



Deliverable Phase 2 – Climate risk assessment

Assess Multiple Climate Risks in Attica Region and improve Adaptation Strategy and Risk Management Plans using CLIMAAX Framework and Toolbox (AtticaReAdy)

Greece, Region of Attica

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transparent and harmonised Climate Risk Assessment approach



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Abbreviations and acronyms

Abbreviation / acronym	Description
AOI	Area of Interest
CCAP	Climate Change Adaptation Plan
CoP	Community of Practise
CP	Civil Protection
CRA	Climate Risk Assessment
DRM	Disaster Risk Management
EU	European Union
FWI	Fire Weather Index
GDP	Gross Domestic Product
HNMS	Hellenic National Meteorological Service
KEMEA	Greek Center for Security Studies
NOA	National Observatory of Athens
NRA	National Risk Assessment
NSCA	National Strategy for Climate Adaptation
RCCAP	Regional Climate Change Adaptation Plan
RCP	Representative Concentration Pathways
RoA	Region of Attica
UNDRR	United Nations Office for Disaster Risk Reduction

Executive summary

The AtticaReAdy sub-project, implemented within the CLIMAAX project under the Horizon Europe Programme, supports the Region of Attica in strengthening climate resilience through a transparent and harmonized Climate Risk Assessment (CRA). Following the completion of Phase 1, which provided a multi-risk overview and identified floods and wildfires as severe and urgent climate risks for the region, Phase 2 advances the assessment by delivering a refined regional and local-scale climate risk analysis.

Phase 2 builds upon the methodological framework and key conclusions of Phase 1, while extending the scope of the assessment. In addition to further refining the analysis of wildfire and flood risks, this phase expands the CRA to include heatwaves, recognizing their growing significance for highly urbanized and densely populated areas such as Attica. Through this approach, Phase 2 strengthens the understanding of climate risks by moving from strategic risk identification to detailed, spatially explicit evidence at regional and municipal level.

It is noted that the heavy rainfall risk assessment workflow was not incorporated into Phase 2 of the analysis. This decision was based on limitations related to the availability, spatial resolution and consistency of the precipitation datasets required for robust hazard modelling at regional and local scale. In accordance with the applicable contractual obligations, which foresee the implementation of refined risk assessment workflows for heatwaves or heavy rainfall, priority was given to the heatwave workflow due to its high relevance for the densely urbanized environment of the Region of Attica and the availability of suitable high-resolution datasets.

The main objective of Phase 2 is to enhance the resolution, relevance and operational value of climate risk information. This is achieved through the adaptation of the CLIMAAX Framework and Toolbox to the regional context of Attica and through the increased use of national and local datasets. The refined workflows allow hazard, exposure and vulnerability patterns to be analyzed in a harmonized manner, supporting comparability across hazards while producing outputs that are directly applicable for regional and local planning.

For heatwaves, the assessment provides a detailed spatial depiction of surface thermal stress across the Region of Attica and its interaction with population distribution and social vulnerability. The results highlight pronounced intra-urban differences and identify overheated areas where elevated temperatures coincide with higher concentrations of vulnerable population groups, particularly elderly residents. These findings offer a clearer basis for identifying priority areas for heat-risk mitigation and targeted adaptation interventions.

For wildfires, Phase 2 delivers high-resolution hazard and risk mapping across the Region of Attica under current and near-future climate conditions. The analysis confirms that wildfire risk is primarily concentrated in wildland–urban interface areas, where hazardous conditions overlap with vulnerable communities and critical infrastructure. In addition to population-related impacts, the assessment identifies transport corridors exposed to elevated wildfire hazard, underlining potential challenges for emergency access, evacuation and continuity of services.

For floods, the refined analysis focuses specifically on the Cephissus River and builds on the Phase 1 findings by applying localized flood hazard layers at multiple return periods and integrating them with exposure and vulnerability information. The results support a more detailed understanding of flood-prone areas along the Cephissus corridor and their potential impacts on residents and critical infrastructure, complementing the wildfire and heatwave assessments within a consistent multi-risk framework.

Overall, Phase 2 delivers a high-resolution, municipality-level climate risk evidence for floods, wildfires and heatwaves across the Region of Attica. By translating the broad risk priorities identified in Phase 1 into detailed spatial insights, the assessment strengthens the analytical foundation for climate adaptation planning and disaster risk management. The results directly support the refinement of the Regional Climate Change Adaptation Plan, the update of Civil Protection preparedness planning, and the prioritization of resilience investments.

Through its focus on refined analysis, local data integration and harmonized methodologies, Phase 2 represents a key step in the AtticaReAdy project. It enhances the practical usability of climate risk information and contributes to the overall project objective of supporting informed decision-making and strengthening climate resilience across the Region of Attica, in line with the goals of the CLIMAAX initiative and the wider EU climate resilience agenda.

Building on the risk evidence produced in Phase 2, Phase 3 of the AtticaReAdy project will focus on the systematic translation of climate risk findings into concrete adaptation measures and improved risk management plans. High-resolution heatwave, wildfire and river flooding risk maps will be used to support the revision of Disaster Risk Management Plans, the implementation and the evaluation of the Regional Climate Change Adaptation Plan, enabling the prioritization of targeted interventions in overheated neighborhoods, high-risk wildland–urban interface zones and flood-prone zones. In parallel, Phase 3 will enhance institutional capacity, facilitate knowledge dissemination through the Climate Adaptation Observatory of the Region of Attica, and ensure the integration of Climate Risk Assessment (CRA) outputs into local planning instruments. By embedding scientific evidence into policy and practice, the project will strengthen long-term climate resilience, preparedness, and adaptive capacity across the region.

1 Introduction

1.1 Background

Region of Attica (RoA) is a self-governed public body, second-level local government organization of the Hellenic Republic, comprising 8 regional units, 66 municipalities among which are 8 islands. Attica stands as Greece's most populous and densely inhabited region and encompasses the urban conglomerate of Athens, which serves as the nation's capital. Attica's population exceeds one-third of the total national population, 3.792.469 residents out of a nationwide total of 10.432.481 (2021 census).

RoA plans and implements policies at regional level and is responsible according to Law 4936/22 to execute the Regional Climate Change Adaptation Plan (RCCAP) and implement the proposed adaptation measures. RoA coordinates according to its territorial competence Civil Protection actions regarding prevention, preparedness, disaster response and implementation of relief actions (Law 4662/2020).

Attica produces approximately 48% of the country's total GDP and maintains its dominant position in the national economy. Regarding the Gross Added Value, the Region of Attica in the primary sector, participates with only 4,35%, in the secondary sector, it holds a large share with 33.38% and in the tertiary sector, it holds the largest share with 47,20%.

The field of health is the center of the main volume of the country's health and welfare services. It brings together approximately 31% of the country's hospital units. At the level of infrastructure, the central airport and the system of the ports of Attica, with the port of Piraeus being the most important, are the main gateways of the country, bringing into contact with the global production network and citizen/visitors. The cultural resources of Attica are particularly remarkable both in terms of their importance and in terms of their number and variety. These cultural resources are distributed throughout the region and are of unique value in a global and national context.

