CLIMAAX
climate ready regions

Deliverable Phase 2 – Climate risk assessment

Viana do Castelo: Climate Action (VC_Climaax)

Portugal, Viana do Castelo Municipality

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

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Document Information

Deliverable Title	Phase 2 – Climate risk assessment
Brief Description	This deliverable presents the regionalized Climate Risk Assessment (CRA) for Viana do Castelo, marking the conclusion of Phase 2. It provides high-resolution operational mapping and quantitative impact analysis for three prioritized hazards: fluvial flooding, wildfires, and extreme precipitation.
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Region/Municipality	Viana do Castelo Municipality
Leading Institution	Viana do Castelo Municipality
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Abbreviations and acronyms

Abbreviation / acronym	Description
APA	Portuguese Environment Agency
APDL	Port Authority
ANEPC – CSREPC	Sub-regional Emergency and Civil Protection Command
CAOP	Official administrative boundaries
CIM Alto Minho	Alto Minho Intermunicipal Community
CMAACVC	Municipal Environment and Climate Change Council
CMVC	Municipality of Viana do Castelo
COS 2023	National Land Use Map, 2023
CPI	Consumer Price Index
CRA	Climate Risk Assessment
DAAC	Environment and Climate Adaptation Division
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DEM	Digital Elevation Models
DGT	Directorate-General for Territory
DGTS	Territorial Management and Sustainability Department
EAD	Expected Annual Damage
EAPD	Expected Annual People Displaced
EMAAC	Municipal Climate Change Adaptation Strategy for Viana do Castelo
ESA	European Space Agency
HR-DEM	High-resolution digital elevation models
ICNF	Portuguese Institute for Nature Conservation and Forests
IDF	Intensity-Duration-Frequency
INE	Statistics Portugal
IPMA	Portuguese Institute for Sea and Atmosphere
IPSS	Private Institutions of Social Solidarity
IPVC	Polytechnic Institute of Viana do Castelo
JRC	Joint Research Centre
LNEG	National Laboratory of Energy and Geology
MCA	Multi-Criteria Analysis
NASA	National Aeronautics and Space Administration
NUTS	Nomenclature of Territorial Units for Statistics
OSM	OpenStreetMap
PC	Civil Protection organic unit
PDEPC	Viana do Castelo District Civil Protection Emergency Plan
PGRI	Flood Risk Management Plan
PIAAC do Alto Minho	Alto Minho Intermunicipal Climate Change Adaptation Plan
PMAC	Municipal Climate Action Plan for Viana do Castelo
PMEPC	Viana do Castelo Municipal Civil Protection Emergency Plan
PNGIFR	National Integrated Management Plan for Rural Fires

POC Caminha-Espinho	Programa da Orla Costeira Caminha - Espinho
PT111	Alto Minho
RF	Random Forest
RCP	Representative Concentration Pathway
RH1	Minho and Lima Hydrographic Region
RNA 2100	National Roadmap for Adaptation 2100
RP	Return periods
SMSBVC	Viana do Castelo Municipal Services
SSP	Shared Socioeconomic Pathways
SUDS	Sustainable urban drainage systems
UMinho-ICT	University of Minho- Institute of Earth Sciences
WUI	Wildland-Urban Interface

Executive summary

This document presents the results of Phase 2 of the VC_Climaax project, focused on the climate risk assessment for the municipality of Viana do Castelo. The central objective of this phase was to overcome the "utility gap" identified in the previous phase, where low-resolution global data proved insufficient for operational planning at the infrastructure and strategic asset levels. The report describes how the municipality utilized high-resolution local data and advanced models to refine prioritized risk workflows, transforming theoretical climate projections into actionable territorial intelligence.

During this second phase, the analysis scale was refined from 100 meters to 10 meters, integrating local LiDAR data and high-resolution digital elevation models (HR-DEM). The main actions included the regionalization of three risk workflows: Fluvial Flooding, Rural Wildfires, and Extreme Precipitation. The achieved results include:

- **Fluvial Flooding:** refined modeling allowed for the identification of an Expected Annual Damage (EAD) of 25.28 million euros and an estimate that 285 citizens (EAPD) are at risk of annual displacement due to severe flooding.
- **Wildfires:** utilizing Machine Learning and the COS 2023 land use map, critical wildland-urban interface zones and systemic failure points in the strategic road network were identified, which could compromise emergency operations.
- **Extreme Precipitation:** through the analysis of 1,321 historical occurrences, 16 critical hotspots were identified and a "drainage gap" was quantified, relating the variation in projected rainfall intensity to the required drainage capacity scaling.

This phase contributes to the overall project by providing a robust scientific basis for the revision of the Municipal Emergency and Civil Protection Plan (PMEPC) and the Municipal Climate Action Plan (PMAC).

The core message is that the regionalization of the analysis is decisive for its operational utility. Climate risk in Viana do Castelo is now a quantifiable and geographically more precise threat, sustained by a history of real events over the last 25 years. The assessment confirms Rural Wildfires as the maximum priority (Very High), followed by Extreme Precipitation and Flooding (High). Although local vulnerability is mapped accurately, the reliance on coarser-scale regional climate models remains a technical challenge known as the "scale paradox."

Phase 3 (through July 2026) will focus on the selection and prioritization of concrete adaptation measures, utilizing a Multi-Criteria Analysis (MCA) to guide sustainable investments.

1 Introduction

1.1 Background

The municipality of Viana do Castelo is located in the north of mainland Portugal, in the NUTS3 Alto Minho (PT111), with an area of approximately 319 square kilometres and a coastline of 24 kilometres. With a resident population of 85,8 (INE, 2021), the municipality has seen a negative demographic trend (-3,2% in 20 years).

The Municipality of Viana do Castelo is responsible for the Civil Protection Service (Law No. 98/2021, of December 31), with competencies in the areas of prevention, risk and vulnerability assessment, planning and support for operations, logistics and communications, awareness and public information.

1.2 Main objectives of the project

Phase 2 of the VC_Climaax project represents a central methodological evolution in Viana do Castelo's resilience strategy, transitioning from macroscopic hazard analysis to an operational decision support capacity. This stage was designed to overcome the limitations identified in Phase 1, where the reliance on global datasets (such as 100m resolution) and generic metrics proved insufficient for detailed planning at the level of infrastructure and strategic assets.

In the previous phase, the analysis was based on European datasets which, while useful for regional characterization, did not allow for the precise identification of local vulnerabilities due to a lack of alignment with the municipality's real topography and low spatial resolution. Furthermore, the original approaches faced difficulties in extracting risk metrics that could be directly integrated into territorial management. The purpose of Phase 2 is, therefore, the regionalization and physical calibration of models, ensuring that climate projections are anchored in the empirical and historical reality of Viana do Castelo.

The primary objectives of this phase focus on transforming raw data into actionable information for risk management and the community:

- **Operational resolution increase:** Refining the analysis scale from 100 meters to 10 meters, integrating high-resolution local data (HR-DEM) to ensure that flood footprints and susceptibility areas respect the real morphology of the terrain.
- **Historical evidence validation:** Replacing purely theoretical models with approaches based on real occurrences, using Machine Learning algorithms and clustering analysis to identify risk hotspots based on the Municipal Civil Protection event history.
- **Socioeconomic recalibration:** Adjusting economic damage functions to local reality, applying updated indicators to obtain financially rigorous loss estimates.

Utilizing the CLIMAAX Handbook methodological framework ensures that Viana do Castelo employs a common, harmonized, and transparent framework, facilitating the comparability of results with other European regions. The workflow structure guarantees scientific rigor and process reproducibility, allowing the municipal technical team to autonomously maintain and update the climate database in the future. Nevertheless, it is the optimization of the models through the integration of local data that truly provides practical utility to this exercise.

By integrating local data, Phase 2 results directly inform the revision of the Municipal Emergency and Civil Protection Plan (PMEPC) and the consolidation of the Municipal Climate Action Plan (PMAC). Consequently, Phase 2 provides the municipality with a robust knowledge base, ensuring that the adaptation measures to be selected in the next phase are geographically precise and technically grounded.

Additionally, this phase capitalized on the updated CLIMAAX Toolbox, applying new and updated workflows provided by the project coordination after Phase 1. This broader application ensured a comprehensive baseline for all prioritized hazards before focusing resources on high-resolution local refinements.

1.3 Project team

The internal team of VC_Climaax project is composed of:

- José Vieira has a degree in Forestry Engineering, a postgraduate degree in Integrated Environmental and Landscape Management, head of the Environment and Climate Adaptation Division (DAAC);
- Maria Elizabeth Matos has a degree in Regional and Urban Planning (DAAC);
- António José da Cruz has a degree in Civil Protection engineering, head of the Civil Protection organic unit (PC);
- Ivone Martins has a degree in environmental engineering, a master’s degree in environmental management and land use planning, training in GIS for socio-environmental applications, and experience in data analysis and management (DGTS).

The scientific team (subcontracted – external support) led by Dr. Renato Henriques, Associate Professor at the University of Minho, Integrated Member of the Institute of Earth Sciences (ICT), specialist in natural risks and climate change.

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

- Ricardo Almendra has a degree in Geography and Planning, and a master's degree in Geography, with a specialization in Spatial Planning and Management;
- Liliana Sousa has a degree in Biology-Geology and a master's degree in Geological Heritage and Geoconservation;
- Ana Rita Caldas has a degree in Biology-Geology and a master's in Biophysics and Bionanosystems.

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 – river floods, wildfire and heavy rainfall – and the integration of local data.
    - 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 development. While the core logic remains consistent with Phase 1, the scoping for Phase 2 was refined to address the 'utility gap' identified by the technical team and strongly reiterated by local stakeholders during initial consultations.

The key evolutions in the Scoping for this phase include:

- **Refinement of objectives:** the analytical focus shifted from a general regional characterization to high-resolution detail at the building and critical infrastructure level.
- **Hazard prioritization:** based on feedback from local actors, resources were concentrated on a technical deep-dive into the three most urgent risks for the municipality: River Floods, Wildfires, and Heavy Rainfall. This allowed for the seamless integration and processing of high-resolution local datasets.
- **Evolution of stakeholder engagement:** the role of partners evolved from initial consultation to direct technical validation. This included the provision of critical primary data (such as georeferenced civil protection incident logs) and direct participation in the assessment of the operational realism of the new high-resolution models.
- **Socioeconomic context calibration:** a critical requirement was identified to localize and calibrate the financial metrics used in damage assessments. This ensures that Expected Annual Damage (EAD) estimates are grounded in Viana do Castelo's specific economic reality, accounting for national inflation indices (CPI) and regional wealth factors.

2.1.1 Objectives

The **VC_Climaax** project maintains its fundamental mission of making Viana do Castelo a more resilient and less vulnerable territory to climate change, in full alignment with the European Union's Mission on Adaptation to Climate Change. The strategic objectives established in the initial phase of the project remain the central pillar of this assessment:

- **Methodological harmonization:** ensuring that climate risk assessments in Viana do Castelo utilize the common CLIMAAX handbook configuration, allowing for the comparability of results at a European scale.
- **Improvement of the decision support framework:** consolidating a risk typification framework that supports the definition of strategic adaptation priorities.
- **Technical capacity building:** supporting both internal and external technical teams in defining robust methodologies for planning, implementation, and monitoring.
- **Integration into municipal planning:** incorporating vulnerability and risk assessment results into territorial management instruments, namely the Municipal Emergency and Civil Protection Plan (PMEPC) and the Municipal Climate Action Plan (PMAC).

In the current Phase 2, these objectives evolve from a theoretical foundation toward an operational decision-support capacity. The expected outcome is the production of actionable risk metrics that enable a transition from general hazard knowledge to the prioritization of concrete investments.

The primary boundary of this assessment was the need to optimize technical and financial resources, focusing the analysis on the three hazards identified as most urgent by local stakeholders: **River Floods, Wildfires, and Heavy Rainfall**.

The main limitation identified is the "scale paradox": while local vulnerability is mapped with point-level precision (e.g., 1,321 historical flood events), the hazard drivers still rely on regional climate models with lower resolution (e.g. EURO-CORDEX at a 12.5 km resolution). This discrepancy requires a cautious interpretation of projections, treating them as regional stress factors applied to a high-resolution local physical reality.

To achieve the proposed objectives, Phase 2 overcame several technical bottlenecks identified during the initial screening:

- **Data resolution:** the reliance on global datasets (JRC 100m), which were insufficient for infrastructure-level planning, was overcome by integrating high-resolution local data (HR-DEM and LiDAR), reaching an operational scale of 10 meters.
- **Rigidity of original models:** workflows configured for other regions were recalibrated for Viana do Castelo's reality, including the creation of conversion dictionaries for national land use (COS 2023) and the adjustment of economic damage functions to regional CPI and GDP.
- **Computational stability:** processing large volumes of climate data required the optimization of memory and cache management routines within the algorithms, ensuring the necessary stability for the municipal team to update the climate database autonomously in the future.

Finally, the engagement strategy was refined through targeted surveys to the Municipal Council for the Environment and Climate Change (CMAACVC) – municipal advisory body on climate action that brings together a diverse group of local and regional actors – ensuring that technical results integrate empirical knowledge and the needs of local stakeholders.

2.1.2 Context

Previous studies and initiatives related to the typification of territorial risks and vulnerabilities, and the preparation of risk maps, identified the risk typologies of greatest interest to explore within the scope of the CLIMAAX project. Historical records of climate-related events from 2000 to the present allow us to identify the locations at greatest risk and the main consequences of each event.

The following initiatives and plans were considered for identifying needs and priorities:

- History of occurrences/events associated with climate change [to periods: 2000-2020, and 2020 to current moment;
- Risk identification and characterization studies;
- Viana do Castelo Municipal Civil Protection Emergency Plan (PMEPC);
- Viana do Castelo District Civil Protection Emergency Plan (PDEPC);
- Flood Risk Management Plan (PGRI) for the Minho and Lima Hydrographic Region (RH1);

- Climatological Normal (1971-2000 and 1981-2010);
- Climate Scenarios for Mainland Portugal in the 21st Century;
- National Roadmap for Adaptation 2100 (RNA 2100);
- Alto Minho Intermunicipal Climate Change Adaptation Plan (PIAAC do Alto Minho);
- POC Caminha-Espinho;
- National Integrated Management Plan for Rural Fires (PNGIFR);
- Municipal Climate Change Adaptation Strategy (EMAAC) for Viana do Castelo;
- Municipal Climate Action Plan (PMAC) for Viana do Castelo.

These documents, combined with local territorial knowledge and technical expertise, allowed for the identification of the primary risks associated with climatic events:

- High temperatures and heatwaves;
- Excessive rainfall;
- Rising sea levels;
- Strong winds.

The Municipal Climate Action Plan (PMAC) was formally approved in February 2025 and is currently in force, succeeding the previous Municipal Strategy for Adaptation to Climate Change (EMAAC). In this context, the CLIMAAX project provides a fundamental contribution by deepening and validating the assessment of territorial risks and vulnerabilities through the processing of local data. The implementation of the CLIMAAX framework and toolbox has significantly improved the Risk Typification Framework, facilitating better decision-making regarding adaptation strategies and priorities.

Regarding data availability for this project, the following primary sources for climate-related risk assessment in Viana do Castelo were identified and leveraged during Phase 2:

- Multi-thematic cartography from national institutions (DGT, LNEG, IPMA, etc.);
- Aerial and satellite imagery (ESA, DGT, CIGeoE, Instituto Hidrográfico, UM, etc.);
- Meteorological and climate and hydrographic data (IPMA, ESA, APA);
- Low-resolution altimetry data (NASA, ESA, DGT);
- High-resolution altimetry data (HR-DEM and Lidar data; CIM Alto Minho, UM);
- Historical climate related risk events and impact (CMVC, APA, ICNF, UM, etc.);
- Costal dynamics data (UM, APA).

The results of this risk and vulnerability assessment will be incorporated into municipal planning documents, namely the PMEPC, and shared with the entities of the Municipal Civil Protection Commission. This dissemination is essential to support technically informed decision-making based on scientific data, fostering the adoption of new measures by public authorities, private agents, and citizens alike.

Compared to the initial scoping, Phase 2 marks a transition from a theoretical hazard screening to an empirical, data-driven risk validation. The primary evolution lies in the integration of high-resolution local datasets – such as LiDAR-derived DEMs and localized historical occurrence logs – allowing the assessment to move beyond regional averages toward a sub-municipal scale of analysis. This shift ensures that the project's technical outputs are no longer just academic projections, but operational tools calibrated to the territorial reality and infrastructure-level needs of Viana do Castelo.

2.1.3 Participation and risk ownership

In Phase 2, stakeholder engagement evolved from institutional identification to active technical validation. The process centered on a direct consultation with all members of the Municipal Council for the Environment and Climate Change (CMAACVC)—over 30 entities ranging from local government to civil society and research centers—allowing for the resolution of the previously identified "utility gap". These stakeholders contributed directly to the project through:

- Provision of georeferenced historical records;
- Identification of priority risks;
- Classification of sectors based on vulnerability to climate risks;
- Validation of the operational utility of the new high-resolution maps.

