land Cover Map (COS 2023 - DGT), allowing for a detailed analysis at the agroforestry plot and built-environment scale.
- **Socioeconomic Recalibration:** European damage functions were localized using a Regional Wealth Factor based on CIMAT's GDP per capita and updated to the Portuguese Consumer Price Index (CPI) of 2024. This calibration ensures that economic damage estimates reflect the actual costs of reconstruction and agricultural revenue loss in the region.
- **Operational and Indirect Impact Metrics:** Beyond direct economic losses, new metrics were calculated to support decision-making, such as Expected Annual People Displaced (EAPD) and the indirect impacts of critical infrastructure disruption (e.g., closures of strategic forest roads or water supply failures).

The following subsections detail the specific refinement applied to each of the four priority hazards (Wildfires, Droughts, River Floods, and Heatwaves).

2.3.1 Hazard #1 – Wildfire fine-tuning to local context

In Phase 1 (the reference baseline), wildfire — the dominant climate hazard in the region (around 61% of the 2005–2022 occurrences) — was characterised through the Fire Weather Index (FWI), a coarse meteorological index (~12 km CORDEX grid). The FWI defines when conditions favour fire but lacks spatial detail (where) and structural sensitivity, leaving a utility gap for Civil Protection and local planning. Phase 2 therefore transitioned, within the CLIMAAX toolbox, to the machine-learning (ML) wildfire workflow.

The original Random Forest algorithm proved unable to extrapolate trends under climate scenarios and exhibited a critical climate–altitude confounding (cool, wet upland shrublands burn frequently, while warm, dry agricultural valleys do not, for lack of fuel), wrongly predicting a decrease in future hazard under warming. Following consultation with the workflow's authors (CIMA Research Foundation), a Portuguese-context version was shared (a hybrid logistic-regression head — which ensures climate extrapolation — coupled with a monotonically-constrained XGBoost). On this version, local refinements were implemented: expanding the training domain to three NUTS II regions (breaking the altitude–temperature correlation and yielding a physically sound positive MAT coefficient of +0.606), mapping COS 2023 (Série 2) to national fuel types (1–4), and extending the risk assessment into three high-resolution layers based on the INE BGRI 2021 census (subsection level) and 10 m LiDAR.

The Phase 1 to Phase 2 change is, first, a workflow migration (FWI → ML, described above); the table below then documents the fine-tuning of the ML workflow to the local context, comparing the default CLIMAAX Handbook workflow with the enhanced version (consistent with the other hazards in this report).

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Modelling & training	Random Forest, single area	Hybrid logistic-regression head + monotonic XGBoost (PT-adapted); training over 3 NUTS II (MAT +0.606)
Land cover	CORINE Land Cover	COS 2023 (Série 2, DGT)
Fuel / plant functional types	Generic EFFIS values	National fuel types 1–4 (Portuguese literature)
Fire history & resolution	EFFIS database; DEM 50–500 m	ICNF burned area 1990–2023; 100 m hazard, 10 m LiDAR exposure
Vulnerability & exposure	JRC rasters; generic OSM	JRC + BGRI 2021 (subsection) population; OSM elements with classes adapted to the territory
Risk output	Single risk indicator	Three-layer risk (area / infrastructure / population) + parish prioritisation + burned-area validation

Key improvements include:

- **Climate-signal correction:** wide-domain training (3 NUTS II) resolved the altitude–temperature confounding, yielding a positive MAT coefficient (+0.606) and physically sound future projections.
- **Land-cover / fuel gap resolved:** national fuel mapping covers all COS 2023 classes, correcting the European error that assigned zero flammability to other broad-leaved forest (5118).
- **High-fidelity demographics:** subsection-level BGRI 2021 census replaces global models (WorldPop), capturing that the resident population is concentrated in non-burnable valleys.
- **Tactical infrastructure risk and validation:** 10 m LiDAR enabled assessment of 20 m fuel-management strips along roads and of 342 critical assets by buffer-hazard fraction; the hazard was validated against the 1990–2023 burned-area record.

Table 2-2 Data overview workflow #1 – Fire (ML approach)

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **Climate (CHELSA V2.1):** Continuous bioclimatic variables MAT, MAP, and SHM (historical 1991–2010; RCP 4.5/8.5 scenarios for 2041–2060 and 2081–2100 horizons; MPI-CSC-REMO2009 model).	· **JRC Vulnerability (PESETA IV):** European scale (~12.5 km) social, economic, and ecological sensitivity indices (reprojected to EPSG:3763). · **Fine Population Vulnerability (BGRI 2021 - INE):** General residential	· **Land Use (COS 2023 DGT):** Land cover (Series 2) clipped to CIMAT and rasterized to 100 m, excluding non-burnable classes. · **Critical Infrastructure (OSM / Municipalities):** Tactical inventory of 342	· **Continuous Susceptibility (0–1):** Spatial probability of fire occurrence at 100m generated by the corrected hybrid model (Logistic Regression head + monotonic XGBoost).

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **Orography (LiDAR DGT):** Micro-topographic variables derived from the 100m national DEM: elevation, slope, aspect, and terrain roughness. · **Fire History (Target):** Official perimeters of cumulative burned areas from 1990 to 2023 (ICNF/DGT) for machine learning training, calibration, and empirical validation.	(hab/km²) and elderly (aged ≥ 65) densities across the 5,197 contiguous subsections of NUT III Alto Tâmega. · **Risk Structure:** Contingency matrix crossing discretized hazard (1–6) with vulnerability classes (1–3), saturating at maximum risk class 5.	georeferenced public utility assets split into 8 typologies (health, schools, safety, and social assets). · **Road Network (OSM):** road segments (primary, secondary, tertiary) with a 20m bilateral buffer to simulate fuel management strips.	· **Discretized Hazard (1–6):** Hazard classes resulting from the 3x4 contingency matrix (historical susceptibility frozen at the 0.348/0.688 susceptibility cut-offs (historical [0.5, 0.75] quantiles) × 4 national Fuel Types). · **Area-Based Risk (Layer 1):** Percentage (%) of parish area under high population, economic, and ecological risk (Risk classes 4 and 5).

2.3.1.1 Hazard assessment

Hazard expresses the probability of a cell burning if ignited, combining continuous ML susceptibility (100 m) with national fuels. The logistic-regression head processes large-scale climate predictors (MAT, MAP, SHM) and initialises the XGBoost, which refines the prediction under strict climate monotonicity using 10 m LiDAR terrain derivatives (elevation, slope, aspect, roughness) and neighbourhood percentages of COS 2023 land cover. Wide-domain training across three NUTS II corrected the climate sign in the head, establishing a physically sound positive temperature coefficient (MAT +0.606) and resolving the climate–altitude confounding.

COS 2023 classes were mapped to national fuel types 1–4, validated in Portuguese literature (Independent Technical Commission 2017/2018; Fernandes; Viegas; ICNF): Type 4 (very flammable) — eucalyptus, maritime pine and continuous shrubland; Type 3 (flammable) — oaks, chestnut, cork and holm oak, other broad-leaved forest, stone pine, grasslands and agro-silvopastoral classes; Type 2 (low flammability) — agriculture, orchards, vineyards and olive groves; Type 1 (non-burnable) — urban, water, wetlands, rock and sparse vegetation. The historical susceptibility was classified into three classes using the [0.5, 0.75] quantiles — stable cut-offs at 0.348 and 0.688, frozen for the future — and intersected with the four fuel types through a 3×4 contingency matrix (Tonini et al. 2020) to yield the 1–6 hazard scale.

Validation against ICNF burned areas (1990–2023) confirms the model's physical realism: the burned-area rate increases monotonically with the hazard class — 16.2% (class 2), 27.2%, 55.9%, 60.9% and 71.0% (class 6). High classes (5–6) occupy 41.1% of the territory but concentrate 54.7% of the burned area (1.33×). High hazard classes rise from 41.1% (historical) to 52.4% under the worst case (RCP 8.5 / 2081–2100) — a strong signal (+11 pp) consistent with the continental interior — with a monotonic increase across all future states, the time horizon dominating over the emissions pathway.

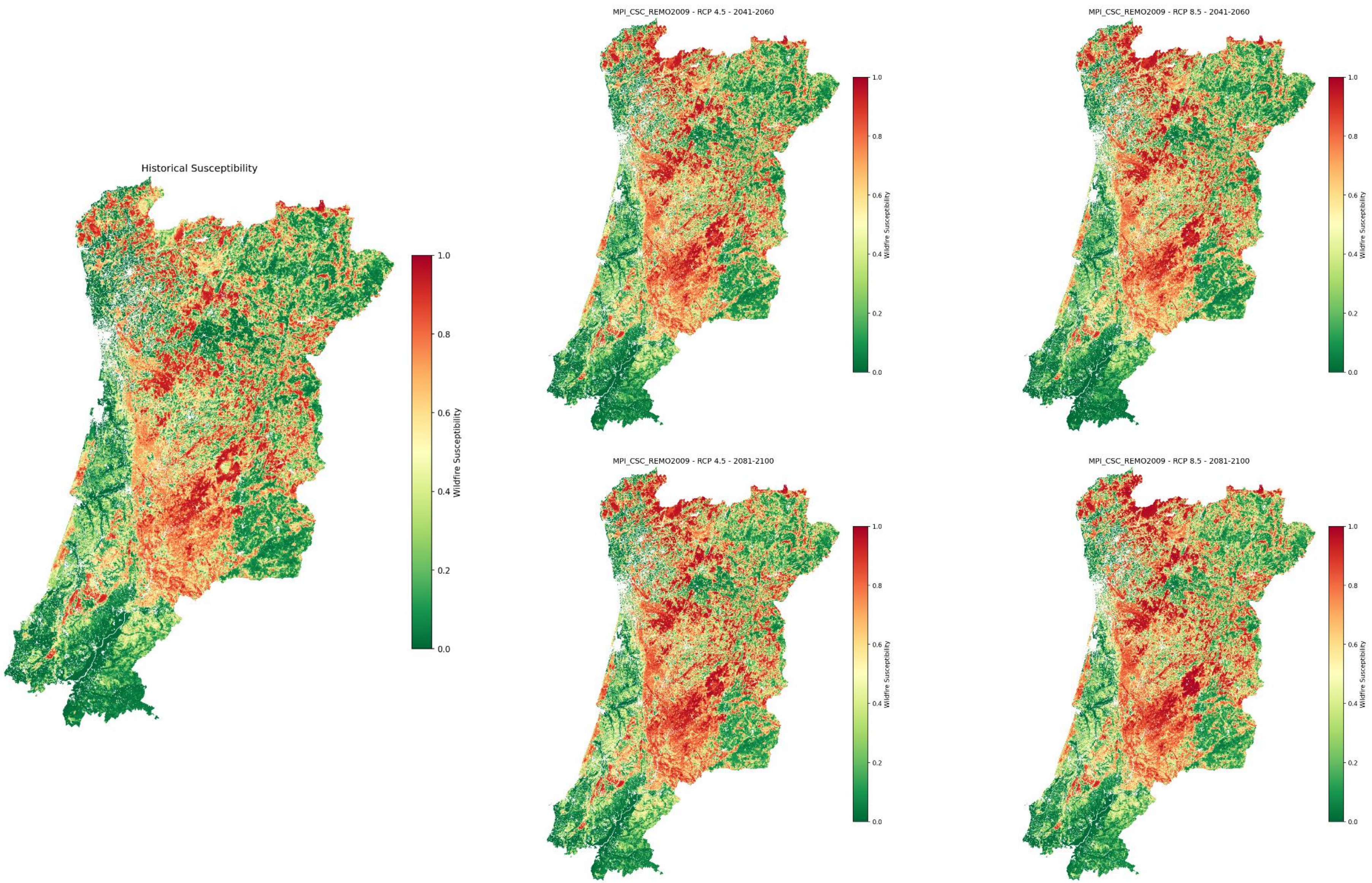


Figure 2-4 Wildfire structural susceptibility (continuous index, 0–1) across the model's training domain (NUTS II Norte, Centro and Oeste e Vale do Tejo): historical baseline (1991–2010) and four climate projections — RCP 4.5 and RCP 8.5, for 2041–2060 and 2081–2100 (regional climate model MPI-CSC-REMO2009)

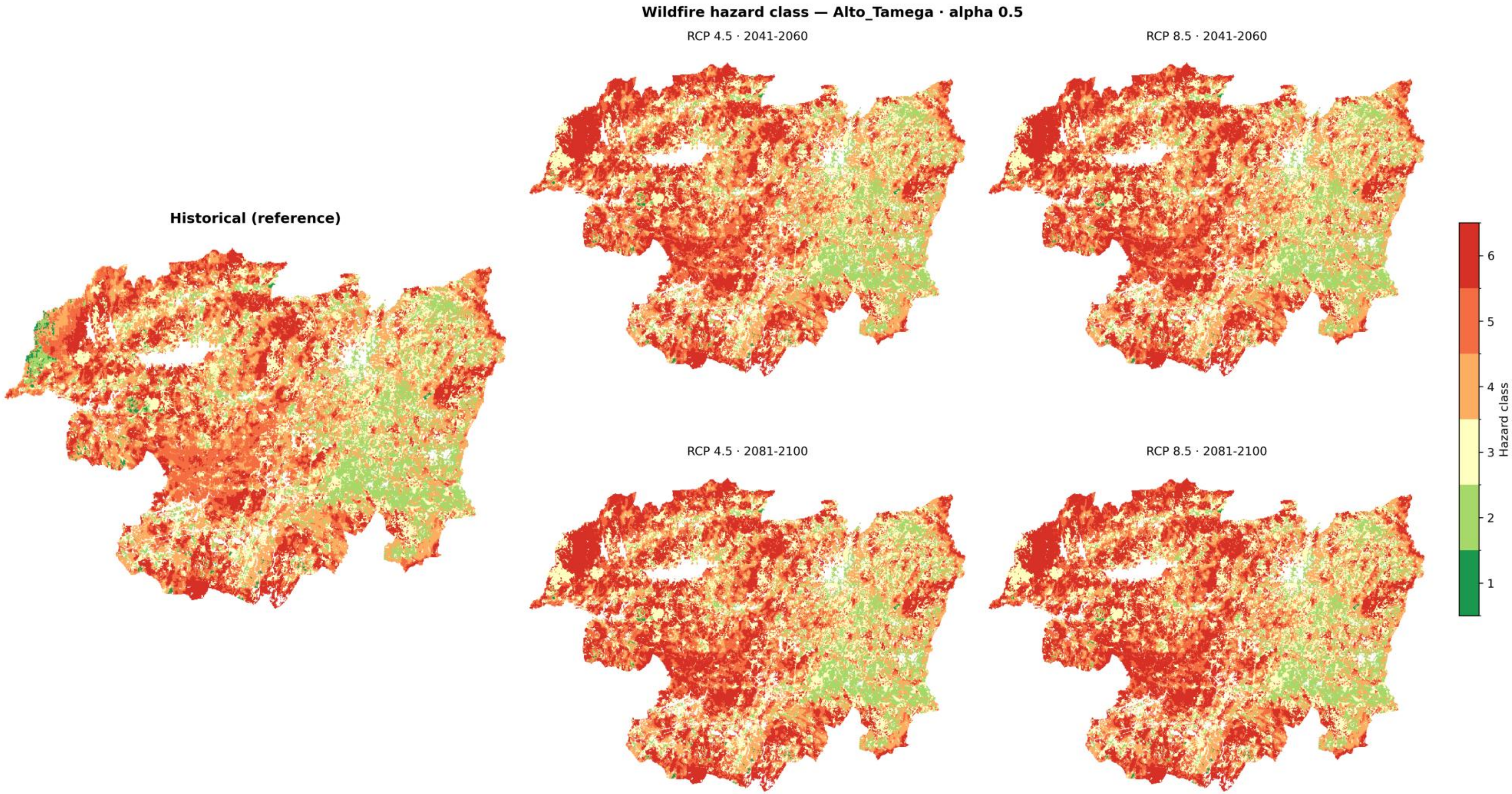


Figure 2-5 Wildfire hazard (discrete classes 1–6) for the Alto Tâmega e Barroso region: historical baseline (1991–2010) and four climate projections — RCP 4.5 and RCP 8.5, for 2041–2060 and 2081–2100 (regional climate model MPI-CSC-REMO2009).

2.3.1.2 Risk assessment

Risk results from the contingency-table intersection of vulnerability/exposure (1–3) with the 1–6 hazard, yielding risk classes from 1 (very low) to 5 (very high, saturated). It is reported across three layers of increasing detail. Headline risk percentages refer to the reference scenario RCP 4.5 / 2081–2100 unless stated, whereas the accompanying risk maps illustrate the worst-case RCP 8.5 / 2081–2100, to make the upper bound of the climate signal visible. Risk magnitude rises relative to Phase 1 — a correction of the earlier underestimation, confirmed by the burned-area validation, not inflation.

- **Layer 1 — area vulnerability (JRC, ~12.5 km):** high classes — population 57.0%, economic 47.1%, ecological 36.7%; the ecological maximum concentrates in Montalegre and the PNPG. Limitation: the JRC index resolves to only a handful of distinct values across CIMAT, lacking tactical detail.
- **Layer 2 — infrastructure exposure (10 m LiDAR):** road-network high risk 59.2% (20 m buffer) and 342 critical assets (OSM, with classes adapted to the territory), scored as the % of a 250 m buffer in hazard ≥ 5 (under 25%, 25–50%, over 50%). Several assets worsen under future climate, with Montalegre the tactical priority, ahead of Chaves, Ribeira de Pena and Vila Pouca de Aguiar. This is the product directly actionable for Civil Protection.
- **Layer 3 — fine population (BGRI 2021, 100 m):** the 5,197 INE subsections replace WorldPop; high population risk reaches 37.1% of the total and 35.3% of the elderly (≥65) — markedly below Layer 1 (57.0%). The population resides in protected valleys (fuel types 1–2), whereas severe hazard dominates the uninhabited forested slopes: real risk concentrates along the narrow wildland-urban interface (WUI).
- **Parish prioritisation (CAOP 2024):** ranking elderly-population risk identifies isolated, highly-aged mountain parishes surrounded by continuous Type-4 shrubland — led by Montalegre (Tourém, Outeiro, Covelo do Gerês), with Sabroso de Aguiar (Vila Pouca de Aguiar), Calvão e Soutelinho da Raia (Chaves) and Covas do Barroso (Boticas).

Indirect impacts are considered qualitatively: post-fire soil erosion and loss of regeneration capacity, water contamination by ash, degradation of high-value protected ecosystems, and the cascading interaction with drought and heatwaves (fire acting as a risk multiplier).

Territory message: high hazard and risk with a clear climate worsening (continental interior); population exposure concentrated in the valleys and real human risk at the wildland-urban interface. Adaptation priority: the ageing interior parishes of Montalegre. Limitations: the JRC economic/ecological components remain coarse (~12.5 km) — only population was refined; exposure and vulnerability are held at present-day conditions, so inter-scenario risk variation derives solely from the projected climate; results are robust in relative prioritisation, not in absolute values.

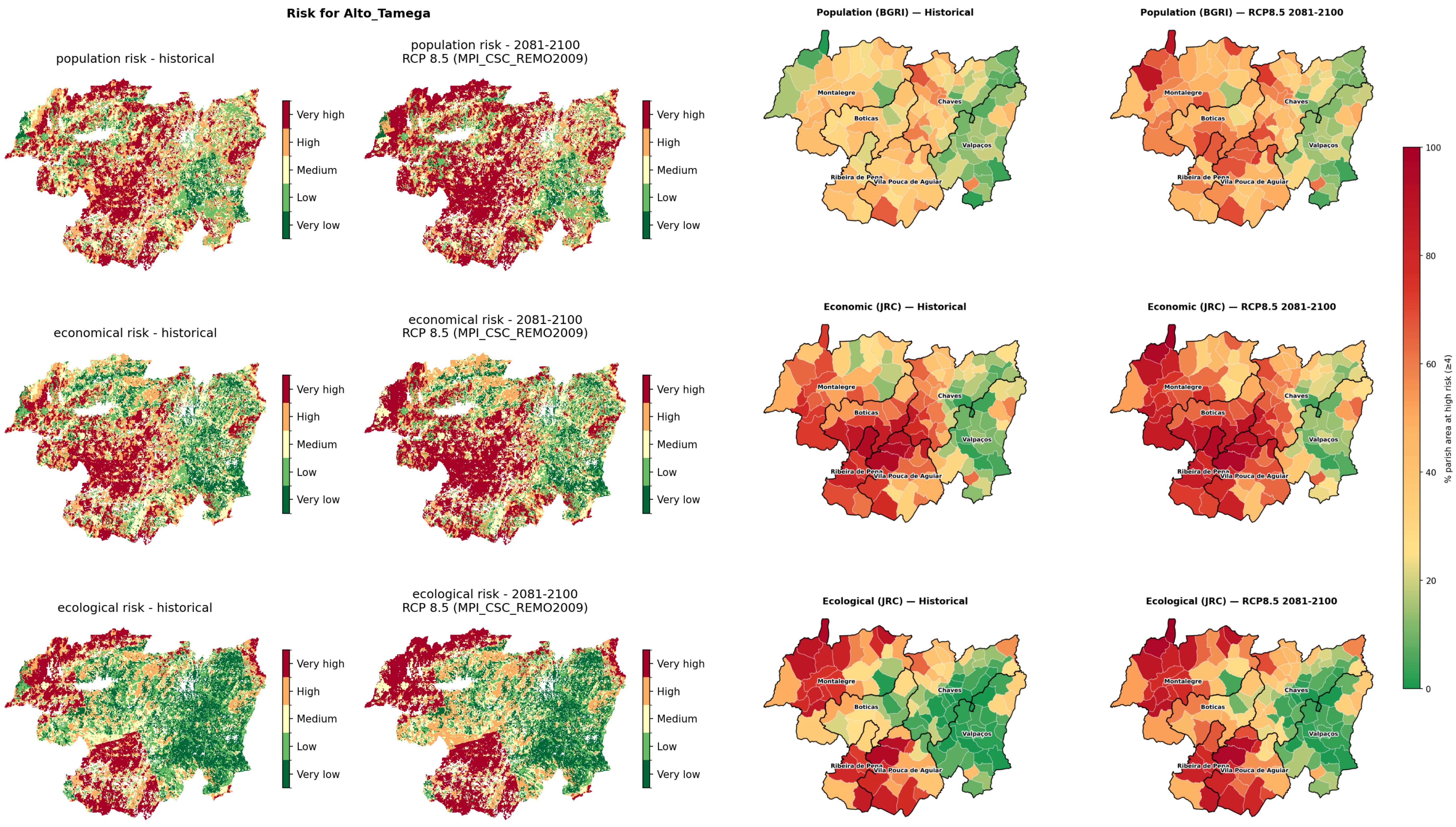


Figure 2-6 Area-based wildfire risk for the Alto Tâmega e Barroso region across three dimensions — population (BGRI 2021), economic and ecological (JRC) — under the historical baseline and end-of-century RCP 8.5 (2081–2100; MPI-CSC-REMO2009). Left columns: per-pixel risk classes (very low to very high). Right columns: aggregation by parish, expressed as the percentage of each parish's area in high-risk classes (≥4), with municipalities labelled. The economic and ecological components derive from the JRC indices (effective resolution ~12.5 km) and are therefore spatially smoother than the BGRI-based population.