The current state of the urban natural environment has as its main characteristics the unplanned residential expansion, the traffic problems, the deficient urban and peri-urban greenery and the lack of open public spaces, which are important and constantly worsening problems. Attica is particularly vulnerable to high-impact weather events, as it has faced extensive deforestation and urbanization over the years. The latest scientific indicators indicate that the Mediterranean and, by extension, Greece, represent one of the hotspots of the evolving environmental crisis. Inevitably, the Metropolitan area of Attica cannot be exempt from this new reality. The emergence of new forms of risks and crises, the occurrence of more extreme events, the larger scale of disasters, the complexity and intricacy of hazards and crises, and the appearance of risks during ongoing disasters and crises are just a few of the new challenges that must be immediately integrated into the operational planning of the region.

RoA faces a spectrum of climatic and geophysical risks, including floods, wildfires, droughts, heatwaves, landslides and earthquakes. This high-risk profile necessitates urgent and robust disaster preparedness, adaptation and mitigation efforts. According to the results of the studies on the vulnerability assessment and the impact of CC in Greece conducted by the Bank of Greece, RoA shows the highest vulnerability based on size and population density regarding wildfires. Only the city of Athens hosted a remarkable 5.72 million tourists from around the world for the year 2018, amplifying the already heightened degree of vulnerability. RoA has witnessed a distressing loss of its forests, amounting to 33% in the last seven years. 405.000ha out of 1.230.000ha of forested areas have succumbed to wildfires, constituting 33% of the total forest area. Moreover, its urban character intensifies the annual heatwaves. Rising temperatures and urban heat islands increase the risk of illness and even death mainly to the most vulnerable residents. Taking into consideration the fatal floods of the recent past, the population density and the percentage of households that the CC

impacts will seriously affect their wellbeing, flood is another major risk for the region. Based on the above fact, heatwaves, floods and wildfires can be considered the major risks for RoA. These challenges call for new tools and new approaches in the realm of Civil Protection and Climate Adaptation.

1.2 Main objectives of the project

Climate change is increasingly affecting regions, cities and local communities through more frequent and intense extreme weather events, placing growing pressure on people, infrastructure, ecosystems and public services. In this context, Climate Risk Assessment (CRA) constitutes a fundamental tool for understanding how climate-related hazards interact with exposure and vulnerability, and for supporting risk-informed decision-making in climate adaptation and disaster risk management.

The overall objective of the AtticaReAdy project is to strengthen the capacity of the Region of Attica to understand, prepare for and manage climate risks through a structured, transparent and harmonized assessment process. By developing robust climate risk profiles, the project aims to support the design of effective adaptation measures, improve preparedness and response planning, and contribute to the long-term resilience of the region and its communities.

Building on this overarching objective, Phase 2 of the project focuses on advancing the Climate Risk Assessment from a strategic and screening-level analysis to a refined regional and local-scale evaluation. While Phase 1 established the general risk context and prioritized key hazards, Phase 2 aims to enhance the depth, resolution and practical relevance of the assessment for regional authorities, municipalities and local stakeholders.

The main objective of Phase 2 is to generate high-resolution, location-specific climate risk evidence that can directly inform planning and prioritization processes. This is achieved through the application of the CLIMAAX Handbook and Toolbox in a regionally adapted manner, ensuring a consistent methodological framework while allowing flexibility to reflect local characteristics and needs.

A central component of Phase 2 is the increased integration of national and local datasets into the CRA workflows. The use of locally relevant information—such as detailed population statistics, region-specific hazard indicators, land-use data and infrastructure layers—enhances the accuracy and credibility of the results and enables a more realistic representation of climate risks across the diverse territorial context of Attica. This approach strengthens the ownership of the assessment by regional and municipal actors and improves its applicability for real-world decision-making.

Through the combined use of the CLIMAAX Handbook and locally grounded data, Phase 2 provides significant added value for the Region of Attica. It supports the identification of local risk hotspots, highlights vulnerable population groups and critical assets, and facilitates the prioritization of adaptation and preparedness measures at municipal and regional level. In doing so, Phase 2 strengthens the link between scientific analysis and policy implementation, contributing to more targeted, effective and evidence-based climate resilience actions.

Overall, Phase 2 represents a key step in the AtticaReAdy project by transforming general climate risk understanding into actionable, spatially explicit knowledge. It enhances the capacity of the Region of Attica and its municipalities to manage climate risks in a coordinated and informed manner, reinforcing the project's contribution to resilient development and alignment with the objectives of the CLIMAAX initiative and the wider EU climate resilience agenda.

1.3 Project team

AtticaReAdy exploited the use of the tools of CLIMAAX for Phase 2 with the engagement of the region's staff from Autonomous Directorate of Civil Protection and Directorate of Environment and Climate Change; that have experienced scientists from different fields and the mandate to execute the Regional CCAP (Law 4936/22), the DRM Plans and civil protection actions regarding prevention, preparedness, disaster response and implementation of relief actions (Law 4662/2020).

The team that worked during Phase 2 consisted of:

- Dr Passas Nikos, Geologist, Head of the Directorate of Civil Protection with years of experience in Disaster Risk Assessment and Management
- Akrivos Constantinos, Engineer, Head of the Directorate of Environment and Climate Change with years of experience on Environment and Climate Change Adaptation.
- Dr Chalari Ioanna Chemist, Officer of the Directorate of Civil Protection with climate, environment and disaster management knowledge
- Dr Parapouli Maria Chemist, Officer of the Directorate of Environment and Climate Change with climate and environment knowledge
- Msc Paparrigopoulos Thodoris, Engineer, Officer of the Directorate of Civil Protection with data processing skills and experience from his participation in a number of European projects.
- Ms Eliza G. Diakogeorgiou, Hydraulic and Environmental Infrastructure Engineer, specialized in hydraulic and hydrological analysis.
- Mr Efstratios Dimopoulos, Environmental Engineer, with climate and environmental expertise.
- MSc Alexandros Massas, Environmental Physicist, with expertise in climate and environmental analysis.

1.4 Outline of the document's structure

The structure of the document follows the CLIMAAX Framework, which consists of a five-step assessment cycle, starting with Scoping in Section 2.1, where the objectives and the regional context are presented in brief. In Section 2.2, Risk Exploration is analyzed, focusing on the selection of priority hazards, the choice of appropriate workflows from the CLIMAAX Handbook and the identification of the most relevant scenarios for the Region of Attica. Section 2.3 describes how the selected CLIMAAX workflows were adapted and applied at regional and local level. The hazard and risk assessment are presented using the Heatwave workflow, the Wildfire ML workflow and the River Flooding workflow, with emphasis on the integration of local and national datasets.

The final two steps of the CLIMAAX Framework are presented in Sections 2.4 and 2.5, which include the refined key risk assessment findings and preliminary monitoring and evaluation considerations, as these steps will be further elaborated in a more executive manner in the subsequent phases of the project. The conclusions of Phase 2 are presented in Section 3, the evaluation of project progress in terms of key performance indicators (KPIs) is included in Section 4, and the supporting documentation and references used in this deliverable are provided in Sections 5 and 6, respectively.

2 Climate risk assessment – phase 2

The impacts of climate change are already being observed at global and European level, with the Mediterranean region widely recognized as a climate hotspot particularly exposed to future impacts. Climate projections indicate that extreme weather events are expected to increase in both frequency and intensity, including heatwaves, droughts, flooding and extreme precipitation. Combined with rising socio-economic pressures, these trends pose significant challenges for regions with limited adaptive capacity.

In this context, the availability of robust climate risk assessments that support well-informed decision-making is increasingly critical. Such assessments provide the foundation for effective risk management, enabling authorities to anticipate impacts, prioritize actions and strengthen long-term resilience.