Among the wide range of consulted entities, the active participation of the following in Phase 2 stands out:

- **Public Administration and Civil Protection:** Municipality of Viana do Castelo (CMVC), Intermunicipal Community of Alto Minho (CIM Alto Minho), and the Sub-regional Emergency and Civil Protection Command (ANEPC – CSREPC).
- **Infrastructure and Services:** Águas do Alto Minho, Port Authority of Douro, Leixões and Viana do Castelo (APDL), and Viana do Castelo Municipal Services (SMSBVC).
- **Economic Sector:** CEVAL (Business Confederation of Alto Minho).
- **Environment and Academia:** Polytechnic Institute of Viana do Castelo (IPVC), Rio Neiva - Environmental Defense Association (NGO), Barroselas School Cluster, and the Alto Minho Professional Artistic School (ARTEAM).

In Viana do Castelo, **risk ownership** is structured through a collaborative governance model:

- **Identification and assessment:** primary responsibility lies with the Municipality of Viana do Castelo (CMVC), specifically through the Civil Protection and Environment departments, with the support of technical experts. The CMAACVC acts as a strategic advisory body, ensuring alignment with the Municipal Climate Action Plan (PMAC), approved in February 2025.
- **Mitigation and operational response:** the Municipal Civil Protection Commission is the central hub for mitigation, coordinating fire departments, security forces (GNR, PSP), the health authority, and sectoral managers.

- **Representatives of vulnerable groups:** priority groups are institutionally represented by School Clusters (children), IPSS – Private Institutions of Social Solidarity (elderly and dependents), and Forestry and Agricultural Associations (exposed economic sectors).

Historically, acceptable risk levels have been implicitly defined by the safety thresholds of the Municipal Emergency and Civil Protection Plan (PMEPC). With Phase 2, the Municipality introduced quantitative metrics to inform this plan and territorial management instruments.

2.1.4 Application of principles

The **VC_Climaax** project integrates the fundamental principles of the CLIMAAX framework to ensure that the Climate Risk Assessment (CRA) is technically robust, transparent, and socially responsible. The application of these principles was guided by a **direct consultation process** with local stakeholders, which aligned technical models with the territory's operational reality.

A. Social justice, equity, inclusivity

While Phase 2 focused on biophysical and economic refinement, the commitment to "just resilience" was ensured through the introduction of human impact metrics and the diversity of voices in the process:

- **Human exposure metrics:** through the Expected Annual People Displaced (EAPD) metric, the model identified that 285 citizens are at risk of annual displacement due to flooding. This provides an objective basis for prioritizing the protection of people over purely economic assets.
- **Inclusivity in consultation:** inclusivity was guaranteed through the involvement of the Municipal Council for the Environment and Climate Change (CMAACVC), covering diverse sectors (Civil Protection, education, environment, economy, infrastructure). This ensured that the risk diagnosis and assessment were not merely an internal exercise but reflected the concerns and empirical knowledge of different social groups. Initiatives like "Safe Village, Safe People" and the "Village Condominium" (funded by the Environmental Fund) are key examples of this principle in action. By focusing on parishes located in forest territories, these programs bridge the gap between municipal planning and local vulnerability, ensuring that self-protection strategies and fuel management are co-designed with the most exposed social groups, thus promoting equitable climate resilience.
- **Roadmap for phase 3:** social justice needs identified by local actors during consultation – such as the monitoring of isolated elderly populations and areas of energy poverty – were documented as qualitative interpretation criteria. These will serve as a basis for selecting and prioritizing adaptation measures in the final phase of the project.

B. Quality, rigour, transparency

Quality, Rigour, and Transparency are ensured through the adoption of structured workflows that minimize bias and guarantee methodological consistency. The regionalized analysis for Viana do Castelo is transparently documented, integrating local data with full traceability of inputs and outputs.

- **Addressing the 'utility gap':** technical integrity was elevated in Phase 2 to resolve the "utility gap" identified during consultation (where less than 10% of stakeholders considered Phase 1 information fully clear and useful for local planning).
- **Rigor and resolution:** precision was guaranteed by transitioning to a 10-meter operational scale (LiDAR) and utilizing national fuel model calibration (COS 2023), responding to local stakeholders' demands for high-precision data.
- **Empirical validation:** model quality was reinforced by integrating georeferenced historical records provided by the consulted entities, allowing theoretical projections to be confronted with real-world occurrences.
- **Open science and transparency:** all analyses followed structured CLIMAAX workflows and are documented in the Zenodo repository, ensuring full data traceability and reproducibility. Modifications and improvements in each workflow are explicitly marked and commented on in the code as results of the Viana do Castelo technical team's input.

C. Precautionary approach

The precautionary approach is applied to manage the uncertainties inherent in climate risks, prioritizing early action against potentially irreversible damage. The project explores multiple future climate and socioeconomic scenarios rather than relying solely on historical data. In the severity assessment, the possibility of cascading effects (such as human loss or ecosystem destruction) is explicitly considered.

- **Consensus-driven prioritization:** this principle guided the management of climate uncertainties by prioritizing hazards identified as most critical by the local community. Consequently, risk prioritization followed a consensual basis validated by stakeholder consultation. More than half of the consulted local actors (58.3%) identified Wildfires as the most severe and urgent hazard currently facing the municipality, followed by river floods (16.7%), and extreme precipitation (8.3%).
- **Urgency-based prioritization:** Finally, the methodology reflects the precautionary principle by encouraging decision-making even in the face of scientific uncertainties, ensuring that Viana do Castelo's municipal planning is prepared to protect critical functions and the most vulnerable populations.

2.1.5 Stakeholder engagement

Stakeholder engagement in the **VC_Climaax** project was structured to ensure that the technical rigor of the analysis was complemented by regional empirical knowledge. During Phase 2, interaction evolved from mere dissemination to a co-production model, where stakeholder feedback directly catalyzed the technical refinements of the Climate Risk Assessment (CRA).

The Municipality utilized a multi-channel approach to ensure broad participation:

- **Direct consultation:** an online survey was launched (Figure 2-1) specifically targeting representatives of the Municipal Council for the Environment and Climate Action (CMAACVC), a multidisciplinary body covering more than 30 entities (including emergency services, academia, and environmental NGOs).

- **Direct contacts:** direct contacts were established to collect local information and data for integration into the priority risk workflows.
- **Contextual dissemination:** to ensure informed responses, stakeholders received the Phase 1 Report (D1). This allowed participants to understand the methodological basis before evaluating the proposed improvements for Phase 2.
- **News publication:** news regarding the progress of VC_Climaax was disseminated through the Municipality's institutional channels and its close partner network (Figure 2-2).
- **Dedicated point of contact:** the email address vc_climaax@cm-viana-castelo.pt was established as a permanent channel for technical queries and data sharing.

Figure 2-1 Extract from the local stakeholder consultation survey

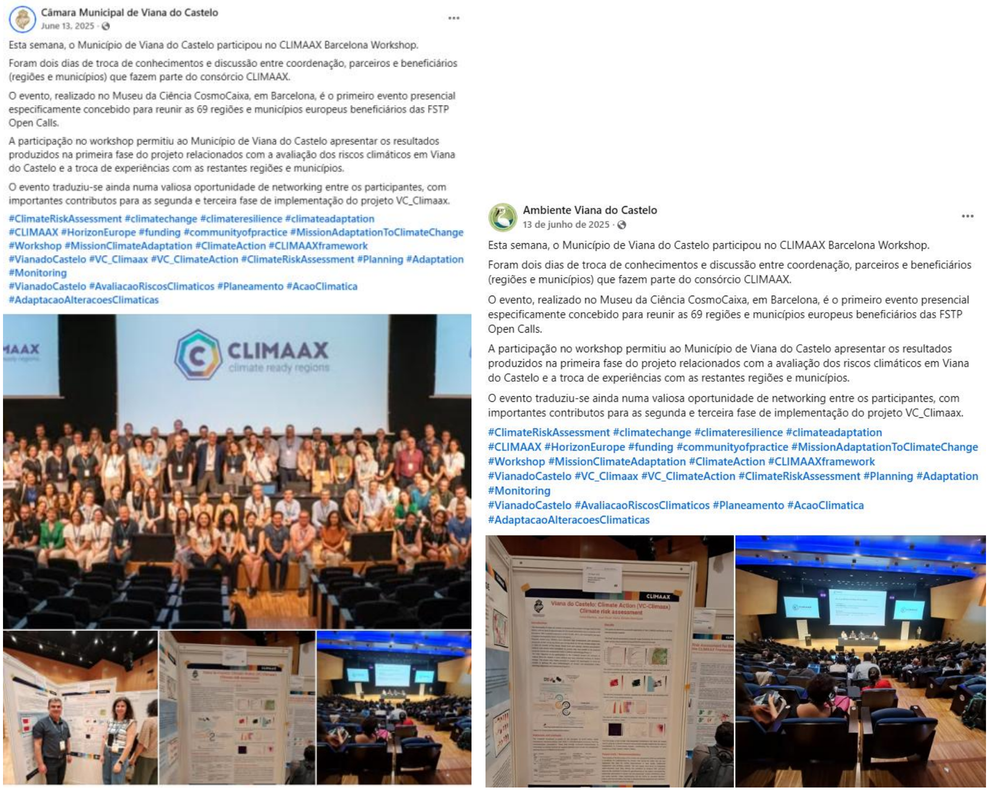


Figure 2-2 Project dissemination on the Municipality's institutional platforms

Stakeholder feedback evidenced high project awareness but revealed a critical "utility gap", as only a small fraction of respondents found the Phase 1 resolution useful for local planning. In light of the demand for local data, stakeholders prioritized wildfires (58.3%) and river floods (16.7%) as the greatest threats.

Regarding the impact on project results, stakeholder feedback was not merely recorded; it shaped the Phase 2 methodology:

- **Technical leap:** responding to the resolution deficit, the team upgraded the modeling to a 10-meter operational scale, using LiDAR data and the COS 2023 land use map.
- **Empirical validation:** since georeferenced historical records were provided, it was possible to validate climate models against an inventory of real-world occurrences.
- **Operational integration:** results will be used directly in updating the PMEPC and monitoring the PMAC. Stakeholders also recommended that Nature-Based Solutions (NbS) be treated as a core pillar of future urban interventions.

Table 2-1 Stakeholder Engagement Impact

Phase 1 Limitation	Stakeholder Feedback	Phase 2 Improvement
Coarse Resolution (~100m)	Insufficient for local planning.	10m resolution (LiDAR-based) for high-precision mapping.
Generic Land Use (CORINE)	Lacked precision for fires.	COS 2023 (93 local land-use classes).
Abstract Exposure	Need to protect specific assets.	Integration of 11 layers of Critical Infrastructure.

Phase 1 Limitation	Stakeholder Feedback	Phase 2 Improvement
Theoretical Risk	Request for real-world validation.	Data-driven analysis (historical events).

The main difficulties encountered centered on the challenge of translating complex physical models and algorithms (such as *Random Forest*) into language accessible to decision-makers, and on managing stakeholder availability and coordination with the technical team's agenda, which prevented the realization of a joint and broad in-person session (scheduled for late 2025). This session will be held immediately after the completion of Phase 2, supported by the results obtained.

Key Outcomes from the Stakeholder Consultation

The online survey was sent to all participants and members of the Viana do Castelo Climate Change Monitoring Municipal Commission (CMAACVC). A total of 12 complete responses were received from a diverse and qualified sample (including Civil Protection, environmental NGOs, academia, the business sector, and port authorities). These contributions underpin the strategic decisions and technical prioritizations detailed in this report.

The main findings of the consultation are:

- **Validation of the need for high resolution:** only 8.3% of respondents considered the global-scale information (Phase 1) fully useful for their operations, validating the effort to transition to the 10-meter operational scale carried out in this phase.
- **Consensus on risk prioritization:** stakeholders achieved a strong consensus on Wildfires as the most severe and urgent risk (58.3% of responses), followed by River Flooding (16.7%).
- **Focus on critical assets:** partners highlighted the vulnerability of "engineering structures" (bridges and tunnels) and the strategic road network, which led to the integration of specific infrastructure layers into the risk analysis.
- **Emerging concerns:** the survey brought topics such as coastal erosion and the salinization of the Lima River to the debate, identified as critical gaps to be addressed in future studies.
- **Response needs:** the need to decentralize emergency resources to inland parishes was identified, aiming to mitigate the concentration of resources in the urban core.
- **Guidelines for adaptation**: there is a strong preference for the implementation of Nature-Based Solutions (NbS) and the inclusion of social vulnerability metrics (e.g., isolated elderly populations) in the measures to be designed in Phase 3.

2.2 Risk Exploration

Risk exploration builds on the scoping phase by screening the climate-related hazards and risks most relevant to the local context. By integrating stakeholder insights with factual evidence, this phase facilitates the selection of appropriate risk workflows and climate scenarios for subsequent quantitative analysis, ensuring that the assessment is both locally anchored and consistent with the CLIMAAX framework.

2.2.1 Screen risks (selection of main hazards)

The Screen Risks phase in Phase 2 focuses on justifying the refinement of hazard selection compared to the Phase 1 Deliverable. Initially, four hazards were identified: River Floods, Wildfires, Heavy Rainfall, and Storms. In this phase, the municipality has prioritized **Wildfires, River Floods, and Heavy Rainfall (Extreme Precipitation)** for high-resolution analysis, while temporarily excluding Storms to ensure a deeper.

The prioritization of these three hazards is empirically supported by a robust inventory of historical occurrences between 2000 and 2025:

- **Wildfires:** a total of **2,425 rural fire occurrences** were recorded over the last 25 years, representing the most frequent and persistent hazard in the territory.
- **Heavy Rainfall and Floods:** combined, these events accounted for **1,313 occurrences** in the same period, often leading to systemic disruptions in urban drainage and road networks.

This historical record confirms that these hazards are not just theoretical possibilities but recurring events that consistently affect the municipality's infrastructure and population.

Data from the Copernicus Interactive Climate Atlas for the North of Portugal region confirms a clear worsening trend that justifies this selection:

- **Wildfire Risk:** projections indicate an increase in the frequency and intensity of fire-prone weather conditions due to rising average temperatures and prolonged dry spells (escalation of the Fire Weather Index - FWI).
- **Extreme Precipitation:** despite a trend towards lower annual total precipitation, the Atlas indicates an increase in the intensity and frequency of heavy rainfall events (R20mm and RX1day indices). This "wet-get-wetter" pattern in short bursts directly increases the risk of flash floods and drainage failure.

The decision to focus on these three hazards is validated by two converging factors:

- **Stakeholder consensus**: 58.3% of local actors identified Wildfires as the most severe and urgent hazard, while River Floods and Extreme Precipitation constitute the remaining primary concerns of the community.
- **Strategic resource allocation**: by focusing on these three, the project transitioned from 100-meter global datasets to a 10-meter operational scale (LiDAR-based). This allows the risk assessment to move from an indicative regional tool to an operational building-level analysis.

Regarding the exposure analysis for the three selected risks, Phase 2 represents a significant advancement through the integration of a detailed municipal inventory of buildings and critical infrastructure. This approach overcomes the generalizations of the global datasets used in Phase 1, allowing the risk assessment to transition from a merely indicative tool to an operational.

2.2.2 Choose Scenario

The selection of scenarios for the Climate Risk Assessment (CRA) in Viana do Castelo balances scientific rigor with a precautionary approach to ensure municipal planning is robust against emission uncertainties. The following scenarios and time horizons were selected for the three priority hazards:

- **River Flooding (Floods):** RCP 4.5 (intermediate) and RCP 8.5 (high emissions) scenarios were utilized. The analysis covered all available return periods (1 in 10, 50, 100, 200, and 500 years), projected for the 2030-, 2050-, and 2080-time horizons, allowing for the assessment of the progressive worsening of the hazard throughout the century.
- **Wildfires (Fire):** The hazard analysis included the RCP 4.5 (intermediate) and RCP 8.5 (high emissions) scenarios. All the period available for historical data and 2041–2060 as future period.
- **Extreme Precipitation (Heavy Rainfall):** RCP 4.5 (intermediate) and RCP 8.5 (high emissions) scenarios. The time horizon for future projections ranges from 2041 to 2070, enabling the modelling of variations in the intensity and frequency of extreme 3-hour and 24-hour events.

The project combined climate hazards with socio-economic data through spatial intersection and methodological recalibration:

- **Spatial resolution matching**: land use and infrastructure data were resampled to match the 10-meter high-resolution hazard maps generated via LiDAR, ensuring that damage estimates are spatially precise.
- **Monetary valuation**: climate-induced hazards (e.g., flood depths) were intersected with the recalibrated economic exposure layers to quantify potential financial losses and infrastructure failure points.

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 VC_Climaax, advanced implementation levels are adopted to adapt global models to the reality of the territory, ensuring greater spatial and thematic precision.

To establish a comprehensive multi-hazard baseline, a broad suite of workflows from the updated CLIMAAX Toolbox was successfully executed and tested during this phase:

- **Floods:** *Coastal flooding, River flooding, Flood damage and population exposure,* and *River discharge analysis.*
- **Heavy Rainfall:** *Extreme Precipitation.*
- **Fire:** *Wildfire FWI, FWI response model,* and *Wildfire ML.*

While all these workflows were implemented using the project's standard methodologies, this report focuses its detailed analysis on the specific hazards and workflows where regionalized refinement with high-resolution local data integration was achieved. This methodological refinement focuses specifically on the risks of wildfires, fluvial floods, and heavy rainfall events, generating outputs (maps and metrics) ready for the damage assessment phase. The regionalization strategy is based on the targeted improvement of each component of the risk equation, ensuring results that are more faithful to the local scale.