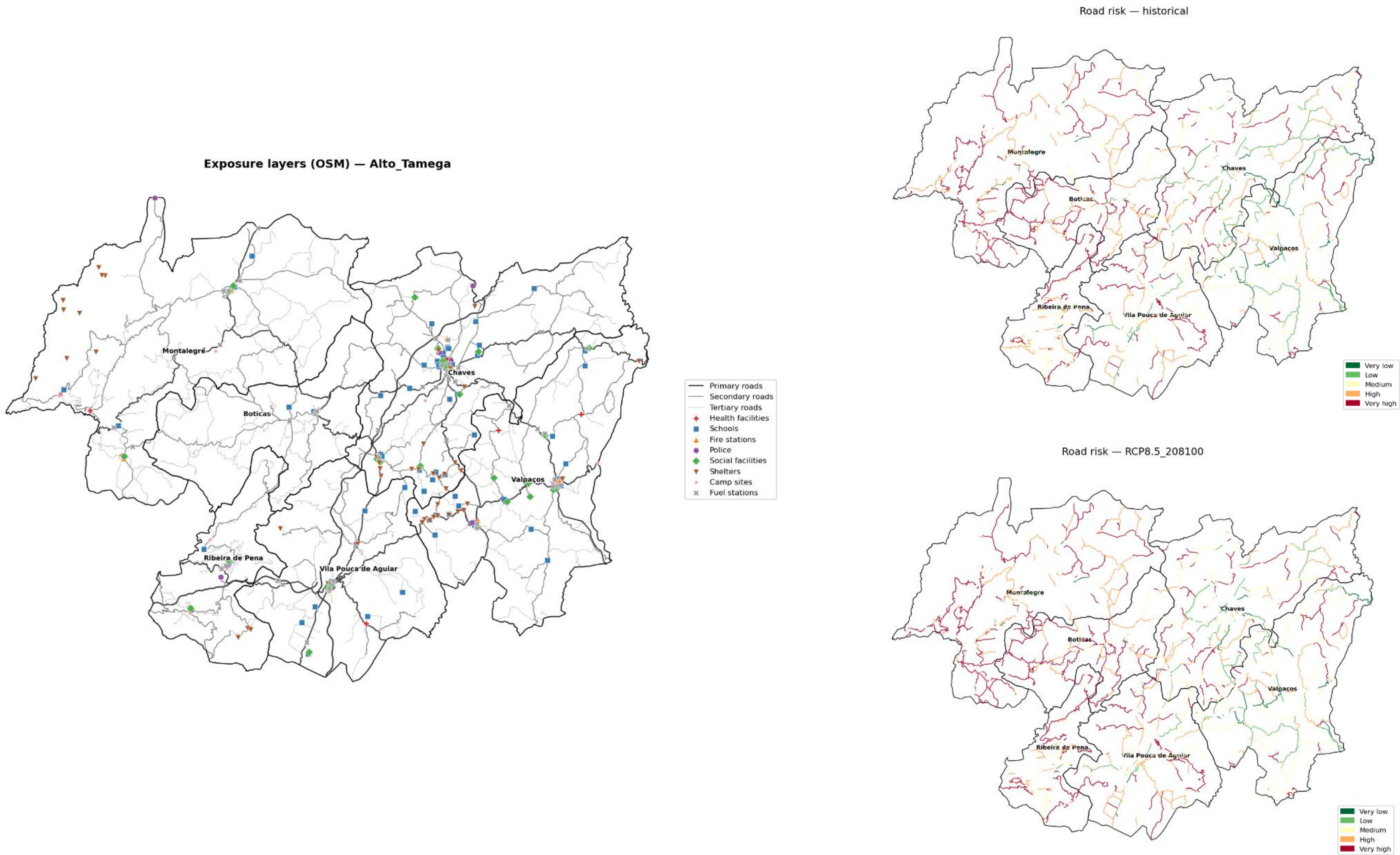


Figure 2-7 Layer 2 — infrastructure and road exposure to wildfire in the Alto Tâmega e Barroso region. Left: OSM exposure inventory — road network by hierarchy (primary/secondary/tertiary) and point critical assets by type (health, schools, fire/police stations, social facilities, shelters, campsites, fuel stations), with municipalities labelled. Right: road-network risk under the historical baseline and end-of-century RCP 8.5 (2081–2100; MPI-CSC-REMO2009), in five classes (very low to very high). Risk on the road network is obtained by crossing the hazard with the road hierarchy within a 20 m buffer.

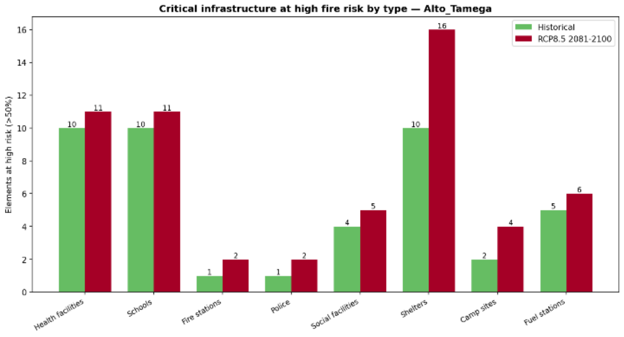


Figure 2-8 Critical infrastructure at high wildfire risk by asset type (Alto Tâmega e Barroso), historical baseline vs end-of-century RCP 8.5 (2081–2100). Risk is assessed as the fraction of each asset's 250 m buffer in high hazard (classes ≥ 5), binned as low (<25%), medium (25–50%) and high (>50%); bars count elements in the high-risk class.

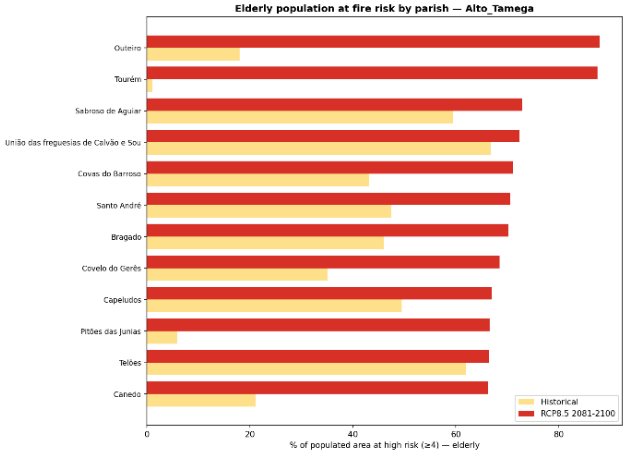


Figure 2-9 Elderly population (≥65) at high wildfire risk by parish, historical baseline vs end-of-century RCP 8.5 (2081–2100), expressed as the percentage of each parish's elderly population in high-risk classes (≥4).

2.3.2 Hazard #2 – Droughts finetuning to local context

The CLIMAAX toolbox provides two drought workflows. The relative drought index (WASP, with a Data Envelopment Analysis for cross-regional comparison) was applied in Phase 1 and carried over unchanged here – its indicative, inter-regional nature offers limited margin for local refinement – so Phase 2 concentrated on the agricultural (non-staple) workflow, detailed below.

2.3.2.1 Agricultural Drought

In Phase 1, the agricultural drought risk assessment relied on generic European standard crops, such as maize, wheat, and potatoes. While useful for a macroscopic and strategic characterization, these crops did not represent the socioeconomic fabric and identity crops of the Alto Tâmega e Barroso region. Furthermore, physical exposure was based on the global SPAM dataset and economic losses were estimated through global aggregated values from the GAEZ model, creating a significant "utility gap" for local planning decisions.

In Phase 2, a profound tactical reorientation of the workflow was executed through an agronomic and economic "portugalization" process, completely replacing abstract global data with high-resolution real-world datasets sourced from national and regional statistics.

The central methodological transition was the shift to the new *non-staple* crop workflow, enabling the integration of the region's high-value permanent and identity crops: **chestnuts** (requested by ~73% of consulted stakeholders due to the dense groves in Valpaços, Chaves, and Vila Pouca de Aguiar), **vineyards**, and **olive groves**. To support this refinement, the technical team restructured the model's pipeline by integrating the actual cultivated area at the parish level from the 2019 Agricultural Census of Statistics Portugal (INE). Real production was estimated using recent NUTS II Norte crop yield statistics (INE Crop Production), and economic losses in euros (€) were calculated using raw material market prices extracted from EUROSTAT for Portugal. Additionally, crop cycle start and end dates were adjusted to reflect the actual agronomic calendar of mainland Portugal (Climate Zone 3), and a critical soil data gap ("NaN") in the Alto Rabagão reservoir was resolved, preserving the analytical integrity of the Barroso plateau.

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Assessed Crops	Generic European staple crops (maize, wheat, potatoes, beans, barley, sorghum).	Local high-value permanent crops: chestnuts, vineyards, and olive groves.
Crop Calendar	Generic global FAO dates based on macro-climatic zones.	Agronomic calendar of mainland Portugal adjusted for all crops.
Exposure Data	Global SPAM production grid and GAEZ aggregated area data.	Actual cultivated area at the parish level (CAOP 2024) based on the Agricultural Census (INE).
Economic Valuation	Generic global weighted prices from the GAEZ-V5 model.	Real market prices of raw materials in Portugal (EUROSTAT, multi-year average).
Spatial Intersection	Simple "point-in-polygon" method, creating spatial distortions at the climate grid transition.	Area-weighted spatial intersection, distributing crop exposure with geometric rigor.
Soil Data (AWC)	Global soil dataset containing gaps ("No Data") over inland water bodies.	Spatial imputation of internal gaps (Alto Rabagão reservoir) using a neighborhood average.
Impact Metrics	Abstract physical yield loss indices lacking local operational utility.	Direct financial revenue losses in euros (€) and aggregated damage estimates at the parish scale.

Key improvements include:

- **National Agronomic Calibration**: Replacement of generic crop dates with official parameters adjusted to Climate Zone 3 of mainland Portugal, aligning water-stress calculations for both original and newly added crop species.
- **Resolution of the Barroso Soil Gap**: Imputation of Available Water Capacity (AWC) over the Alto Rabagão reservoir pixel recovered a vast agricultural area on the Montalegre plateau that was erroneously masked out in Phase 1.
- **High-Resolution Parish-Level Exposure**: The elimination of the global SPAM grid and its replacement with actual INE crop areas aggregated at the parish level (CAOP 2024) enabled the exact geographic mapping of agricultural assets.
- **Financial Loss Assessment in Euros**: Cross-referencing crop areas (INE), regional yields (NUTS II), and real raw material selling prices (EUROSTAT) converted abstract physical indices into tangible economic losses, directly supporting regional policymaking.

Table 2-3 summarizes the data sources and the results generated during the refinement of the agricultural drought workflow.

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

Hazard data	Vulnerability data	Exposure data	Impact metrics/Risk output
· **Climate (EURO-CORDEX):** Downscaled projections (~12.5 km) of cumulative precipitation and potential evapotranspiration (PET) (historical 1986–2015; RCP 2.6/4.5/8.5 scenarios). · **Soil (AWC):** Soil Available Water Capacity (250 m) with neighborhood-average imputation (3x3) to fill data gaps over the Alto Rabagão reservoir.	· **Physiological Parameters (FAO-56/33):** Crop coefficients Kc, cycle stages, and yield response factors Ky adapted to Portugal for chestnut (deciduous proxy), olives, and vineyards. · **Irrigation (GAEZ 2015):** Spatial mask identifying irrigated vs. rainfed crop parcels, defining the baseline sensitivity to water stress. · **JRC Vulnerability (PESETA IV):** Standardized regional sensitivity indicators (regional GDP per capita and % of rural population).	· **Agricultural Area (Censo INE 2019):** Actual rainfed surfaces per parish (chestnut: 11,251 ha; olive: 6,749 ha; vineyard: 3,463 ha). · **Regional Yields (INE 2024):** Mean crop yields per hectare (t/ha) based on official Crop Production statistics for the Norte NUTS II region. · **Market Prices (EUROSTAT):** 2019–2024 annual averages in Portugal for wine grapes, chestnut, and olives (via "Other olives" proxy). · **Area-Weighted Intersection:** Area-preserving geometric downscaling (EPSG:3763) to map fine vector parishes into coarse climate grid cells, avoiding spatial errors.	· **Physical Yield Loss (%):** Percentage crop yield reduction driven by simulated soil moisture deficit in each climate grid cell. · **Economic Losses (€):** Direct financial loss estimates per pixel (12 km) computed as: Area × Yield × Price × Yield Loss (Chestnut: ~€2.19M; Vineyard: ~€1.85M; Olive: ~€0.98M). · **Parish-Level Analysis (PMAC):** Estimated economic losses aggregated across the 118 civil parishes (CAOP 2024 DGT), with Valpaços concentrating 14 of the top 15 priority areas.

Hazard assessment

The agricultural drought hazard assessment focuses on the physical effect of water deficit on crop development. To ensure the model's reliability in the region, essential refinements were applied to the baseline climate and agronomic data, overcoming the limitations identified in Phase 1.

The first major correction took place within the soil data. The global soil dataset originally used marked water bodies, such as the Alto Rabagão reservoir, as "no data" (NaN) zones. At the resolution of the CORDEX climate model (~12.5 km), this mask erased a real and extensive agricultural area from the map, excluding vital parts of Montalegre's (Barroso) productive zone from the calculations. To resolve this issue, the technical team applied an imputation algorithm, filling in the soil's Available Water Capacity (AWC) using the neighborhood average, thereby preserving the integrity of the territory. Figure 2-10 illustrates this corrected baseline layer.

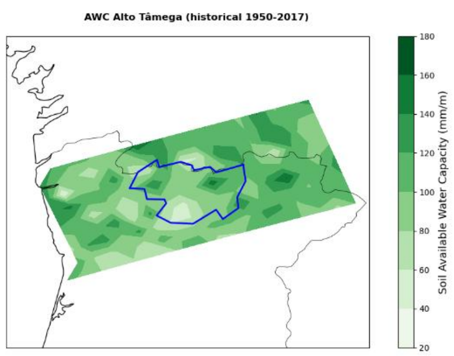


Figure 2-10 Soil Available Water Capacity (AWC), with imputation correction for internal water bodies, representing the physical baseline for agricultural drought

The second critical refinement focused on plant development dates. The original workflow relied on generic FAO calendars that proved to be misaligned with the national reality. The start and end dates of the crop cycles under analysis were recalibrated to strictly reflect the agronomic calendar of mainland Portugal (Climate Zone 3)[1].

It is important to note that, due to the absence of official FAO physiological and calibration parameters for chestnut trees (Castanea sativa) within the original CLIMAAX crop table, the modeling of this vegetation cover was based on an analogical approximation to temperate deciduous fruit trees. The cycle parameters were adopted as the best available scientific proxy for the region's biophysical reality. Consequently, the economic loss estimates in euros for this crop should be interpreted as exploratory.

The final hazard is expressed through the Relative Physical Yield Loss metric (%), which reflects the direct impact of water stress on crop yield. Recognizing the vital importance of these crops to the socioeconomic matrix of Alto Tâmega e Barroso, the analysis evaluated the detailed impact on the region's three strategic permanent crops: chestnuts, vineyards, and olive groves.

Unless otherwise stated, all drought figures contrast the near future (2026–2046) with the end of the century (2071–2090) under RCP 2.6, 4.5 and 8.5. Figure 2-11, Figure 2-12, and Figure 2-13 illustrate this drop in productivity for each of these crops.

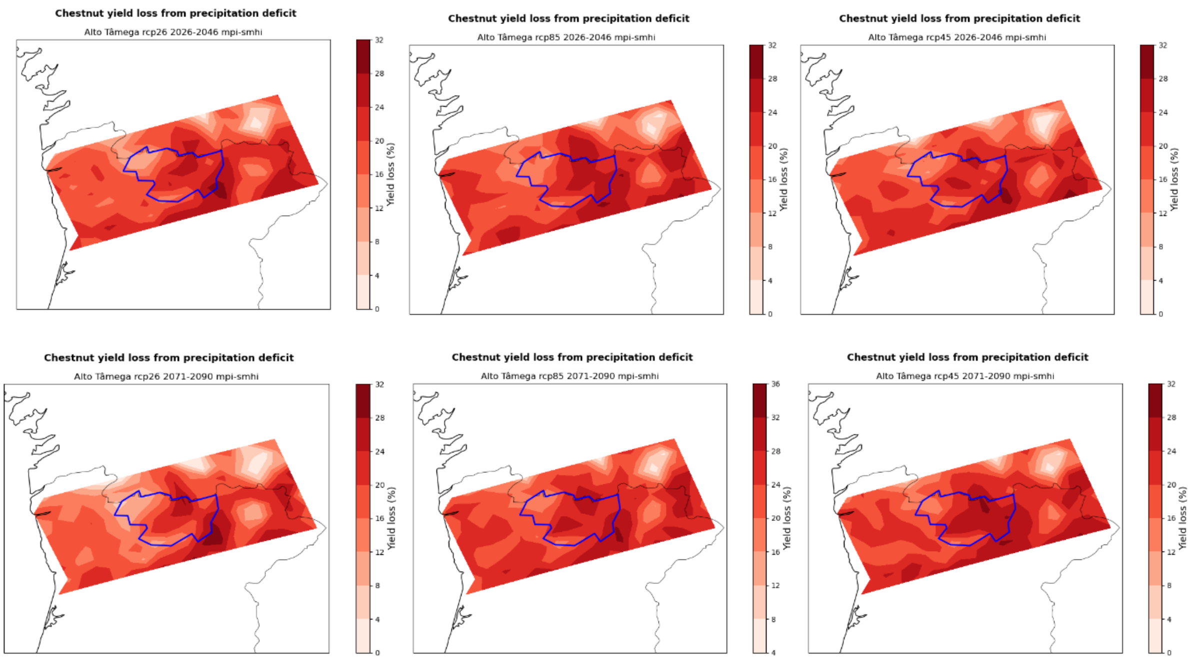


Figure 2-11 Projections of physical yield loss (%) for chestnut due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

[1] Methodological note: It is important to state that, as there are no official FAO parameters for the Chestnut crop, the model assumed approximation values by analogy to deciduous fruit trees; therefore, the physical results for this crop should be read as a conservative baseline.

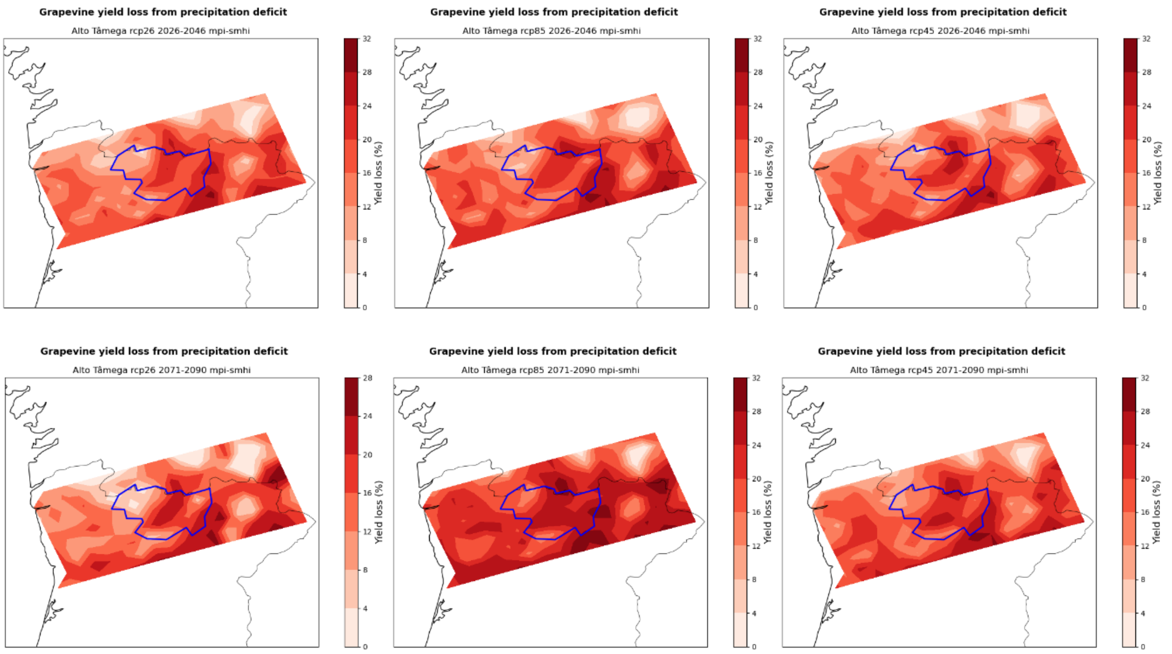


Figure 2-12 Projections of physical yield loss (%) for grapevine due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

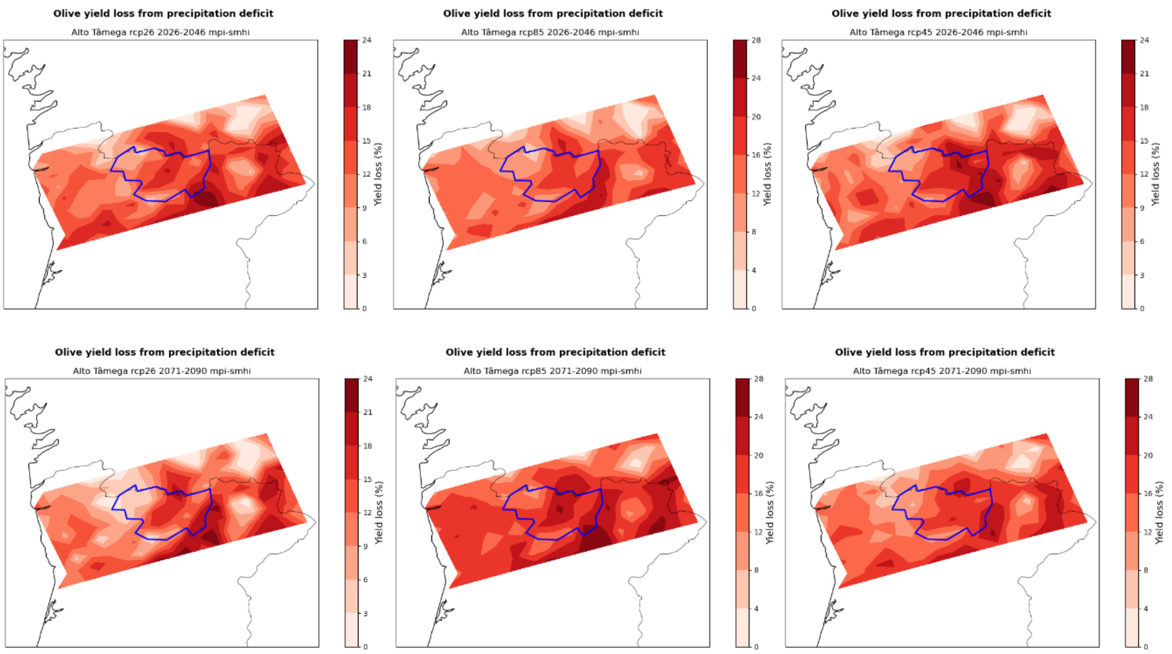


Figure 2-13 Projections of physical yield loss (%) for olive due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

The cross-cutting analysis of the scenarios demonstrates a progressive worsening of physical yield loss throughout the century, with particular severity in the highest emissions scenario (RCP 8.5). This drop in yield, which universally affects the agricultural vitality of the entire region, serves as the direct basis (input) for the Risk Assessment stage, where this biophysical impact will be converted into concrete financial revenue losses for producers.

Risk assessment

The true qualitative leap in Phase 2 materializes in the risk calculation. Economic vulnerability is no longer an abstract global estimate (based on aggregated damage functions); it is now calculated using a formula anchored in the socioeconomic reality of Alto Tâmega e Barroso.

The economic loss per crop was quantified by translating the physical yield drop (%) into direct financial revenue losses. The formula applied cross-referenced the following official data:

- *Loss (€) = Parish Area (ha) [INE - Agricultural Census] x Productivity (t/ha) [INE - NUTS2] x Raw Material Price (€/t) [EUROSTAT] x Physical Loss (%) [Climate Model]*

To ensure maximum spatial precision when transitioning from the administrative boundaries of the parishes (CAOP 2024) to the resolution of the climate grid, the technical team applied an advanced area-weighted intersection method. This method replaced the initial "point-in-polygon" approach, preventing the creation of artificial hotspots and ensuring that agricultural exposure was distributed in a mathematically exact and realistic manner across the entire territory.

The estimates show that annual losses (revenue loss due to precipitation deficits, assuming a non-irrigated scenario) reach millions of euros and threaten the core of the region's primary sector. Taking the short/medium-term scenario (2026–2046) under the RCP 2.6 climate trajectory as a baseline reference, the estimated annual economic losses for Alto Tâmega e Barroso stand at approximately **€2.19 Million** for Chestnuts, **€1.85 Million** for Grapevine, and **€0.98 Million** for Olive.

Figure 2-14, Figure 2-15 and Figure 2-16 illustrate the spatial projection of these direct financial losses (in euros) for each of these three strategic crops.