2.1 Scoping

The Climate Risk Assessment builds the foundation for Disaster Risk Management (DRM) and Climate Change Adaptation Plans (CCAP) in Attica by identifying the nature and extent to which climate change and its impacts may harm the region, specific sectors, and local communities. Quantifying and assessing climate risk—as the result of the interaction between hazard, exposure, and vulnerability—is essential to support evidence-based decision-making and future planning.

The assessment process was informed not only by technical analyses but also by stakeholder engagement activities, including peer-to-peer exchanges with other regions and project partners and collaboration with a non-governmental organization, which contributed local knowledge and feedback on risk priorities. In addition, expert knowledge was incorporated in the development and interpretation of the river flooding workflow, through targeted feedback from a sector specialist, contributing to the robustness and relevance of the assessment.

Through the identification of current and future key risks and impacts on people, assets, and ecosystems, the assessment supports the targeted allocation of resources, the design of adaptation policies and projects to reduce vulnerability and risk, and the establishment of a baseline against which the effectiveness of adaptation policies and actions can be monitored over time.

It is noted that a dedicated heavy rainfall risk assessment workflow was not included in Phase 2 of the analysis. This decision was driven by constraints related to the availability, spatial resolution, and consistency of precipitation datasets necessary to support robust hazard modelling at regional and local scales. In line with the relevant contractual requirements, which allow for the implementation of refined risk assessment workflows for either heatwaves or heavy rainfall, priority was assigned to the heatwave workflow.

The scoping process was conducted in accordance with the CLIMAAX Framework, ensuring consistency with the standardized European methodology for Climate Risk Assessment.

2.1.1 Objectives

The Climate Risk Assessment (CRA) for the Attica Region aims to provide a robust, spatially explicit understanding of priority climate risks and to support the design and implementation of targeted adaptation and risk-management measures. During Phase 1, the CRA focused on fluvial floods and wildfires, identifying both hazards as severe and urgent risks with significant socio-economic implications, particularly in densely populated areas and along critical transport corridors. Building on these findings, Phase 2 extends and deepens the analysis by operationalizing the CLIMAAX wildfire ML, heatwave and river flooding

workflows for the Attica Region and by progressively replacing pan-European default inputs with regionally and nationally relevant datasets wherever feasible.

The specific objectives of Phase 2 are to adapt and implement the CLIMAAX wildfire, heatwave and river flooding workflows to the Attica context using local and national data sources (e.g. land surface temperature data from NOAA, population statistics from ELSTAT, and region-specific exposure layers), to produce harmonized hazard, exposure and vulnerability layers and corresponding risk maps that can be aggregated at municipal and NUTS3 level, and to ensure that the workflows are transparent, reproducible and transferable to other regions participating in the CLIMAAX programme. The resulting evidence base is intended to support regional and municipal climate adaptation planning, civil protection and emergency preparedness, and the integration of CRA outputs into related sectoral strategies and resilience initiatives.

The expected outcomes of Phase 2 include a consistent set of hazard and risk products for heatwaves and wildfires, comprising maps, indicators and reproducible scripts, as well as an improved understanding of where vulnerable population groups and critical infrastructure are exposed to climate-related hazards.

The assessment is subject to several data-related limitations. Exposure data for transport infrastructure are currently available only as a single aggregated road network layer, which does not allow a robust differentiation between primary, secondary and tertiary roads and therefore necessitates a simplified treatment of road exposure and vulnerability. In addition, no regionally consistent dataset capturing socio-economic and ecological vulnerability specific to the Attica Region was available at the time of analysis; therefore, a **JRC ecological vulnerability index** was used as a proxy layer to ensure coverage of environmental sensitivity, with the understanding that this represents a pan-European approximation rather than a fully localized assessment.

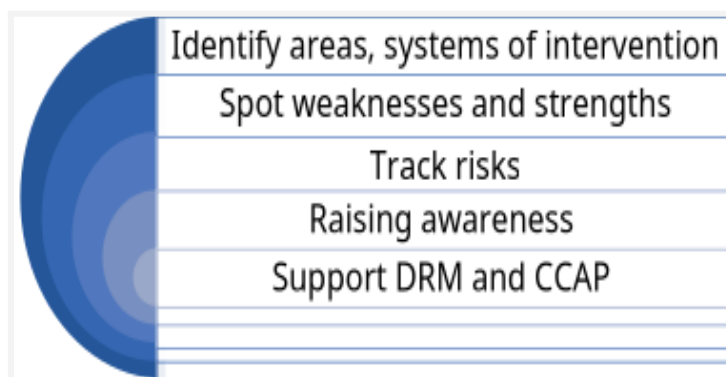


Figure 2-1 Objectives of CRA

2.1.2 Context

Climate hazards and associated risks in the Region of Attica have traditionally been addressed through a combination of national and regional planning instruments, emergency management frameworks and sectoral policies. At national level, climate-related risks are assessed within the framework of the National Risk Assessment (NRA), developed in accordance with the guidelines of the United Nations Office for Disaster Risk Reduction (UNDRR) and relevant European Union guidance. In parallel, Civil Protection planning in Greece is regulated through Law 4662/2020, which requires the integration of risk assessment outcomes into emergency preparedness, response and recovery planning at national, regional and local level.

At European level, flood risk management is guided by Directive 2007/60/EC, under which flood hazard and flood risk maps have been developed for designated Areas of Potential Significant Flood Risk. These assessments support the preparation of Flood Risk Management Plans and provide an important basis for understanding flood-related impacts under different scenarios. In addition, Greece has adopted a National Strategy for Adaptation to Climate Change, which establishes overarching objectives, guiding principles and sectoral priorities for adaptation across national, regional and local governance levels.

Within this framework, the Region of Attica is responsible for the implementation of the Regional Climate Change Adaptation Plan (RCCAP), which translates national priorities into regional action. The RCCAP identifies climate-sensitive sectors—including urban environment, health, infrastructure, water management, biodiversity, forests and civil protection—and includes climate projections and scenario-based analyses. However, while these strategies and plans provide an essential policy foundation, their effective implementation at regional and municipal level requires more detailed, spatially explicit and locally relevant climate risk information.

Recent experience has demonstrated the growing exposure of Attica to climate-related hazards. Wildfires have increased in frequency and extent, particularly in peri-urban and wildland–urban interface areas, while intense rainfall events and fluvial flooding have caused significant human and economic losses in densely built environments. At the same time, the metropolitan character of Attica amplifies heat-related impacts, placing increasing pressure on vulnerable population groups, public health systems and urban infrastructure. These challenges are further intensified by high population density, ageing infrastructure and complex land-use patterns.

Within the wider regional and national development context, climate risks pose increasing challenges to economic activity, mobility, public services and social cohesion. The functioning of transport networks, health and social care services, housing and urban systems, environmental management and civil protection operations are all sensitive to climate impacts, highlighting the need for integrated and cross-sectoral risk assessment approaches.

In this context, Phase 2 of the Climate Risk Assessment seeks to address key limitations identified in previous assessments, including insufficient spatial resolution, limited integration of local datasets and the difficulty of translating high-level risk information into operational planning. By refining the analysis at regional and municipal scale and by strengthening the linkage between hazards, exposure and vulnerability, Phase 2 aims to support more targeted adaptation and preparedness interventions.