The regionalization strategy was based on three fundamental pillars of methodological refinement:

- **Spatial and thematic precision:** the analysis evolved from 100-meter global datasets to a 10-meter operational scale, supported by local LiDAR data. Thematic precision was enhanced by replacing CORINE with the national COS 2023 map (93 land cover classes), enabling street- and parcel-level analysis.
- **Socio-economic recalibration:** damage functions were localized using a Regional Wealth Factor and updated to 2024 values. This calibration ensures that economic damage estimates reflect the actual replacement costs in the region.
- **Operational impact metrics:** in addition to economic losses, new metrics were calculated to support political and technical decision-making, notably the EAPD (Expected Annual People Displaced) for human safety and the "drainage gap" for infrastructure resilience.

This regionalized analysis also integrated 11 layers of critical municipal infrastructure, allowing for the assessment of indirect impacts and cascading effects. The following subsections detail the specific refinement applied to each of the three priority hazards, consolidating the scientific basis required for the selection of adaptation solutions in Phase 3.

2.3.1 Hazard #1 - Floods fine-tuning to local context

The riverine flood risk assessment in Phase 1 was primarily based on European and global datasets from the Joint Research Centre (JRC), with a spatial resolution of 3 arc-seconds (approximately 100 meters). Although these data allowed for a systematic regional characterization, the results proved too "coarse" for the municipal planning needs of Viana do Castelo. As identified in the D1 report and reinforced by stakeholder feedback, the low spatial resolution prevented the precise identification of exposed buildings and critical infrastructure, often resulting in incorrect overlaps in built-up urban areas.

This Phase 2 was designed to address these weaknesses through a regionalization strategy based on three fundamental pillars:

- **Increased spatial resolution:** transitioning from a 100m scale to a 10-meter operational scale by integrating the local High-Resolution Digital Elevation Model (HR-DEM) and LiDAR data.
- **Topographic realism:** replacing simple statistical interpolations with a physics-based downscaling algorithm that respects actual terrain topography and hydrological connectivity.
- **Preservation of detail in risk:** reversing the resampling logic to ensure that economic damage calculations do not degrade hazard precision.

Thus, the following sub-sections detail how this transition from global data to local models enables the generation of results with direct operational utility for the revision of the Municipal Emergency and Civil Protection Plan (PMEPC) and the Municipal Climate Action Plan (PMAC).

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Flood map resolution	Static: ~100m (native JRC resolution).	**Adaptive**: adjusted to local DEM resolution (e.g., 5m, 10m, or 20m).
Land use handling	Flood maps were degraded to match 100m land use resolution.	**Land use is upsampled** to match the high resolution of the flood hazard (Upsampling).
DEM requirement	None (used relative water depths).	**Optional/Recommended**: integration of local HR-DEM/LiDAR for physical realism.
CRS handling	Fixed to EPSG:3035.	**Auto-detect** and robust conversion to EPSG:3035.
Resolution configuration	N/A (fixed provider resolution).	**Fully adaptive**: the system automatically reads metadata from the user's DEM file.
Cartographic output	Standard low-resolution notebook figures.	**High-resolution map cells** added (20x16 inches at 300 DPI).
Economic calculation	Based on EU average GDP values (Huizinga 2017).	**Local adjustment (Viana do Castelo)**: utilizes regional GDP and updated 2024 Portuguese CPI.
Building classification (OSM)	Generic international categories.	**National customization**: inclusion of common Portuguese classes (e.g., cafés, restaurants, parish councils).
Exposed population	Resampled to the native 100m resolution.	**Building-level precision**: EAEP/EAPD metrics calculated at DEM resolution (e.g., 10m).
Critical infrastructure visualization	Fixed marker sizes (size 100).	**Optimized legibility**: markers and symbols adjusted (size 60) for dense municipal maps.
Technical stability	Risk of *IndexError* when using mixed resolutions.	**Bug fixes**: explicit CRS metadata preservation and array dimension synchronization.
Flood map resolution	Static: ~100m (native JRC resolution).	**Adaptive**: adjusted to local DEM resolution (e.g., 5m, 10m, or 20m).

Key improvements include:

- **Physics-based downscaling:** Implementation of the *downscale_flood_with_dem* function using a flood-fill algorithm, ensuring hydrological connectivity and preventing "ghost floods" in disconnected high-elevation areas.
- **Topographic fidelity:** Utilization of local LiDAR-derived HR-DEM (5m and 10m resolutions) to capture micro-topographies and physical barriers ignored by global models.
- **Reverse resampling logic:** Inversion of the standard resolution approach by upsampling land use (LUISA 100m) to match the 10m flood hazard resolution, preserving high-precision flood boundaries during damage calculations.
- **Socioeconomic recalibration:** Adjusted economic damage curves using a Regional Wealth Factor (0.868) based on local GDP per capita and updated to the 2024 Portugal Consumer Price Index (1.25 inflation factor).

- **Human safety metrics:** Introduction of the Expected Annual People Displaced (EAPD) metric, using a critical depth threshold of >1.0 meter to distinguish between general exposure and severe life-safety risks.

Table 2-2 summarizes the data sources and outputs generated during the refinement of the riverine flood risk workflow (River Flood). This phase of the VC_Climaax project marks a decisive technical transition, where European and global-scale data from Phase 1 were integrated with local Digital Elevation Models (DEM) and high-resolution LiDAR data, enabling a spatial detail ten times higher (from 100m to 10m). Furthermore, vulnerability parameters were "portugalized" by adjusting damage curves with Viana do Castelo's regional GDP and the 2024 Consumer Price Index (CPI), ensuring that financial impact metrics are credible and tailored to the municipality's reality and for local decision-makers.

Table 2-2 Data overview workflow #1 – Floods (River Floods & Flood building damage and population exposed)

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **JRC high-resolution river flood maps** (v3, 2024) for return periods: 10, 50, 100, 200, and 500 years. · **Aqueduct Floods dataset for future climate scenarios** (RCP 4.5 and 8.5 for 2030, 2050, and 2080 horizons). · **Local Refinement:** High-resolution Digital Elevation Model (DEM) and municipal LiDAR data for physical 10m downscaling.	· **JRC depth-damage functions** for LUISA land-use classes. · **Local/National Adjustments**: Damage curves corrected with Portugal's **2024 Consumer Price Index (CPI)** and **Viana do Castelo's GDP per capita**.	· **LUISA land cover 2018** (upsampled to **10m resolution**). · **OpenStreetMap (OSM)**: Buildings and infrastructure with classifications adapted to the national context (e.g., cafés, parish councils). · **GHSL Population**: Population distribution maps at 3 arc-seconds (~100m). · **Critical Infrastructure**: Detailed municipal inventory (11 specific layers).	· **Economic damage maps** (estimates in million €). · **Expected Annual Damage (EAD)**: Integration of financial losses by return period. · **EAEP / EAPD**: Expected annual population exposed and displaced. · **Critical infrastructure exposure**: Visual identification of systemic failure points.

2.3.1.1 Hazard assessment

The flood hazard assessment was extensively refined to transition from a regional scale (~100m) to a local operational scale of 10 meters. This enhancement was achieved through the integration of a high-resolution Digital Elevation Model (DEM) and LiDAR data from the Viana do Castelo territory.

The core of this enhancement is the implementation of a physics-based downscaling algorithm (*downscale_flood_with_dem*), which uses hydraulic principles to convert JRC global flood depths into absolute water surface elevations. The methodology included:

- **Water surface level calculation:** for each flooded cell, the absolute water surface elevation is calculated at the cell centroid, allowing for realistic spatial interpolation.
- **Hydrological connectivity (flood fill):** a "flood fill" technique ensures the flood extent is physically connected to the main river channels, eliminating isolated "puddles" or artifacts that often appear in low-resolution models.

- **Topographic realism:** The refinement ensures flood boundaries follow the actual terrain, meaning water is only mapped where the terrain elevation is lower than the interpolated water level.

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

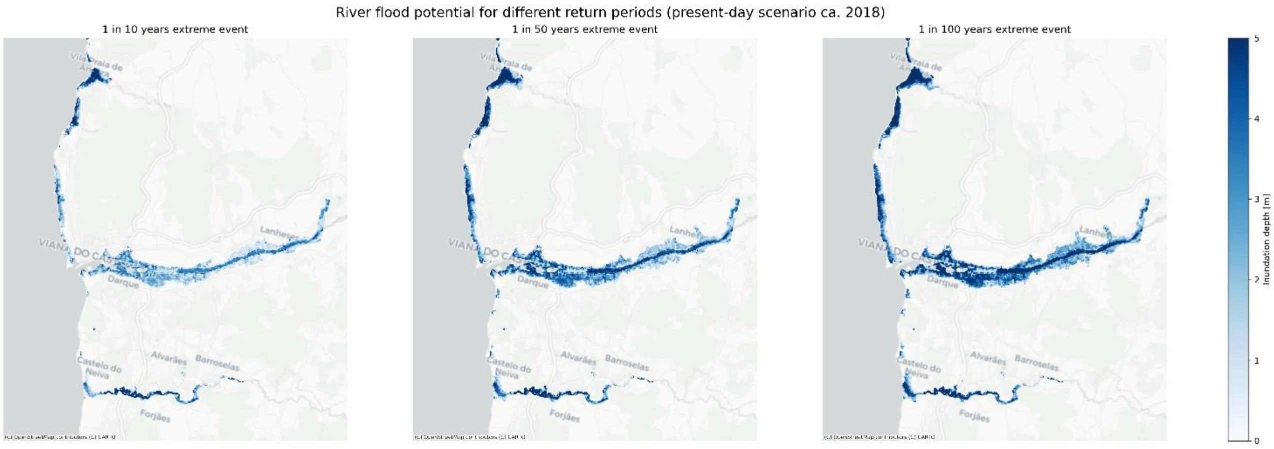


Figure 2-3 River flood potential (inundation depth [m]) for different return periods: 10, 50 e 100 years (present-day scenario ca. 2018), Viana do Castelo Municipality - 10m Resolution.

This first map demonstrates the precision gain achieved. Unlike Phase 1, where boundaries were pixelated, the 10m refined map shows water intrusion precisely following the drainage lines and topographic depressions of Viana do Castelo, allowing for the identification of individual buildings at risk.

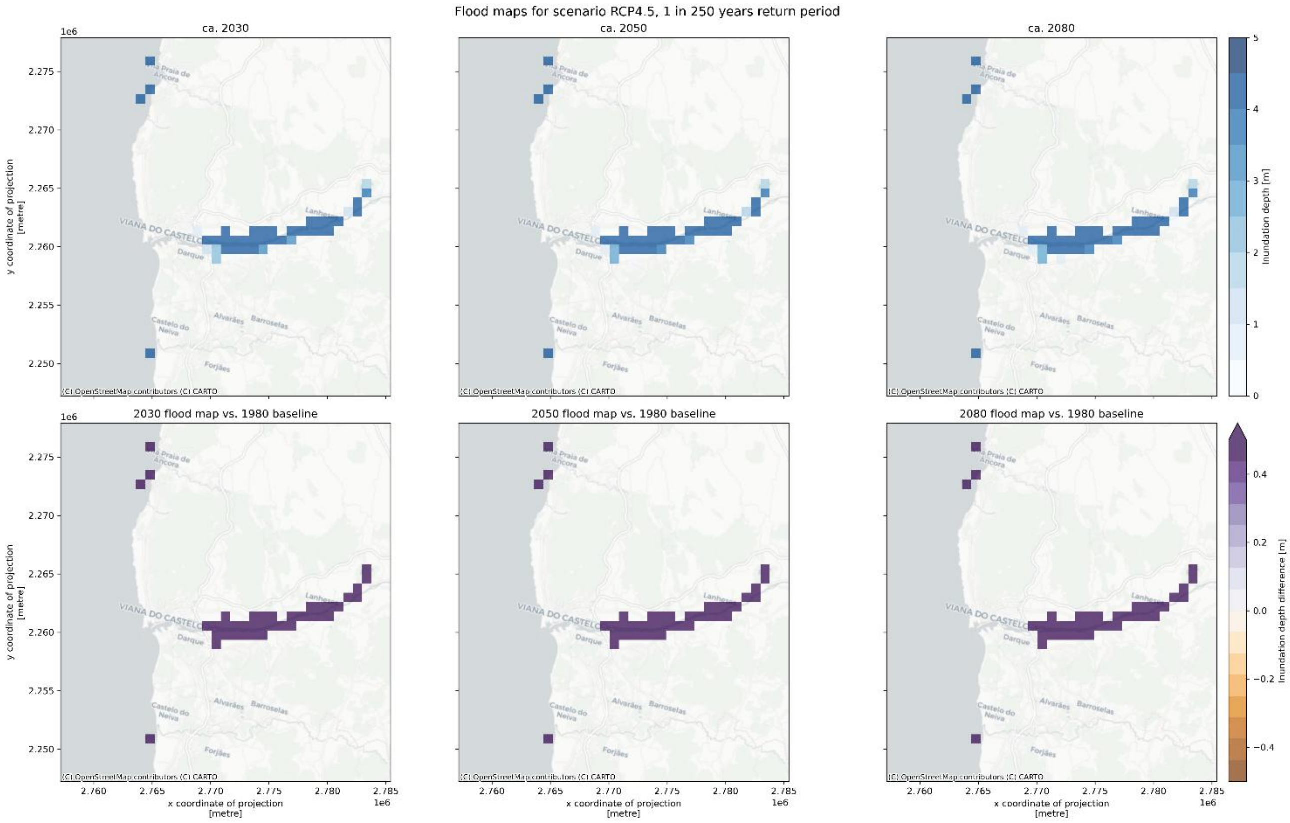


Figure 2-4 Flood maps (inundation depth [m]) for scenario RCP 4.5 (return period: 250 years), Viana do Castelo Municipality.

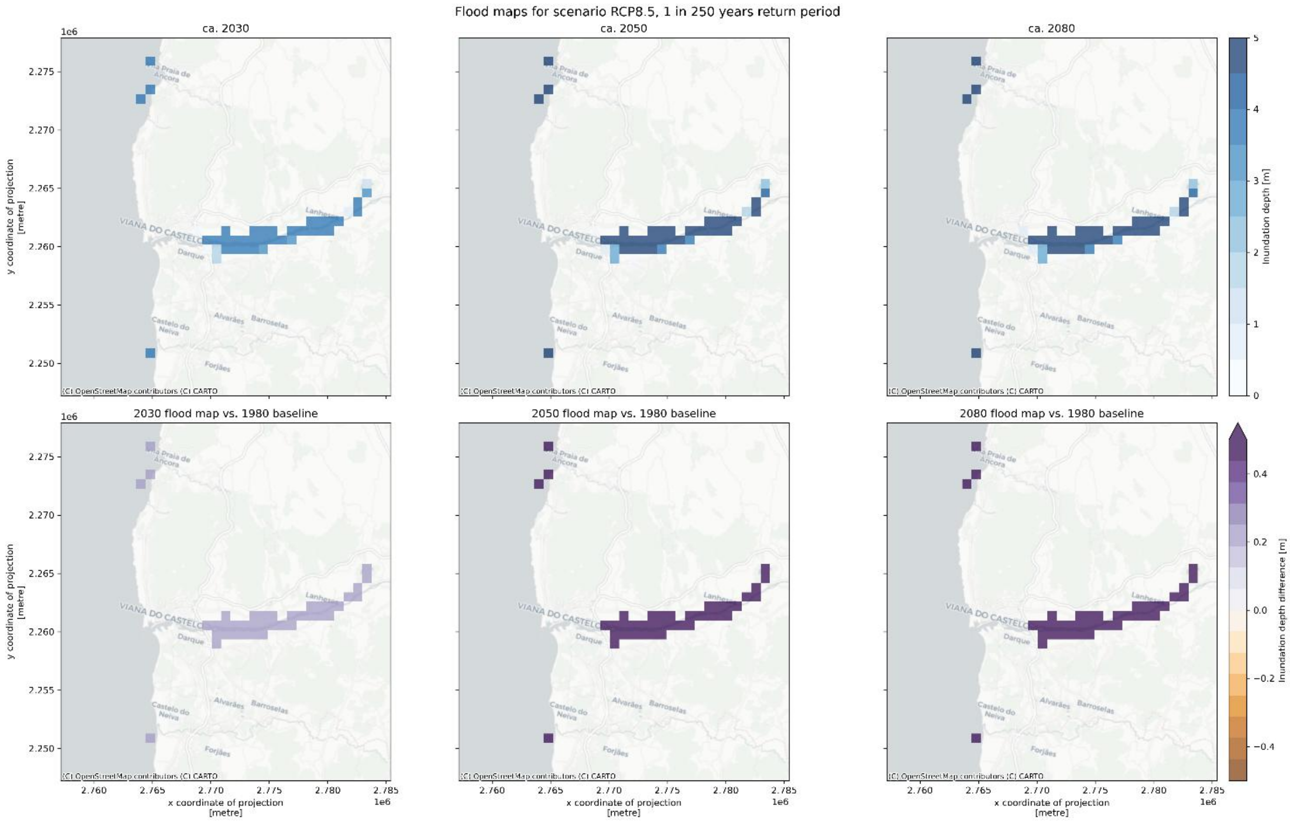


Figure 2-5 Flood maps (inundation depth [m]) for scenario RCP 8.5 (return period: 250 years), Viana do Castelo Municipality.

2.3.1.2 Risk assessment

The Phase 2 risk assessment was operationalized through two complementary workflows that allowed for the quantification of flood consequences at different decision scales:

A. Economic Damage Analysis by Land Use ("River Flooding" Workflow)

The risk assessment in Phase 2 introduced a critical inversion of the data resampling logic. In Phase 1, precision was lost because flood maps were downsampled to match the coarse land-use resolution (100m). In the refined workflow, the land use (LUISA) is upsampled to match the high resolution (10m) of the flood map, preserving the detail of flood boundaries during damage calculations. Using the refined 10m flood extent, this process identified cross-sector financial losses (e.g., industrial areas, agriculture, and transport infrastructure).