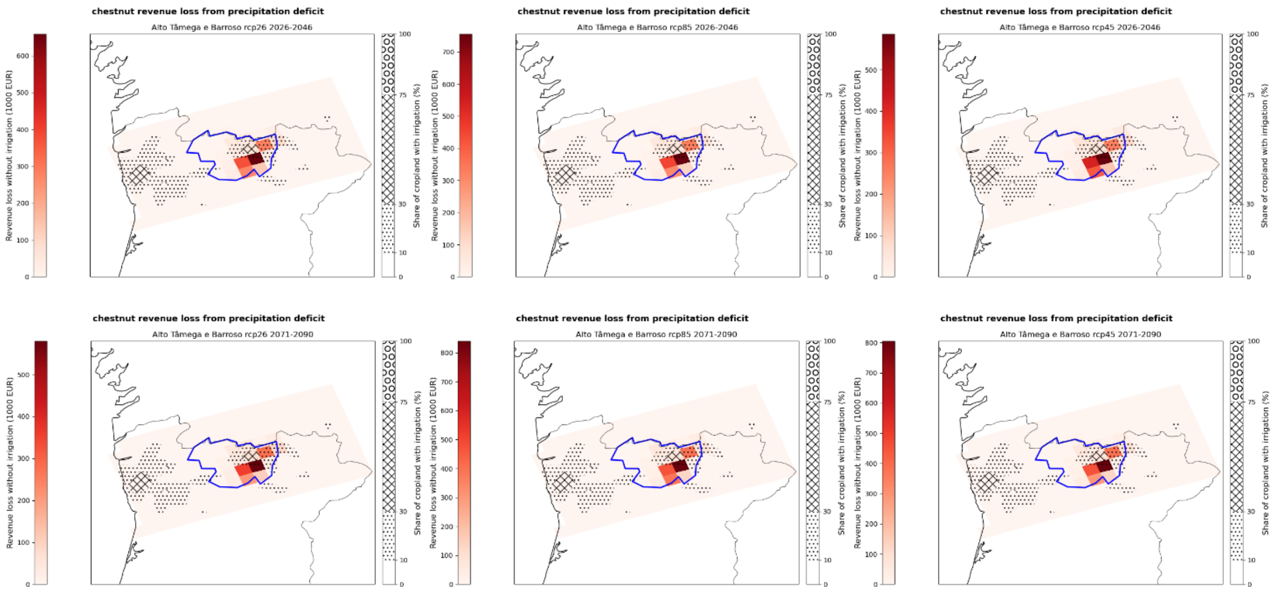


Figure 2-14 Spatial distribution of potential revenue losses (€) for chestnut due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

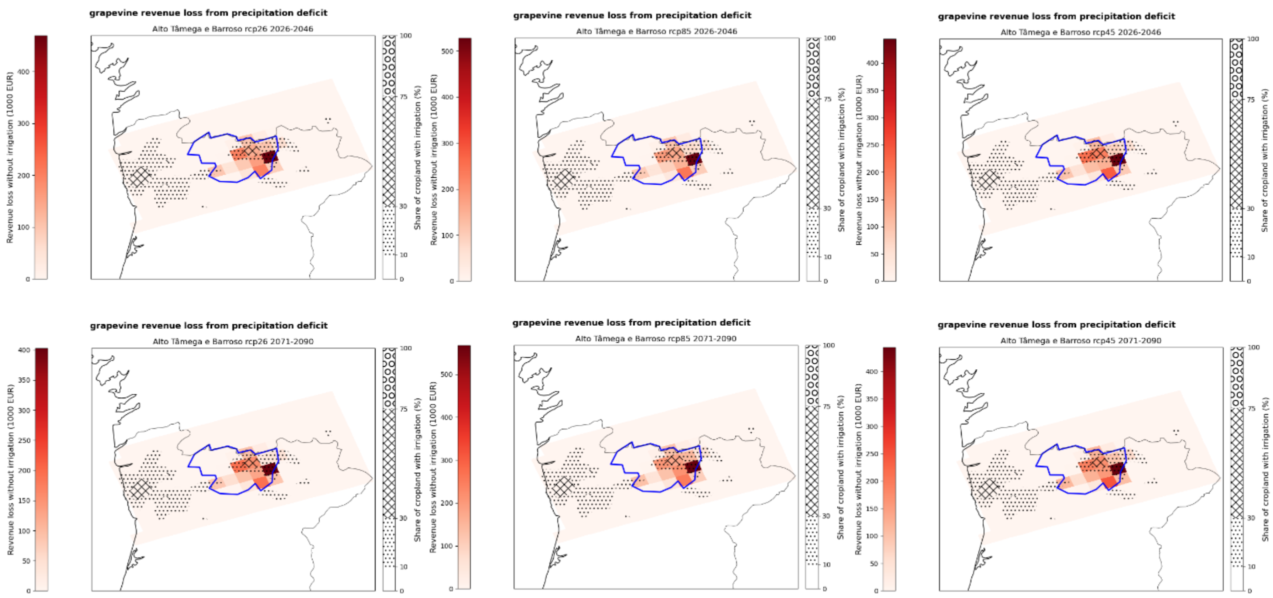


Figure 2-15 Spatial distribution of potential revenue losses (€) for grapevine due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

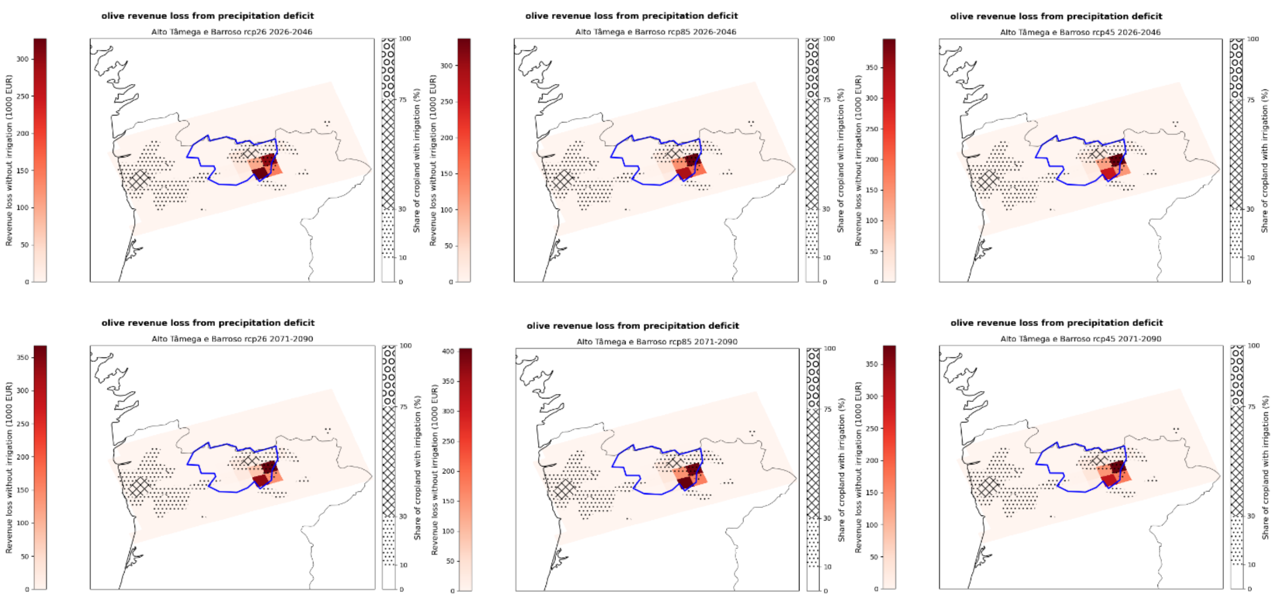


Figure 2-16 Spatial distribution of potential revenue losses (€) for olive due to precipitation deficit, comparing near future (2026-2046) and end-of-century (2071-2090) horizons under RCP 2.6, RCP 4.5 and RCP 8.5 scenarios.

To provide local decision-makers with directly actionable data for the revision of Municipal Climate Action Plans (PMAC), the results modeled on the climate grid were aggregated and transposed onto the administrative boundaries of each parish. The fine differentiation at this level results from variations in exposure (cultivated area per parish), while the climate signal remains consistent with the regional grid.

Figure 2-17, Figure 2-18, and Figure 2-19 present the spatial distribution of financial losses at the parish level, disaggregated for each crop (chestnuts, vineyards, and olive groves).

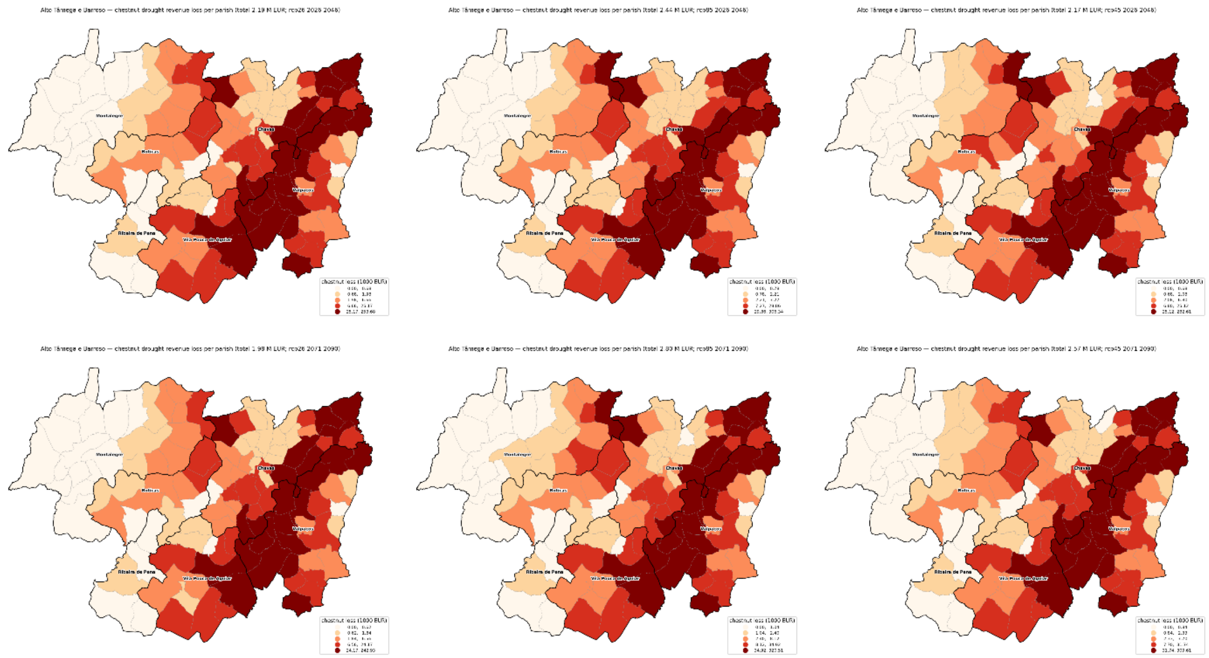


Figure 2-17 Expected revenue loss (€) per parish for chestnut due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5).

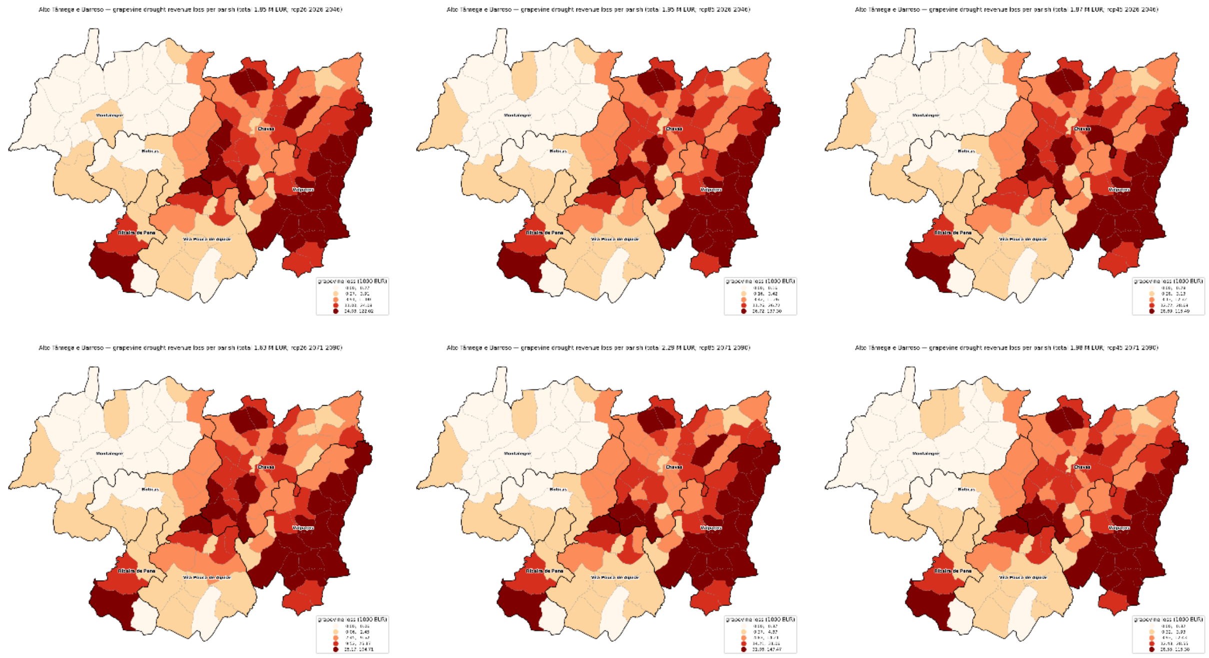


Figure 2-18 Expected revenue loss (€) per parish for grapevine due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5).

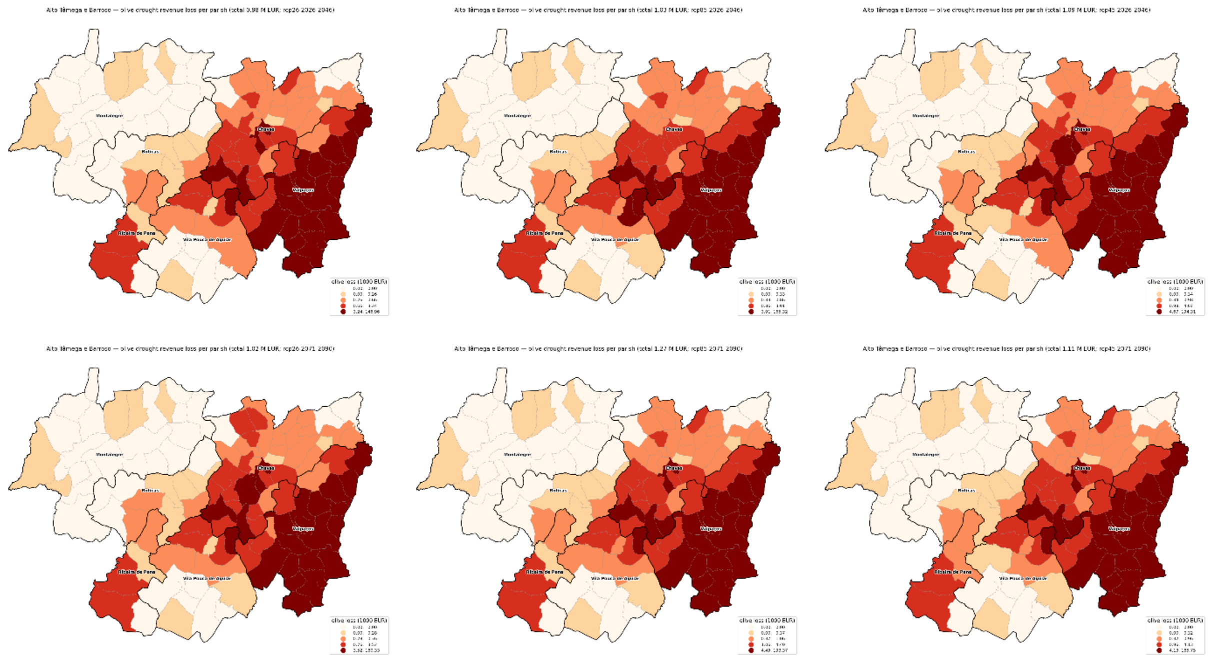


Figure 2-19 Expected revenue loss (€) per parish for olive due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5).

The consolidation of these sectoral impacts allows for the calculation of the aggregate economic risk of agricultural drought in the territory. Figure 2-20 illustrates the total losses for the three strategic crops by parish, highlighting the overall economic impact on the primary sector at the local scale for each scenario and time horizon.

The cross-referencing of these financial results with geographic distribution reveals a fundamental asymmetry. Vulnerability to agricultural drought in Alto Tâmega e Barroso is not diffuse; it has a very clear primary location that remains consistent regardless of the climate scenario or time horizon analyzed. This concentration is unequivocally demonstrated by the analysis of the 15 most affected parishes (Figure 2-21).

As cross-cuttingly illustrated across the various panels, out of the 15 parishes with the highest economic risk in the entire CIMAT region, 14 consistently belong to the municipality of Valpaços, with the remaining position occupied by a parish from the municipality of Chaves (specifically Vidago, present in the RCP 2.6 scenarios for 2026–2046 and 2071–2090, as well as in the RCP 4.5 scenario for 2026–2046). The risk proves to be systemic for Valpaços, which is justified by the fact that this municipality combines the largest expanses of planted area for the three crops (7,025 ha of chestnut, 6,127 ha of olive grove, and 1,854 ha of vineyard) with the most water-stressed climate conditions in the entire territory. The composition of the loss varies locally—with chestnuts leading in chestnut-orchard (*souto*) parishes (e.g., Carrazedo de Montenegro, Padrela, and Tazem) and vineyards and olive groves dominating in others—but the municipality of Valpaços establishes itself globally as the primary territorial priority for adaptation.

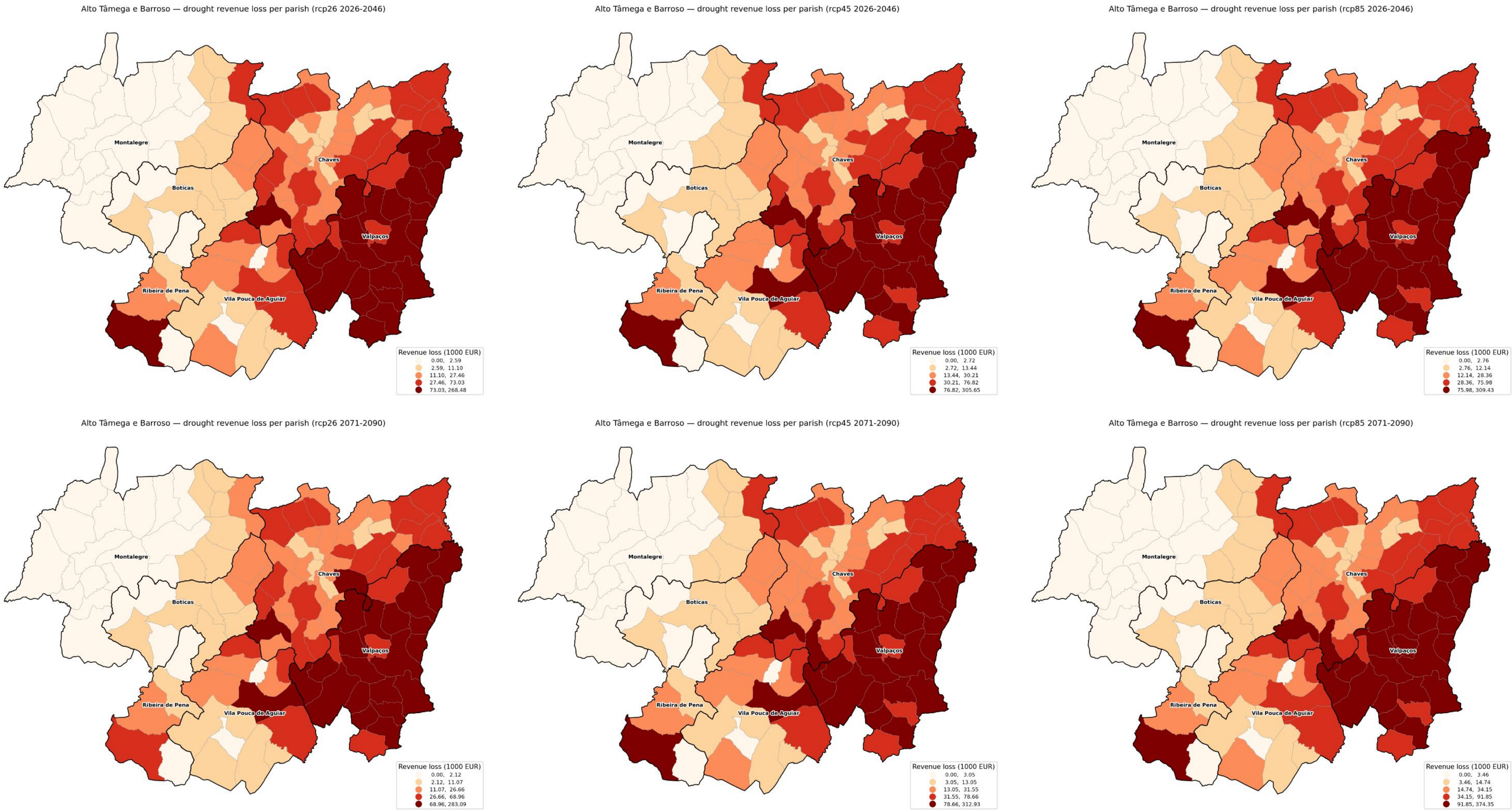


Figure 2-20 Aggregated expected revenue loss (€) per parish (chestnut, olive, and grapevine combined) due to precipitation deficit (2026-2046 vs. 2071-2090, under RCP 2.6, 4.5, and 8.5).

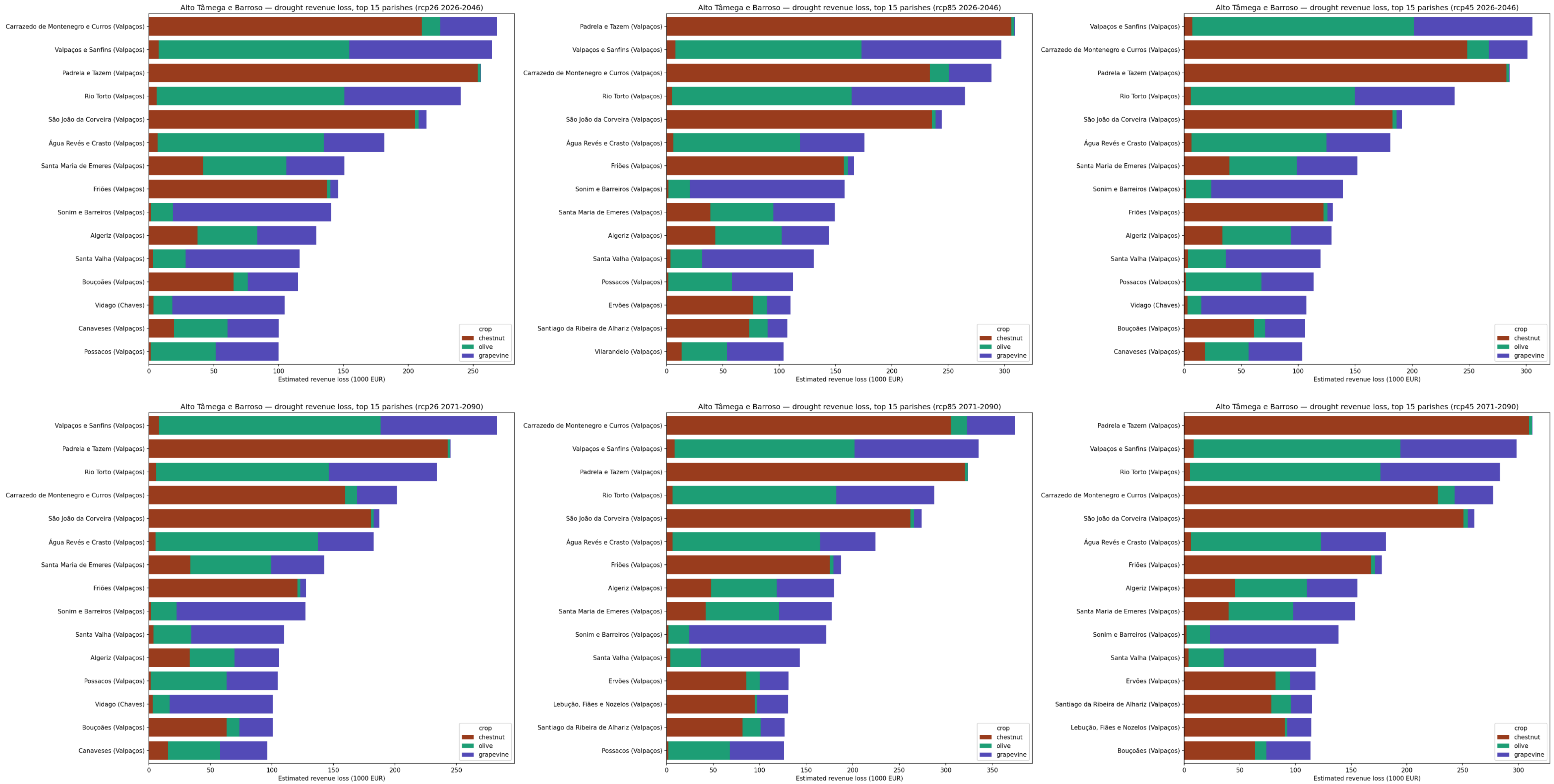


Figure 2-21 Top 15 parishes with the highest expected economic risk (revenue loss in €) from agricultural drought across all scenarios and time horizons, disaggregated by crop.