While Phase 2 does not focus on the detailed design of adaptation measures, the resulting risk maps and indicators provide critical input for interventions such as urban heat mitigation, protection of vulnerable population groups, wildfire prevention and preparedness in wildland–urban interface zones and safeguarding of critical infrastructure and transport corridors. In doing so, the refined assessment supports the broader objective of enhancing climate resilience in the Region of Attica and strengthening alignment between climate adaptation policy, civil protection planning and sustainable regional development.

2.1.3 Participation and risk ownership

Stakeholder participation in Phase 2 of the CLIMAAX project builds on the governance and engagement structures established during Phase 1. In that initial phase, a Community of Practice (CoP) was established, bringing together representatives from the Region of Attica, municipal authorities, and other relevant stakeholders. The CoP played a pivotal role in validating preliminary climate risk assessment results and in identifying priority hazards and key analytical needs.

During Phase 2, stakeholder engagement shifted toward supporting the technical refinement, validation, and operationalization of the CLIMAAX heatwave, flood and wildfire workflows. While the institutional landscape and overall risk-ownership structure remained unchanged, collaboration deepened in practical and technical terms. Regional authorities and municipal representatives were actively involved in reviewing input datasets, validating methodological assumptions, and providing feedback on intermediate and final outputs. This iterative exchange—facilitated through dedicated bilateral consultations—ensured that the analytical workflows were scientifically robust, locally grounded, and directly responsive to regional planning priorities. As a result, Phase 2 not only enhanced the technical quality of the assessments but also strengthened institutional ownership, usability, and the long-term integration of CLIMAAX results into policy and operational practice.

Risk ownership in the Attica Region is organized within existing Greek institutional structures. Responsibility for the identification and assessment of climate risks lies primarily with the Region of Attica, supported by project partners and technical experts through the implementation of the Climate Risk Assessment and the integration of updated scientific knowledge and data. Responsibility for risk mitigation and adaptation measures rests with sectoral departments, such as those responsible for environment, civil protection, transport, health and education, as well as with municipal authorities, which are tasked with planning and implementing structural and non-structural measures within their respective mandates, informed by CRA outputs.

Priority groups and exposed areas are defined based on the vulnerability and exposure patterns identified through the CRA. These include elderly and dependent populations, residents of overheated urban districts, and communities located at the wildland–urban interface or along transport corridors exposed to high wildfire risk. Representatives of these groups are typically engaged through municipal and regional governance structures and social services rather than through dedicated stakeholder organizations within the scope of Phase 2. The needs and sensitivities of these groups are explicitly reflected in the vulnerability indicators and exposure datasets used in the Phase 2 workflows.

At present, formal and quantitative information regarding acceptable or tolerable levels of climate risk—such as regulatory thresholds or design standards—is not explicitly defined in available regional documentation. Determination of such thresholds falls within the remit of competent authorities and is expected to be addressed in subsequent planning and policy processes. The CRA provides an evidence base to support these discussions by identifying relative risk levels and priority areas, without prescribing normative risk-acceptance criteria.

The AtticaReAdy CoP core group comprises five key institutions, including an NGO First Responder, ensuring both institutional authority and operational field expertise within the partnership. During Phase 2, strong collaboration was further consolidated through the active engagement of additional municipalities, which contributed local exposure and vulnerability data and supported the validation and practical application of risk assessment outputs. In Phase 3, the strengthened CoP core group will take a leading role in organizing a dedicated regional workshop aimed at informing and mobilizing the majority of the 66 municipalities of the Region of Attica. Particular emphasis will be placed on engaging regional and municipal officers formally mandated to prepare, revise, and implement Disaster Risk Management (DRM) Plans and Climate Change Adaptation Plans (CCAPs). This workshop will serve as a strategic interface between scientific outputs and institutional decision-making, facilitating the translation of risk evidence into actionable planning measures. Phase 3 will also prioritize the structured dissemination of results through the Climate Adaptation Observatory of the Region of Attica. Communication actions will include policy briefs, technical guidance notes, targeted information packages, and stakeholder-oriented materials specifically designed to support the integration of AtticaReAdy findings into local and regional planning processes.

Beyond public authorities, the project will reach out to social groups and key economic sectors to communicate projected short- and long-term changes in hazard patterns and associated risks. By strengthening risk awareness and providing access to localized, high-resolution climate information, AtticaReAdy will promote proactive risk reduction, informed investment decisions, and self-protection strategies. While outreach efforts will be broad and inclusive, municipalities will remain the primary target group. Priority will be given to the most vulnerable municipalities—those facing high exposure to heatwaves, wildfires, or flooding, as well as those with limited technical, financial, or administrative capacity to design or update DRM and adaptation plans. Through targeted capacity-building and the provision of accessible, decision-ready risk intelligence, Phase 3 aims to reduce preparedness gaps and enhance long-term climate resilience across the region.

2.1.4 Application of principles

The Phase 2 Climate Risk Assessment for the Attica Region applies the CLIMAAX principles of social justice, equity and inclusivity, quality, rigor and transparency, and the precautionary approach through the selection of datasets, the design of indicators, and the way results are produced and communicated. Across heatwaves, wildfires and floods, the analysis is structured consistently around the CLIMAAX risk concept—risk as a function of hazard, exposure and vulnerability—so that outputs are both scientifically robust and directly usable for planning and prioritization.

Social justice, equity and inclusivity are incorporated by explicitly representing socially vulnerable and priority groups, and by focusing on assets and services that are essential for safety and continuity during extreme events. In the heatwave workflow, age-structured population statistics at municipal level are cleaned and transformed into gridded layers that capture the spatial distribution of children, working-age adults and elderly residents. These are used to compute and normalize vulnerability indicators (e.g., elderly ratio, dependency ratio and composite social vulnerability indices), enabling the identification of neighborhoods where exposure overlaps with comparatively higher vulnerability. In the wildfire workflow, population vulnerability is represented through established indices and is complemented by exposure layers for critical elements such as the road network—a key determinant of emergency access, evacuation capacity and service continuity. In the flood workflow, equity considerations are addressed by linking inundation depth (by return period) with population exposure and sensitive groups where available, while also analyzing potential disruption to critical transport corridors needed for response and evacuation. Together, these choices ensure that risk mapping does not only describe physical hazard, but highlights where impacts are likely to be most disproportionate for populations with higher sensitivity and lower coping capacity.

Quality, rigor and transparency are ensured through adherence to CLIMAAX technical guidance, systematic data handling, and reproducible implementation. Inputs are drawn from open and institutional sources (e.g., Copernicus services, CORINE land cover, EFFIS, National Observatory of Athens, LST products, national statistics and regional datasets), and all spatial layers are subjected to consistent preprocessing steps, including cleaning, reprojection, harmonization and alignment on common analysis grids suitable to each workflow. This includes a WGS84-aligned grid for heatwave LST analysis, an EPSG:3035 100 m grid for wildfire susceptibility and hazard, and a harmonized setup for flood depth rasters and hydrographic layers clipped to the Attica AOI and aligned with exposure/vulnerability datasets to support comparable results across return periods. The workflows are implemented using Python scripts, GDAL and the scientific Python stack within a structured, region-specific directory (`data_Attica/`), enabling traceability, repeatability and straightforward updates as new data become available. Key methodological choices and limitations—such as scenario selection, aggregation rules for municipal/NUTS reporting, class thresholds and assumptions in

exposure/vulnerability construction—are explicitly documented so that outputs can be interpreted correctly and audited if needed.