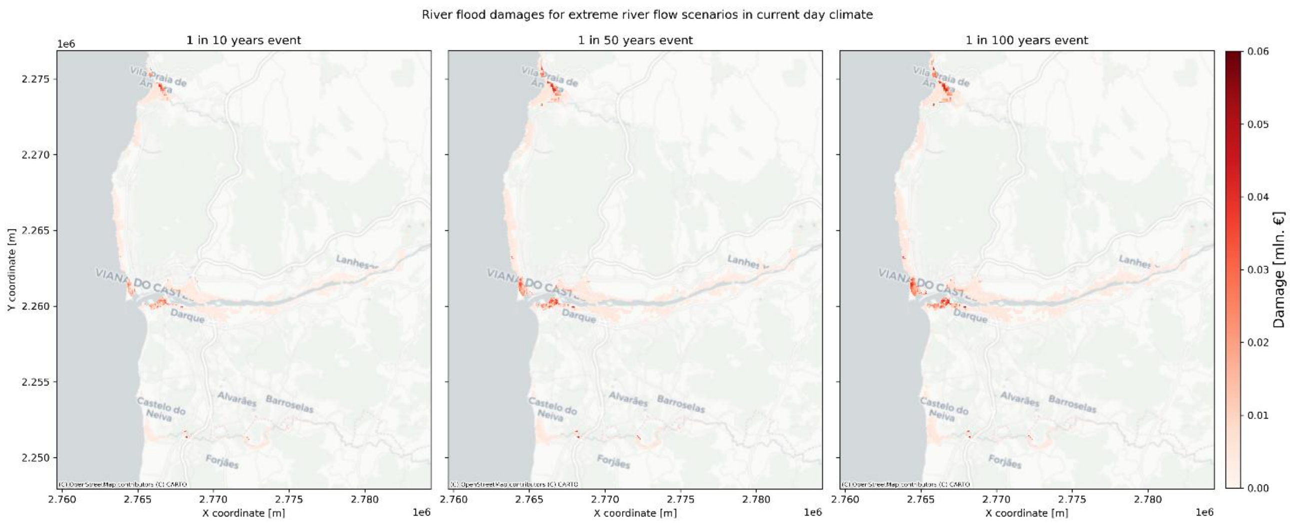


Figure 2-6 River flood damages (mln. €) for extreme river flow scenarios in current day climate (to different return periods: 10, 50 and 100 years) in the Viana do Castelo Municipality.

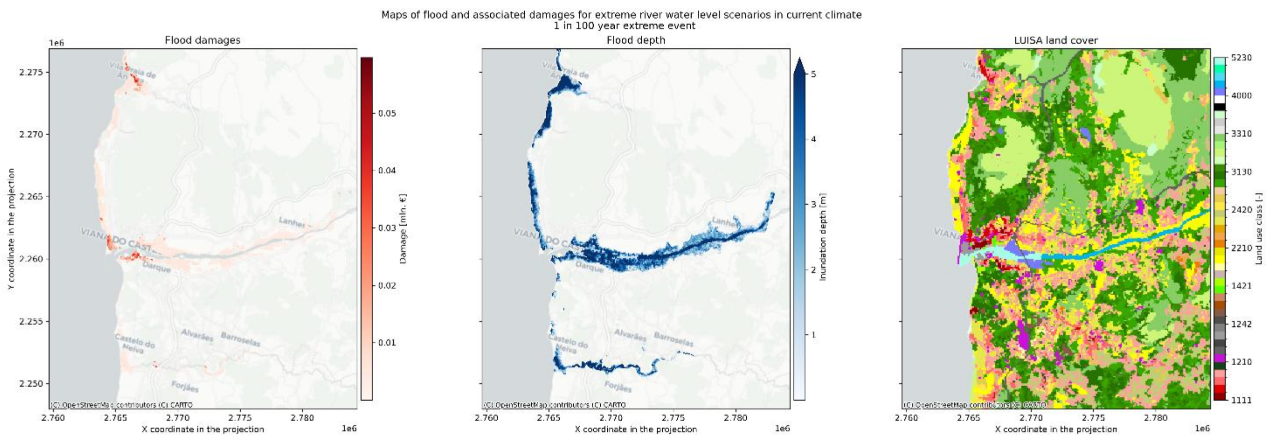


Figure 2-7 Maps of flood (inundation depth [m]) and associated damages (mln. €) for extreme river water level scenarios in current climate (LUISA land cover 2018) in the Viana do Castelo Municipality.

B. Granular Impact on Buildings and Population ("Flood building damage and population exposed" Workflow)

This approach marks a significant advancement of Phase 2 by deepening the analysis at the individual asset level and human safety through rigorous customization to the national context:

- **Portuguese (and coastal) context adjustment:** new infrastructure classes adjusted to Viana do Castelo's reality were added and validated. This included integrating specific typologies for the port and coastal industrial sectors, as well as essential public utility equipment.
- **Economic recalibration:** depth-damage curves were adjusted using the Regional Wealth Factor (0.868) and updated by Portugal's 2024 CPI (1.25 factor), ensuring estimates reflect actual local reconstruction costs.
- **Social impact metrics:** the model distinguished between merely exposed population and population in severe danger. Using a depth threshold of > 1.0 meter, it was estimated that 285 people would be at real risk of annual displacement (EAPD) due to the loss of safety and habitability conditions.

Figure 2-8 highlights the risk evolution between a high-frequency event (10-year return period) and an extreme scenario (500-year). It shows that essential infrastructures — including water sanitation networks, power substations, and port assets — are compromised at the earliest threshold. The 500-year scenario serves as the baseline for "worst-case" planning, delimiting areas where resilience must be absolute to prevent cascading failures of municipal services.

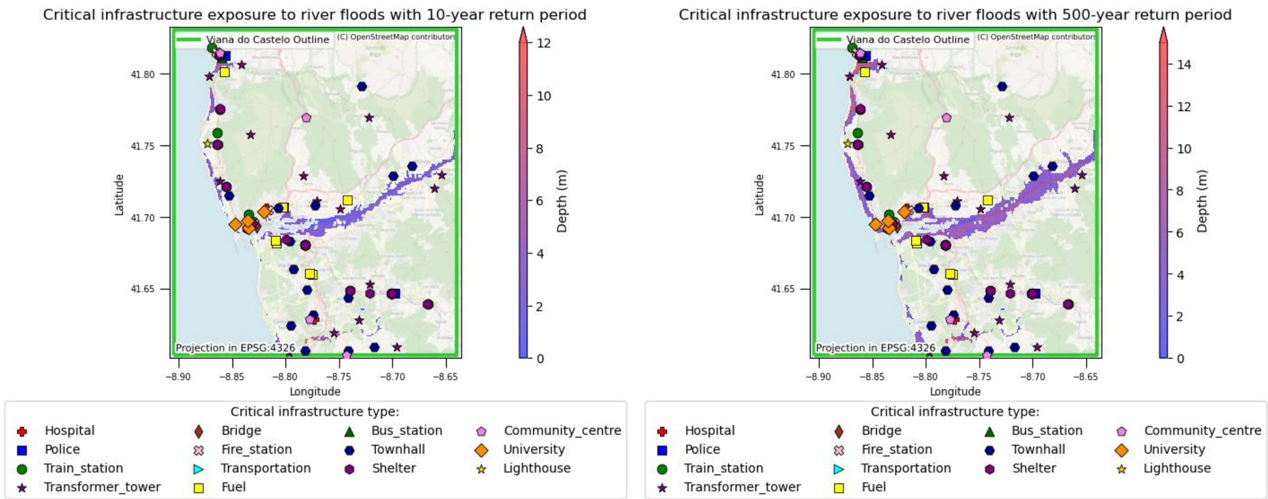
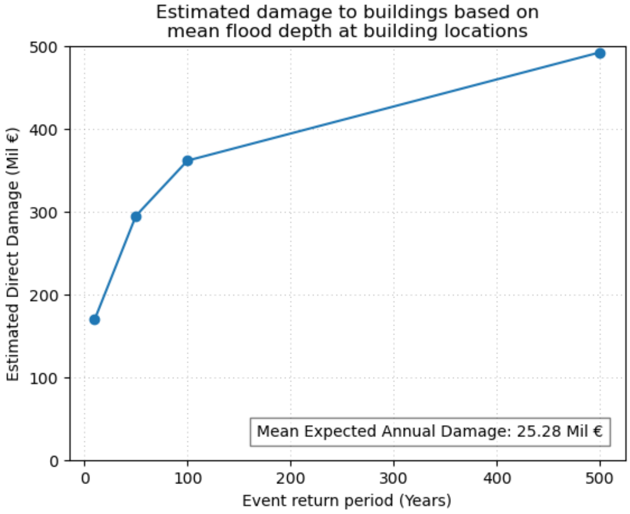


Figure 2-8 Critical infrastructure exposure to river floods (to different return periods: 10 and 500 years) in the Viana do Castelo Municipality.

Figure 2-9 synthesizes the relationship between flood depth, economic losses, and human impact. The plot reveals a non-linear progression: while minor damages occur frequently, the Expected Annual People Displaced (EAPD) curve shows critical jumps beyond the 1.0-meter depth threshold. This analysis supports the estimated annual values of 25.28 M€ in damages and 285 people requiring actual displacement, providing actionable data and a financial basis for justifying the cost-benefit of future adaptation measures.



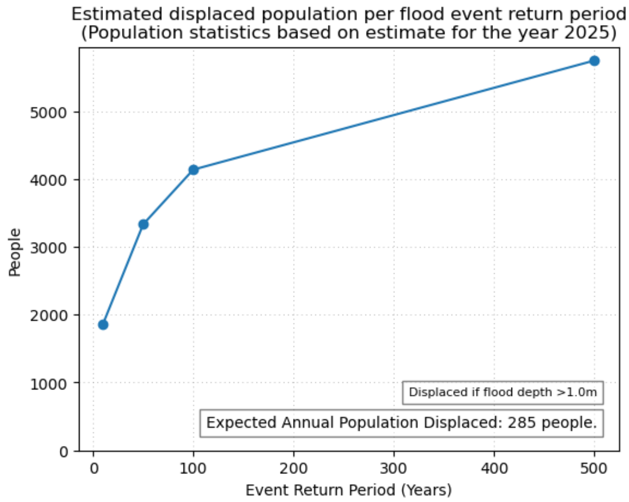


Figure 2-9 Expected Annual Damage (EAD) and People Displaced (EAPD) Curve Plots in the Viana do Castelo Municipality.

2.3.2 Hazard #2 - Fire finetuning to local context

During Phase 1 of the VC_CLIMAAX project, wildfire risk assessment for Viana do Castelo was based on the FWI Risk Assessment workflow. However, for this second phase, the wildfire risk workflow "Risk assessment for wildfire (machine learning approach)" was refined due to its higher specificity, versatility, and adaptability to the local territory.

The original evaluation of this workflow relied on global datasets and generic land cover classifications (CORINE), which lacked the necessary detail to capture the specificities of the Portuguese forest landscape. Phase 2 was designed to address these limitations through a localized strategy built on three pillars:

- **Hyper-local spatial resolution:** transitioning from a 100m scale to a 10-meter operational scale by integrating the National Land Use Map (COS 2023).
- **Scientific fuel calibration:** replacing generic European values with a manual conversion dictionary based on national research, assigning maximum hazard to critical species like *Eucalyptus* and *Maritime Pine*.
- **Comprehensive exposure network:** expanding analysis to a detailed municipal inventory of 11 specific critical infrastructure layers.

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Analysis Resolution	Static: 100m	**Adaptive: 10m** (adjusted to local COS/LiDAR resolution).
Land Use Source	CORINE Land Cover (44 classes)	**COS 2023 - DGT** (93 detailed classes).
Fuel Classification	Generic JRC/EFFIS values	**National customization**: Manual mapping of Portuguese forest species to Fuel Types (1-4).
Climate Dataset	Standard C3S FWI indices	**CHELSA V2.1**: High-resolution (30 arc sec) climatologies for optimized ML training.

Aspect	Original Workflow	Enhanced Workflow
Exposure Scope	Roads and generic buildings	**11 Municipal layers**: Including health facilities, schools, and filling stations.
Technical Stability	Connection errors in large downloads	**Kernel Cleanup**: Implementation of memory management and cache clearing for stable processing.

Key improvements include:

- **Spatial precision**: upgraded analysis from a 100m grid to a 10m resolution, enabling a detailed assessment of the Wildland-Urban Interface (WUI).
- **National land use integration**: replaced the European CORINE dataset with the COS 2023 **(DGT)**, which provides 93 thematic classes tailored to the Portuguese territory.
- **Localized fuel calibration**: implementation of a manual conversion dictionary for Fuel Types (1–4), assigning maximum hazard (Fuel Type 4) to critical local species like *Eucalyptus* and *Maritime Pine* based on national scientific literature.
- **Expanded exposure network**: integrated the complete CMVC critical equipment network, covering 11 categories including health facilities, schools, public safety hubs, and filling stations, moving beyond simple road network analysis.
- **Cartographic noise reduction**: applied advanced post-processing and masking techniques to remove statistical noise from non-burnable surfaces, such as water lines and dense urban areas.

The transition to the machine learning approach necessitated a comprehensive restructuring of the input data architecture to ensure the model could accurately reflect the Portuguese forest context. By moving beyond generic global providers, Phase 2 integrated high-resolution local environmental drivers with official national records, such as the ICNF burnt area perimeters and the COS 2023 land cover. This integration, summarized in Table 2-3, represents a 'portugalization' of the risk assessment, where high-fidelity hazard data is intersected with a multi-layered municipal exposure network to produce actionable risk metrics tailored to Viana do Castelo's specific reality.

Table 2-3 Data overview workflow #2 – Fire (ML approach)

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **CHELSA V2.1:** High-resolution climate variables (bioclimatic, consecutive dry days, and frost days). · **Burnt Territories (ICNF):** Georeferenced burnt area perimeters (2009–2024) used for model training and validation. · **HR-DEM:** LiDAR-derived topographical variables (elevation, slope, and aspect) at 10m resolution.	· **JRC Population Vulnerability**: Aggregated index based on the Wildland-Urban Interface (WUI) context. · **National Fuel Calibration**: Manual conversion dictionary for Fuel Types (1-4) tailored to Portuguese species (*Eucalyptus, Maritime Pine*). · **Economic & Ecological Vulnerability**: Restoration cost	· **COS 2023 (DGT)**: National land use map with high thematic resolution (93 classes). · **Critical Infrastructure**: 11 specific municipal layers (health, schools, public safety, and energy assets). · **Strategic Road Network**: Hierarchical classification (Primary, Secondary, Tertiary) for emergency accessibility.	· **High-Resolution Hazard Maps**: Susceptibility and intensity classes at a 10m scale. · **Multi-Scenario Risk Projections**: Historical baseline (1991–2020) vs. Future horizons (RCP 4.5/8.5). · **Systemic Failure Points**: Identification of critical assets and access routes in "Very High" risk zones. · **Aggregated Risk Indices**: Final risk classification at

Hazard data	Vulnerability data	Exposure data	Impact metrics/Risk output
	estimates and biodiversity indices.		Municipal and NUTS3 levels for regional planning.

2.3.2.1 Hazard assessment

The wildfire hazard assessment was extensively refined by transitioning from generic European indices to a localized Machine Learning (Random Forest) model. This approach allowed the integration of high-resolution municipal data, ensuring the results reflect the specific biophysical and climatic characteristics of Viana do Castelo.

The first stage of the refinement involved replacing the Phase 1 CORINE datasets with the **COS 2023** from the Directorate-General for Territory (DGT). This dataset provides a thematic resolution of 93 classes, which is essential for accurate fuel type mapping in the Portuguese context.

To ensure maximum geographical consistency, this spatial improvement was further reinforced by integrating the municipality's High-Resolution DEM and the official administrative boundaries (CAOP). This process allowed for a precise clipping and alignment of the land cover data with the local topography, ensuring that the 10-meter operational scale is perfectly synchronized with the physical reality of the territory.

Figure 2-10 represents the foundational layer for wildfire modelling. The transition to COS 2023 allowed the team to precisely identify critical fuel loads, such as *Eucalyptus* and *Maritime Pine* massifs, which are assigned maximum hazard levels in the localized fuel calibration dictionary. The 10m resolution ensures that the Wildland-Urban Interface (WUI) is captured with operational accuracy.