It is worth noting that in no scenario or time horizon does any parish from Montalegre appear in the Top 15, which necessitates the declaration of a crucial interpretive limitation identified by the technical team: the "Area vs. Identity Value Paradox." The risk model evaluates absolute exposed area and not symbolic, cultural, or Protected Designation of Origin (PDO/DOP) value. Consequently, although the chestnut is a historical and culturally inseparable crop of Montalegre (Barroso), the massive economic risk appears mapped in Valpaços (Terra Fria) and extends to Chaves. This occurs because Valpaços holds 62% of the region's entire chestnut orchard area (and Chaves 22%), compared to only about 3% concentrated in Montalegre. This caveat ensures transparency in decision-making: future adaptation measures in Phase 3 must consider that the apparent "low absolute financial risk" of Montalegre does not invalidate the vital urgency of protecting its valuable and identity-defining chestnut ecosystem, even if its total area is smaller.

2.3.3 Hazard #3 – Heatwaves finetuning to local context

In Phase 1, the heatwave hazard in the Alto Tâmega e Barroso region was evaluated using generic European thermal thresholds and a climatologically restricted baseline. Population exposure relied on global datasets (WorldPop/GHS-POP), which lacked spatial precision and failed to isolate highly vulnerable demographic cohorts. This created a significant "utility gap", making it impossible to plan targeted emergency responses or identify urban thermal hotspots.

In Phase 2, the workflow was substantially enhanced through three strategic actions:

1. **Calibration of National Thresholds (IPMA):** Standard European thresholds were replaced with official metrics from the Portuguese Institute for Sea and Atmosphere (IPMA) for "Very hot day" and "Tropical night", adapting the duration of the hydro-thermal cycle.
2. **High-Resolution Demographic Vulnerability (BGRI 2021):** WorldPop was replaced with official census tracts from Statistics Portugal (INE) at the statistical subsection level, focusing the analysis on the residential density of the elderly population (age ≥ 65 years) – the cohort of highest epidemiological vulnerability to thermal stress.
3. **Satellite-Based Urban Heat Island Analysis (LST ~100m):** Development of a micro-urban Land Surface Temperature model derived from Landsat 8/9 satellite imagery at 100m resolution. This model was calibrated during the historic July 2022 heatwave (the most severe in July since 1941), mapping the urban heat island of Chaves at block scale and intersecting it with critical health and social care facilities.

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Maximum Temperature Threshold	Generic value of 25.0 °C (or 28.0 °C for frequency).	**35.0 °C** (IPMA official definition for "Very hot day").
Minimum Temperature Threshold	Generic value of 22.0 °C.	**20.0 °C** (IPMA official definition for "Tropical night").
Heatwave Duration	5 consecutive days.	**6 consecutive days** (official Portuguese criterion).
Climatological Reference Baseline	Reduced and non-standardized period.	Robust climatological reference period of **1971–2005**.
Vulnerability Indicator	Aggregated total population (WorldPop).	**Elderly population density (age ≥ 65 years)** at subsection level.
Risk Spatialization	Coarse climate grid of ~12 km.	**Dual complementary scales:** Regional at parish level (~12 km) and Micro-urban at 100m derived from satellite (LST).

Aspect	Original Workflow	Enhanced Workflow
Exposed Critical Assets	Generic OpenStreetMap roads and buildings.	**Healthcare facilities and elderly nursing homes** mapped with physical precision over urban-thermal interface.

Key improvements include:

- **Physiological Adjustment for Tropical Nights**: The integration of the 20 °C minimum temperature threshold is epidemiologically critical for Portugal, capturing the lack of nocturnal thermal recovery linked to cardiovascular morbidity spikes.
- **Mapping of Isolated Elderly Hotspots (BGRI 2021)**: Replacing smoothed global population grids enabled the precise location of vulnerable elderly clusters within urban historical centers and isolated mountain villages.
- **Identification of Critical Urban Thermal Hotspots**: The July 2022 satellite-based LST model in Chaves revealed that the paved historical center reached surface temperatures exceeding **52.0 °C**, confirming a prominent Urban Heat Island.
- **Quantile-Based Risk Categorization**: Classifying future risk into 10 quantile classes avoided scale suppression caused by demographic skewness, delivering highly contrasted and operationally useful risk maps.

Table 2-4 Data overview workflow #3 – Heatwaves

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **Climate (EURO-CORDEX):** Large-scale daily temperature series (~12.5 km) of Tmax and Tmin (historical 1971–2005; RCP 4.5/8.5 scenarios for 2011–2040, 2041–2070, and 2071–2100 horizons). · **IPMA Thresholds (Xclim):** Physical calibration of local extremes: Very hot day (Tmax ≥ 35.0 °C) and Tropical night (Tmin ≥ 20.0 °C) for at least 6 consecutive days. · **Satellite Temperature (LST Landsat):** Surface temperature at ~100m resolution extracted for the extreme July 2022 heatwave (Planetary Computer).	· **Demographics (BGRI 2021 INE):** Residential density of the elderly population (aged ≥ 65 years)—the demographic group with the highest epidemiological vulnerability to extreme heat. · **Classification by Quantiles:** Demographic classification into 10 classes at the civil parish level (quantiles) to prevent flattening by density outliers. · **Asset Validation:** Spatial overlay of nursing homes and hospitals integrated as a qualitative validation and operational response reference.	· **Official Boundaries (CAOP 2022 DGT):** Geometry of the 118 civil parishes of Alto Tâmega e Barroso aligned with the 2021 Census. · **Critical Assets (OSM):** Exposed public facilities mapped spatially: hospitals, healthcare centers, elderly nursing homes, and day care facilities. · **School Exposure (OSM):** Mapping of 27 school facilities for dedicated exposure analysis of children (secondary vulnerable group).	· **Hazard Indicators (1–10):** Temporal projections of heatwave days per year, event frequency, and occurrence index, calibrated to IPMA standards. · **Future Projected Risk (2–20):** Combined risk score at the parish scale (sum of hazard class 1–10 and vulnerability class 1–10), highlighting the threat in the Chaves valley. · **Micro-Urban Risk (~100 m):** Urban heat island risk in the Chaves city center (LST × BGRI 2021 elderly density), capturing the scale paradox for NbS planning.

2.3.3.1 Hazard assessment

The heatwave hazard assessment in Phase 2 was based on a dual methodological approach to ensure robustness: the calibration of the Xclim model (based on user-defined absolute thresholds) and the maintenance of EuroHEAT (based on apparent temperature percentiles). EuroHEAT was kept intact from Phase 1, serving exclusively as a multi-model reference for cross-validating worsening trends.

The true qualitative leap occurred in Xclim, where the generic thresholds of the original workflow were fully recalibrated to the official metrics of the IPMA. The heatwave index (heat_wave_index) is now calculated only when the maximum temperature (Tmax) reaches or exceeds 35.0 °C ("Very hot day") for a minimum period of 6 consecutive days. Additionally, in the bivariate indices (day and night), the minimum temperature threshold was adjusted to 20.0 °C ("Tropical night"). This nighttime inclusion is vital for the Portuguese context, as the lack of nocturnal thermal recovery is a determining factor in heat-related mortality.

The calibration produced a drastic and desirable correction in the results: while in Phase 1 the model identified up to ~100 days/year of "heatwaves" (since it used a very low threshold of 25 °C that could not distinguish extreme events from normal summer days), the calibrated Phase 2 model identifies a maximum of ~18 days/year under the IPMA metric. This reduction ensures that the workflow now measures extreme heat with real relevance for Public Health and Civil Protection planning.

To ensure geographic reproducibility and validate the territory's topographic discrepancies, two crucial coordinates were pinned directly in the code:

- **Chaves (Valley/Urban - 41.7400 -7.4700):** Represents the area of highest population density and the valley floor, where the highest occurrence of extreme episodes is expected.
- **Montalegre (Plateau/Altitude - 41.8254 -7.7874):** Represents the interior at an altitude of ~1000m, serving to validate the model's physical coherence, as tropical nights (≥ 20.0 °C) are expectedly rare at these elevations.

Finally, the hazard assessment requires declaring technical limitations ("Scale Paradox"): the climate hazard remains dependent on the native resolution of ~12.5 km from EURO-CORDEX. This means the hazard acts as a broad regional signal (where a single pixel can cover several civil parishes). Furthermore, the Xclim analysis relies on a single climate model (the GCM-RCM pair mpi_m_mpi_esm_lr / clmcom_clm_cclm4_8_17), and readings are recommended as period averages (2011–2040 vs. 2041–2070) rather than a year-by-year analysis, given the high sensitivity of rare events to interannual variability.

Two reference conventions are used: the point-based IPMA indices follow the EURO-CORDEX 30-year windows (1971–2005 baseline; 2011–2040 / 2041–2070 / 2071–2100), whereas the spatial relative-change maps and the risk assessment use a 1986–2015 reference with the 2016–2045 / 2046–2075 horizons. To materialize these projections, the hazard is evaluated on two fronts: the local temporal evolution and the spatial distribution of the threat within the territory.

The point-based assessment allows for an understanding of how the hazard worsens over time. The following panel of graphs illustrates the projection of three distinct hazard metrics (Occurrence Index, Event Frequency, and Total Number of Days), strictly calibrated to the absolute thresholds of the IPMA. This assessment is presented side-by-side for the territory's two strategic validation points: Chaves (valley floor) and Montalegre (plateau).

The visual comparison of these metrics clearly shows that the increase in hazard is not uniform; the higher-emissions scenario (RCP 8.5) dictates a substantial and acute worsening of extreme heat in the valley (visible in the escalation of the bars in the left column), whereas Montalegre's high altitude (right column) continues to offer a natural thermal refuge, keeping the occurrence of tropical nights and extremely hot days at residual or zero values (Figure 2-22).

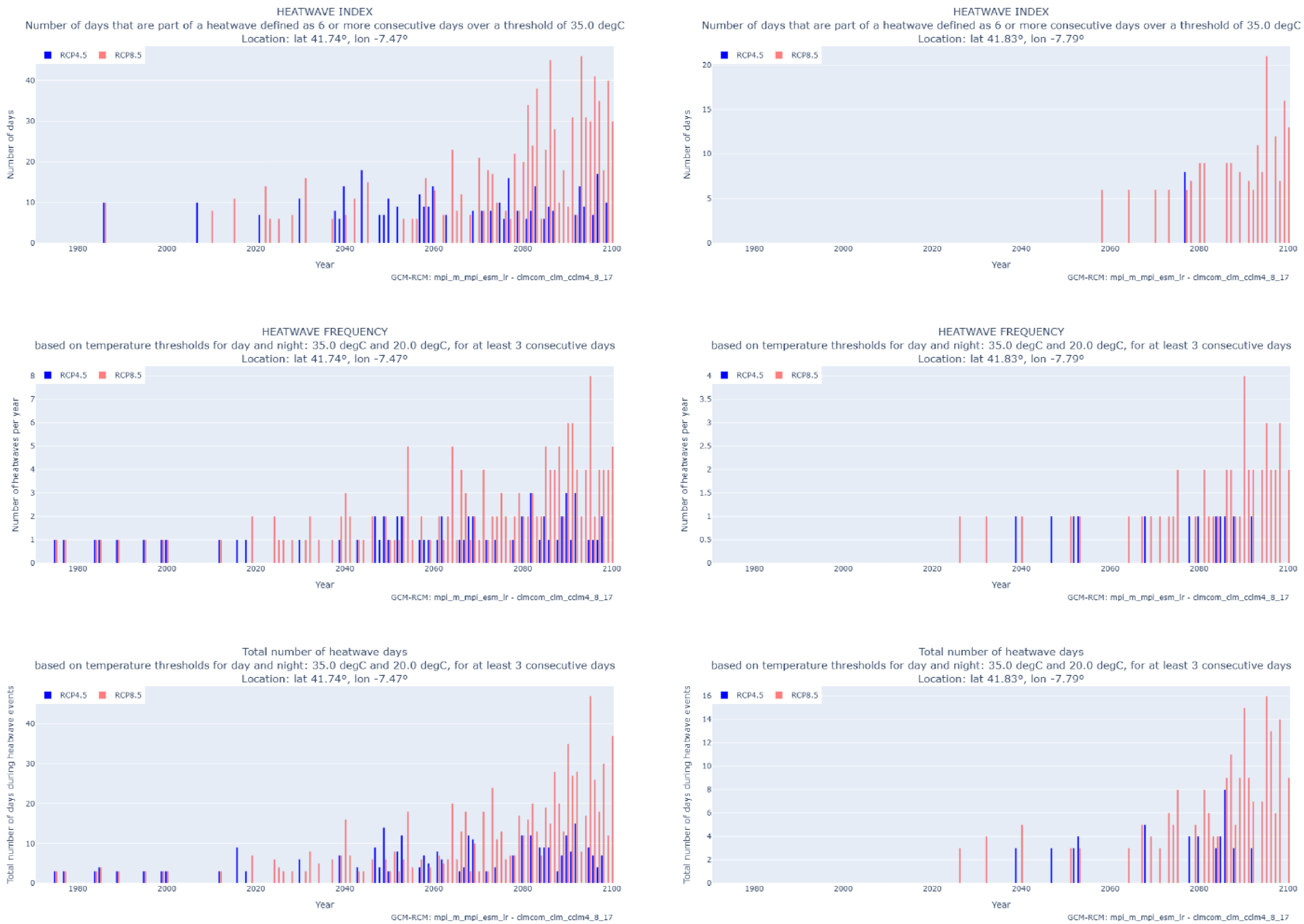


Figure 2-22 Projected heatwave hazard indices (Occurrence, Frequency, and Total Days) based on IPMA absolute thresholds (Tmax ≥ 35°C for ≥ 6 consecutive days). The panel compares the historical baseline with RCP 4.5 and RCP 8.5 scenarios for Chaves (valley, left column) and Montalegre (plateau, right column).

In addition to point-based readings, it is fundamental to understand how climate change is distributed geographically across the civil parishes of CIMAT. The generated hazard maps reflect the magnitude of the relative change in the occurrence of heatwaves, comparing the historical period (1986–2015) with future horizons (2016–2045 and 2046–2075) under the RCP 4.5 and RCP 8.5 scenarios.

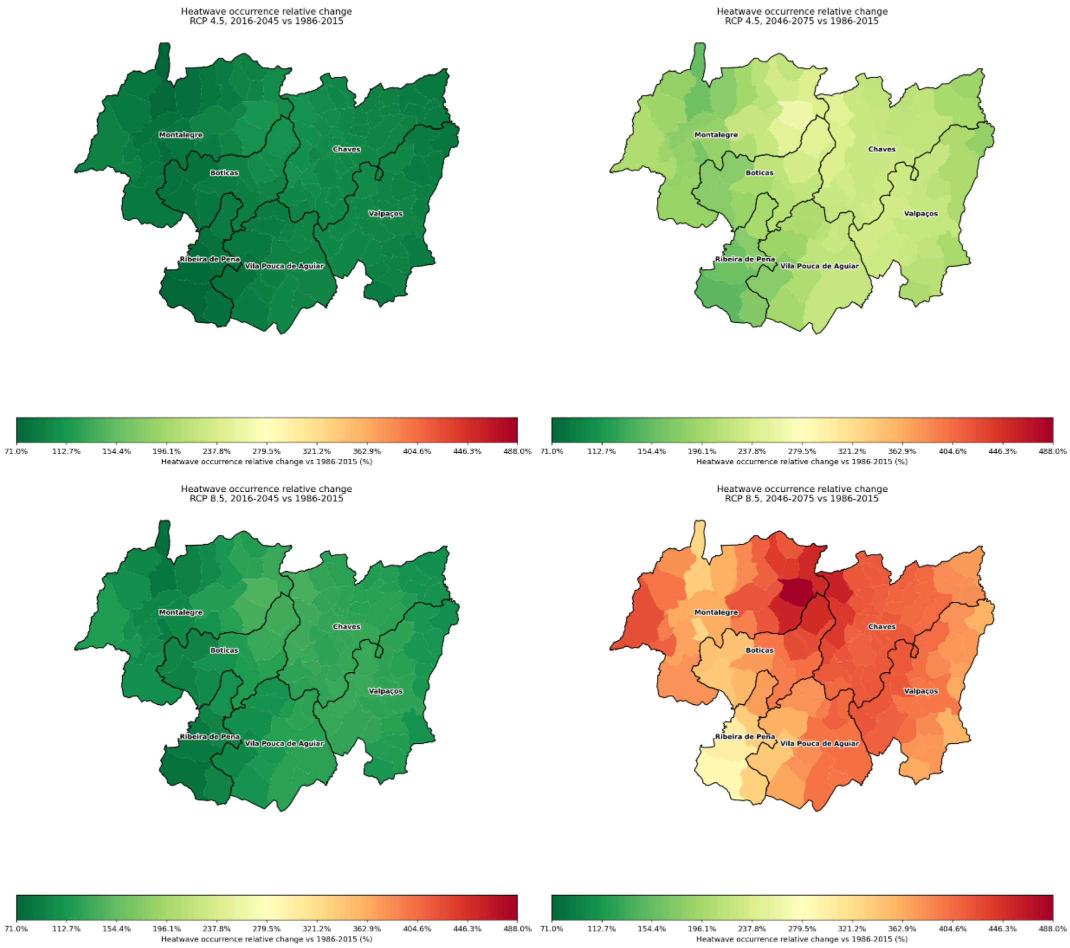


Figure 2-23 Spatial distribution of the relative change in heatwave occurrence across Alto Tâmega e Barroso parishes, comparing future horizons (2016-2045 and 2046-2075) against the historical baseline under RCP 4.5 and RCP 8.5.

To facilitate the integration of this territorial data into municipal planning instruments, the workflow reclassified this magnitude of change onto a standardized scale from 1 to 10 (where 10 represents the most severe worsening). The reclassified map highlights that the north-central civil parishes (along the Chaves valley axis) face the most intense climate pressure, contrasting with the lower relative worsening projected for the southwestern region (Barroso).

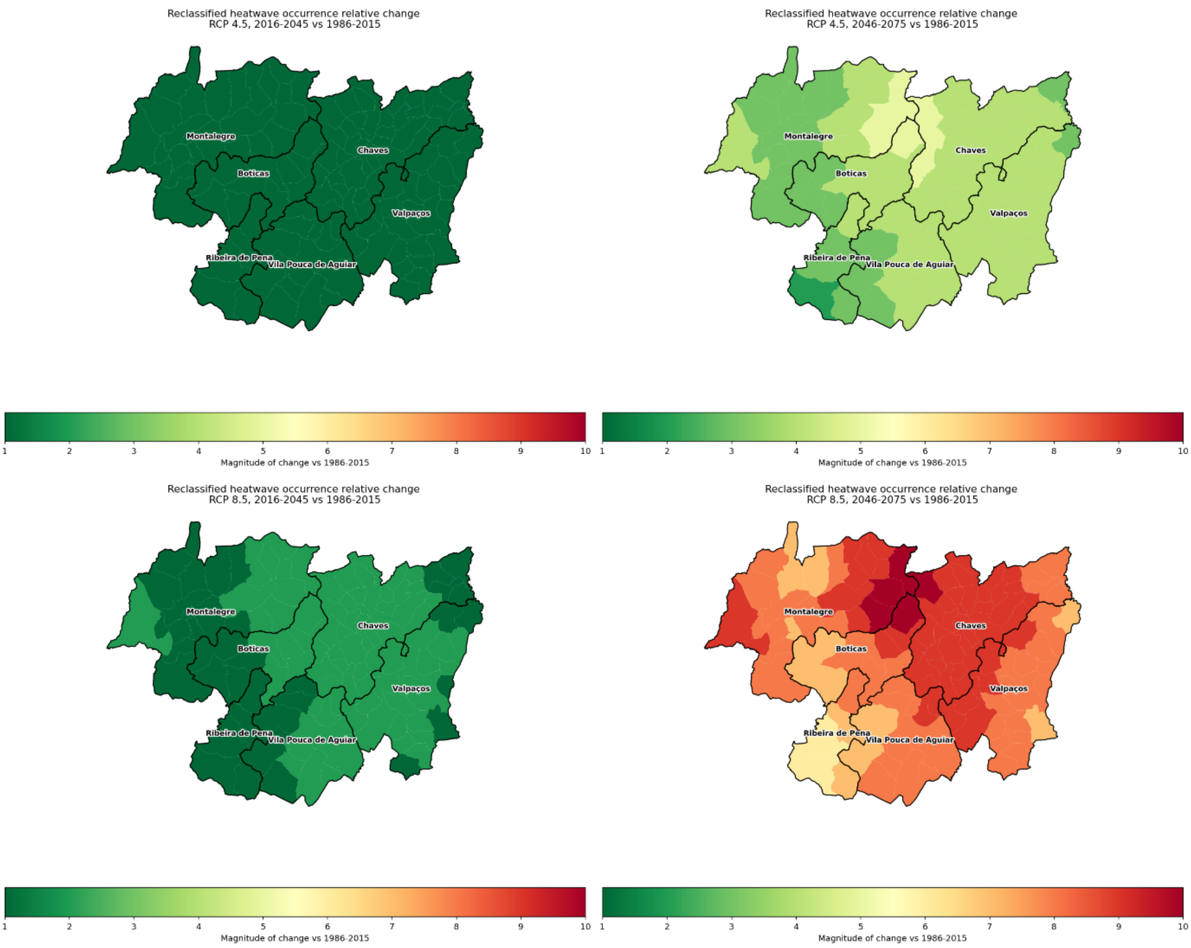


Figure 2-24 Reclassified magnitude of change (scale 1-10) in heatwave occurrence per parish, highlighting the highest hazard increase in the central-northern valley areas under future climate scenarios.

2.3.3.2 Risk assessment

The heatwave risk assessment in Phase 2 results from cross-referencing the climate hazard (already calibrated to IPMA thresholds) with the socioeconomic vulnerability of the territory.

The vulnerability analysis focused on the most critical age group, which presents the strongest epidemiological evidence of susceptibility and heat-related mortality: the elderly population (≥ 65 years). To ensure precision, the data were processed at the statistical subsection scale (preserving small, dense urban centers) and subsequently aggregated into the official civil parish geometry (CAOP 2022).

As the primary indicator of vulnerability, the elderly population density (elderly/km^2) was adopted and classified into 10 classes using the quantile method. The choice of quantiles (instead of equal intervals) was a crucial technical decision: it prevents high-density extremes (such as the civil parish of Santa Maria Maior in Chaves) from flattening the scale, thereby ensuring a territorially differentiated, legible, and useful map for prioritizing emergency and civil protection measures at the municipal level.