The precautionary approach is reflected in how uncertainty is managed and how risk evidence is framed for decision-making. For wildfires, the analysis compares a historical reference period (1991–2010) with a near-future climate configuration under an intermediate pathway (RCP4.5, 2021–2040), highlighting where hazard and risk may increase even under moderate climate change, and supporting early prioritization of preparedness in emerging hotspots. For floods, precaution is operationalized by evaluating multiple return periods, including low-probability/high-impact scenarios, to ensure that planning accounts for potentially severe consequences even when event likelihood is low. Across hazards, results are presented as decision-support products rather than precise predictions, acknowledging uncertainty while still providing actionable evidence to guide anticipatory measures, strengthen preparedness, and protect vulnerable populations and critical infrastructure.

2.1.5 Stakeholder engagement

Stakeholder engagement in the CLIMAAX Climate Risk Assessment for the Attica Region builds on the participatory foundations established in Phase 1 and was further consolidated throughout the project to ensure that risk assessment outputs are policy-relevant, operationally usable, and aligned with institutional mandates. From the outset, the objective has been to bridge scientific analysis and decision-making by actively involving regional and municipal authorities in shaping the scope, priorities, and interpretation of results. During Phase 1, members of the Community of Practice (CoP)—including representatives from municipalities and the Region of Attica—contributed to validating preliminary hazard and risk findings and identifying priority areas for further investigation. These exchanges highlighted the importance of adopting a multi-hazard perspective covering floods, wildfires, and heatwaves; strengthening public communication of climate risks; and reinforcing the link between technical risk assessments and formal planning and regulatory instruments.

In Phase 2, the assessment process was informed by a structured combination of technical analysis and targeted stakeholder consultation. Focused exchanges were conducted with regional and municipal authorities to review datasets, methodological assumptions, and intermediate outputs. Scientific institutes contributed strategic and methodological support to the overall implementation process, helping ensure coherence between analytical workflows and policy objectives. In parallel, expert input from a sector specialist was integrated into the flood risk assessment workflow, enhancing the scientific robustness and applied relevance of the results.

Engagement in Phase 2 placed particular emphasis on producing spatially explicit, decision-oriented outputs. The analysis generated high-resolution maps and indicators—including overheated area maps, wildfire population-risk maps, and road exposure and risk maps—specifically designed to support technical dialogue with stakeholders and facilitate integration into regional reports and decision-support systems. Project objectives and intermediate findings were communicated to the stakeholders through these visual and quantitative products, accompanied by clear methodological documentation outlining assumptions, limitations, and appropriate interpretation. Moreover, data structures and analytical scripts were organized in a transparent and reproducible manner, enabling regional and municipal technical staff to replicate, update, and adapt the analyses within their routine workflows. This approach supports institutional learning, continuity, and long-term capacity building.

At the same time, several structural challenges identified in Phase 1 remained relevant in Phase 2. These included limited availability of municipal staff for sustained engagement, heterogeneous levels of technical capacity across institutions, and constraints related to data access and sharing. Such factors influenced the intensity and frequency of stakeholder interactions and reinforced the need for clear, accessible outputs and adaptable analytical tools. Addressing these constraints is recognized as an ongoing effort and will inform

the design of future engagement, capacity-building, and dissemination activities within and beyond the CLIMAAX project (Phase 3), with the aim of further strengthening the science–policy interface and enhancing regional climate risk governance.

2.2 Risk Exploration

2.2.1 Screen risks (selection of main hazards)

The Region of Attica is characterized by a typical Mediterranean climate, with mild and relatively wet winters and hot, dry summers. Precipitation is mainly concentrated between October and April, while annual rainfall remains generally low, with spatial variability between coastal, eastern and northern parts of the region. Extended dry periods during summer, combined with high temperatures, create favorable conditions for both heat stress and wildfire occurrence. In the densely built-up areas of the Athens metropolitan basin, urban morphology, high impervious surface coverage and limited green infrastructure further intensify thermal conditions, amplifying the impacts of extreme heat events.

Over recent decades, Attica has experienced an increasing occurrence of extreme climate-related events, with particularly pronounced impacts from wildfires. Forest fire activity has intensified both in frequency and severity, especially in peri-urban and wildland–urban interface areas where settlements, infrastructure and natural vegetation coexist. Numerous wildfire incidents with significant environmental, social and economic consequences have been recorded in the region (Arianoutsou et al., 2023). Among the most severe events, the wildfire that affected the Mati area in July 2018 resulted in the tragic loss of 102 human lives and extensive property damage across approximately 1,300 hectares, highlighting the extreme vulnerability of exposed communities (Efthimiou et al., 2020).

Recent scientific evidence further confirms the critical wildfire risk profile of Attica. A long-term analysis of fire activity covering the period 1977–2024 indicates a persistent increase in burned area and a growing recurrence of fires within short time intervals (Arianoutsou et al., 2024). The study shows that approximately half of the regional territory has burned at least once during this period, with a substantial proportion of areas experiencing repeated fire events.

Effective wildfire management therefore requires long-term, spatially explicit risk assessment approaches that consider the combined dynamics of hazard, exposure and vulnerability. At regional and local level, such assessments can support the prioritization of fuel management actions, the planning of prevention infrastructure and the optimization of firefighting resources. Preventive strategies informed by robust risk evidence are widely recognized as more sustainable and cost-effective compared to response-oriented suppression measures alone.

In addition to wildfires, extreme heat represents an increasingly critical climate-related risk for the Region of Attica. Recurrent and intense heatwave episodes, combined with the pronounced urban heat island effect in the area (Santamouris et al., 2007), place growing pressure on public health systems and disproportionately affect vulnerable population groups, including elderly and dependent individuals. The severity of heat-related impacts in the Athens metropolitan area was clearly demonstrated during the extreme heatwave of July–August 2021, when air temperatures in the city center reached up to 43.9 °C, corresponding to the second highest maximum temperature recorded since 1900 based on the historical temperature time series of the National Observatory of Athens weather station at Thissio (Giannaros et al., 2023).

These impacts are expected to intensify under future climate conditions, particularly in densely populated neighborhoods with limited adaptive capacity, supporting the need to address heatwaves as a standalone hazard within the climate risk assessment framework.

Flood risk also remains a major concern for the Region of Attica, particularly in urban catchments and river basins where intense rainfall events intersect with high exposure of population, buildings and critical infrastructure. Past flood events have demonstrated the high sensitivity of densely urbanized areas to

short-duration, high-intensity precipitation, with significant implications for civil protection operations, transport networks and local economic activity. A particularly severe flash flood event affected the area of Mandra in Western Attica on 15 November 2017, resulting in 24 fatalities and substantial economic losses (Diakakis et al., 2019). This event highlighted the combined effects of intense rainfall, urbanization, uncontrolled construction and land-use changes on flood vulnerability. Scientific evidence further indicates that hydrological regimes are increasingly influenced by climate change, with studies reporting a rise in both the intensity and frequency of flood events driven by human-induced climatic modifications (Galanaki et al., 2021).