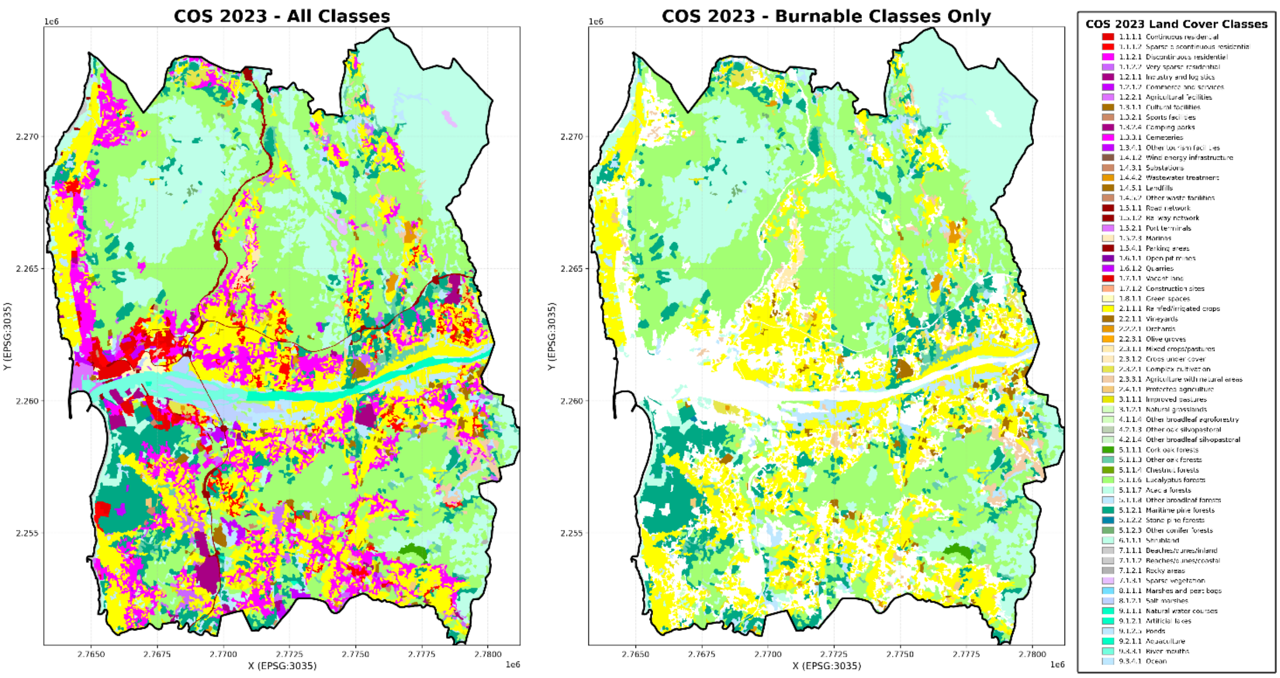


Figure 2-10 High-Resolution Land Cover (COS 2023) at 10m resolution (all classes and burnable classes only)

The Random Forest (RF) model was trained using 10 climatic variables from the CHELSA V2.1 dataset and historical burnt perimeters (2009–2024) provided by the Portuguese Institute for Nature

Conservation and Forests (ICNF). The model identifies areas with a higher probability of fire occurrence based on topography and historical climate drivers (Figure 2-11).

The susceptibility map displays a continuous score where higher values (yellow) indicate a greater statistical probability of fire occurrence. The model correctly identifies the eastern and central forest massifs, such as the *Serra da Padela*, as highly susceptible zones due to the combination of steep slopes and high fuel accumulation.

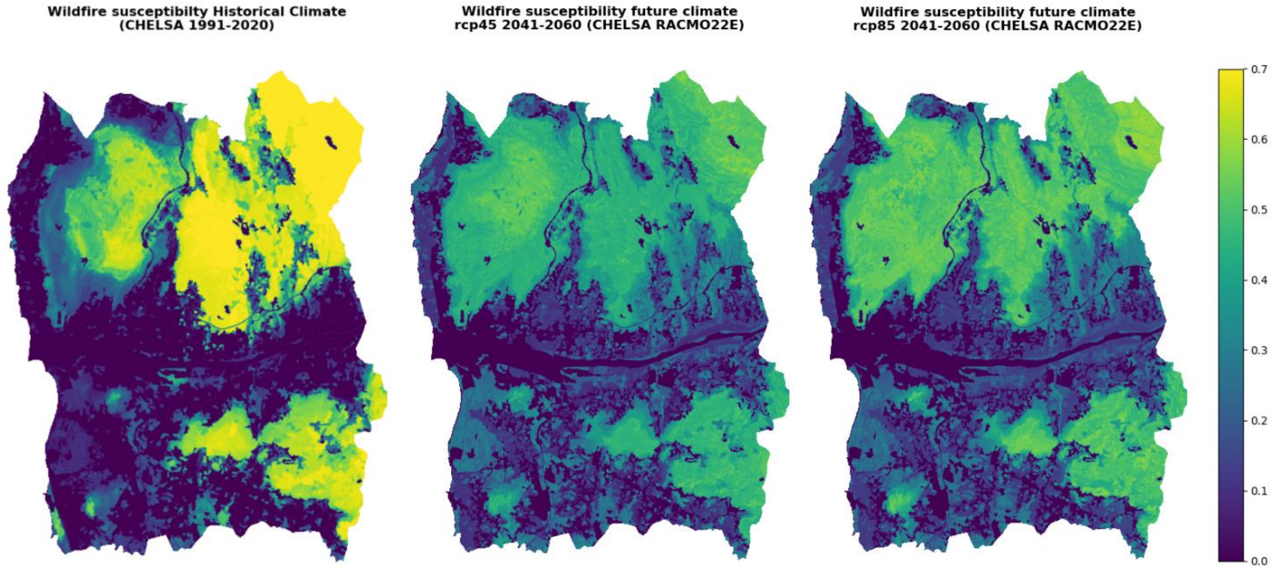


Figure 2-11 Wildfire Susceptibility Map derived from Random Forest modeling – Historical baseline (1991–2020) vs Future (2041-2060, RCP 4.5 and RCP 8.5) in the Viana do Castelo Municipality.

The final hazard maps (Figure 2-12) categorize wildfire intensity into six classes (from "Very Low" to "Extreme"). These maps combine susceptibility with specific fuel load characteristics to provide an actionable tool for the Civil Protection services.

Figure 2-12 Wildfire Hazard Map – Historical (1991-2020) vs Future (2041-2060, RCP 4.5 and RCP 8.5) in the Viana do Castelo Municipality.

The final hazard output highlights that a significant portion of the municipality falls within the "Very High" (red) and "High" (orange) hazard categories. These areas are concentrated in the interior forest zones, validating the historical occurrence patterns. While future projections (RCP 8.5) show a maintenance of these "Very High" levels, the results are considered a conservative baseline for local decision-makers, as tree-based models like Random Forest do not extrapolate beyond the ranges found in historical training data (a known limitation of tree-based models).

2.3.2.2 Risk assessment

The Phase 2 risk assessment transformed wildfire hazard intensities into actionable operational data by intersecting high-resolution susceptibility maps with the municipality's socioeconomic and infrastructural fabric. The use of 10m resolution allowed the team to pinpoint exactly which schools, health centers, and filling stations fall within "Very High" hazard zones.

The first step in the risk analysis involved the integration of Viana do Castelo's comprehensive critical equipment network. So, a significant technical leap in Phase 2 was the transition from generic exposure data to a comprehensive, high-resolution inventory of Viana do Castelo's critical assets. While the original workflow relied mostly on basic road networks, the enhanced analysis integrated 11 specific municipal layers (Figure 2-13), totalling thousands of individual features across the territory.

The following assets were georeferenced and integrated into the 10-meter resolution exposure model:

- **Public and educational services:** 132 public services and 87 schools.
- **Social and health infrastructure:** 86 social welfare facilities, 51 health facilities, and 16 emergency shelters.
- **Safety and economic assets:** 39 civil protection and public safety hubs, 54 hotels, and 20 filling stations.
- **Strategic transport network:** 17,279 primary road segments, 12,314 secondary road segments, and 16,717 tertiary road segments.

Figure 2-13 identifies the spatial distribution of health facilities, schools, public safety hubs, and energy assets. The high density of critical equipment in the coastal urban core contrasts with the vulnerability of isolated infrastructure in the interior parishes. This inventory serves as the exposure foundation for calculating systemic risk under present and future climate conditions.

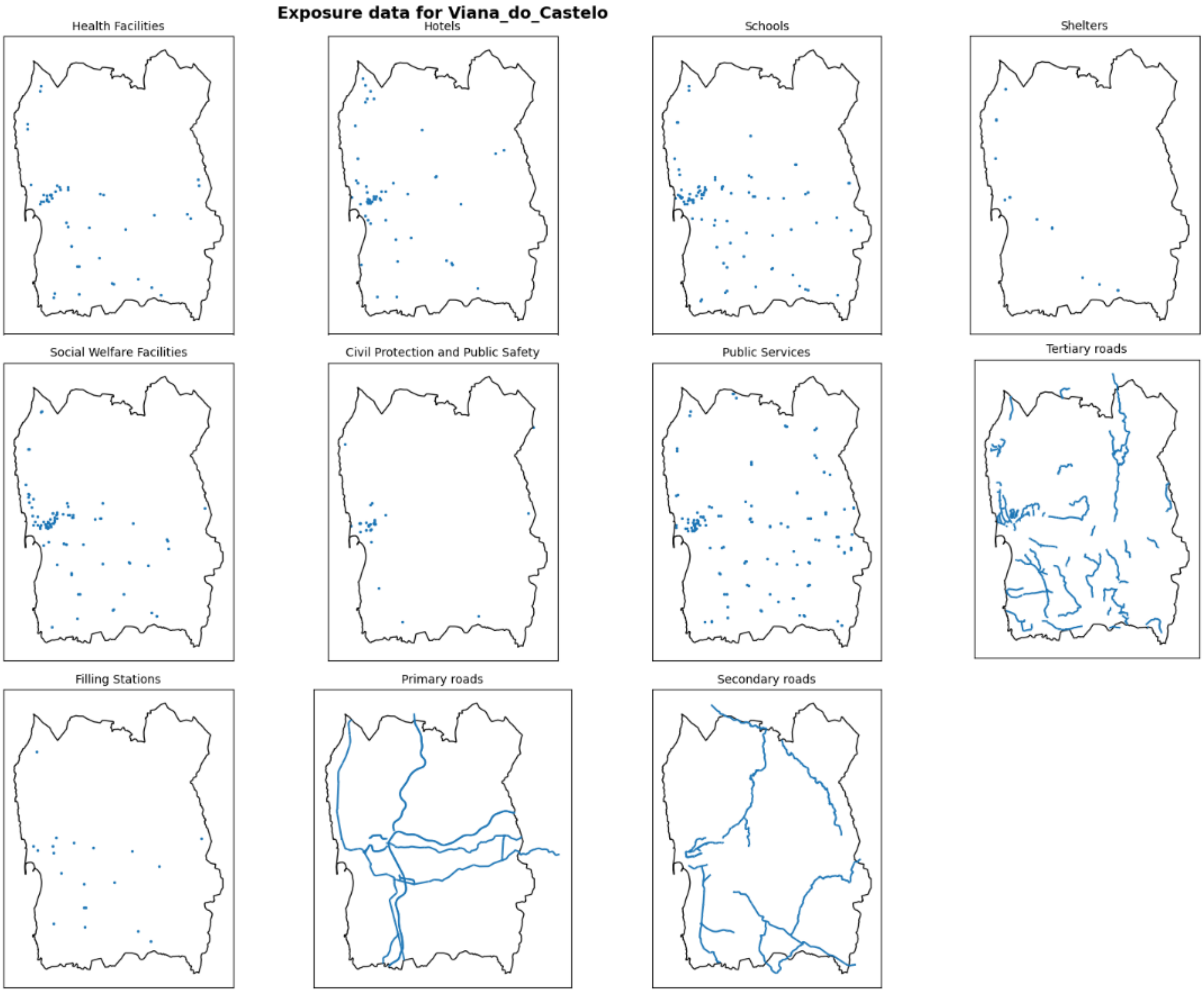


Figure 2-13 Detailed municipal exposure network including 11 critical infrastructure layers

The risk calculation was disaggregated into three pillars: population, economic, and ecological risk. By training the Random Forest model on historical burnt perimeters and projecting it onto climate scenarios (RCP 4.5 and 8.5), the municipality can now visualize the territorial distribution of risk for the 2041–2060 horizon (Figure 2-14).

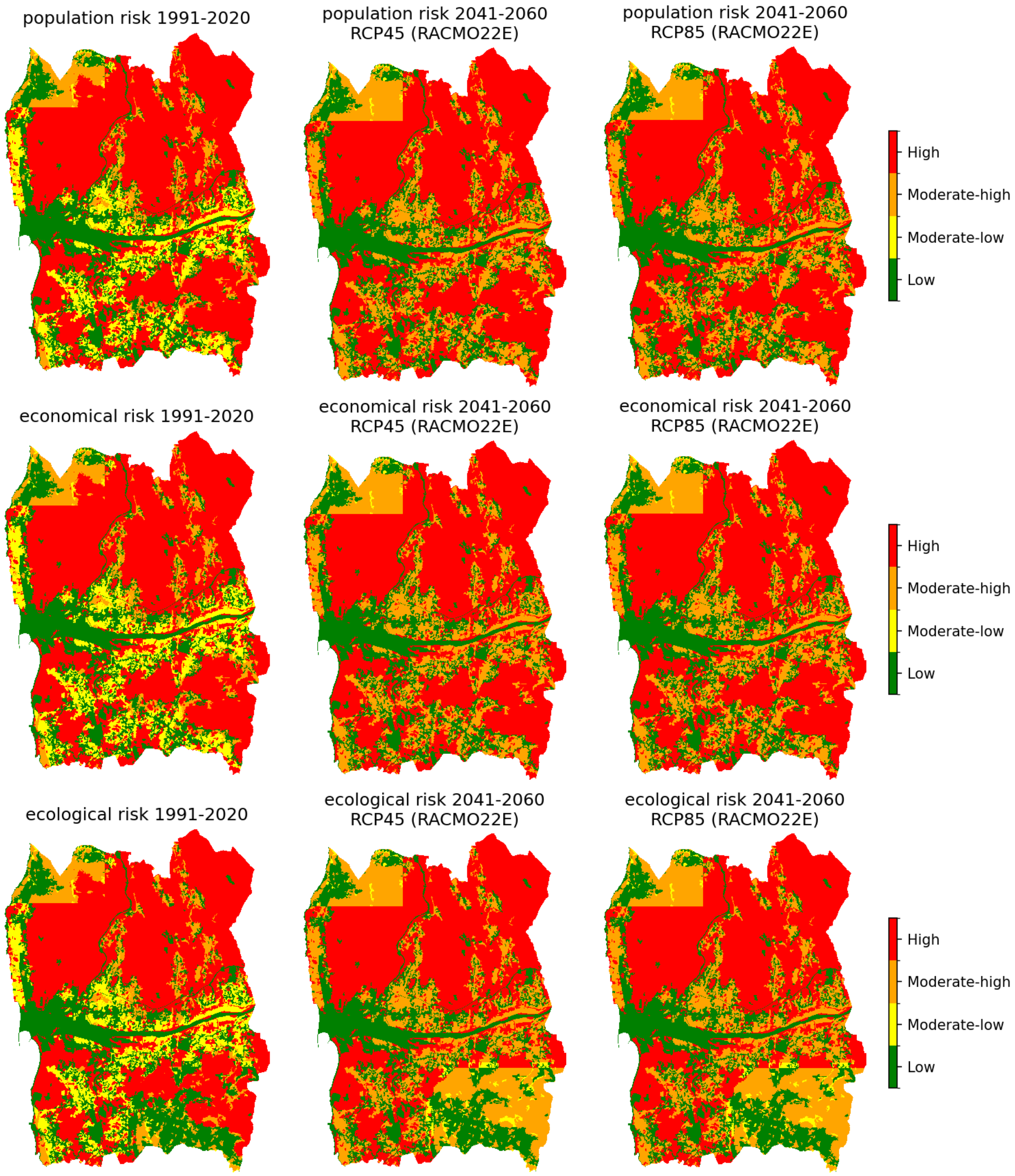


Figure 2-14 Comparative Wildfire Risk (Population, Economic, and Ecological) for Historical, RCP 4.5, and RCP 8.5 scenarios in the Viana do Castelo Municipality.

The risk maps demonstrate a persistent concentration of "High" and "Moderate-High" risk (red and orange) in the eastern forest massifs and the *Serra da Padela*. The transition from historical to future scenarios shows a stabilization of risk in these areas, rather than a decrease, reinforcing the need for structural prevention measures.

A key achievement of the enhanced workflow was the stability analysis of the strategic road network. By analysing 17,279 road segments, the model identifies which primary and secondary access routes are most likely to be compromised during a fire event, directly impacting emergency response times and evacuation safety (Figure 2-15).

This visualization pinpoints critical "red" segments in the secondary and tertiary road networks that connect the urban center to the interior forest zones. High-risk segments identified in the southern and eastern corridors are particularly concerning for the Municipal Emergency and Civil Protection

Plan (PMEPC), as they represent potential bottlenecks where fire could simultaneously cut off access for firefighting forces and trap residents during evacuations.