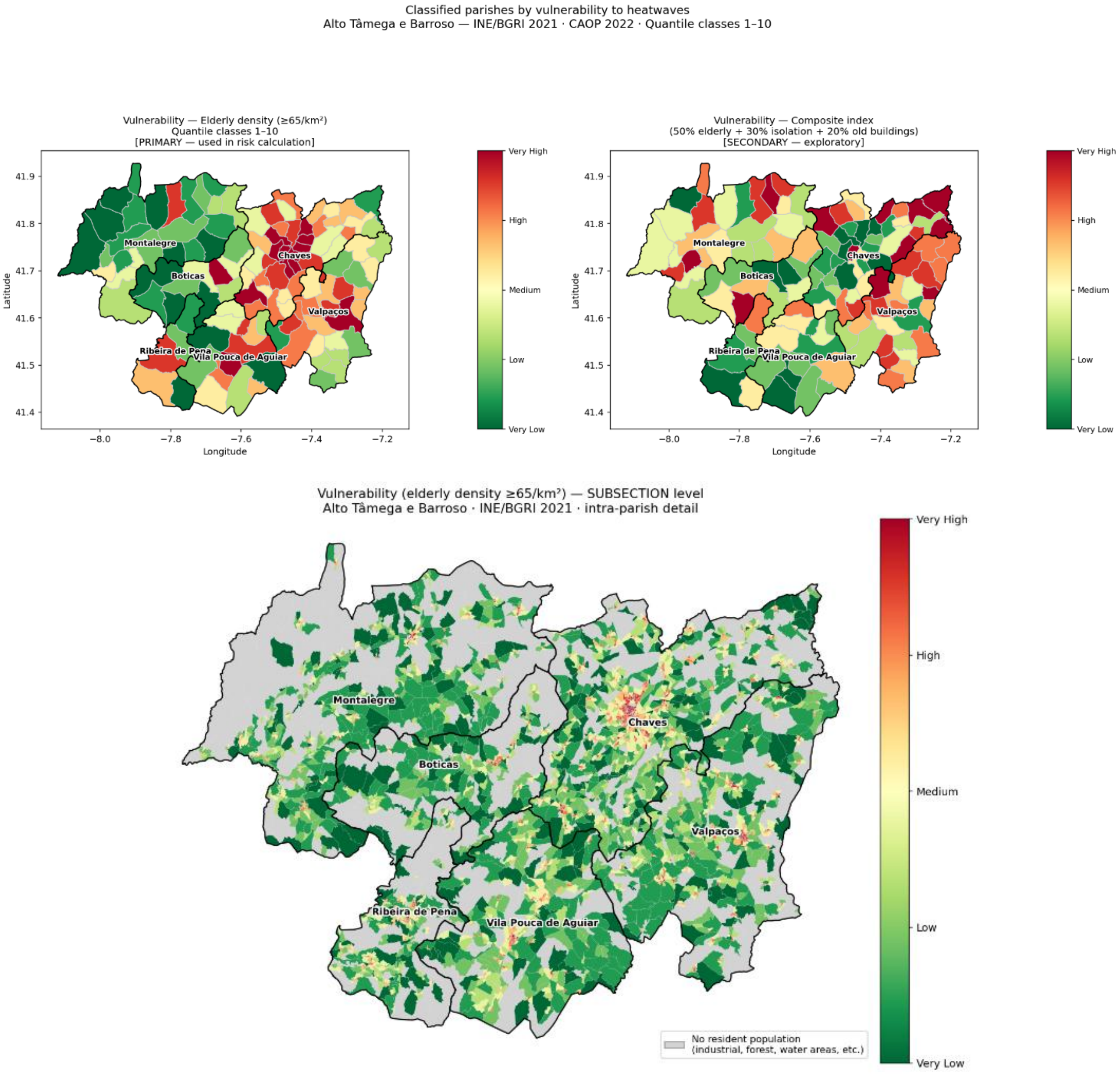


Figure 2-25 Spatial distribution of heatwave vulnerability in the Alto Tâmega e Barroso region, based on the density of the elderly population (≥65 years) (BGRI 2021). The panel presents the vulnerability classified by quantiles at the parish level (top) alongside the high-resolution intra-parish detail at the statistical subsection level (bottom).

The heatwave risk assessment coordinates two distinct spatial scales that complement each other without being merged.

The final risk was calculated by directly adding the climate hazard class (1 to 10) to the demographic vulnerability class (1 to 10), generating a risk index with a score ranging from 2 to 20.

The results reveal a strong spatial coherence stemming from the region's topographic contrast. The risk of extreme heat is heavily concentrated in the south-central/eastern part of the territory (the Chaves valley axis), where the highest climate hazard perfectly overlaps with the largest concentrations of elderly population. In contrast, the plateau areas in the southwest (such as Barroso and Montalegre), despite having highly aged populations, fall into lower overall risk classes because the thermal hazard (frequency of tropical days and nights) is substantially lower at high altitudes.

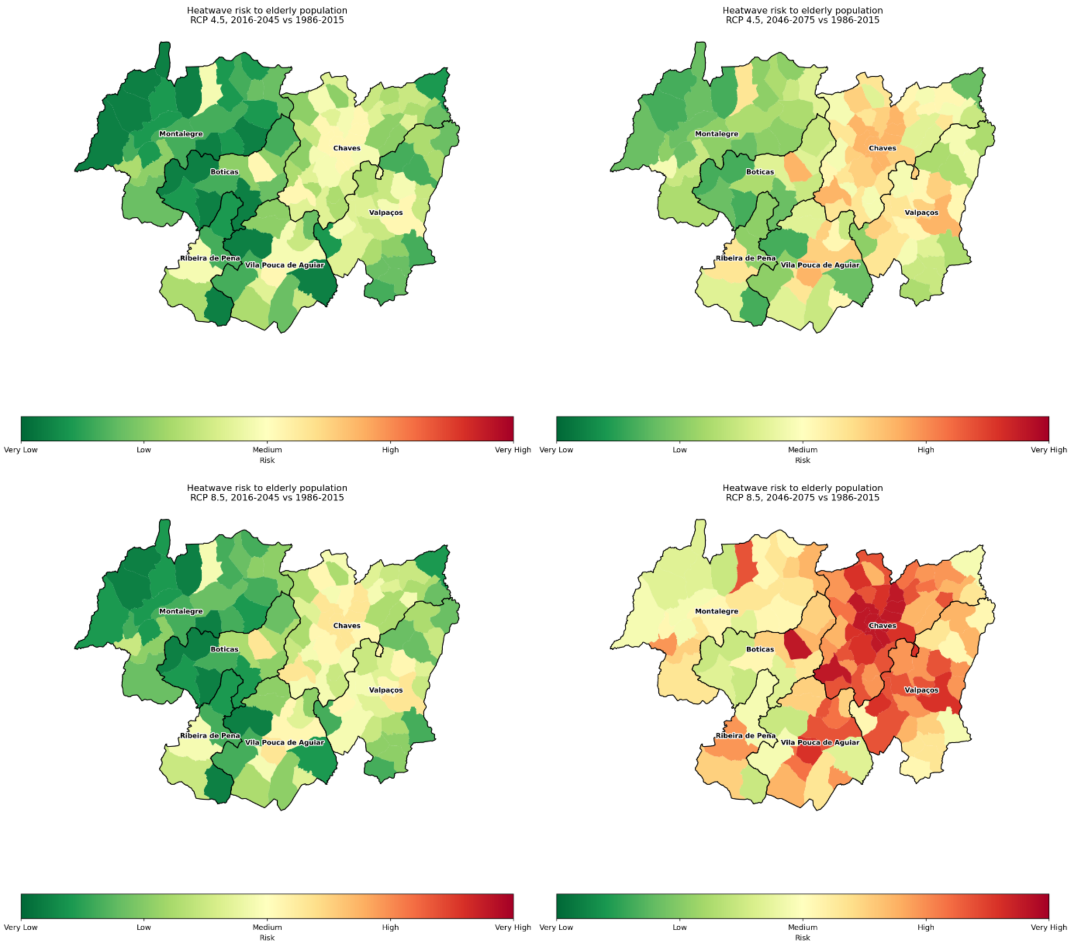


Figure 2-26 Projected heatwave risk at the parish level for Alto Tâmega e Barroso across future horizons (2016-2045 and 2046-2075) under RCP 4.5 and RCP 8.5 scenarios. The risk index (2-20) highlights the concentration of threat in the central valley axis.

The analysis of the most severe, long-term scenario (RCP 8.5 for the 2046–2075 horizon) demonstrates a dramatic worsening of risk (with classes ranging between 8 and 19). The assessment of the Top 15 civil parishes at highest risk underscores the weight of urban and valley zones. The municipality of Chaves heavily dominates the top of the ranking (occupying roughly 12 out of the 15 positions, with Santa Maria Maior at the absolute top). However, the municipal seats of the remaining councils (Boticas e Granja, Vila Pouca de Aguiar, Valpaços, and Sanfins) also emerge as risk hotspots, reinforcing the message that urban heat islands combined with an aging population represent the front line of municipal exposure.

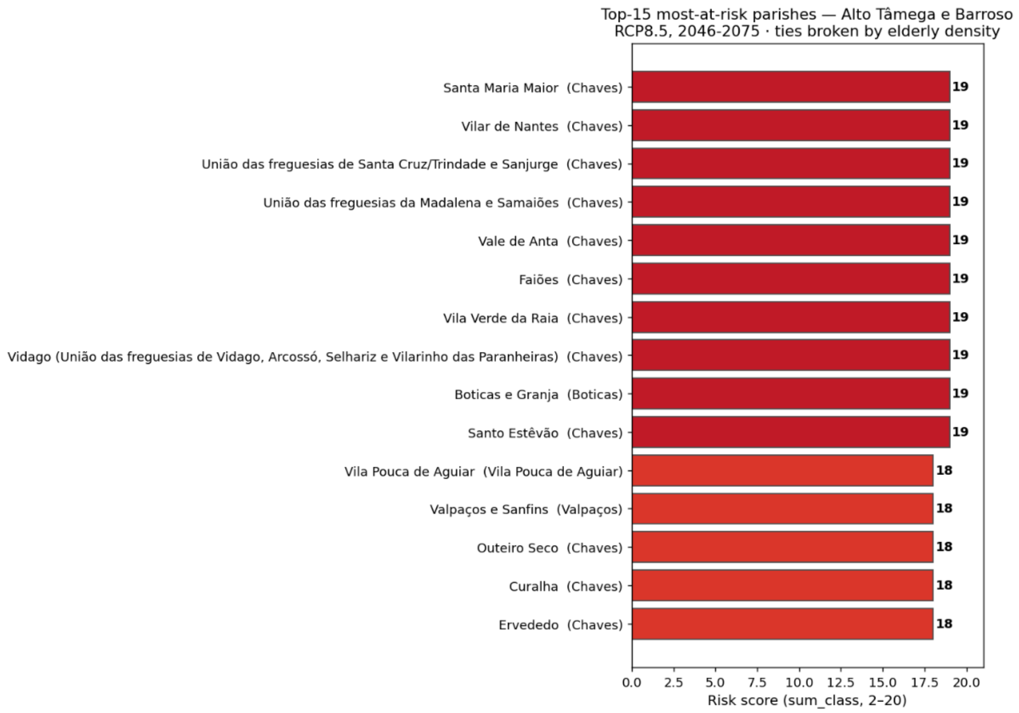


Figure 2-27 Top 15 parishes at highest risk of heatwaves under the worst-case scenario (RCP 8.5, 2046-2075) and a synthesized risk heatmap aggregated at the municipal level.

Observed Urban Heat: Satellite LST Analysis (Chaves)

While climate projections (EURO-CORDEX) provide insight into future regional trends, their native resolution (~12.5 km) is insufficient to capture the "urban heat island" effect at the street level. To bridge this gap and deliver concrete operational data, the risk assessment was complemented by a high-resolution (~100 meters) observational analysis based on satellite-derived Land Surface Temperature (LST). This analysis focused exclusively on the urban fabric of Chaves (~7x7 km), identified as the most densely populated and vulnerable cluster in the region.

To characterize the city's structural heat island, imagery from the Landsat 8/9 satellites (official Level-2 product obtained via the Microsoft Planetary Computer) captured during the severe heatwave of July 2022 was utilized. To prevent the analysis from reflecting a single day-to-day anomaly, the model adopted a multi-image strategy, combining four clear-sky scenes (July 7, 8, 23, and 31) and extracting the maximum temperature per pixel. The validation of this data showed surface temperatures ranging between 30.2 °C and 52.6 °C (with an average of 42.5 °C) on July 8, values that are perfectly consistent with the overheating of urban surfaces.

At this urban scale, census details could be fully leveraged. Vulnerability was calculated using the density of the elderly population (≥65 years) at the statistical subsection level (BGRI 2021), covering 537 subsections and 6,056 elderly residents within the study area. This vector layer was rasterized to match the satellite's thermal grid, enabling an exact cross-reference between heat exposure and the presence of this vulnerable population.

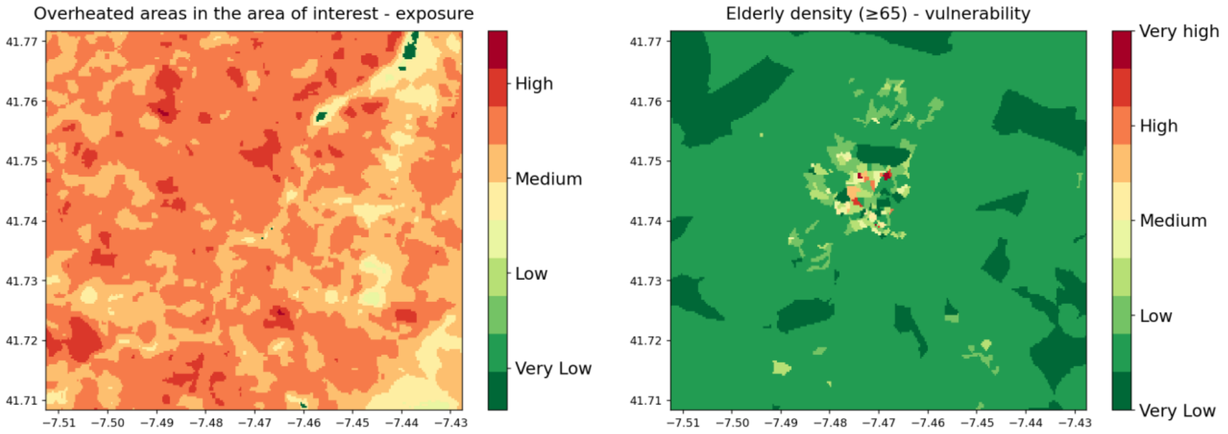


Figure 2-28 Comparison between Land Surface Temperature (LST) demonstrating the urban heat island effect and heatwave vulnerability (elderly population density) in the urban area of Chaves.

The final risk results from the summation of a matrix combining 10 LST classes with 10 elderly density classes. To translate this risk into tactical and response planning, the model overlaid the locations of critical infrastructure extracted from OpenStreetMap (OSM). The analysis primarily highlights the exposure of 4 elderly care facilities (nursing homes/day centers) and 19 healthcare facilities embedded within the urban fabric of Chaves.

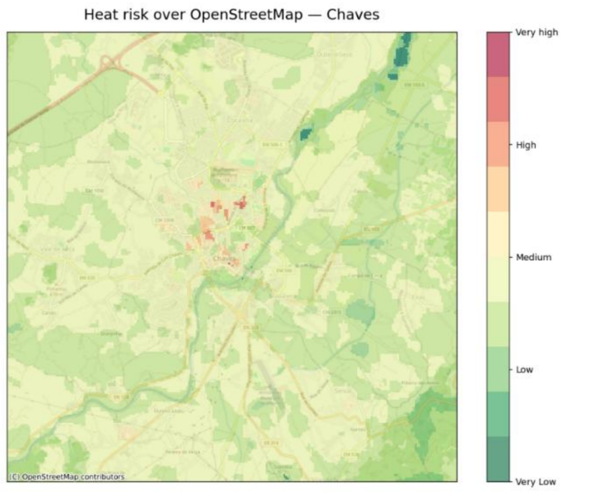


Figure 2-29 High-resolution urban heat risk in Chaves, highlighting the exposure of critical health and elderly care infrastructure over a geographical basemap.

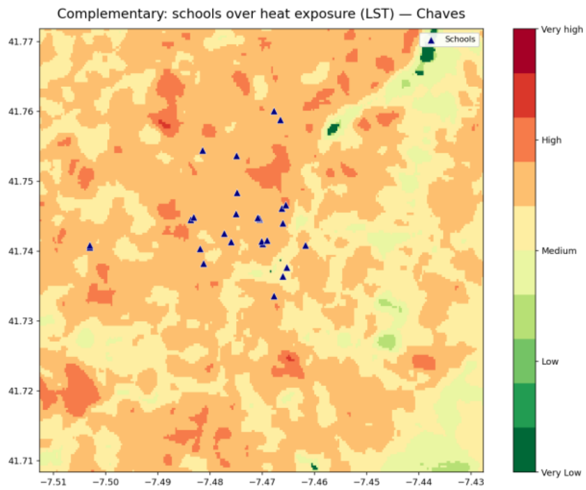


Figure 2-30 Complementary exploratory analysis: Exposure of educational facilities (schools) to structural urban heat islands (LST) in the city of Chaves.

As a complementary exploratory product, an isolated map was generated by cross-referencing the location of 27 schools (OSM) with the heat map (LST). This methodological separation is crucial: since children spend the hottest part of the day at school rather than at home, residential density would not serve as an accurate indicator for this specific group.

2.3.4 Hazard #4 – River Floods finetuning to local context

In Phase 1 (reference baseline), the river flood hazard and risk assessment relied exclusively on pan-European statistical databases from the JRC (at a coarse spatial resolution of approximately 80 meters) and the global Aqueduct Floods model. These datasets presented severe physical limitations over the alluvial channel of the Tâmega River and generated a systematic "lateral leakage" error over the Chaves valley, delivering indicative maps useful only for macro-regional framing but entirely lacking the orographic fidelity required to guide municipal Civil Protection actions.

In Phase 2, a profound structural replacement of this European statistical model was executed, integrating national and local ultra-high-resolution engineering models and datasets:

- **APA Hydrodynamic 2D Model (MIKE 21 FM):** Flood hazard modeling within the Area of Significant Potential Flood Risk (ARPSI) of Chaves was replaced with official hazard maps developed by the Portuguese Environment Agency (APA) under the Flood Risk Management Plan (PGRI RH3 2022-2027)[2]. This 2D hydrodynamic model is based on hydraulic calibration over high-density LiDAR topographic surveys (0.5-meter resolution).
- **Local Socioeconomic Recalibration (COS 2023):** The generic LUISA land-use map (~100m) was replaced with the official national Land Use Map at 10-meter resolution (**COS 2023, DGT**), reclassified into damage classes through a 71-class tactical equivalence matrix. Additionally, JRC economic damage curves were "portugalized" using a Regional Wealth Factor (**0.797**) – derived from Alto Tâmega's actual 2010 GDP per capita (**€10,907**) – and adjusted for 2024 inflation using Statistics Portugal's (INE) Consumer Price Index (CPI deflator of **1.3176**).
- **Granular Human Safety (Censos BGRI 2021):** The global WorldPop population grid was completely replaced with official national census tracts from the **BGRI 2021 (INE)** at the statistical subsection level, enabling the precise estimation of exposed and displaced residents (using a critical life-safety water depth threshold of >1.0 m).

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Hazard Model	Pan-European statistical model (JRC v3).	Physics-based 2D hydrodynamic model (MIKE 21 FM, APA).
Spatial Resolution	~80m (JRC River Flood Hazard Maps).	Operational 10-meter grid (950,177 grid cells).
Topographic Data (DEM)	Low vertical resolution EU-DEM / SRTM.	High-resolution 0.5-meter LiDAR topographic survey (DGT / Municipality).
Future Climate Forcing	Global-scale Aqueduct Floods (~300–750 m).	Frequency-shift method derived from the SMHI E-HYPEcatch hydrological model.
Land Use (Exposure)	Continuous European LUISA map (~100 m).	Official COS 2023 (DGT) rasterized at 10-meter resolution.
Demographic Exposure	Estimated global densities from WorldPop / GHS-POP.	Official Census data at the BGRI 2021 statistical subsection level (INE).
Financial Calibration	Generic European replacement baseline values (Huizinga).	Regionalization based on native PT11B GDP (€10,907) and 2024 INE CPI deflator (1.3176).

Key improvements include:

- **Elimination of Physical Leakage Errors**: The 2D APA hydraulic modeling on 0.5m LiDAR vertical data resolved the false slope floodings detected in Phase 1, confining the flood footprint strictly to the actual floodplain of the Tâmega River.
- **Outstanding Empirical Validation (2% Deviation)**: For the 100-year return period (T=100), the model estimated 2,348 exposed residents, representing a deviation of merely 2% compared to the official historical baseline of 2,301 inhabitants referenced by the APA in Chaves' official ARPSI datasheet, confirming the demographic accuracy of the downscaled model.

[2] Formally approved by Council of Ministers Resolution No. 63/2024.

- **Dual-Scale Independent Modeling**: Structural distinction between Workflow 02 (macro, financial losses on land-use parcel areas using COS 2023) and Workflow 03 (micro, structural building-by-building damage on OpenStreetMap footprints), preventing urban damage overestimation by separating real physical buildings from open yards and arruements.
- **Consolidated Economic Harmonization**: The integration of the local €10,907 GDP per capita and the 1.3176 CPI deflator in both modeling workflows ensured absolute financial consistency, guaranteeing that all flood loss estimates are reported under contemporary Portuguese monetary baselines.

Table 2-5 Data overview workflow #4 – River Floods

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **Hydrodynamics (APA PGRI RH3):** Official inundation depths (MIKE 21 FM; T=20, 100, and 1000) generated over Chaves ARPSI based on 0.5m municipal LiDAR. · **Regional Hazard (JRC v3):** Pan-European statistical river flood maps (~80m resolution) for return periods of 10, 50, 100, 200, and 500 years for territorial context. · **Projected Discharge (SMHI E-HYPEcatch):** Projected daily future discharge and peak flows for the 2050 horizon under RCP 4.5 and RCP 8.5 scenarios. · **Frequency-Shift:** Statistical conversion (*frequency-shift*) of E-HYPEcatch hydrological simulations into future return periods.	· **JRC Damage Functions:** European depth-damage curves (Huizinga) applied to municipal building stocks and land use classes. · **Socioeconomic Calibration (INE):** CIMAT real 2010 GDP (**€10,907**; Regional Wealth Factor of **0.797**) and 2024 Consumer Price Index (CPI) deflator of 1.3176. · **Human Safety:** Critical threshold of direct risk-to-life defined as water depth exceeding 1.0 m.	· **Land Use (COS 2023 DGT):** National land cover at 10m mapped to LUISA damage categories via a 71-class tactical crosswalk. · **Building Footprints (OSM):** Individual geometries of municipal buildings intersected with simulated water depths in Chaves. · **Fine Population (BGRI 2021 INE):** Resident census counts processed at the scale of statistical subsections within Chaves.	· **Land-Use Damage:** Asset losses under T=100 (€260M total; €139M urban and €117M agriculture in Chaves) and regional damage maps. · **Structural Damage (Chaves):** Building-by-building direct damage estimates under T=100 (~€86.0M) and Expected Annual Damage (EAD: ~€3.86M/year). · **Human Displacement (Chaves):** Estimated 2,348 exposed and 1,553 displaced residents under T=100, and Expected Annual People Displaced (EAPD: ~69/year). · **Demographic Validation (APA):** Agreement with merely 2% deviation compared to the official PGRI reference for Chaves ARPSI (2,348 exposed vs. 2,301 APA).