According to the Copernicus Climate Atlas¹, climate projections for the study area under the high-emissions scenario SSP5-8.5 indicate a pronounced intensification of climate extremes. Relative to the pre-industrial reference period (1850–1900), annual daily maximum temperatures are projected to increase by approximately 1.7 °C in the near future (2021–2040), with warming reaching up to about 5.7 °C by the end of the century (2081–2100). In parallel, projections show a marked increase in the duration of dry periods. Consecutive dry days are expected to rise by around 10 days in the near future, increasing progressively to approximately 35 additional dry days by the end of the century under the same emissions scenario.

Additionally, although average precipitation indicators and the number of wet and heavy rainfall days are projected to decrease, climate projections point to an increase in short-duration, high-intensity precipitation extremes, as reflected by rising values of maximum 1-day precipitation. For the area of interest, projected changes indicate an increase of approximately +1.5 mm/day in the near term (2021–2040), rising to about +1.8 mm/day in the long term (2081–2100).

In addition, due to limitations in the availability, spatial resolution and consistency of high-resolution precipitation datasets suitable for standalone hazard modelling at regional scale, and in accordance with the applicable contractual obligations, heavy rainfall was not implemented as a separate workflow in Phase 2. Its impacts are nevertheless captured through the river flood hazard and risk assessment workflows, which incorporate precipitation-driven flood hazard layers and hydrological modelling outputs.

Building on the screening carried out in Phase 1, which identified floods and wildfires as priority hazards, Phase 2 updates and refines the risk screening step by expanding the scope of the assessment to include heatwaves as an additional priority hazard. This expanded hazard portfolio reflects both observed impacts and emerging climate trends, as well as stakeholder concerns regarding urban heat stress and public health risks.

Based on this updated screening, Phase 2 focuses on wildfires, heatwaves and floods as the main climate-related hazards for detailed analysis. This selection ensures continuity with Phase 1 while capturing the added value of Phase 2, which aims to deepen the assessment through higher spatial resolution, improved harmonization across hazards and increased integration of national and local datasets. The refined screening provides the foundation for the subsequent regionalized risk analysis and supports the development of actionable, municipality-level climate risk information for the Region of Attica.

2.2.2 Choose Scenario

Phase 2 applies scenario-based approaches where appropriate, following the CLIMAAX Framework and the planning needs of the Region of Attica.

For wildfires, a historical reference period (1991–2010) is used to train and evaluate a Random Forest susceptibility model, while future conditions are represented using a near-term climate period (2021–2040) under RCP4.5, based on the CLMcom_CCLM regional climate model configuration. RCP4.5 is selected as a moderate emissions pathway suitable for near- to medium-term planning, supporting direct comparison

¹ Retrieved from: <https://atlas.climate.copernicus.eu/atlas>

between historical and future wildfire hazard patterns within policy-relevant time horizons (e.g., RCCAP revision cycles and municipal planning).

For heatwaves, Phase 2 focuses on present-day conditions using observed/derived thermal data rather than climate-projection scenarios. Specifically, Land Surface Temperature (LST) for June–October 2023 is used to characterize warm-season heat stress and produce hazard indicators and overheating classes. This choice reflects both data availability and the Phase 2 objective to provide actionable, locally grounded evidence of current heat exposure patterns.

For floods, scenario selection is operationalized through the use of multiple flood return periods (e.g., RP50/RP100/RP1000 where available), which provide a structured way to represent a range of event severities, including low-probability/high-impact conditions. Flood-depth rasters by return period are processed consistently to enable comparison of exposure and potential impacts across severity levels.

2.3 Regionalized Risk Analysis

2.3.1 Wildfire ML Workflow

Table 2-1 Data overview for the Wildfire ML workflow

Hazard data	Vulnerability data	Exposure data	Impact metrics/Risk output
RCP45 202140 CKMcom_CCLM data for fire historic data	JRC data for economical and ecological index	Shapefile of Hospitals, Schools, Roads, Shelters (deliverable from other European projects)	Wildfire susceptibility maps (continuous, 0–1) for historical conditions and future RCP4.5 (2021–2040) conditions.
Climate variables related to fire danger and fuel availability (ECLIPS-2.0–based climate dataset)	Custom created index for population index based data from ELSTAT		Population-based wildfire risk maps (categorical, 4 levels: Low /Moderate-low / Moderate-high / High) produced by coupling 3-class vulnerability (low/medium/high) with the 6-class hazard via a 3×6 contingency matrix (computed for historical + RCP4.5).
Land cover / vegetation data (CORINE Land Cover reclassified)			Road-network risk outputs: road exposure raster + risk-along-roads map (same contingency approach; road hierarchy simplified due to a single aggregated road layer).
Topographic conditions derived from DEM (Specifically for the Attica Region)			

2.3.1.1 Hazard assessment

Data used

For the implementation of the FIRE hazard workflow, all required datasets were collected from multiple sources and organized under a dedicated root directory (e.g. `data_Attica/`), following the standard folder structure used in the CLIMAAX FIRE notebooks to ensure consistency and reusability of existing functions. Separate subfolders were created for each data category (e.g. `dem/`, `veg/`, `climate/`, `fires/`, `hazard/`). A pan-European DEM at 100 m resolution (EPSG:3035) was copied into the `dem/` folder, while climate predictors from the ECLIPS-2.0 dataset were downloaded for both the historical period (1991 – 2010) and the selected RCP4.5 future scenario (2021 – 2040), unpacked, and stored in clearly structured subdirectories.

Vegetation data were based on a CORINE Land Cover raster reclassified to three-digit CLC codes and accompanied by an Excel lookup table mapping CLC classes to fuel types, both placed under `veg/`. Historical burned-area data were obtained from the Copernicus EFFIS database and stored as a national-level shapefile in the `fires/` directory, preserving key attributes such as fire date and country. An Attica regional boundary shapefile was also installed and used systematically to clip all raster and vector datasets. This explicit and consistent directory setup allowed all scripts to reference data via relative paths, ensuring a portable and reproducible wildfire hazard workflow.

Digital elevation model (DEM)

The digital elevation model formed the core of the wildfire hazard workflow and was prepared starting from the pan-European DEM (100 m resolution, EPSG:3035), which was clipped to the Attica regional boundary using GDAL to produce a study-area-specific raster. Based on this clipped DEM, a standard set of terrain variables—slope (in degrees), aspect, eastness and northness (derived from trigonometric transforms of aspect), and surface roughness—was generated using shared CLIMAAX helper functions and stored as individual GeoTIFF files. During preprocessing, minor misalignments were detected between the DEM grid and the vegetation raster, including small differences in extent and pixel alignment.

To ensure full spatial consistency across all wildfire hazard inputs and avoid systematic spatial offsets, the DEM and its derived terrain layers were resampled and aligned to the vegetation raster using a dedicated raster-alignment procedure. The resulting aligned DEM and terrain derivatives were then used as the common reference grid for all raster datasets in the wildfire hazard workflow.