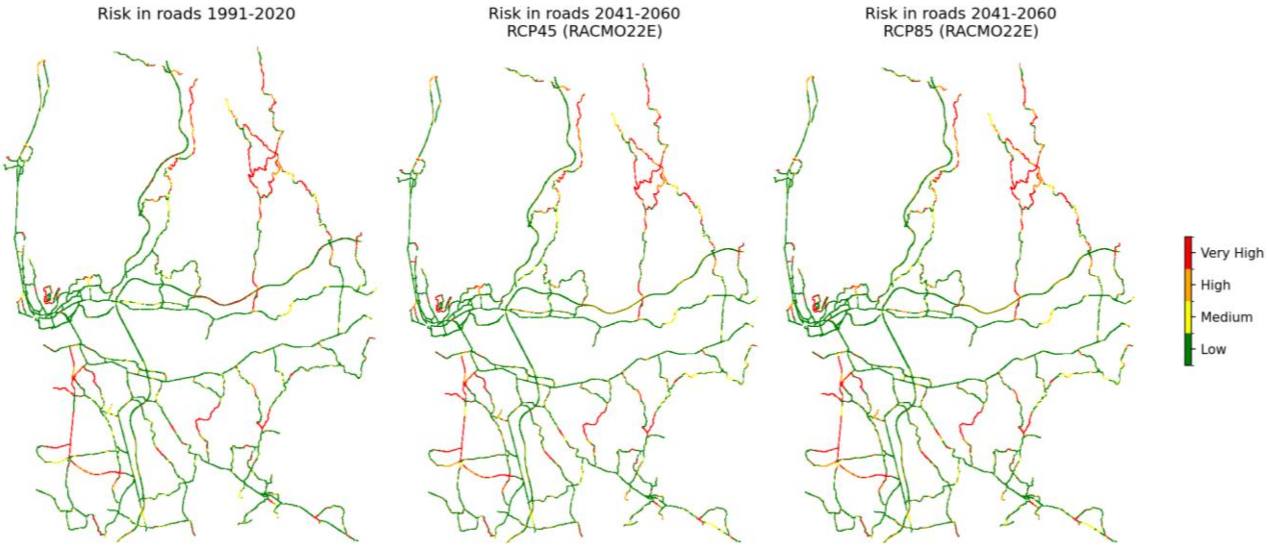


Figure 2-15 Wildfire risk for the strategic road network across historical and future climate scenarios in the Viana do Castelo Municipality.

The results of this refined analysis indicate that wildfire remains the most severe risk in terms of territorial extent and systemic impact. The move to 10m resolution has allowed the municipality to transition from theoretical risk to operational intelligence, identifying exactly which assets and routes require immediate intervention to ensure municipal resilience during the next climate horizon.

2.3.3 Hazard #3 - Heavy rainfall finetuning to local context

The assessment of extreme precipitation in Viana do Castelo serves as a prime example of the "Scale Paradox" in climate modelling. While the evaluation of the hazard remains tethered to regional-scale projections, the risk assessment was refined to bridge the gap between these broad climate signals and the municipality's documented historical reality. While the evaluation of the hazard strictly followed the original workflow of the CLIMAAX toolbox, the subsequent risk assessment was refined to anchor these broad projections in the municipality’s specific historical and geographical context.

The extreme precipitation and pluvial flood risk assessment in Phase 1 was based on a limited set of theoretical coordinates and generic climate indices, which did not account for the complex urban drainage reality of Viana do Castelo. Phase 2 was designed to bridge this gap by transitioning to a data-driven approach anchored in 25 years of local occurrence history.

This enhancement was built on three fundamental pillars:

- **Empirical validation:** Moving from theoretical points to an inventory of 1,321 georeferenced historical flood events (2000–2025) provided by the Municipal Civil Protection.
- **Statistical hotspot identification:** Implementing the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm to identify 16 geographic clusters of recurring occurrences.

- **Engineering-oriented metrics:** Translating climate projections into operational requirements, such as the required increase in drainage capacity to mitigate future flooding.

Key differences summary:

Aspect	Original Workflow	Enhanced Workflow
Methodological Basis	Theoretical/Site-specific points	**Empirical/Data-driven**: Based on 1,321 historical records (2000-2025).
Hotspot Detection	Manual selection of single points.	**Algorithmic Clustering**: Using DBSCAN to identify objective hotspots.
Spatial Reference	Mixed CRS (often causing misalignments).	**Robust CRS Transformer**: Auto-conversion to EPSG:3035 with axis-order validation.
Data Resolution	Standard EURO-CORDEX grid.	**Regionalized Analysis**: Climate data intersected with high-density occurrence clusters.
Output Metrics	Simple change in rainfall mm.	**Operational Metrics**: % increase in drainage capacity required per hotspot.
Technical Stability	Memory crashes with large NetCDF files.	**Memory Management**: Implementation of cache flushing and kernel optimization.

Key improvements include:

- **Data-driven empirical methodology:** transitioned from theoretical site analysis to a robust study anchored in 25 years of municipal history. By integrating an inventory of **1,321 georeferenced historical flood events** (2000–2025), the model shifted focus from theoretical potential to areas with proven, recurring vulnerability.
- **Algorithmic hotspot identification:** applied the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm to objectively identify 16 distinct spatial clusters. This ensured that the 10 most critical hotspots selected for detailed climate projection represented the most severe and systemic problem areas in the municipality.
- **Engineering-based risk metrics:** applied engineering-based risk metrics to translate abstract climate projections into actionable urban planning guidance. This involved quantifying infrastructure reinforcement needs (e.g., +2% drainage capacity for high-risk areas) to uphold safety standards against future climate scenarios
- **Geospatial integrity and CRS validation:** Developed a dedicated coordinate transformer (LAEA EPSG:3035 to WGS84 EPSG:4326) with axis-order validation. This technical refinement ensured perfect spatial alignment between the Municipal Civil Protection records and the global climate models.
- **Computational stability and data management:** Implemented advanced Kernel and cache cleanup routines to process massive EURO-CORDEX data volumes (600MB+ segments). These optimizations prevented system crashes and ensured the integrity of the full data acquisition process.

Building on the necessity for local relevance, the heavy rainfall assessment was anchored in a robust data-driven methodology that shifts from theoretical hazard potential to proven historical recurrence. By processing over two decades of municipal incident logs, the analysis utilized the **DBSCAN algorithm** to identify 16 geographic clusters from **1,321 georeferenced flood records** provided by the Municipal Civil Protection. The datasets and methodological framework summarized in Table 2-4 highlight how this empirical foundation was intersected with climate projections to derive actionable engineering metrics.

Table 2-4 Data overview workflow #3 – Extreme precipitation

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
· **EURO-CORDEX:** Precipitation data for both the Historical baseline and Future projections (2041–2070). · **Historical IDF Curves:** Intensity-Duration-Frequency curves for Viana do Castelo. · **CHELSA V2.1:** Bioclimatic variables for baseline validation.	· **Historical Flood Recurrence:** Vulnerability proven by the density of the 1,321 georeferenced incidents. · **Drainage Capacity Baseline:** Current municipal drainage design standards.	· **Historical Records:** Civil Protection georeferenced flood events (2000-2025). · **Top 10 Hotspots:** Most critical clusters identified via DBSCAN algorithm. · **Critical Equipment:** Proximity of schools and health hubs to identified clusters.	· **Rainfall Intensity Δ:** Percentage change in extreme precipitation events. · **Drainage Gap Analysis:** Required increase (%) in drainage capacity per hotspot. · **Adaptation Priority Index:** Ranking of hotspots based on future climate intensity.

2.3.3.1 Hazard assessment

The hazard evaluation was grounded in the regional climate projections provided by the EURO-CORDEX ensemble, specifically utilizing the ICHEC-EC-EARTH / KNMI-RACMO22E model chain. This analysis sought to estimate changes in precipitation flux for extreme events with a 10-year return period, comparing the historical baseline (1976–2005) against mid-century projections (2041–2070).

This regional approach operates at a resolution of 0.11º (approximately 12.5 km), which presents a significant spatial constraint for municipal planning: a single pixel covers nearly the entire territory of Viana do Castelo[3]. Consequently, the climate driver is treated as a uniform regional signal. For the mid-century horizon (2041–2070), the model projects modest and almost identical increases in extreme rainfall intensity of approximately +1% to +2% for both RCP 4.5 and RCP 8.5 scenarios. These results, while conservative, are typical of regional models before the late-century divergence of scenarios and do not account for local orographic influences.

To characterize this hazard, the municipality relies on the statistical fitting of historical and future data to produce Intensity-Duration-Frequency (IDF) curves. These curves provide the theoretical baseline, indicating that even a small percentage increase in intensity can shift the frequency of extreme events. Figure 2-16 illustrates this uniform regional signal, comparing the historical baseline with the RCP 4.5 projection. It demonstrates that despite the modest increase, there is a visible upward shift in intensity across all analysed return periods.

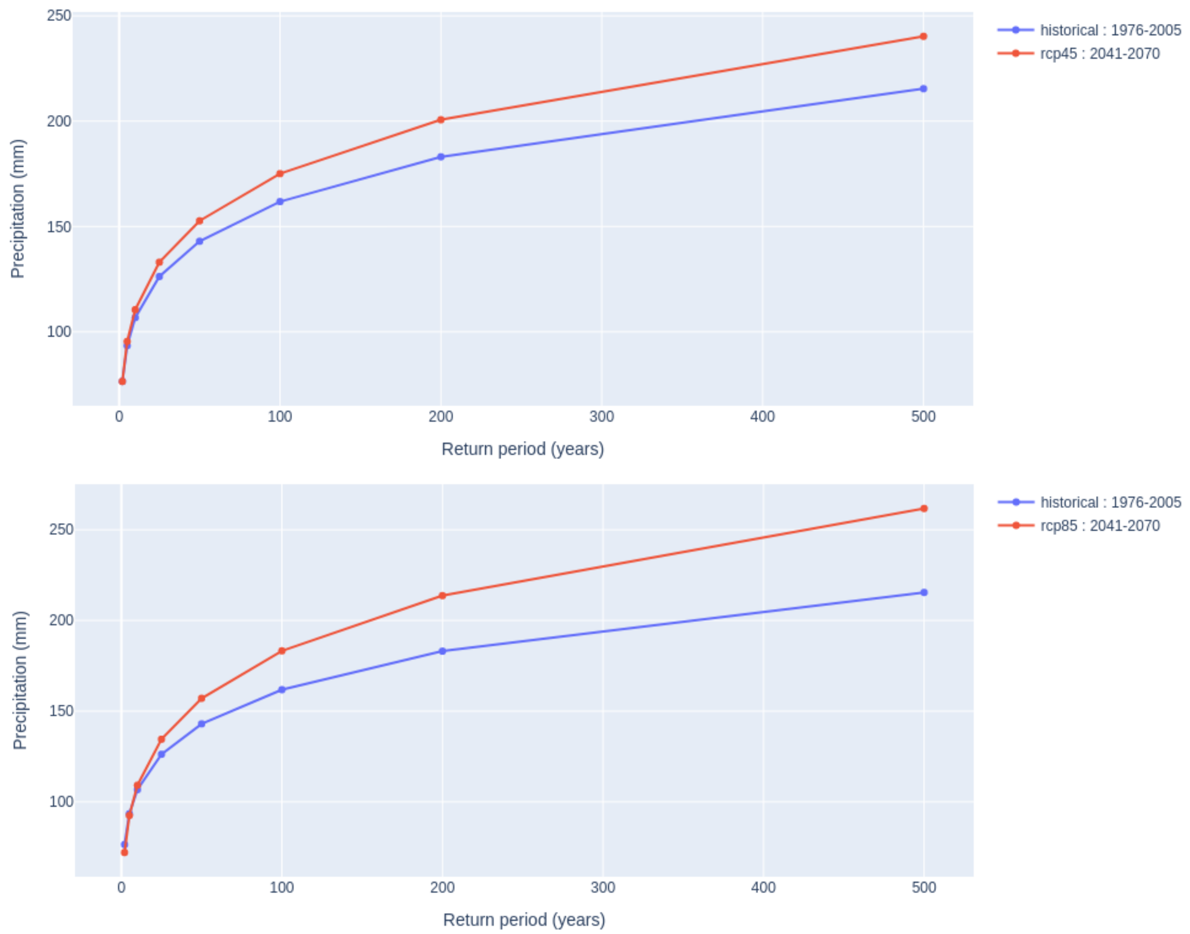


Figure 2-16 Mean precipitation for 24h duration events over Viana do Castelo (Baseline vs. RCP 4.5 and RCP 8.5).

Complementing this analysis, Figure 2-17 presents the maps of absolute precipitation and relative change for the territory. The pixelated nature of the map highlights the "Scale Paradox," where the coarse 12.5 km resolution assigns nearly identical climate deltas to the entire municipality, regardless of local topographical variations.

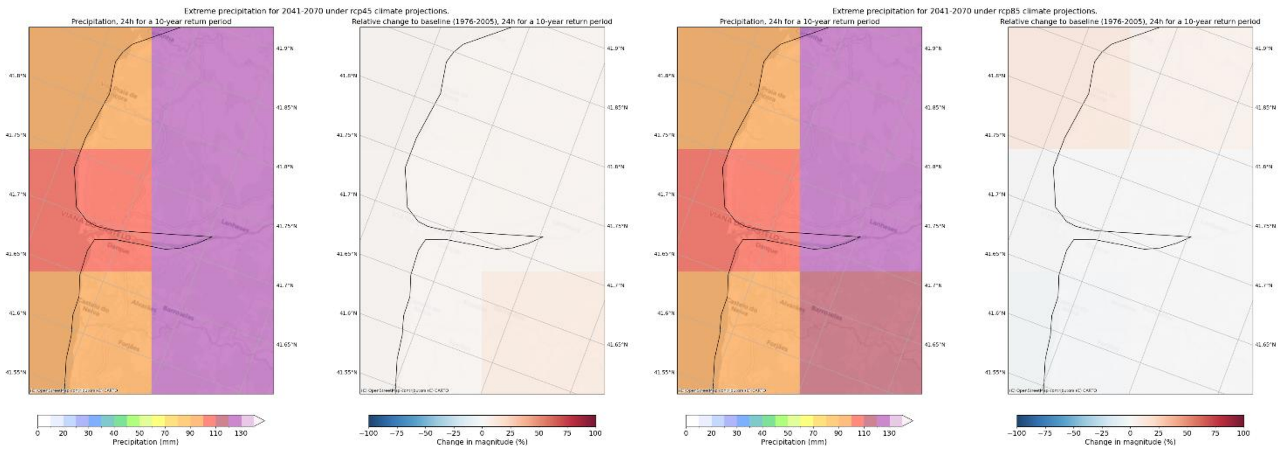


Figure 2-17 Absolute precipitation (left) and relative change (right) for a 10-year return period under RCP 4.5 and RCP 8.5.

2.3.3.2 Risk assessment

The true refinement in Phase 2 occurred in the risk assessment stage, where Machine Learning was employed not to change the climate resolution, but to provide spatial prioritization. Recognizing that the climate model is "blind" to street-level differences, the municipality integrated its own empirical evidence to identify where the system is already failing.

The core of this refinement was the integration of a georeferenced inventory of 1,321 historical flood events recorded between 2000 and 2025. As shown in Figure 2-18, the temporal distribution reveals a significant variability in annual occurrences, while the seasonal analysis confirms that the vast majority of incidents reported to Civil Protection are concentrated between October and January.

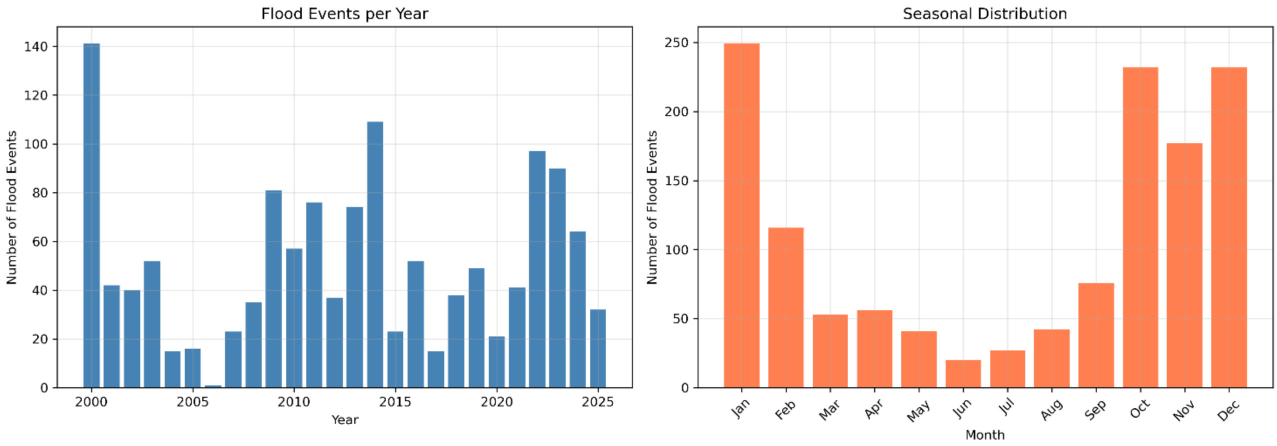


Figure 2-18 Distribuição Temporal e Sazonal (Ground Truth)

To manage this volume of data, the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm was used to identify 16 dense clusters of recurring incidents. From these, the 10 most critical hotspots were selected to act as the "ground-truth" focus for the risk analysis (Figure 2-19) The paradox is evident here: while most of the 10 hotspots are physically located within the same regional CORDEX pixel, their historical behavior and vulnerability are vastly different.