2.3.4.1 Hazard assessment

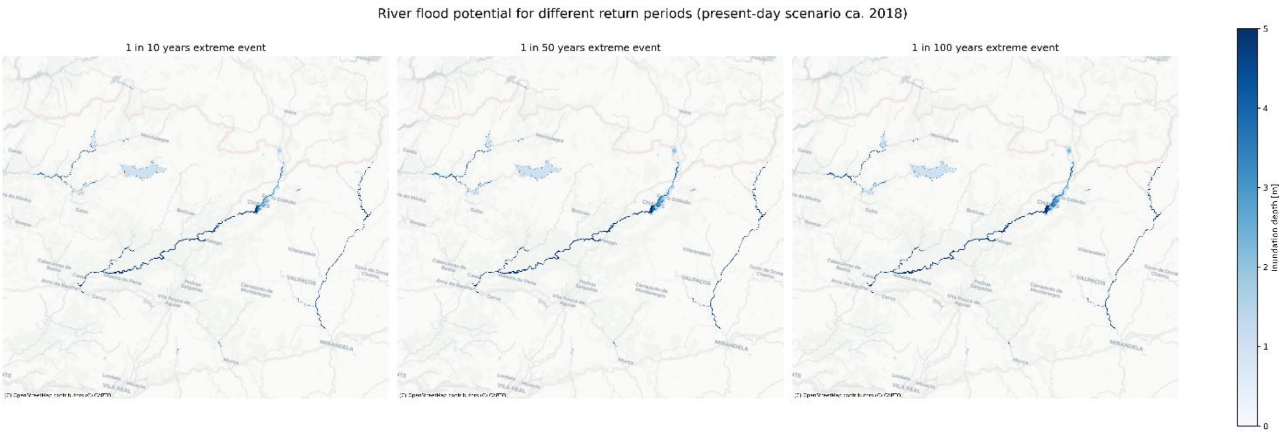
To ensure that the hazard assessment complies with tactical planning criteria and municipal utility, the analysis adopted an approach proportional to the quality of the available data, dividing the river flood hazard assessment into two scalar focuses: the macro-regional overview (NUTS III) and the detailed urban analysis (Chaves).

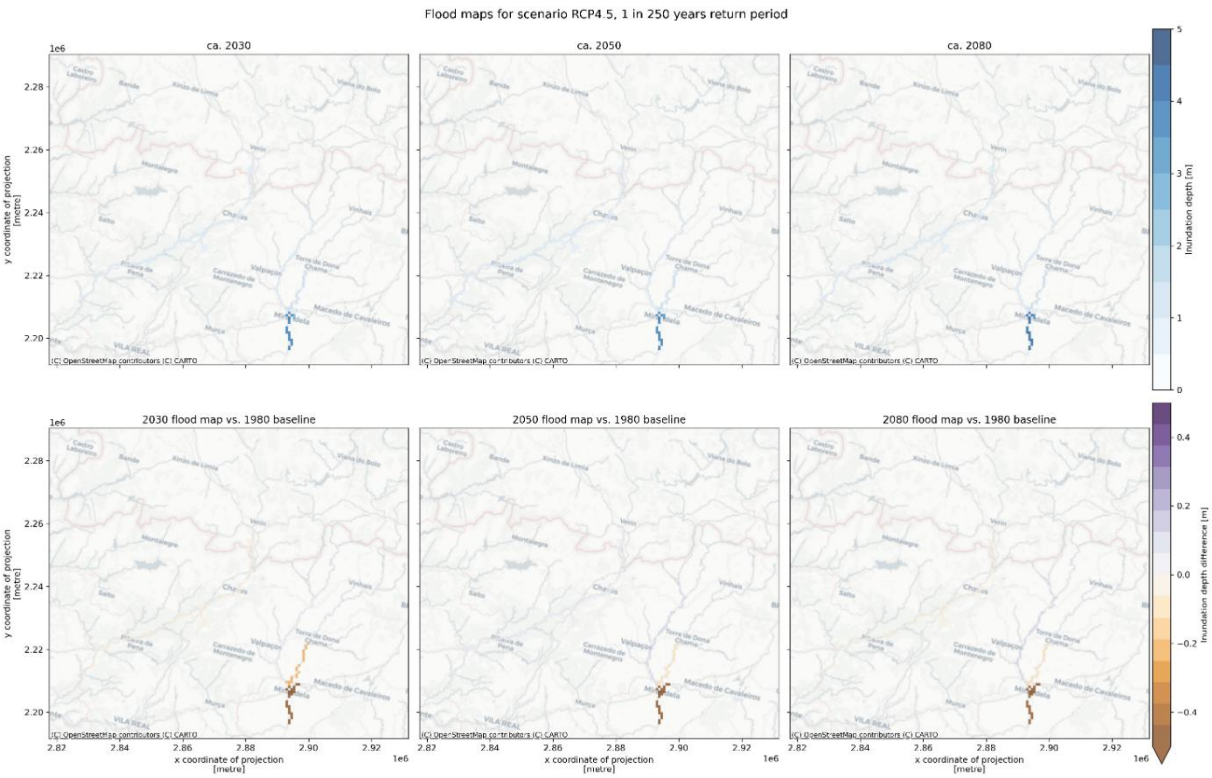
A. Regional Overview (Alto Tâmega e Barroso – JRC and Aqueduct)

At the regional level, the JRC baseline model (*River Flood Hazard Maps*) was retained to provide the macro-territorial context and the historical baseline scenario. For future climate projections across this vast scale, data from the Aqueduct Floods model were utilized under the RCP 4.5 and RCP 8.5 scenarios.

The frequency-shift replacement of Aqueduct (described below) was applied only to the Chaves tactical run, where APA hydrodynamic hazard and E-HYPEcatch discharge are available; at the regional scale Aqueduct is retained solely as a coarse, indicative benchmark.

Although they possess a coarser resolution, the integration of these models makes it possible to visualize the macro-distribution and progression of the hazard footprint along the entire Tâmega Valley and the remaining basins within the NUTS III region, serving as a comparative benchmark.





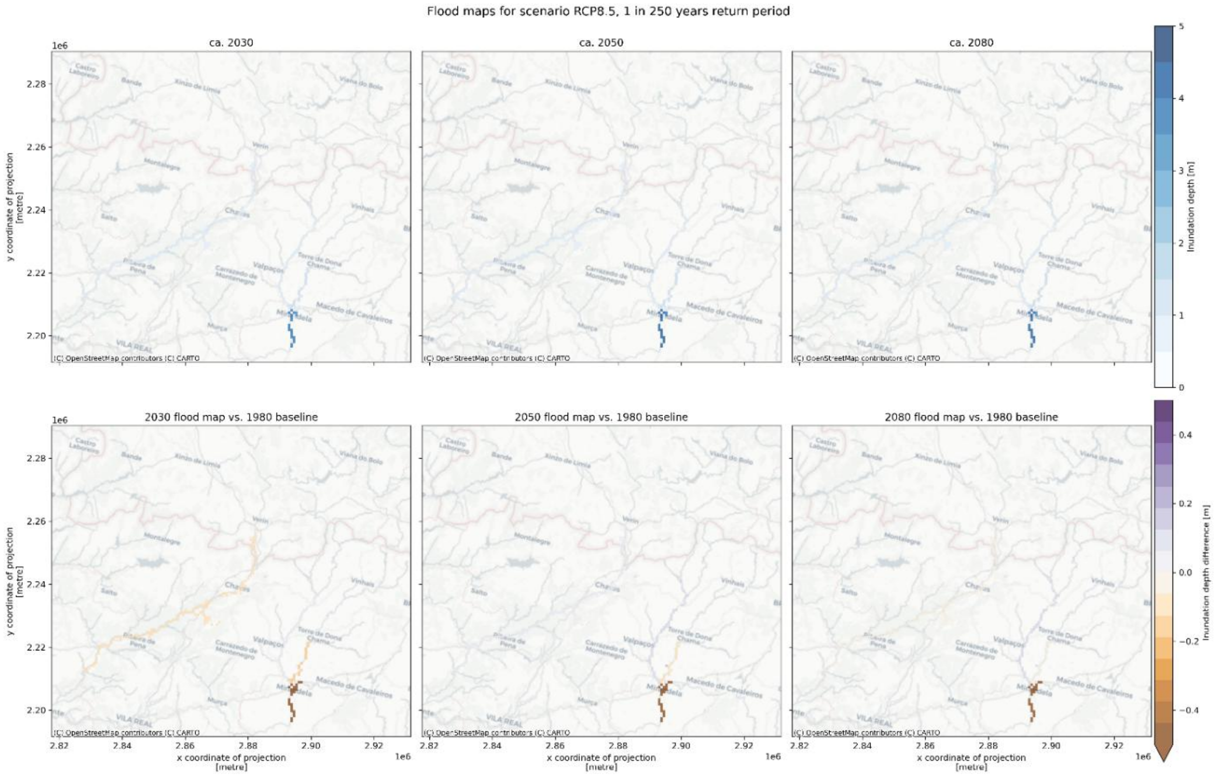


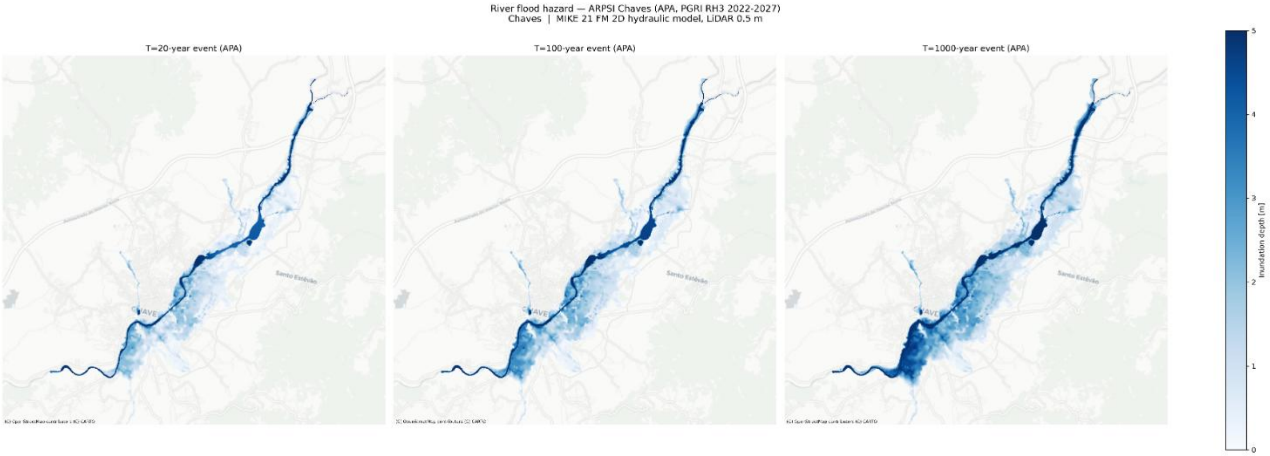
Figure 2-31 Regional River flood hazard overview for Alto Tâmega e Barroso, illustrating the present-day baseline (JRC) alongside future projections under RCP 4.5 and RCP 8.5 scenarios (Aqueduct Floods).

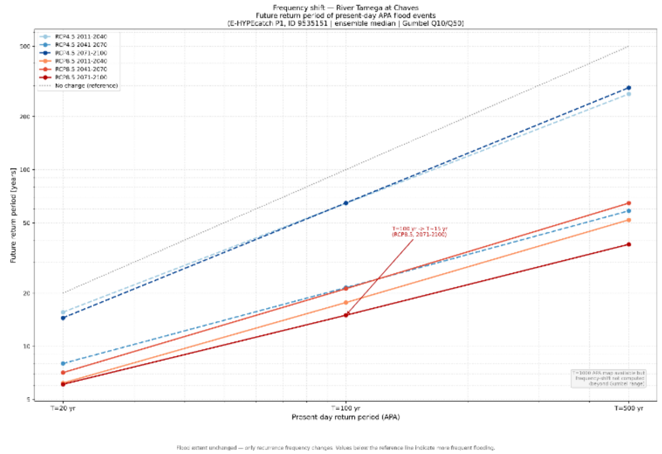
B. Urban Detail (Chaves – APA and Frequency-Shift Method)

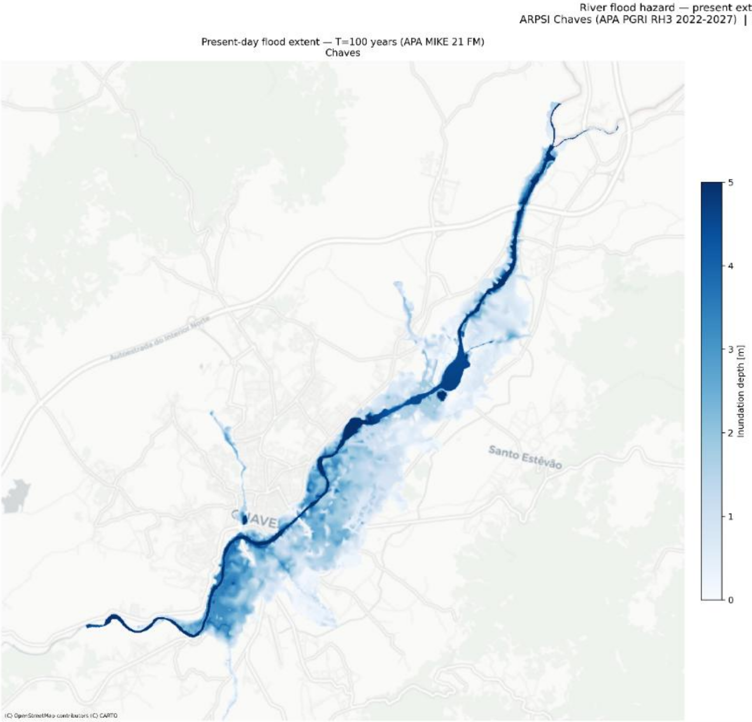
The truly refined, tactical evaluation (the *Chaves detail run*) focused on the Area of Significant Potential Flood Risk (ARPSI) of Chaves. To achieve this, the European statistical approximation was abandoned in favor of the official two-dimensional hydrodynamic model from the Portuguese Environment Agency (MIKE 21 FM), modeled over the municipality's 0.5-meter LiDAR DEM.

This shift transformed the nature of the hazard data from a "generic statistical estimate" to a "physically proven" flood extent, operating at a tactical resolution of approximately 10 meters. The APA model provides the exact flood footprint for historical return periods of 20, 100, and 1,000 years.

Regarding the future impact of climate change on the Chaves urban fabric, the uncertainty of the Aqueduct model was replaced by the rigorous frequency-shift method, sustained by river flow projections from the SMHI E-HYPEcatch (Copernicus) model. Assuming spatial stationarity of the flood pattern, the modeling mathematically proved the worsening of the threat: under the high-emissions scenario (RCP 8.5) for the 2071–2100 horizon, an extreme event that currently occurs once every 100 years (T=100) will have a return period of approximately 15 years, becoming ~6.7 times more frequent.







Future return period of present-day flood events
(E-HYPEcatch P1, ID 9535151 | Gumbel Q10/Q50 | ensemble median)

Present RP	RCP4.5 2011-2040	RCP4.5 2041-2070	RCP4.5 2071-2100	RCP8.5 2011-2040	RCP8.5 2041-2070	RCP8.5 2071-2100
T=20 years	~16 yr	~8 yr	~14 yr	~6 yr	~7 yr	~6 yr
T=100 years	~64 yr	~22 yr	~65 yr	~18 yr	~21 yr	~15 yr
T=500 years	~268 yr	~58 yr	~291 yr	~52 yr	~65 yr	~38 yr

T=1000 years | APA hydraulic map available — frequency-shift not computed (beyond Gumbel range)

Flood extent and depth unchanged — only recurrence frequency changes. Spatial pattern assumed stationary. Values: ensemble median of 6 GCM-RCM pairs.

Figure 2-32 High-resolution River flood hazard for the Chaves urban area derived from APA 2D hydraulic models (T=100), alongside the frequency-shift table and log-log chart detailing the acceleration of extreme events under future climate scenarios.

2.3.4.2 Risk assessment

The river flood risk assessment has transitioned from a generic European estimate to an exact quantification, supported by the future hydrological dynamics of the Tâmega basin and the economic reality of Trás-os-Montes. The risk was evaluated across two complementary dimensions: the worsening of flow dynamics (water volume and frequency) and the tactical quantification of the generated economic damage within the territory.

A. Hydrological Dynamics and Worsening of Risk (River Discharge)

Before quantifying financial damages, the workflow evaluated the progression of the baseline hydrological risk using river flow modeling (*River Discharge Analysis*). This analysis focused on the catchment basins of Chaves and the main axis of the Tâmega River.

Comparing the historical baseline (1991–2005) with future projections for Periods 1 and 2 (P1 and P2), the modeling highlights a structural alteration in the river's regime, which acts as the primary driver of the worsening risk:

- **Seasonality and Monthly Means:** The analysis of monthly means (*monthly_means*) reveals a shift in the temporal distribution and flow peaks during critical winter months, increasing pressure on the main riverbed within the Veiga de Chaves.
- **Duration Curves and Extremes:** The flow-duration curves (*flow-duration_curve*) and absolute extreme metrics (*extremes_absolute_values*) prove a significant increase in both the magnitude and exceedance probability of extreme flood events in future projections. This increase in hydrological volume provides the physical justification supporting the altered return frequencies of flood events.

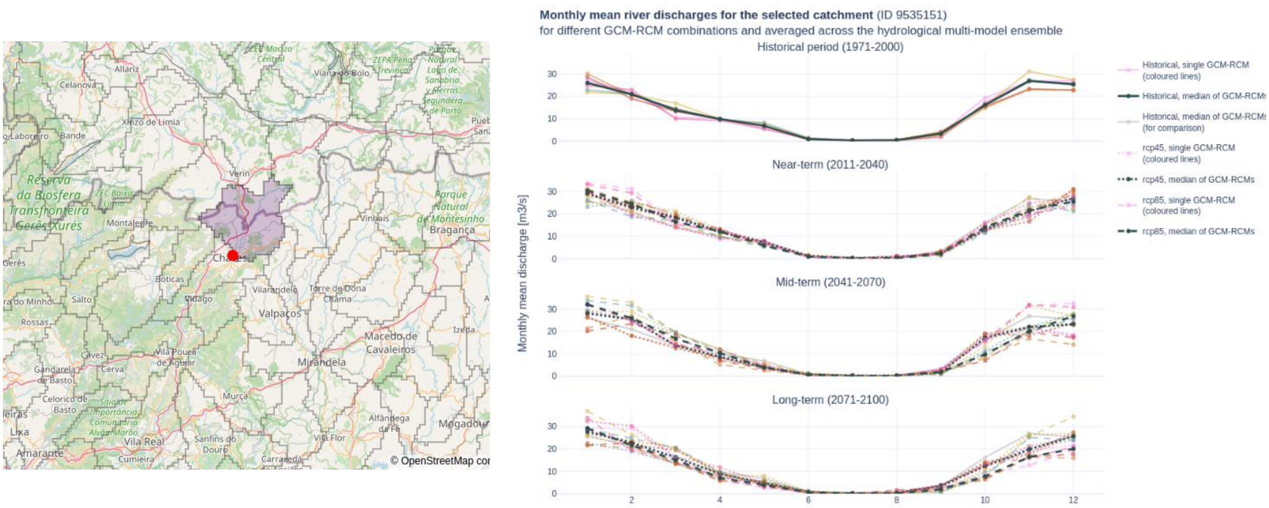


Figure 2-33 Hydrological risk context: Catchment area for the Chaves sub-basin (left) and projected shifts in monthly mean river discharge from the historical baseline to future scenarios (right).

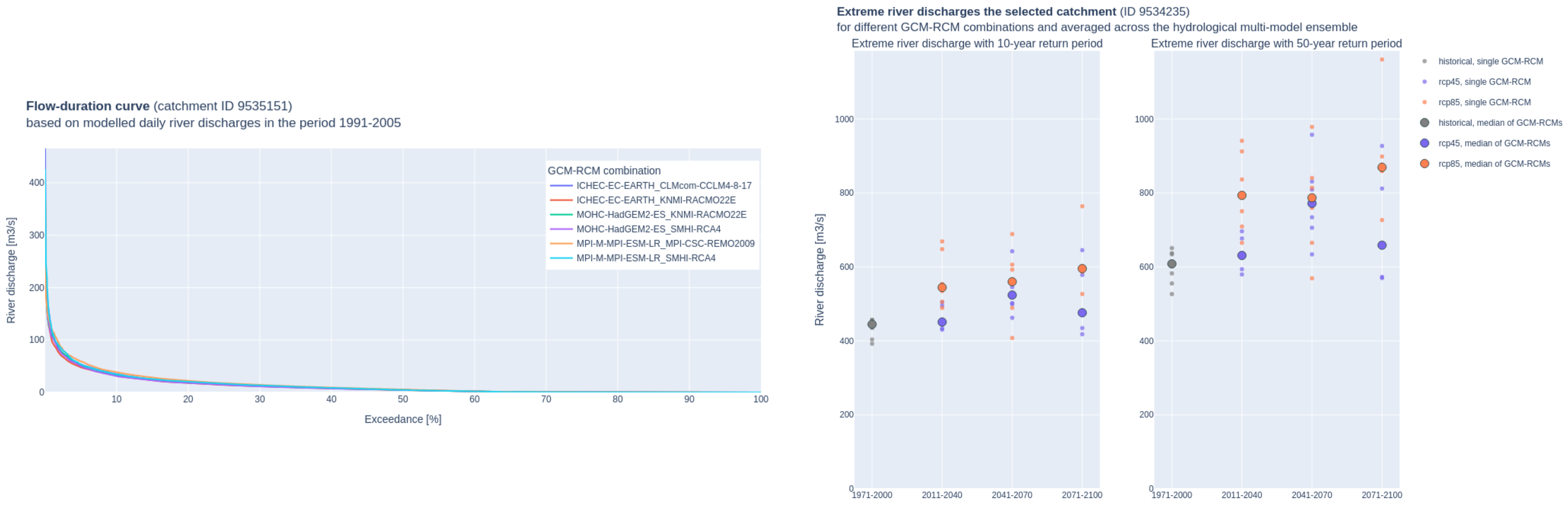


Figure 2-34 Exceedance probability and extreme discharge values, illustrating the intensification of peak flows and extreme water volumes in future climate scenarios (P2) compared to the historical baseline.

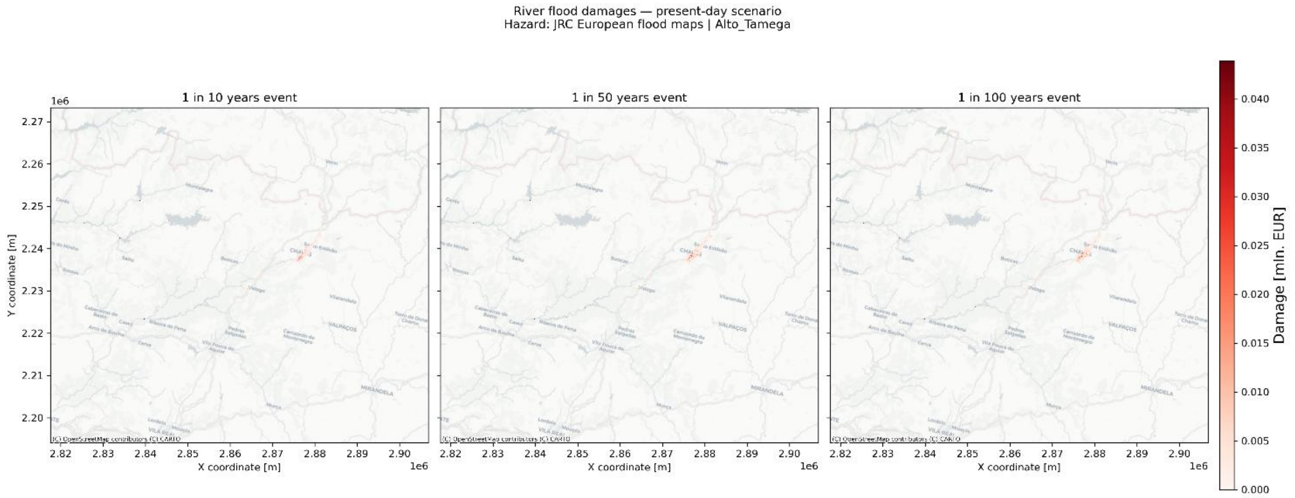
B. Land Use-Based Economic Damage Analysis (COS 2023)

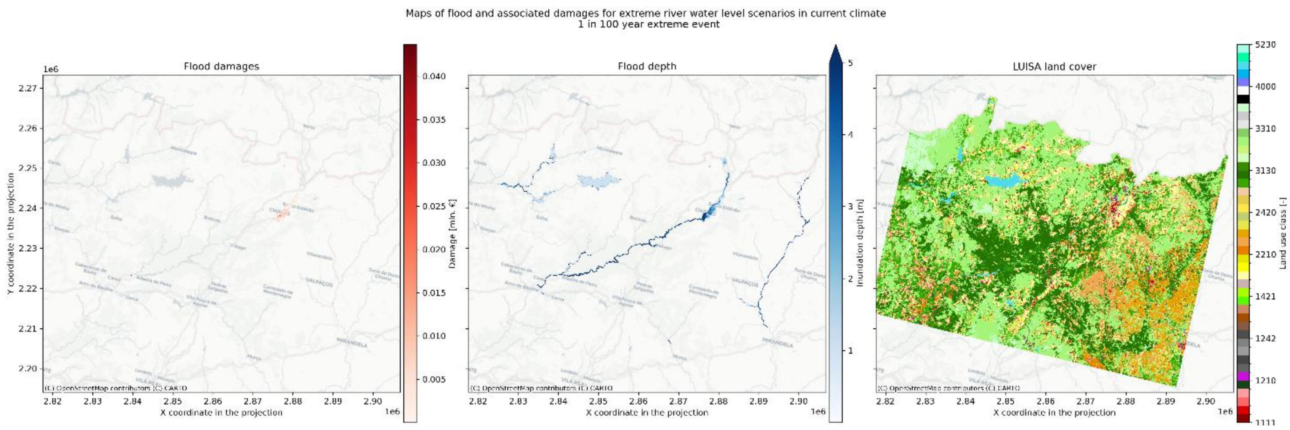
To translate this hydrological worsening into actual financial risk, the European land-use mapping (LUISA) was fully replaced by the Portuguese Land Use and Land Cover Map (COS 2023 at 10m) through a 71-class tactical equivalence matrix.