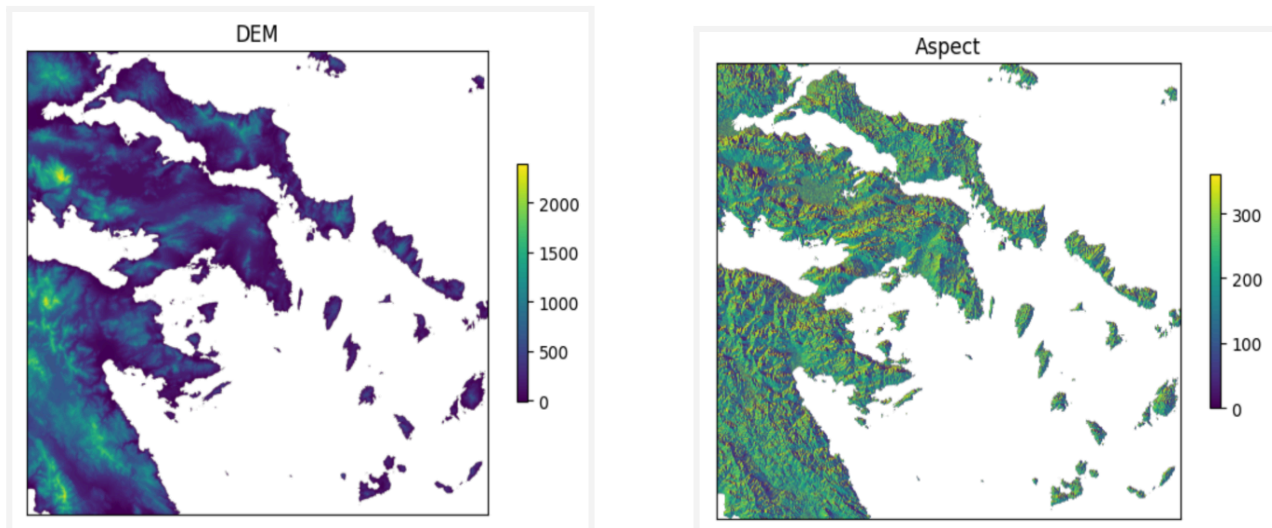


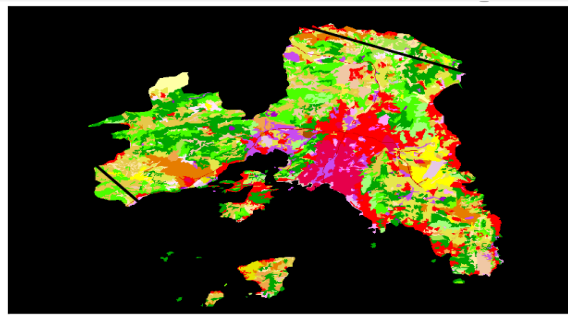
Figure 2-2 Digital Elevation Model (left) and derived aspect (right) for the Region of Attica, generated from the pan-European DEM (100 m resolution) and used as core terrain inputs in the wildfire hazard workflow. Elevation values are shown in meters above sea level, while aspect is expressed in degrees (0–360).

Land cover mapping

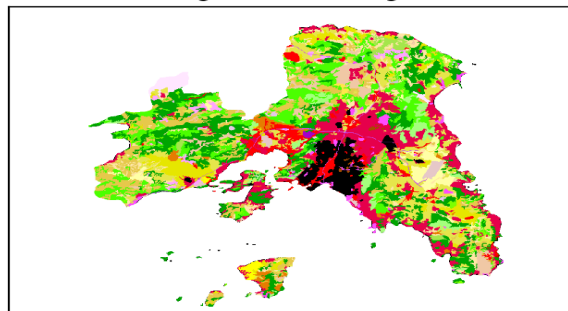
Vegetation and fuel conditions were represented using a CORINE Land Cover raster already reclassified to three-digit CLC codes, which was further processed to make it suitable for the Attica wildfire analysis. The raster was first reprojected to EPSG:3035 where necessary, resampled to the common 100 m resolution, and clipped to the Attica regional boundary so that it matched the aligned DEM grid. Following CLIMAAX guidelines, a set of non-burnable land-cover classes (such as urban and industrial areas, transport infrastructure, bare rock, glaciers, and water bodies) was then masked out by assigning them a value of zero, while burnable areas retained their original CLC codes, resulting in a burnable-area vegetation raster.

This raster was subsequently converted into fuel-type classes by applying a lookup table from an accompanying Excel file that maps CORINE classes to representative fuel categories (e.g. forest, shrubland, herbaceous fuels), with non-burnable areas remaining unchanged. Visual comparison plots between the original CORINE raster and the derived burnable and fuel-type layers were produced to confirm that reprojection, masking, and class-to-fuel mapping were applied correctly.

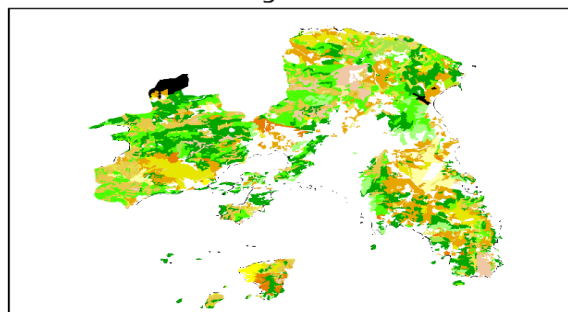
Corine Land Cover - Attica



Original CLC (3-digit)



CLC after removing non-burnable classes



CLC_CODE	
0 — No data/Not Burnable	223 — Olive groves
111 — Continuous urban fabric	231 — Pastures
112 — Discontinuous urban fabric	241 — Annual crops associated with permanent crops
121 — Industrial or commercial units	242 — Complex cultivation patterns
122 — Road and rail networks and associated land	243 — Land principally occupied by agriculture, with significant areas of natural vegetation
123 — Port areas	244 — Agro-forestry areas
124 — Airports	311 — Broad-leaved forest
131 — Mineral extraction sites	312 — Coniferous forest
132 — Dump sites	313 — Mixed forest
133 — Construction sites	321 — Natural grasslands
141 — Green urban areas	322 — Moors and heathland
142 — Sport and leisure facilities	323 — Sclerophyllous vegetation
211 — Non-irrigated arable land	324 — Transitional woodland-shrub
212 — Permanently irrigated land	331 — Beaches, dunes, sands
213 — Rice fields	332 — Bare rocks
221 — Vineyards	333 — Sparsely vegetated areas
222 — Fruit trees and berry plantations	334 — Burnt areas

Figure 2-3 CORINE Land Cover (CLC) data for the Region of Attica. The top panels show the original 3-digit CLC classification (top) and the corresponding land-cover map after removal of non-burnable classes (bottom). The bottom panel presents the resulting burnable land-cover mask used as input to the wildfire hazard workflow. Non-burnable classes (e.g. artificial surfaces, water bodies, and other excluded categories) were filtered out prior to further analysis.

Climate predictors

Climate forcing for the wildfire hazard model was provided by bioclimatic predictors from the ECLIPS-2.0 dataset, using both a historical configuration (1991 - 2010) and a future configuration corresponding to the RCP4.5 scenario from the CLMcom_CCLM model for the period 2021 - 2040. For each configuration, a consistent set of 14 climate variables was selected, including temperature- and precipitation-related indicators such as mean temperature of the warmest month, continentality, aridity indices, annual mean temperature, total precipitation, and seasonal climate metrics. All climate rasters were retrieved from the installed ECLIPS-2.0 directories, accounting for minor naming inconsistencies in the historical folder, and were then reprojected, resampled, and clipped using GDAL to match exactly the aligned DEM grid in terms of coordinate reference system, spatial resolution, and extent. A dedicated consistency check was applied to verify that each climate raster shared the same grid geometry as the DEM. The resulting aligned climate predictor layers were organized into separate directories for the historical and future scenarios, providing harmonized climate inputs for subsequent wildfire hazard modeling.