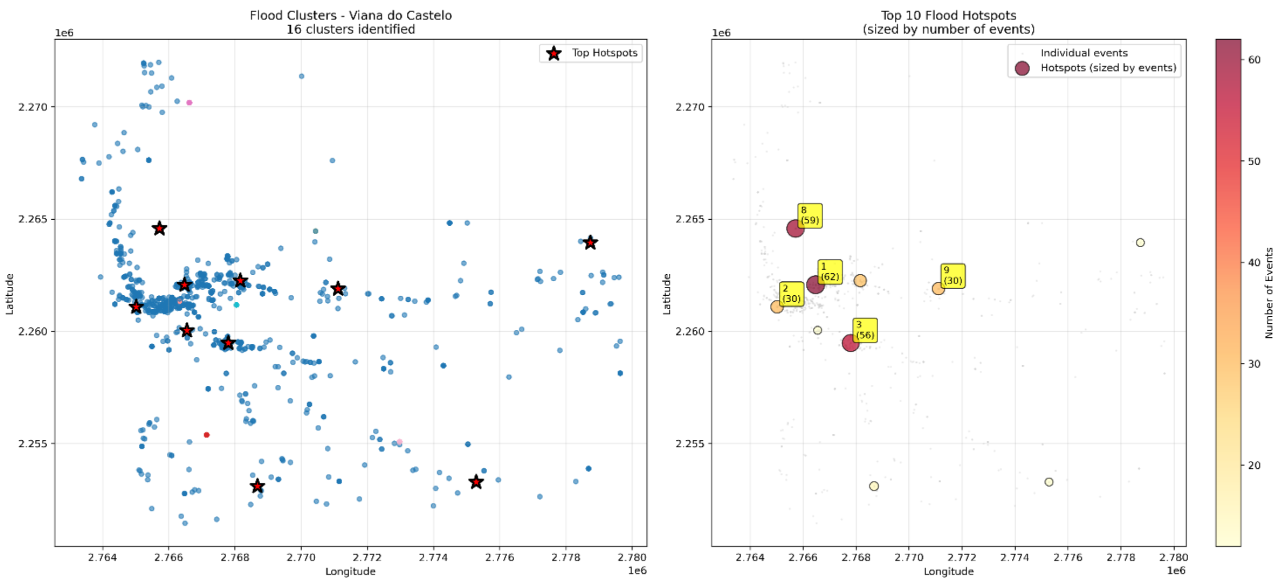


Figure 2-19 Identification of the 10 critical rainfall hotspots through DBSCAN clustering of historical events in Viana do Castelo Municipality

By crossing the uniform +2% regional rainfall delta with the documented failure points, Phase 2 transformed abstract climate projections into municipal engineering requirements. The model quantified the "drainage gap", revealing that in the most sensitive areas, a minor increase in hazard translates into a disproportionate risk. As evidenced in Figure 2-18, Hotspot 13 (Rua da Ameixoeira) is the most critical: a 2% increase in extreme rainfall intensity requires a +9% increase in drainage capacity to maintain current safety levels, as the projected return period for current critical events drops from 10 to 7 years 10.

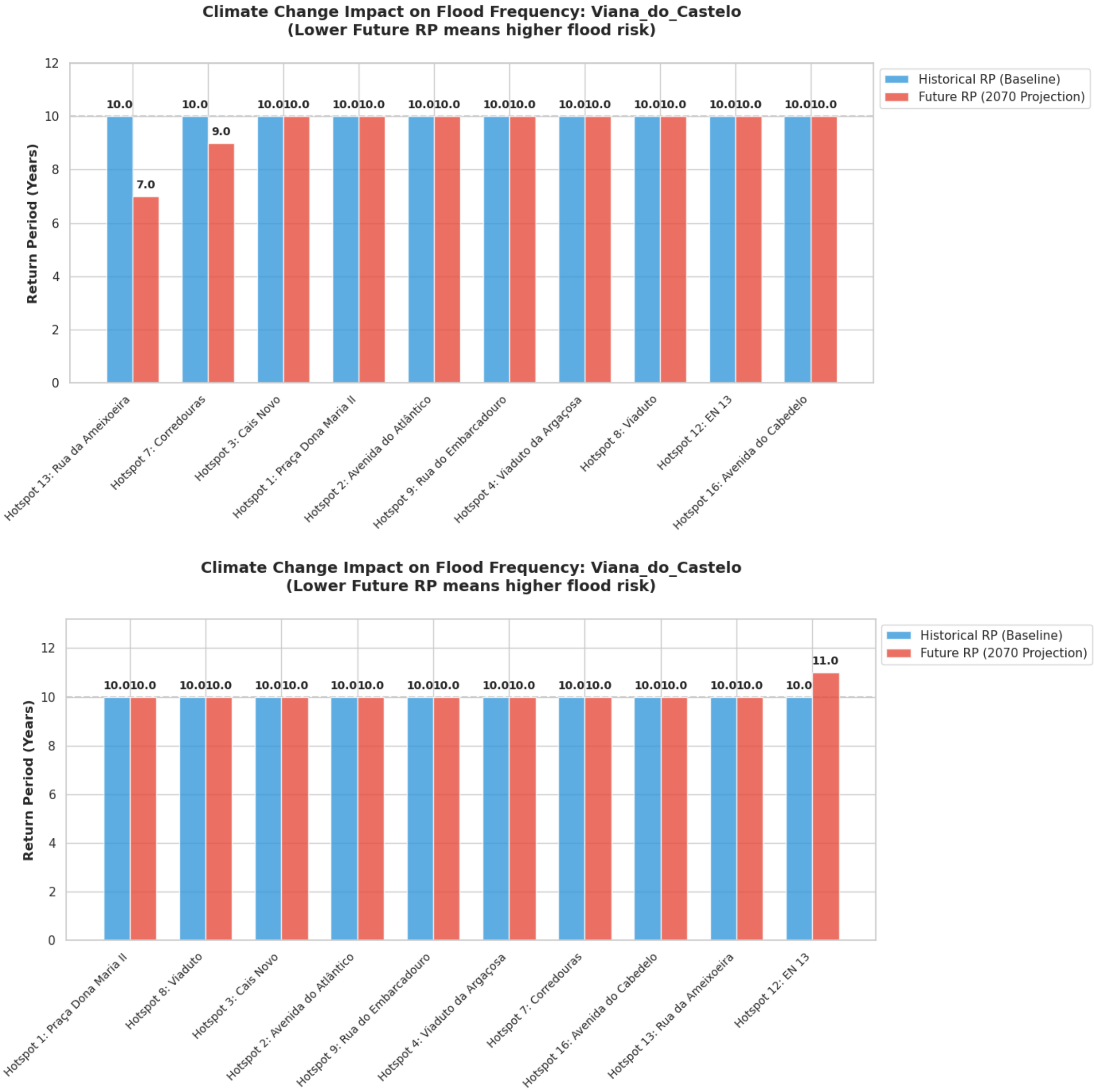


Figure 2-20 Climate change impact on flood frequency per hotspot

A critical finding in the Heavy Rainfall assessment is the significant resolution gap between the empirical historical data and the regional climate projections. While the **DBSCAN algorithm** allowed the municipality to identify 10 micro-scale hotspots of recurring flooding, the **EURO-CORDEX (0.11º)** climate model operates at a scale where a single pixel (approx. 12.5km) covers nearly the entire municipality.

- **Spatial overlap:** In Viana do Castelo, most of the 10 identified hotspots are contained within a single climate model pixel. Consequently, the current regional projection assigns the exact same climate delta (+1-2% increase in rainfall intensity) to all these distinct urban areas.
- **Methodological constraint:** This confirms that regional climate models are currently unable to distinguish between the specific orographic or urban heat island effects that might affect one hotspot over another.

The following table summarizes the relationship between the regional climate inputs and the localized risk outputs obtained through the refined workflow.

Metric	Historical Data (Risk Input)	Climate Projections (Hazard Input)
Resolution	**High (Point-level)**: Based on 1,321 georeferenced events.	**Low (~12.5 km)**: Based on regional EURO-CORDEX grid cells.
Workflow Role	Identifies **WHERE** the systemic failures occur.	Estimates **HOW MUCH** the rainfall intensity changes.
Key Result	**10 Hotspots** with specific drainage needs.	**Uniform deltas** ($+1$-2%) applied across the municipality.
Operational Output	**Drainage Gap (+9%)**: Localized engineering requirement.	**Regional Intensity shift**: Broad climatic pressure.

2.3.4 Additional assessments based on local models and data

To bridge the gap between regional European modelling and municipal operational needs, Phase 2 implemented a series of additional assessments. These analyses leveraged high-resolution local datasets and advanced computational models to ensure that the climate risk results are directly applicable to Viana do Castelo's planning instruments, specifically the Municipal Emergency and Civil Protection Plan (PMEPC) and the Municipal Climate Action Plan (PMAC).

2.3.4.1 Hazard assessment

The hazard component was recalculated using physics-based and advanced statistical algorithms to ensure topographical and empirical realism:

- **High-resolution hydraulic downscaling:** for River Floods, the downscale_flood_with_dem algorithm was implemented using local LiDAR and HR-DEM data to reach a 10-meter resolution. Unlike simple interpolations, this method uses hydrological connectivity (flood-fill) principles, ensuring that flood boundaries strictly respect the municipality's actual physical barriers and topography.
- **Machine learning wildfire modelling:** the wildfire hazard was processed through a Random Forest model, trained with the historical burnt areas from ICNF (2009–2024) and high-fidelity bioclimatic variables. This model was calibrated with a national fuel dictionary (COS 2023), assigning maximum hazard (Fuel Type 4) to critical species like Eucalyptus and Maritime Pine, a level of detail unavailable in the generic European CORINE system. This allows susceptibility mapping to reflect the specific fire history and environmental drivers of the Viana do Castelo territory.
- **Algorithmic hotspot identification:** for heavy rainfall, the **DBSCAN** algorithm was applied to an inventory of 1,321 georeferenced historical records from Civil Protection (2000–2025).

This method identified 16 geographic clusters of recurring incidents, empirically validating where the municipal drainage system presents systemic failures.

2.3.4.2 Risk assessment

The risk assessment was deepened through the creation of localized impact functions and a comprehensive exposure inventory:

- **Socioeconomic recalibration of damage curves:** within the "*Flood building damage and population exposed*" workflow, the code was modified to include the Regional Wealth Factor (0.868)—based on Viana do Castelo's GDP per capita—and the 2024 Portuguese Consumer Price Index (factor 1.315). This ensures that the Mean Expected Annual Damage (EAD) of 25.28 M€ reflects actual current reconstruction costs in the municipality.
- **Human safety and displacement metrics:** an additional social impact assessment introduced the Expected Annual People Displaced (EAPD) metric. By applying a critical depth threshold of >1.0 meter, the model identifies that 285 people are at severe annual risk, providing high-resolution data for emergency evacuation planning.
- **Systemic critical infrastructure exposure:** an exhaustive exposure network was built by integrating 11 layers of municipal critical equipment. This analysis assesses risk for 480+ individual assets and 17,279 primary road segments, identifying potential failure points in emergency response corridors.
- **Engineering-based drainage gap analysis:** for Heavy Rainfall, climate projections were translated into municipal engineering requirements. The model quantified the "drainage gap"—identifying, for example, that a 2% increase in rainfall intensity requires a +9% increase in drainage capacity in hotspots like Rua da Ameixoeira to maintain current safety levels.

It is critical to acknowledge that all climate risk assessments are subject to inherent uncertainties. These arise from three main sources: Input Uncertainty (the accuracy of regional climate models), Model Uncertainty (the assumptions within the ML and hydrological algorithms), and Spatial Uncertainty (e.g. the gap between climate pixels and territorial features).

The methodological transparency of Phase 2 acknowledges inherent limitations:

- **Conservative nature of ML:** the Random Forest model for wildfires is conservative, as it does not extrapolate risks beyond the climatic limits recorded in the historical training data, serving as a prudential baseline for decision-makers.
- **Precision vs. Engineering Studies:** while the 10m spatial refinement improves municipal interpretability, these risk analyses do not replace detailed engineering studies required for the design of physical defences or complex hydraulic infrastructures.
- **Uniform climate signal:** due to the native resolution of EURO-CORDEX (12.5 km), projected increases in rainfall intensity (approx. +2%) are applied uniformly to all urban hotspots, as the pixel scale still ignores micro-climatic variations

In Phase 2, the municipality adopted a precautionary and Empirical approach. Instead of treating climate projections as deterministic predictions, they were used as "stress factors" applied to a robust foundation of historical ground-truth (e.g., ICNF burnt areas and Civil Protection logs). This strategy minimizes the impact of model uncertainty by ensuring that the resulting risk maps are anchored in events that have already demonstrated the territory's vulnerability.

Summary of data limitations and uncertainties:

Risk Category	Main Limitation	Technical Impact	Mitigation/Refinement in Phase 2
River Floods	Inundation Depth Data	JRC maps are based on global models (~100m).	Integration of LiDAR-derived HR-DEM and Flood-Fill to correct topography to 10m.
Wildfire (ML)	Model Extrapolation	Random Forest models do not extrapolate beyond historical training ranges.	Results represent a conservative baseline. Fuel types were manually calibrated using COS 2023.
Heavy Rainfall	Spatial Resolution	EURO-CORDEX pixel (approx. 12.5 km) is too coarse for urban drainage.	Used DBSCAN on 1,321 historical events to anchor regional deltas in local "ground-truth."
Socioeconomic	EU-Average Costs	Generic damage functions may over/underestimate local reality.	Applied Regional Wealth Factor (0.868) and 2024 CPI for financial accuracy.

2.4 Key Risk Assessment Findings

The Key Risk Assessment step evaluates the results of the regionalized risk analysis from Phase 2, integrating high-resolution technical refinement with the empirical experience of local actors. This assessment jointly considers: (i) Severity of impacts, now quantified at the building and critical infrastructure level thanks to downscaling to a 10-meter scale; (ii) Urgency of action in the face of future risk evolution and hazard dynamics under the RCP 4.5 and 8.5 scenarios; (iii) Resilience capacity of the local system to anticipate, respond, and recover.

The evaluation was conducted following the harmonized CLIMAAX logic, with results designed for discussion with decision-makers, experts, and priority groups. This process was reinforced by direct consultation with representatives of the CMAACVC. Their contributions allow for the translation of scientific findings into operational adaptation priorities for the municipality.

2.4.1 Mode of engagement for participation

Although the engagement process was described in section 2.1.5, the risk evaluation phase (Key Risk Assessment) allowed for a deep reflection on the operational utility of the models. The feedback gathered from the CMAACVC strategic partners was instrumental in validating the following dimensions:

- **Validation of operational resolution:** partners corroborated that the transition to the 10-meter (LiDAR) scale would resolve the "utility gap" of Phase 1. Feedback emphasized that assessment at the most detailed level is the only viable basis for updating emergency plans such as the PMEPC.
- **Consensus on priority and urgency:** local risk perception coincided with climate projections, with more than half of the stakeholders classifying Rural Wildfires as the most severe and urgent threat. This empirical validation legitimized the technical focus and investment in Machine Learning models for this specific hazard.

- **Resilience and capacity gaps:** the consultation revealed critical weaknesses in the response system, specifically the centralization of emergency resources in the urban core. This feedback transformed the resilience capacity assessment, moving from an analysis of total resources to an analysis of geographical dispersal, which will be a central pillar in Phase 3.

2.4.2 Gather output from Risk Analysis step

The gathering of outputs from the Regionalized Risk Analysis (Section 2.3) consolidates the quantitative data and high-resolution modelling that underpin the final assessment of severity, urgency, and capacity. Based on the implemented workflows, the specific results are as follows:

- **River Flooding (Floods) results:** Hazard maps were generated with a 10-meter resolution (refined via LiDAR and flood-fill) defining flood extent and depth, accompanied by building-level economic damage estimates via *DamageScanner* (recalibrated with a Wealth Factor of 0.868 and inflation of 1.25) and the calculation of EAPD (*Expected Annual People Displaced*) to quantify the risk of citizen displacement.
- **Wildfire (Fire) results:** The primary output consists of Fire Weather Index (FWI) projections for the RCP 4.5 and 8.5 scenarios, cross-referenced with 11 layers of municipal critical infrastructure and the COS 2023 land use map, allowing for the identification of zones where severe meteorological hazards coincide with strategic assets and validating the models against a history of real occurrences.
- **Extreme Precipitation (Heavy Rainfall) results:** The results highlight variations in the intensity and frequency of extreme events for the 2041–2070 horizon, the identification of priority geographical hotspots through spatial clustering (DBSCAN) of 1,313 historical occurrences, and the "Drainage Gap" analysis, which quantifies the insufficiency of the current drainage network under new runoff scenarios.

These technical outputs, characterized by their high resolution and regionalization, ensure that the assessment of severity and urgency is no longer merely indicative but becomes an operational basis for designing adaptation measures in Phase 3.

2.4.3 Assess Severity

Severity assessment interprets the quantitative results of the risk analysis, focusing on the magnitude of physical, social, and economic impacts. This analysis prioritizes the identification of potentially irreversible losses and the occurrence of cascading effects that could compromise the municipality's systemic functions. Severity assessment for each risk was conducted according to four categories: **limited, moderate, substantial, and critical**.

- **River Flooding (Floods):** The transition to "critical" is justified by the potential for irreversible consequences in industrial areas and port infrastructure in Viana do Castelo. Extreme events are projected to become more severe with increased flow rates in future horizons, potentially causing disruptions to critical riverside infrastructure. The use of *DamageScanner* revealed massive financial damages that could destabilize supply chains (cascading effect). The EAPD metric (285 displaced people) confirms a high-magnitude human impact.

    - Current: Moderate | Future: Critical.
- **Wildfires (Fire):** The analysis integrated multidimensional vulnerability (human, economic, and ecological), identifying risks of irreversible consequences in wildland-urban interface (WUI) zones and protected areas. Severity is heightened by the irreversibility of biodiversity loss in protected areas and the risk of loss of human life in the Wildland-Urban Interface (WUI). The history of 2,425 occurrences demonstrates a frequency that already overburdens local systems.
    - Current: Substantial | Future: Critical.
- **Extreme Precipitation (Heavy Rainfall):** Severity is driven by the increased intensity of short-duration events (3h and 24h). Although of smaller geographical magnitude than floods, their frequency (1,313 historical events) causes constant systemic disruptions to urban functioning. The "drainage gap" projects a worsening that will directly affect the economic sector and urban mobility.
    - Current: Substantial | Future: Substantial.