The economic parameterization (Huizinga depth-damage curves) underwent a deep local calibration: the native GDP per capita of NUTS III Alto Tâmega e Barroso (€10,907, under the formula's 2010 baseline year) generated a "Regional Wealth Factor" of 0.797, correcting the European estimates that were disconnected from the reality of Trás-os-Montes. Subsequently, to update these values to real-world 2024 reconstruction costs, the Portuguese Consumer Price Index (CPI) was applied (1.3176 inflation factor).

To guarantee territorial consistency, economic damage was modeled at two separate scales:

1. **Regional Overview (Alto Tâmega e Barroso):** By running the model over the JRC global hazard footprints, a macro-regional risk quantification was obtained for the entire NUTS III region. The impact demonstrates a heavy agricultural damage component distributed along the region's river axes. At the 100-year return period, the aggregated regional damage reaches around €731 million, of which roughly 45% falls on agriculture — well above the urban share — reflecting the agroforestry exposure of the wider Tâmega Valley.



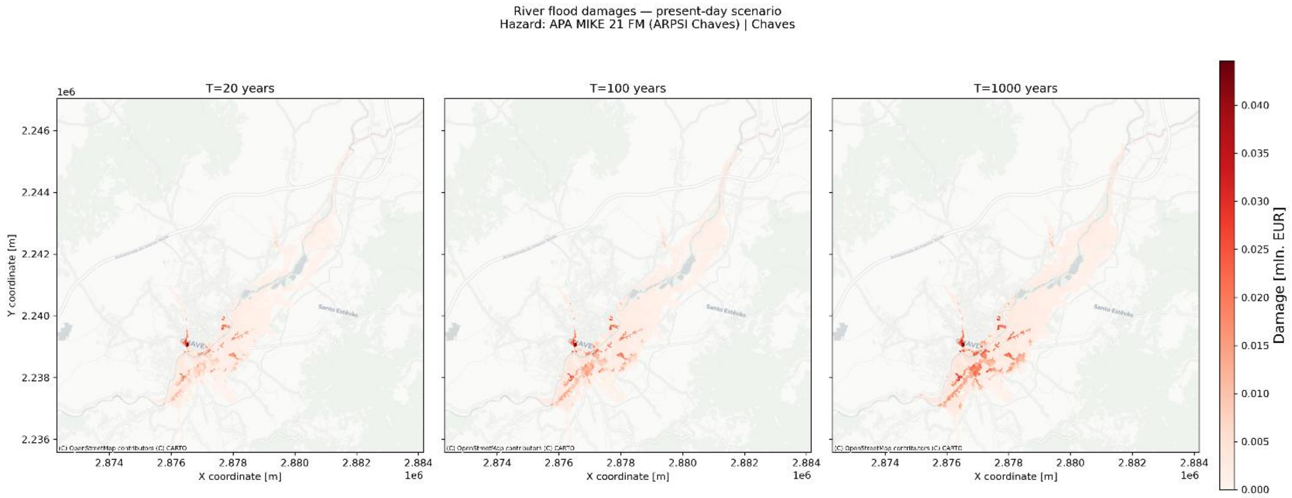


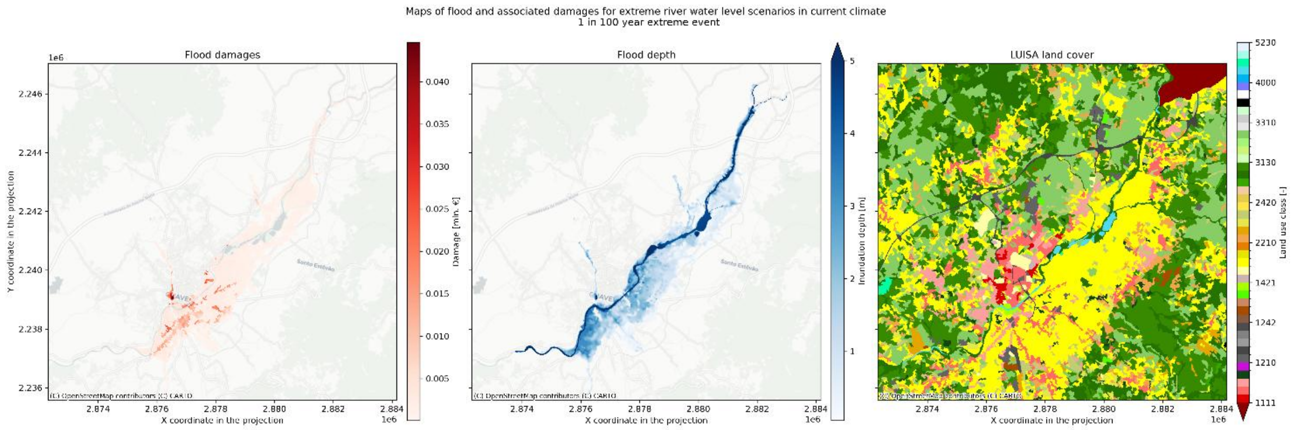
```
================================================================
DAMAGE BY REPORTING PARCEL – Alto Tamega e Barroso (regional extent (JRC context))
================================================================
Parcel                                          RP10      RP50     RP100     RP200     RP500
-----------------------------------------------------------------------------------------------
Urban & built-up (LUISA 1xxx)                 213.44M   268.41M   283.76M   302.32M   321.03M
Agriculture & agroforestry (LUISA 2xxx)       259.85M   312.67M   331.08M   348.37M   367.77M
Forest & natural vegetation (LUISA 3xxx)      105.81M   113.88M   116.31M   119.00M   122.31M
Water bodies (LUISA 5xxx)                       0.00M     0.00M     0.00M     0.00M     0.00M
-----------------------------------------------------------------------------------------------
TOTAL                                         579.10M   694.96M   731.15M   769.70M   811.11M
```

Figure 2-35 Regional economic risk assessment for river floods in Alto Tâmega e Barroso, presenting the aggregated damage overview, spatial distribution for the 100-year return period, and damage categorization per land use parcel.

2. Tactical Detail Overview (Chaves ARPSI): In the detailed assessment for the Chaves ARPSI (crossing the COS 2023 urban fabric with the official APA flood footprint), the restrictive precision of the hydrodynamic model projects a more accurate financial impact. Under an event associated with a 100-year Return Period (T=100), the estimated land-use losses reach €260 million. The structure of this damage illustrates the territory's exposure matrix:

- **Agriculture (~€117M | 45% of damage):** The Veiga de Chaves sustains the greatest territorial impact (26.7% of the flooded area). It should be noted, however, that the model may still slightly overestimate the arable crops in this area relative to their actual market values.
- **Urban Built Environment (~€139M | 53% of damage):** The consolidated urban fabric of Chaves accounts for only 7% of the physical flooded area but is responsible for the largest share (about 53%) of the total financial impact, highlighting the extremely high unit cost of urban exposure. Under an absolute extreme scenario (T=1,000), the total local damage would rise to €363 million.





```
=================================================================
DAMAGE BY REPORTING PARCEL — Alto Tamega e Barroso (ARPSI Chaves)
=================================================================
Parcel                                          RP20     RP100    RP1000
--------------------------------------------------------------------------
Urban & built-up (LUISA 1xxx)                 95.61M   138.79M   198.42M
Agriculture & agroforestry (LUISA 2xxx)       83.25M   116.87M   158.02M
Forest & natural vegetation (LUISA 3xxx)       3.28M     4.41M     6.06M
Water bodies (LUISA 5xxx)                      0.00M     0.00M     0.00M
--------------------------------------------------------------------------
TOTAL                                        182.13M   260.07M   362.50M

Reference (APA PGRI RH3 ficha, T100):
  Population affected : 2 301 inhabitants
  Establishments      : 2 212
  Urban damage share  : 53.4% of T100 total
```

Figure 2-36 High-resolution tactical risk assessment for the Chaves ARPSI, highlighting massive economic exposure driven by urban fabric (T=100), alongside categorical damage breakdown and spatial mapping.

2.3.4.3 Flood building damage and population exposure (Complementary Workflow)

Assuming that a Risk Assessment must have a direct application in Civil Protection operational planning, the project implemented a complementary workflow focused exclusively on safeguarding human life and structural integrity at the building scale, applied to the Area of Significant Potential Flood Risk (ARPSI) of Chaves.

This methodological decision is justified by the exclusive availability of official high-resolution 2D hydrodynamic hazard data (APA's MIKE 21 FM model, calibrated over Chaves Municipality's 0.5 m LiDAR topographic survey), which is the only dataset in the territory capable of supporting a building-by-building analysis with scientific rigor. For the remaining five municipalities of CIMAT, flood risk is evaluated at the land-use parcel scale using JRC area hazard maps, preventing low-confidence building-level extrapolations in areas where validated local hydraulic models are unavailable.

The major methodological innovation of this complementary assessment was the exact crossing of water depths from the official APA hydrodynamic model with building geometries extracted from OpenStreetMap (OSM) and Portugal's high-precision census geometry (Geographical Information Reference Base – BGRI 2021 from INE), operating at the statistical subsection level.

A. Damage to the Built Environment, Critical Infrastructure, and Aggregated Risk (EAD)

The transition to the building scale allowed for the isolation of structural damage and the vital services network. The analysis revealed that, for an extreme event with a 100-year return period (T=100), losses strictly allocated to building superstructures settle at approximately €86.0 million. In an absolute extreme scenario ($T=1,000$), this value rises to €122.7 million.

Integrating these values across all probabilities generates an Aggregated Risk (Expected Annual Damage – EAD) of approximately €3.86 million annually. The high level of reliability of this result is consolidated by being perfectly aligned, in terms of order of magnitude, with the urban land-use analysis carried out in the previous workflow (evaluated at €139M), with the slight difference being justified by the fact that this method strictly accounts for building footprints and not the interstitial public space.

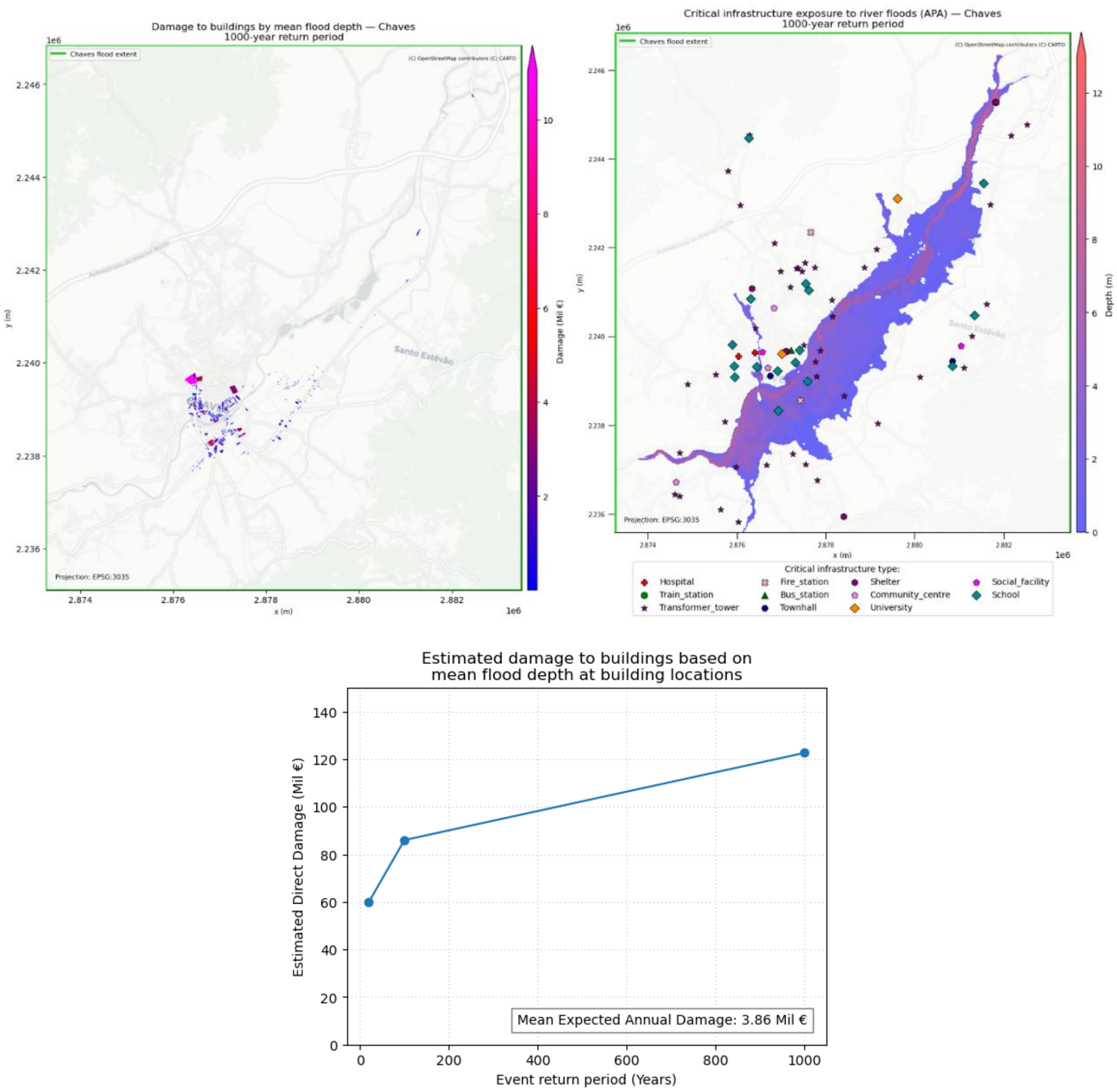


Figure 2-37 High-resolution structural impact in Chaves. The panel illustrates the spatial distribution of building damage and exposed critical infrastructure for a 1000-year return period, supported by the Expected Annual Damage (EAD) curve.

B. Demographic Exposure, Displacement, and Official Validation

To quantify the critical risk to human life and the loss of habitability, metrics for exposed individuals and Displaced Population were extracted. A flood depth exceeding 1.0 meter was adopted as the critical safety threshold, the level at which the viability and safety of residential ground floors are assumed to be lost.

The reliability of this demographic assessment was independently confirmed with an unparalleled level of precision. The local CLIMAAX_AT model estimated 2,348 exposed residents under a $T=100$ event. Comparing this figure with the official technical datasheet of the APA's PGRI (which defines the impact for the same scenario at 2,301 residents), the modeling achieves a near-perfect agreement, recording a deviation of merely 2%. This result unequivocally attests to the quality of the calibration performed using the census data (BGRI 2021).

From an emergency planning and displacement perspective:

- **High-Frequency Scenario ($T=20$):** The model estimates the exposure of 2,100 people and the displacement of 1,086 citizens.

- **100-Year Extreme Scenario ($T=100$):** There are 2,348 exposed individuals, which would force the severe displacement of **1,553 citizens** due to severe flooding (>1.0m) of their homes. In the 1,000-year worst-case scenario, this number rises to 1,988 displaced individuals.
- **Annualized and Long-Term Aggregated Metrics:** Continuous exposure of approximately 111 people/year is expected, which translates into an operational metric of 69 people requiring displacement per year (EAPD – *Expected Annual People Displaced*).

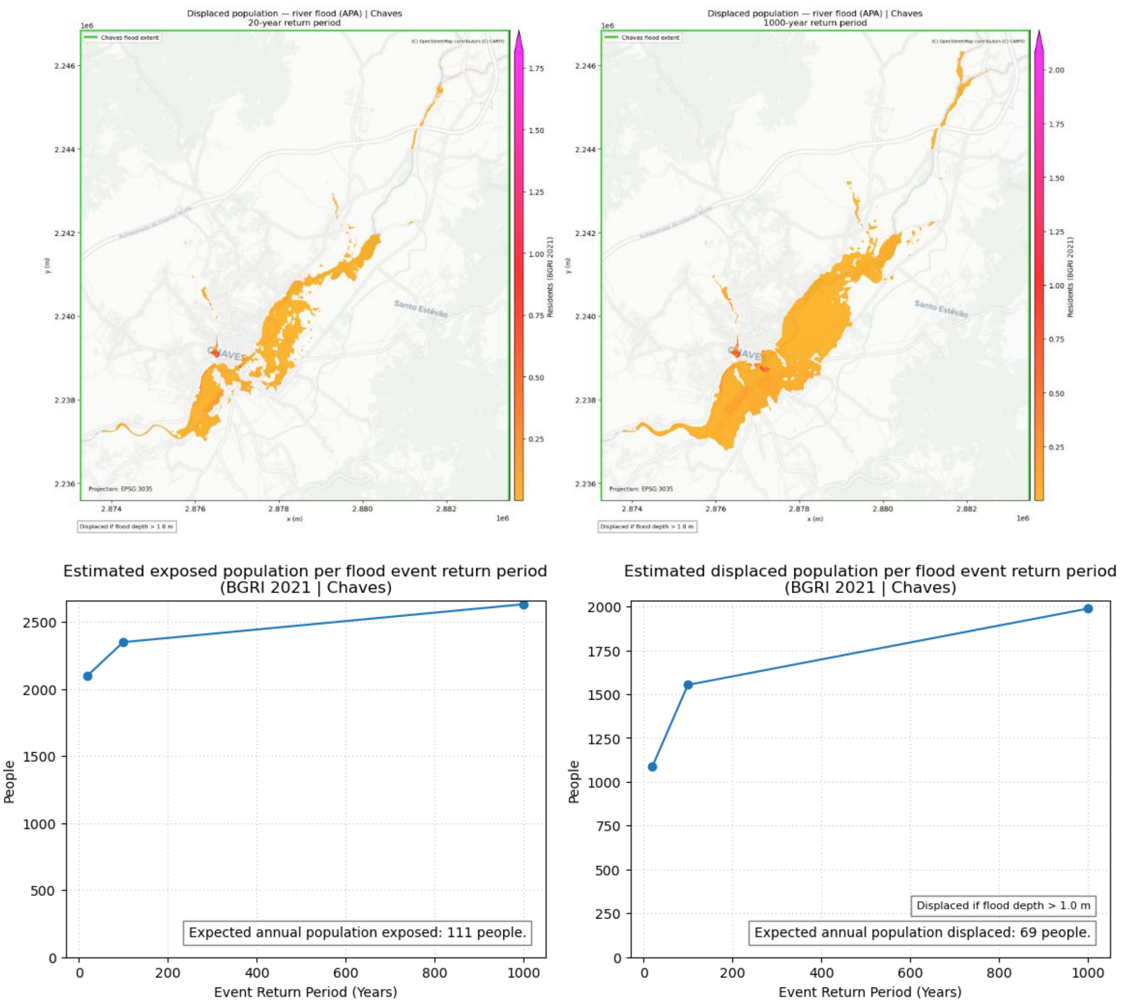


Figure 2-38 Comparative analysis of human displacement across frequent and extreme events. The maps highlight populations in building footprints with inundation depths >1.0m, accompanied by the Expected Annual People Displaced (EAPD) and exposed statistical curves.

The interpretation of these annualized metrics (EAD) — namely their reduction compared to the Phase 1 estimate (~€10.0M vs. ~€3.86M annually) — does not signify that the territory "now faces less risk," but rather that the model is now more conservative and physically accurate. This reduction essentially reflects three factors: first, the absence of the high-frequency $T=10$ event in the APA catalog, which constitutes the probabilistic band that injects the greatest mathematical weight into the annualized damage calculation; second, the use of the actual APA flood geometry (eliminating the error of physically impossible lateral flooding caused by the generic 80m European model); and third, the difference in the overall range of evaluated return periods. Consequently, the annualized values of the two phases should not be directly compared, with the Phase 2 value being considerably more defensible for planning purposes.

2.3.5 Additional assessments based on local models and data

Beyond the four standard CLIMAAX workflows, Phase 2 mobilized a set of local models, datasets and tools to anchor the results in the territory's physical and observed reality. These additional analyses underpin the hazard and risk components described above and ensure their direct applicability to the municipalities' planning instruments.

2.3.5.1 Hazard assessment

On the hazard side, a national 2 m LiDAR digital terrain model (DGT) was acquired through a dedicated, integrity-checked download pipeline and aggregated to the working grids (100 m for the wildfire hazard; 10 m for the exposure layer), providing terrain derivatives (slope, aspect, roughness) far more detailed than the European defaults.

2.3.5.2 Risk assessment

On the risk side, exposure and vulnerability were refined with national microdata: the INE BGRI 2021 census (population and elderly density at the statistical-subsection level) and the 2019 Agricultural Census, combined through an area-weighted intersection. Critical infrastructure and the road network (OSM elements, with classes adapted to the territory) were assessed on the 10 m LiDAR grid through buffer-based hazard metrics, producing outputs directly usable by civil protection. Where the standard workflow proved computationally heavy, the processing was optimized — for example, replacing an iterative dilation loop with connected-components labelling — so that the full regional runs could be reproduced efficiently.

2.4 Key Risk Assessment Findings

This section presents the strategic synthesis and evaluation of the results generated in the Regionalized Risk Analysis (Section 2.3) for the four priority climate hazards in the Alto Tâmega e Barroso Region: rural wildfires, agricultural droughts, heatwaves, and river floods. Following the methodological guidelines of the European CLIMAAX consortium, the high-resolution physical and demographic quantitative risk outputs are interpreted and contextualized in an integrated manner to support local decision-making.

The assessment is based on the concurrent coordination of three fundamental analytical dimensions: (i) the **severity** of biophysical, social, and economic impacts; (ii) the temporal **urgency** of action given the rate of change and acceleration of hazards under future climate scenarios (RCP 4.5 and RCP 8.5); and (iii) the diagnosis of the local system's **resilience capacity**.

This evaluation process was enriched by the active participation of regional strategic partners, enabling the translation of refined scientific evidence into tactical and highly actionable intervention priorities for region's Municipal Climate Action Plans (PMAC) and Municipal Emergency and Civil Protection Plans (PMEPC).

2.4.1 Mode of engagement for participation

The evaluation of key risk findings was developed through a direct link between quantitative numerical modeling and the empirical experience of local actors. Stakeholder engagement followed a co-creation and technical validation model during Phase 2, leveraging inputs gathered during the online Consultative Session and validated responses from the Stakeholder Survey. This participatory process allowed the hazard and risk footprints generated by machine learning and physical simulation models to be compared against the historical incident memory of municipal Civil Protection teams, agricultural and forestry cooperatives, and regional administration authorities. These contributions were decisive for calibrating severity thresholds, characterizing resilience capacity gaps, and validating the prioritization of key risks in the territory, ensuring the necessary institutional legitimacy for the future integration of these results into municipal planning instruments.