2.4.4 Assess Urgency

Urgency reflects the temporal dimension of hazards, considering the rate of aggravation between current and future risk. This metric evaluates the speed of onset (sudden or gradual), persistence, and acceleration trends, determining the window of opportunity for implementing mitigation measures. The urgency assessment for each risk was conducted according to four categories: **no action needed, watching brief, more action needed, and immediate action needed.**

- **River Flooding (Floods):** more action needed.
    - Although influenced by gradual climate changes (slow-onset), floods manifest as sudden events with high disruption potential. Evidence of worsening extreme flows under RCP 4.5 and 8.5 scenarios justifies the urgency of integrating results into infrastructure maintenance cycles and emergency plans.
- **Wildfires (Fire):** immediate action needed.
    - The region faces an extension of the fire season and an increased probability of ignition. Being a highly recurrent hazard in the municipality that can escalate within minutes, urgency is paramount for the implementation of fuel management strips and the strengthening of early warning systems.
- **Extreme Precipitation (Heavy Rainfall):** immediate action needed.
    - This is a sudden-onset hazard with the potential for persistence and aggravation in the near future. The need to adapt urban drainage systems to increasingly frequent events require an immediate response in municipal planning.

2.4.5 Understand Resilience Capacity

Resilience capacity analyses the region's current competence to absorb, adapt, and transform in the face of climate damage. The assessment is structured across the five fundamental capitals – physical, financial, human, social, and natural – allowing for the identification of adaptation gaps and the effectiveness of response mechanisms already in place.

The resilience capacity assessment for each risk was conducted according to four categories: **low, medium, substantial, and high.**

- **River Flooding (Floods):** medium.
    - Physical capital (PMAC/PMEPC plans) is strong, but natural capital – specifically the limited use of Nature-Based Solutions (NbS) and Sustainable Drainage Systems (SuDS) – and financial capital for large-scale works are limiting factors.
- **Wildfires (Fire):** medium.
    - Viana do Castelo has a robust structure for preventive forest management, fuel management strip networks, and coordination protocols between firefighters and patrols. It possesses high human capital (experienced firefighters) and physical capital (management strips), but social capital presents "blind spots" in the geographic dispersal of resources to inland parishes.
- **Extreme Precipitation (Heavy Rainfall):** medium.
    - Physical capital has improved with investment in the modernization of the stormwater network, but stakeholders identified a gap in social and human capital: the centralization of teams in the urban center, which reduces peripheral resilience.

2.4.6 Decide on Risk Priority

The definition of risk priorities for Viana do Castelo results from the synthesis of quantitative technical evidence (meteorological severity and urgency) and the qualitative assessment of local resilience capacity. The process followed the Key Risk Assessment protocol (Figure 2-5), allowing for the prioritization of Phase 3 interventions. Risk priorities are established as follows:

- **Rural Wildfires:** Very High Priority**.**
    - This hazard is classified as the highest priority, having been identified as the most severe and urgent risk. Technical analysis confirms this perception, projecting critical future severity due to the worsening of the Fire Weather Index (FWI) and the risk of irreversible losses in Wildland-Urban Interface (WUI) zones and protected areas. Urgency is immediate, requiring fuel management measures and the decentralization of resources.
- **Extreme Precipitation:** High Priority**.**
    - Classified with high priority due to its sudden-onset nature and significant frequency (1,313 historical occurrences). The identified "drainage gap" and the immediate urgency validated by technical partners require municipal planning to prioritize the

resizing of the stormwater network and the implementation of Nature-Based Solutions (NbS) to mitigate urban flooding and road blockages.

- **River Flooding:** High / Strategic Priority.
  - Although urgency is classified as "More action needed" (focused on longer time horizons), future severity is Critical. The priority focuses on the protection of critical riverside infrastructure and port economic assets. High-resolution results (10m) serve as the basis for the strategic update of emergency plans and land-use restrictions.

This prioritization ensures that VC_Climaax project resources are channelled toward the most critical threats, guaranteeing that adaptation measures are robust against the worst climate scenarios (RCP 8.5) and operational for management entities.

Table 2-5 Key Risk Assessment through risk ranking, considering severity, urgency and resilience capacity

Hazard	***Severity***		***Urgency***	***Resilience capacity***	***Priority***
	current	***future***			
Floods	Moderate	Critical	More action needed	Medium	**High**
Fires	Substantial	Critical	Immediate action needed	Medium	**Very high**
Heavy rainfall	Substantial	Substantial	Immediate 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

The conclusion of Phase 2 of the VC_Climaax project consolidated the learning that regionalizing the analysis is the determining factor for the operational utility of the results. The main lesson learned was the critical need to transition from the global scale (~100m) to a 10-meter local scale—a qualitative leap successfully achieved for fluvial flooding and rural wildfire hazards. Regarding flooding, the integration of local LiDAR and HR-DEM data allowed flood footprints to be aligned with the real topography, eliminating the statistical artifacts from the initial phase. Simultaneously, for wildfires, the replacement of Corine Land Cover with the COS 2023 land-use map guaranteed surgical precision in identifying wildland-urban interface areas. Despite these advances, the analysis of extreme precipitation highlighted the greatest technical difficulty of the process: the reliance on EURO-CORDEX models with a native resolution of 12 km, which imposes barriers to the metric refinement of future projections. To bridge this gap, the project adopted an innovative approach based on local history, identifying geographical hotspots through spatial clustering (DBSCAN) of 1,313 real occurrences, ensuring that prioritization is based on the territory's statistical recurrence, even given the limitations of global climate models.

The role of stakeholders, represented by the CMAACVC, was fundamental at this stage, functioning as a validation and strategic correction mechanism. While initial technical modelling suggested an equitable weight distribution, the participatory process revealed that 58.3% of local actors identify

Rural Wildfires as the maximum urgency, followed closely by the impacts of extreme precipitation. This feedback was decisive in reorienting the technical team, reinforcing that the utility of a Climate Risk Assessment (CRA) depends on its ability to guide measures at the building and street level. Institutional learning is ensured not only by knowledge transfer between specialists and municipal technicians but also by the automation of Jupyter Notebooks, which now include automatic detection of coordinate reference systems (CRS) and simplified interfaces, allowing teams to operate the models autonomously. However, the evaluation detected critical gaps that define the future research agenda: the need to integrate the social dimension of risk (specific vulnerabilities of isolated groups) and continuous training in GIS tools—topics that standard CLIMAAX workflows do not yet fully incorporate.

In terms of efficiency, reusing CLIMAAX workflows accelerated the production of results, but the effort required for the collection, harmonization, and integration of heterogeneous local data was significant, requiring reinforcement in the data processing phase. The strategic decision to temporarily exclude the "storms" hazard proved correct, as it allowed focusing the budget and time on the metric refinement of hazards with the highest potential for structural damage, maximizing the impact of available resources.

To communicate these results, the municipality plans to provide synthesis reports accessible to the public, promoting climate literacy within the community. Currently, the municipality's monitoring system remains reactive and fragmented, supporting the proposal to create a climate change observatory to centrally manage georeferenced historical records. The impact value of this exercise is high: by transposing scientific knowledge directly into the Municipal Climate Change Adaptation Plan (PMAC) and the Municipal Emergency and Civil Protection Plan (PMEPC), the project ensures that Phase 3 adaptation measures—with a particular focus on Nature-Based Solutions (NbS)—are designed based on high-resolution evidence rather than generic global trends.

2.6 Work plan Phase 3

Phase 3 (months 17–22, ending in July 2026) will focus on converting the high-resolution evidence generated in Phase 2 into practical adaptation strategies and updating Viana do Castelo's local planning instruments. This phase aligns with the milestones defined in the Individual Follow-up Plan and focuses on the operationalization of results for the Municipal Climate Action Plan (PMAC) and the Municipal Emergency and Civil Protection Plan (PMEPC).

To ensure the selection of effective and sustainable measures, the municipality will implement a Multi-Criteria Analysis (MCA). This objective scoring system will allow decision-makers to rank potential actions based on:

- **Effectiveness:** degree of risk reduction (e.g., reduction in EAPD or economic damage).
- **Cost-Benefit Ratio:** implementation costs vs. protected asset value.
- **Nature-Based Potential:** preference for solutions (NbS) that enhance biodiversity.
- **Social Acceptance:** feasibility within the local community and land ownership context.
- **Co-benefits:** secondary advantages such as urban cooling or recreational spaces.

Main activities and roadmap:

- **Definition and prioritization of adaptation measures (M17–M22):** based on the high-priority risks identified (wildfires, river floods and heavy rainfall), the team will identify specific local adaptation options to improve the resilience of the territory and its vulnerable groups;
- **Participatory validation workshops (M19):** a 3rd Workshop with Stakeholders is planned for May 2026 to involve the Municipal Civil Protection Commission and potentially the private sector (e.g., insurance companies, agricultural cooperatives) to validate the proposed adaptation pathways;
- **Presentation to policy and decision-makers (M21–M22):** formal sessions will be held in July 2026 to present final results and integration recommendations to the Executive Municipal Council or embedding into the PMAC, PMEPC and Municipal Master Plan (PDM).
- **Final communication and dissemination (M17–M22):** implementation of the communication plan to reach the general public through three regional media articles and the production of a final project publication;
- **International knowledge exchange (M27):** participation in the CLIMAAX workshop in Brussels to share high-resolution downscaling methodologies and lessons learned with other European regions.

Milestones and Deliverables:

- **M6:** Potential local adaptation options identified
- **M7:** Stakeholders participatory processes carried out
- **M8:** Local adaptation options evaluated and prioritized
- **M9:** Recommendations for improve risk management plans formulated
- **M10:** Presentation of the results to policy and decision makers in Viana do Castelo
- **M12:** Attend the CLIMAAX workshop held in Brussels
- **D3:** Contribution to local adaptation strategies and improved risk management plans (due Month 22).

Phase 3 will focus the remaining resources on the risks classified as high-priority during the regionalized analysis (wildfires, river floods and heavy rainfall). Low-priority hazards or those with significant data gaps (e.g., storms not prioritized in the deepening phase) will not be studied in detail to ensure the administrative and financial feasibility of the proposed measures for the most critical threats.

3 Conclusions Phase 2- Climate risk assessment

Phase 2 of the VC_Climaax project marks a decisive transition from regional hazard screening to an operational and data-driven risk assessment for the Viana do Castelo municipality. The primary goal was to bridge the "utility gap" identified in Phase 1, moving from global databases to a high-resolution operational scale capable of informing infrastructure-level planning.

Key Findings:

The regionalized risk analysis provided a robust territorial intelligence base for the three prioritized hazards:

- **River Flooding (physics-based precision):** through the integration of LiDAR data (HR-DEM) and a downscaling algorithm (flood-fill), the municipality achieved a 10-meter resolution that respects the actual terrain morphology. Metrics reveal an average Expected Annual Damage (EAD) of 25.28 million euros and identify that 285 people are at high risk of annual displacement (EAPD) due to flood depths exceeding 1.0 meter.
- **Rural Wildfires (machine learning for strategic prevention):** the transition to a Random Forest model, trained with historical burned perimeters (2009–2024) and the COS 2023 land cover map, allowed for the surgical identification of high-hazard zones. The analysis confirms that the eastern forest massifs remain critical hotspots. Additionally, the model identified systemic failure points in the strategic road network that could hinder emergency response and evacuation.
- **Extreme Precipitation (data-based hotspot identification):** sustained by an inventory of 1,321 georeferenced historical occurrences (2000–2025), the project identified 16 geographic clusters through DBSCAN analysis. A critical result is the "drainage gap," reflecting the variation in extreme precipitation intensity relative to the drainage capacity required to maintain current safety levels.

Challenges Successfully Addressed:

- **Operational resolution:** the project overcame the limitations of coarse 100m global data, providing building-level precision for flood and wildfire risks.
- **Methodological adequacy:** the assessment replaced generic European economic curves and land-use data (CORINE) with localized metrics, including COS 2023 and damage functions adjusted to Portugal's 2024 Consumer Price Index (CPI).

Remaining Challenges:

- **The "Scale Paradox":** although risk is mapped at 10 meters, the baseline climate models (EURO-CORDEX) operate at a regional scale. This discrepancy means that microclimatic or orographical variations within urban hotspots are still largely inferred rather than directly modelled.
- **Conservative nature of models:** the Random Forest model for wildfires is limited in its ability to extrapolate risks beyond those recorded in the training history. This implies that the presented scenarios (RCP 8.5) should be viewed as a "prudential baseline" rather than the absolute worst-case scenario.

- **Social Vulnerability:** although displacement metrics (EAPD) were introduced, a deeper integration of the social dimension—such as the specific needs of isolated elderly populations—remains a qualitative goal for future iterations.

In short, Phase 2 has provided Viana do Castelo with a defensible technical-scientific base for decision-making. The generated territorial intelligence—validated hazard maps, reality-adjusted costs, and identified hotspots—allows for a confident transition to Phase 3. The focus will now shift from diagnosis to solution, utilizing Multi-Criteria Analysis (MCA) to select adaptation measures designed not solely on generic global trends, but on local high-resolution evidence.

4 Progress evaluation

Phase 2 focused on the regionalized and high-resolution deepening of the CLIMAAX Climate Risk Assessment (CRA) methodology, resulting in an operational risk intelligence base for the Viana do Castelo municipality. Throughout this phase, and with the completion of this deliverable, the following milestones were achieved (Table 4-1): M4: High-resolution local data collected and compiled; and M5: Workflows for the different risks refined and improved.

Table 4-1 VC_Climaax overview of milestones (M).

Milestones	Progress
M1: Test the CLIMAAX workflows for the different risks	Achieved *(floods, fire, heavy rainfall and storms)*
M2: Workflows for the different risks successfully applied	Achieved *(floods, fire, heavy rainfall and storms)*
M3: CLIMAAX common methodology for multi-risk climate assessment applied	Achieved *(floods, fire, heavy rainfall and storms)*
M4: High-resolution local data collected and compiled	Achieved
M5: Workflows for the different risks refined and improved	Achieved · 4 Applied: *floods, fire, heavy rainfall and storms.* · 3 Refined: *floods, fire, heavy rainfall.*
M6: Potential local adaptation options identified	Planned for Phase 3
M7: Stakeholders participatory processes carried out	Ongoing (across the project implementation)
M8: Local adaptation options evaluated and prioritized	Planned for Phase 3
M9: Recommendations for improve risk management plans formulated	Planned for Phase 3
M10: Presentation of the results to policy and decision makers in Viana do Castelo	Planned for Phase 3
M11: Attend the CLIMAAX workshop held in Barcelona	Achieved
M12: Attend the CLIMAAX workshop held in Brussels	Planned for Phase 3

In addition to these milestones, Phase 2 achieved the key performance indicators (KPIs) defined for this phase (Table 4-2).

Table 4-2 VC_Climaax overview of key performance indicators (KPIs)

Key performance indicators	Progress
At least 2 risk workflows will be successful applied on Deliverable 1 (multi-risk climate assessment)	Achieved *(floods, fire, heavy rainfall and storms)*
At least 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 Applied[1]: *floods, fire, heavy rainfall and storms.* · 3 Refined: *floods, fire, heavy rainfall.*
At least 1 local adaptation strategy will be explored and improved	Planned for Phase 3
2 emergency and risk management plans will be improved with the results of the risk and vulnerability assessment	Planned for Phase 3
More than 20 stakeholders will be involved in the project's activities	Achieved (partially) – ongoing. At least 12 stakeholders were directly involved and provided feedback on the results obtained in phase 1 (contributing to phase 2).
At least 5 communication actions will be developed to share the start of the project, the results of each of the 3 phases and the final results of the project	Achieved (partially) – ongoing. A communication strategy and Plan has designed. · One communication action (social media) was made about the start of the project (Facebook and Instagram); · One communication action social media) was made about the CLIMAAX workshop in Barcelona (Facebook and LinkedIn); · The VC_Climaax project was disseminated on the Municipality's official website.
A final publication will be produced with the actions and results obtained from participation in the project	Planned for Phase 3
3 notes will be drawn up for political decision-makers based on the results of each of the 3 phases of the project	Planned for Phase 3
3 articles in regional media mentioning the project	Planned for Phase 3

[1] The total number of applied workflows includes new modules released by CLIMAAX coordination during Phase 2, such as River Discharge Analysis and FWI Response models.

5 Supporting documentation

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

- Main Report (PDF)
- Workflows outputs:
    - FLOODS (FLOODS.zip)
    - FIRE (FIRE.zip)
    - HEAVY RAINFALL (HEAVY_RAINFALL.zip)
- Portuguese / Local Datasets:
    - ICNF - Burnt Territory perimeters (1975–2024)
    - DGT - Municipal LiDAR-derived HR-DEM (5m and 10m) (2025)
    - DGT - National Land Use Map (COS 2023)
    - DGT - Official Administrative Map of Portugal (CAOP 2025)
    - CMVC - Municipal Critical Infrastructure (2025)
    - CMVC - Georeferenced historical occurrences - Civil Protection (2000–2025)
- Online stakeholder survey (questionnaire and responses)
- Zenodo link: https://doi.org/10.5281/zenodo.18302894