2.4.2 Gather output from Risk Analysis step

To support the severity and urgency assessment, the key quantitative and cartographic outputs generated in the Regionalized Risk Analysis (Section 2.3) were gathered for the four prioritized hazards:

- **Wildfire (Fire) results:** The corrected hybrid machine learning model projects a consistent worsening of the hazard. Under the extreme long-term scenario (RCP 8.5, 2081–2100), high and very high hazard classes (Classes 5 and 6) expand to cover 52.4% of the territory, representing a 1.3-fold increase compared to the 41.1% observed in the historical baseline. Intersecting this hazard with infrastructure exposure (Layer 2) revealed that 38 critical municipal assets deteriorate their risk class in the future, with a tactical emphasis on mountain shelters located deep within continuous forest stands of Type 4 fuel. The fine-scale demographic vulnerability analysis (Layer 3) showed that severe population risk (Classes 4 and 5) affects 37.1% of the general population and 35.3% of the elderly population (aged ≥ 65), concentrating critically in the mountain parishes of Montalegre.
- **Droughts results:** The transition to the non-staple crop workflow enabled direct economic loss estimates (annual revenue loss driven by severe water stress under rainfed conditions) for the region's identity crops: approximately €2.19 million for chestnuts, €1.85 million for vineyards, and €0.98 million for olive groves. The results reveal an extremely high spatial concentration of risk in the municipality of Valpaços, which holds the largest agricultural area in the region and concentrates 14 of the top 15 most vulnerable parishes in the territory, led by Carrazedo de Montenegro, Padrela e Tazem, and São João da Corveira.
- **Heatwaves results:** Climate hazard calibration using the *Xclim* module with IPMA thresholds projects a sharp increase in very hot days and tropical nights. The fine-scale urban analysis (Landsat LST, ~100m) conducted for the historical heatwave of July 2022 identified a structural urban heat island in the city of Chaves, where paved surfaces in the historic center exceeded 52.6 °C, critically exposing residential areas that concentrate vulnerable elderly densities and multiple social support and healthcare assets.
- **River Floods results:** High-resolution 2D hydraulic modeling (APA MIKE 21 FM) for the Chaves ARPSI shows that, under a centennial event (T=100), flooding generates €260 million in land-use damages (€139 million in urban/residential land and €117 million in agriculture) and ~€86.0 million in direct structural damages to individual buildings (OSM). The integrated demographic assessment estimates that 2,348 residents would be exposed to flooding, with 1,553 directly displaced due to loss of habitability (water depth > 1.0 m).

2.4.3 Assess Severity

The physical, social, and economic severity of impacts was classified into four categories (*limited, moderate, substantial, and critical*), distinguishing present-day pressures from future escalation:

- **Wildfires** | *Current: Substantial → Future: Critical*: Classification evolves from substantial in the present day to critical in the long-term future. The potential loss of human life along the Wildland-Urban Interface (WUI) of isolated and highly aged mountain villages, combined with the irreversible destruction of high-conservation-value habitats within the Peneda-Gerês National Park (PNPG) and extensive productive forest stands, justifies the highest level of systemic severity.
- **Droughts** | *Current: Substantial → Future: Critical*: Severity progresses from substantial to critical due to the structural economic impact on the regional primary sector. Since rainfed agriculture is the economic and social engine of municipalities like Valpaços, successive yield drops in chestnut, vineyard, and olive grove productions threaten the viability of family farms, accelerating agricultural abandonment and physical and demographic desertification.
- **Heatwaves** | *Current: Substantial → Future: Critical*: Severity is classified as critical in the future due to the territory's high intrinsic demographic vulnerability, with 35.0% of the population being elderly. The worsening of extreme temperatures and the urban heat island effect over Chaves' paved urban fabric projects a direct and severe impact on mortality and morbidity for this vulnerable group, placing unprecedented pressure on healthcare and social support networks.
- **River Floods** | *Current: Moderate → Future*: Substantial**:** Severity progresses from moderate to substantial. Although river flooding has a geographical scope restricted to the Tâmega valley, the economic and human safety impacts are of high magnitude within the Chaves urban core. Centennial events have the capacity to paralyze the city's critical functions, block strategic road corridors for emergency response, and cause massive material damage to historic commercial and residential buildings.

2.4.4 Assess Urgency

The urgency for tactical intervention was determined by the rate of change of climate hazards and the immediacy of escalating consequences, classified into four levels (no action needed, watching brief, more action needed, and immediate action needed):

- **Wildfires (Fire)** | *Immediate action needed*: Urgency is critical and immediate. Climate acceleration projects a severe increase in the modelled fire hazard in the near term, overlaying a vulnerable landscape and an aging interior. This demands immediate intervention through the creation of fuel management zones along the wildland-urban interface and the implementation of self-protection and evacuation plans in the most isolated villages of Montalegre.
- **Droughts** | *More action needed*: As a slow-onset hazard, urgency focuses on the need for medium-term structural planning. There is an urgent need to diversify agricultural revenue sources, introduce crop varieties more tolerant to water stress, and implement efficient soil moisture retention and monitoring systems to safeguard the sustainability of Valpaços' chestnut orchards and vineyards.
- **Heatwaves** | *Immediate action needed*: The rapid increase in the frequency and duration of extreme heat events, paired with critical demographic vulnerability, demands immediate action. Measures must focus on the short term through the design of urban contingency plans for Civil

Protection, creation of cooled community shelters, and active shading of pedestrian transit pathways in Chaves.

- **River Flooding (Floods):** *More action needed*: The episodic nature of floods and the existence of consolidated 2D hydrodynamic hazard models from the APA allow urgency to focus on medium-term preventive and operational planning, through the strict revision of flood elevation constraints in municipal Master Plans (PDMs) and the update of evacuation alert thresholds.

2.4.5 Understand Resilience Capacity

Resilience capacity analyzes the region's current competence to absorb, adapt, and transform in the face of climate damage, evaluated across four categories (*low, medium, substantial, and high*) based on five fundamental capitals (physical, financial, human, social, and natural):

- **Wildfires |** *Medium*
  - *Physical and Natural Capital*: The region possesses robust municipal planning instruments (PMAC, PMDFCI, PMEPC) and a structured network of fuel management strips. However, at the landscape planning level, existing programs (PRGP of Serra da Cabreira and Serras do Larouco e Barroso; and PRGP of Terra Fria Transmontana) only cover fragmented parts of the region's vulnerable forest lands. This leaves major continuous forest stands in the Tâmega Valley without integrated landscape-scale planning, driving CIMAT's proactive advocacy for a comprehensive PRGP covering all vulnerable forest areas across the entire Tâmega Valley.
  - *Human and Social Capital*: High technical expertise in forestry and emergency planning, but constrained by demographic desertification and severe aging (35.0% elderly), limiting local community self-protection capacities in the most isolated mountain villages of the Barroso.
  - *Financial Capital*: Limited municipal budgets that are heavily dependent on state transfers and European funds to sustain the extensive maintenance of fuel management strips along the Wildland-Urban Interface (WUI).
- **Droughts |** *Medium*
  - *Physical and Natural Capital:* Presence of water-holding reservoirs (such as the Alto Rabagão), though primarily focused on hydroelectric production and lacking agricultural distribution channels. The region's high-value identity crops (chestnuts, vineyards, and olive groves) are mostly under rainfed conditions, leaving them highly exposed to extreme soil moisture deficits, particularly in the drier, Mediterranean soils of Valpaços.
  - *Human and Social Capital:* Strong local agricultural cooperatives with deep territorial integration (e.g., Coopaços, Coopbarroso), but vulnerable due to the high average age of local farmers and some resistance to adopting precision irrigation systems or climate-resilient crop varieties.
  - *Financial Capital:* Low autonomous investment capital among small family-run farms to fund efficient local irrigation infrastructure or insurance against consecutive crop failures.
- **Heatwaves |** *Low / Medium*

  - *Physical and Natural Capital*: While PMACs establish adaptation targets, there is still a low implementation rate of Nature-Based Solutions (NbS) for cooling microclimates in urban centers (such as Chaves). A critical gap is the absence of a real-time digital weather-health monitoring and early-warning platform.
  - *Human and Social Capital*: A solid network of local health centers, volunteer fire departments, and social support institutions (IPSS) is active, but struggles to continuously monitor and rapidly support isolated and vulnerable elderly residents scattered across remote rural subsections.
  - *Financial Capital*: Scarce municipal funding for deep thermal mitigation urban remodeling or for establishing a generalized network of climatized community shelters.

- **River Floods |** *Medium*
  - *Physical and Natural Capital:* Emergency planning is robust through PMEPCs and the Douro basin PGRI (RH3), paired with highly effective tactical response from local fire departments. However, there is a lack of level and flow sensors (stream gauges) along critical upstream sections of the Tâmega river, limiting early warning times. The stormwater drainage network in Chaves requires deep structural upgrades.
  - *Human and Social Capital:* High public awareness and empirical preparation among Chaves' urban population and riverside commercial owners regarding periodic flood events.
  - *Financial Capital:* The high investment capital required to implement large-scale hydraulic engineering works or massive storm drainage upgrades in Chaves represents a severe constraint for the municipality to achieve full risk mitigation within the ARPSI.

2.4.6 Decide on Risk Priority

The final prioritization of climate risks for the NUT III Alto Tâmega e Barroso results from the systematic intersection of quantitative physical severity classifications (Phase 2), temporal urgency, and the qualitative diagnosis of local resilience capacity. The results are structured in the Table 2-6, ordered to ensure the European comparability required by the CLIMAAX consortium.

The risk priorities for Alto Tâmega e Barroso were established as follows:

- **Wildfires:** *Very High Priority*: This is the most frequent and persistent hazard in the territory, accounting for approximately 61% of regional historical occurrences. The refined machine learning model projects a severe increase in extreme hazard (Classes 5 and 6 growing from 41.1% to 52.4% under RCP 8.5), with severe risk affecting 35.3% of the elderly population. The urgency for action is immediate due to the threat of irreversible human and ecological losses in the Wildland-Urban Interface (WUI) areas of Montalegre.
- **Droughts:** *Very High Priority*: Although a slow-onset hazard, it poses a systemic and massive financial threat to the regional primary sector—CIMAT's main socioeconomic engine. Estimated losses for identity crops (chestnuts, vineyards, and olive groves) exceed €5.0 million annually under the reference scenario, revealing an extremely high vulnerability concentrated in the municipality of Valpaços, which holds 14 of the top 15 extreme-risk parishes.
- **Heatwaves:** *Very High Priority*: It presents critical future severity due to CIMAT's high demographic vulnerability, with 35.0% of the population being elderly. The worsening of extreme

temperatures and the urban heat island effect in Chaves (with surface temperatures exceeding 52.6 °C) demands a short-term focused intervention based on urban contingency plans for Civil Protection and urban shading.

- **River Floods:** *High / Strategic Priority*: It presents a geographic scope restricted to the floodplains of the Tâmega, but with severe and highly concentrated impacts in the Chaves ARPSI (which records 50% of regional river events). Under a centennial event (T=100), losses reach €260 million with 1,553 displaced residents. The urgency of "more action needed" mandates the revision of land-use constraints in municipal Master Plans (PDMs) and the modernization of hydraulic networks.

Table 2-6 Key Risk Assessment through risk ranking, considering severity, urgency and resilience capacity

Hazard	Severity		Urgency	Resilience capacity	Priority
	current	future			
Wildfires	Substantial	Critical	Immediate action needed	Medium	**Very high**
Droughts	Substantial	Critical	More action needed	Medium	**Very high**
Heatwaves	Substantial	Critical	Immediate action needed	Low/Medium	**Very high**
River Flooding	Moderate	Substantial	More action needed	Medium	**High**

Severity	Urgency	Resilience Capacity	Risk Ranking
Critical	Immediate action needed	High	Very high
Substantial	More action needed	Substantial	High
Moderate	Watching brief	Medium	Moderate
Limited	No action needed	Low	Low

2.5 Monitoring and Evaluation

Phase 2 consolidated the central lesson that regionalizing the analysis is the determining factor for the operational utility of the results. The decisive step was replacing pan-European estimates with national data and validating each workflow against the territory's observed record — the 1990–2023 burned area for wildfire and the APA flood-hazard mapping for river floods — which transformed theoretical projections into evidence that can be acted upon at parish and infrastructure level.

Several refinements proved decisive – the nationally-adapted machine-learning model that restored the wildfire workflow's ability to extrapolate hazard, the shift to the region's identity crops, the recalibration of heatwave thresholds to IPMA criteria, and the 71-class COS 2023 damage matrix for floods — each detailed in Section 2.3.

The greatest technical difficulty was the "scale paradox": the reliance on regional climate models and European vulnerability indices with coarse native resolutions, which limits the metric refinement of future projections. This was mitigated by anchoring the analysis in observed history (validation against the burned area and official flood records), by freezing common classification rulers so that the climate signal remains comparable across scenarios, and by enlarging the training domain to break spatial confounding.

The role of local stakeholders — CIMAT, the six municipalities, civil-protection services and agroforestry associations — was fundamental as a validation and strategic-correction mechanism, ensuring that prioritization reflects operational needs. Institutional learning is secured through knowledge transfer to municipal technicians and through reproducible, automated workflows (automatic coordinate-reference-system detection, national LiDAR acquisition pipelines and documented notebooks) that allow teams to operate the models autonomously.

In terms of efficiency, reusing the CLIMAAX workflows accelerated the production of results, although the collection, harmonization and integration of heterogeneous national data required significant effort in the data-processing phase. The evaluation also defined the future research agenda: the absence of a continuous monitoring network for soil moisture and river basins, the need to incorporate future socioeconomic conditions, and the refinement of the still-coarse economic and ecological layers. The region's current monitoring remains largely reactive; the project therefore supports the creation of a shared climate observatory to centralize georeferenced historical records and risk indicators. By transposing this knowledge directly into the municipal climate-action and civil-protection instruments, the assessment ensures that Phase 3 adaptation measures are designed on high-resolution evidence rather than generic global trends.

The transition from a reactive civil protection and climate planning model to a proactive adaptive management framework requires a continuous Monitoring and Evaluation (M&E) strategy. In Alto Tâmega e Barroso, this strategy aims to ensure that the refined Phase 2 risk outputs directly support the updates of the PMAC, PMEPC, and Common Climate Policies. The monitoring is based on the dynamic integration of local datasets and spatial planning policy integration, ensuring that the generated knowledge supports public and private investment decisions based on solid physical and socioeconomic evidence.

Currently, the region's monitoring systems remain mostly reactive and fragmented. To address this limitation and centralize georeferenced historical records, CIMAT is operationalizing two key initiatives co-funded under the Northern Regional Programme (Norte 2030 / Portugal 2030):

1. **Intermunicipal Climate Action Observatory:** A shared technological tool developed over the pre-existing spatial data infrastructure (SDI) of the Alto Tâmega e Barroso Observatory. It serves as a supporting tool to centralize and manage the PMACs' Key Performance Indicators (KPIs) and track trajectories of energy consumption, emissions, and adaptation measures. Beyond these mitigation indicators, the Observatory is designed to ingest the Phase 2 climate-risk signals so that the same indicators assessed in this report are tracked over time and feed the periodic PMAC revision.
2. **Hydrological Sensor Network on the Tâmega River:** Ongoing physical installation of sensors along the critical upstream sections of the river. This real-time telemetry network will feed Civil Protection early-warning systems and accumulate critical hydraulic series to calibrate the local hydrodynamic model, reducing analytical uncertainty.

2.6 Work plan Phase 3

Phase 3 will constitute the final stage of the CLIMAAX_AT project and will focus on converting the high-resolution evidence and assessment results generated in Phase 2 into practical local adaptation strategies. The central objective will be to reduce risks and increase the territory's resilience, transferring this scientific knowledge directly into updating and improving the planning instruments of the 6 municipalities, with a particular emphasis on the PMAC and the PMEPC.

To ensure the selection of effective and financially sustainable adaptation measures, CIMAT will implement a Multi-Criteria Analysis (MCA) based on the logic of the Adaptation Support Tool (AST). This objective scoring system will allow decision-makers to prioritize potential actions based on:

- **Effectiveness:** The degree of risk reduction (e.g., reducing the drop in agricultural revenue or safeguarding infrastructure).
- **Cost-Benefit Ratio:** The costs of implementing the measure compared to the value of the human, natural, or physical capital protected.
- **Nature-Based Potential:** A preference for Nature-Based Solutions (NbS) that promote biodiversity and water retention in the soil.
- **Social Acceptance:** The feasibility of implementation within the local community and compatibility with the rural property framework (fundamental in the agroforestry sector).
- **Co-benefits:** Secondary advantages, such as urban cooling (mitigating heat islands) or the creation of recreational spaces.

The main activities to be developed in Phase 3 will focus on following up on the conclusions of the risk assessment and will include:

- **Identification and assessment of adaptation options (M10, M12):** Based on the 4 priority risks validated in Phase 2, the team will identify and evaluate concrete measures to improve response capacity (e.g., adaptation of agricultural crops, strengthening of drainage, and urban shading).
- **Participatory processes and co-creation (M11):** Conducting direct working sessions with local stakeholders (civil protection services, municipal technicians, and agroforestry associations) to discuss, validate, and prioritize the proposed adaptation pathways, ensuring their feasibility on the ground.
- **Formulation of recommendations (M13):** Technical translation of prioritized measures into actionable recommendations for the revision of PMACs and PMEPCs.
- **Capacity building, communication, and presentation to decision-makers (M14):** Training actions for local technicians, production of a final project publication, and holding a final public event in Alto Tâmega to present the results to policymakers and the general public.
- **International knowledge sharing (M16):** Participation in the CLIMAAX workshop in Brussels to share lessons learned and the downscaling methodologies applied in the region.

To ensure administrative and financial viability, Phase 3 will concentrate resources exclusively on the four priority risks, focusing investment on the threats with the greatest potential for systemic damage to Alto Tâmega e Barroso.

Milestones and Deliverables:

- **M9:** Subcontracting completed - Project Phase 3.
- **M10:** Potential regional/local adaptation options identified.
- **M11:** Participatory processes conducted with stakeholders (Phase 3).
- **M12:** Regional/local adaptation options evaluated and prioritized.
- **M13:** Recommendations formulated to improve risk management plans.
- **M14:** Presentation of results to policymakers in the Alto Tâmega region (final public event).
- **M16:** Participation in the CLIMAAX workshop to be held in Brussels.
- **D3:** Contribution to local adaptation strategies and improvement of risk management plans (Final Document / Deliverable 3).

3 Conclusions Phase 2 - Climate risk assessment

Phase 2 of the CLIMAAX_AT project delivered a regionalized, high-resolution refinement of the Climate Risk Assessment for Alto Tâmega e Barroso, replacing pan-European estimates with local data and models calibrated to the territory's meteorological and socioeconomic specificities. The four priority hazards (wildfire, agricultural drought, heatwaves and river floods) were re-assessed with national datasets – the COS 2023 land cover, the ICNF burned-area record, the INE BGRI 2021 census and 2019 Agricultural Census, IPMA climate criteria and APA flood-hazard mapping – and, where possible, validated against observed records, yielding a knowledge base with the precision required to support operational civil-protection planning and municipal climate action.

The key findings confirm a clear, hazard-specific worsening of risk. Wildfire, the dominant hazard (around 61% of occurrences), shows high structural hazard rising from 41.1% to 52.4% of the territory by the end of the century (RCP 8.5) — validated against the 1990–2023 burned area — with adaptation priority in the ageing mountain parishes of Montalegre. Agricultural drought threatens the region's identity crops, with combined annual revenue losses of the order of €5 million already in the near term, concentrated in the chestnut-orchard areas of Valpaços. Heatwaves intensify along the Chaves valley axis, where the highest hazard coincides with an elderly population (35.0% of residents) and acts as a multiplier of drought and fire. River floods, although spatially concentrated in Chaves, generate severe localized impacts — building damage of about €86 million for a 100-year event, an Expected Annual Damage of €3.86 million, and up to 1,553 people displaced.

Among the challenges successfully addressed, the wildfire workflow overcame a fundamental limitation of the original model — its inability to extrapolate hazard under the modest Atlantic-buffered warming of Portugal — through a nationally-adapted machine-learning model trained over a wide domain and validated against the observed fire record; the agricultural-drought workflow was fully adapted to the national context (identity crops, INE/EUROSTAT valuation, area-weighted exposure); the heatwave thresholds were recalibrated to IPMA criteria with census-based elderly vulnerability; and the flood damage model was rebuilt on a 71-class COS 2023 matrix with a regional wealth factor and 2024 prices, validated against the APA PGRI.

Challenges that remain only partially addressed point to a future research agenda: the still-coarse European components of some risk layers (the JRC economic and ecological indices, at an effective resolution of ~12.5 km); the holding of exposure and vulnerability at present-day conditions, so that inter-scenario variation derives solely from the projected climate; and the absence of a continuous monitoring network for soil moisture and river basins.

Beyond the hazard-by-hazard results, the assessment reveals a defining feature of the territory: the priority hazards converge on the same vulnerable geographies and people – the ageing mountain interior, where heat compounds drought and fire, and the Chaves valley, where heat overlaps with flood exposure. Wildfire, agricultural drought and heatwaves therefore stand as the foremost, mutually-reinforcing adaptation priorities, with river floods a spatially-concentrated but locally severe fourth. By delivering parish-level prioritisation, infrastructure-exposure products for civil protection, and reproducible, traceable workflows, Phase 2 turns this compound-risk picture into an actionable basis for integrated – rather than siloed – adaptation in Phase 3.

4 Progress evaluation

With the submission of this deliverable (D2), Phase 2 met – and in its core technical target exceeded – the milestones and Key Performance Indicators set for the refined risk assessment: against a planned two improved workflows, four were fully refined and validated (wildfire, agricultural drought, heatwaves and river floods). The status of each milestone and KPI is summarised below.

Table 4-1 Overview key performance indicators

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

Table 4-2 Overview milestones

Milestones	*Progress*
M1: Subcontracting carried out - Phase 1 and 2 of the project	Achieved
M2: Test CLIMAAX workflows for different hazards	Achieved
M3: Carrying out participatory processes with stakeholders (phase 1)	Achieved

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

5 Supporting documentation

All outputs, integrated local databases, and complementary methodological reports produced during Phase 2 of the CLIMAAX_AT project have been properly classified and shared in the Zenodo open-data repository, ensuring full traceability, transparency, and reproducibility of the Climate Risk Assessment. The supporting documentation is organized into the following structure, reflecting the methodological transition to high-resolution data:

Main Report:

- Main Phase 2 Report Document (PDF)

Workflow Outputs (High-Resolution Hazard, Exposure, Vulnerability, and Risk Maps)**:**

- FIRE: (FIRE.zip)
- DROUGHTS: (DROUGHTS.zip)
- HEATWAVES: (HEATWAVES.zip)
- RIVER FLOODS: (FLOODS.zip)

Portuguese / Local Datasets (Data used for Phase 2 local refinement):

- DGT – High-Resolution Digital Elevation Models (HR-DEM / LiDAR)
- DGT – Land Use and Land Cover Map (COS 2023)
- DGT – Official Administrative Map of Portugal (CAOP 2022 and 2024)
- INE – Geographical Information Reference Base (BGRI 2021) and Agricultural Census (RA 2019)
- APA – Flood Hazard and Risk Mapping (PGRI RH3; MIKE 21 FM hydrodynamic model; Chaves ARPSI)
- IPMA – Climate normals and heatwave criteria (very hot days and tropical nights)
- EUROSTAT / INE – Crop Production Statistics (NUTS2) and Raw Material Prices
- ICNF - Burnt Area Perimeters (1990-2023)

European and Global Reference Datasets:

- EURO-CORDEX – Regional climate projections (RCP 4.5 and RCP 8.5)
- CHELSA v2.1 – Bioclimatic variables (wildfire susceptibility)
- ECLIPS-2.0 – High-resolution European climate dataset (wildfire forcing)
- Copernicus / SMHI E-HYPEcatch – River discharge series (flood frequency-shift method)
- JRC – River Flood Hazard Maps, Huizinga depth-damage curves, and LUISA exposure layer
- Landsat Level-2 (USGS / Microsoft Planetary Computer) – Land Surface Temperature (heatwaves)
- OpenStreetMap (OSM) – Critical facilities and road network

Annexes:

- Annex I – Stakeholder Consultative Session (05/02/2026): Summary / Results Report — documenting the participatory process, stakeholder feedback and validation of the refined workflows (CIMAT & GeoAtributo; deposited in the CLIMAAX Zenodo community).