Historical fire data

Historical wildfire occurrence was derived from the Copernicus forest-fire database using the Greek national burned-area shapefile, which was processed in a series of cleaning and transformation steps. Fire records were first cleaned by extracting the year of occurrence from the FIREDATE attribute, removing entries with missing or invalid dates, and filtering the dataset to retain only features corresponding to Greece. The cleaned fire polygons were then spatially intersected with the Attica regional boundary to keep only events occurring within or overlapping the study area. Following CLIMAAX recommendations, a few exceptionally large burned-area polygons identified during visual inspection were removed to avoid biasing the model with extreme outliers unrepresentative of the typical fire regime. The remaining fire polygons were reprojected to the common analysis CRS (EPSG:3035) and rasterized onto the 100 m Attica grid, producing a binary fire-occurrence raster in which pixels with at least one recorded historical fire were assigned a value of 1 and all others 0. Diagnostic checks confirmed correct raster values and full spatial alignment with the DEM grid, ensuring suitability for subsequent hazard modelling.

Machine-learning hazard model

Once the DEM, climate, vegetation/fuel, and historical fire layers were fully harmonized on a common grid, a wildfire susceptibility model was trained using the Random Forest approach provided by the CLIMAAX FIRE workflow. Predictor inputs were organized into three raster dictionaries: a terrain dictionary containing the aligned DEM and its derived variables (slope, aspect, eastness, northness, and roughness), a vegetation dictionary based on the burnable vegetation and fuel-type raster, and a climate dictionary comprising the 14 aligned historical ECLIPS-2.0 bioclimatic variables. These predictors were combined with the rasterized fire-occurrence layer and a land mask to extract, for each valid grid cell, a feature vector and a binary response indicating the presence or absence of historical fire. To maintain computational efficiency given the large number of pixels, a representative subset of cells was sampled and split into training and test datasets. A Random Forest classifier with 100 trees and a maximum depth of 10, consistent with the CLIMAAX reference configuration, was then fitted to the training data and evaluated on the hold-out test set using standard performance metrics, including overall accuracy and the confusion matrix, to confirm its ability to distinguish between fire-prone and non-fire areas.

Descriptive statistics of the wildfire susceptibility output indicate values ranging from 0 to approximately 0.99, with a mean susceptibility of 0.15 and a standard deviation of 0.26. Quantile analysis shows that 75% of the study area exhibits susceptibility values below 0.16, while higher susceptibility values (>0.64) are confined to a limited spatial extent.

Hazard maps

The trained Random Forest susceptibility model was applied to produce spatially continuous wildfire hazard outputs across the entire Attica grid for both historical and future climate conditions. For the historical scenario, the aligned terrain derivatives, vegetation and fuel-type layer, and historical ECLIPS-2.0 climate predictors were used to generate a continuous susceptibility raster with values ranging from 0 to 1, which was saved and visualized using a continuous color scale. The same model was then applied to the future RCP4.5 climate configuration (CLMcom_CCLM, 2021–2040), while keeping terrain and vegetation inputs unchanged, resulting in a directly comparable future susceptibility map. To translate these continuous outputs into operational hazard classes, susceptibility values were discretized using percentile-based thresholds derived from the historical distribution, and the resulting classes were combined with fuel-type information through a predefined contingency matrix that assigns hazard levels from very low to extreme. This procedure yielded categorical hazard maps for both historical and future scenarios, with non-burnable or no-data areas coded separately, which were stored and visualized using a consistent legend to support comparison and interpretation.

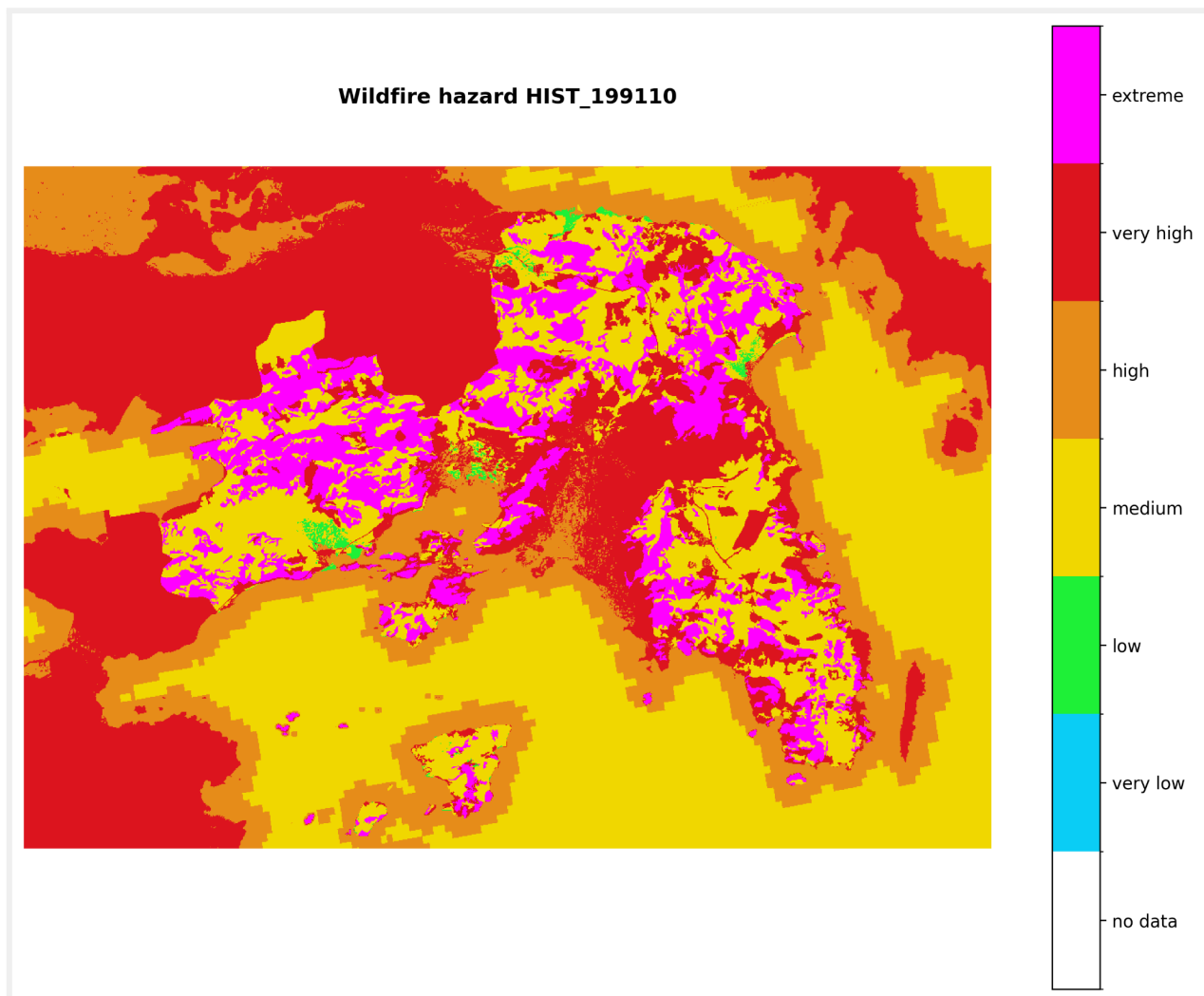


Figure 2-4: Wildfire hazard map for the Region of Attica (historical period 1991 – 2010)

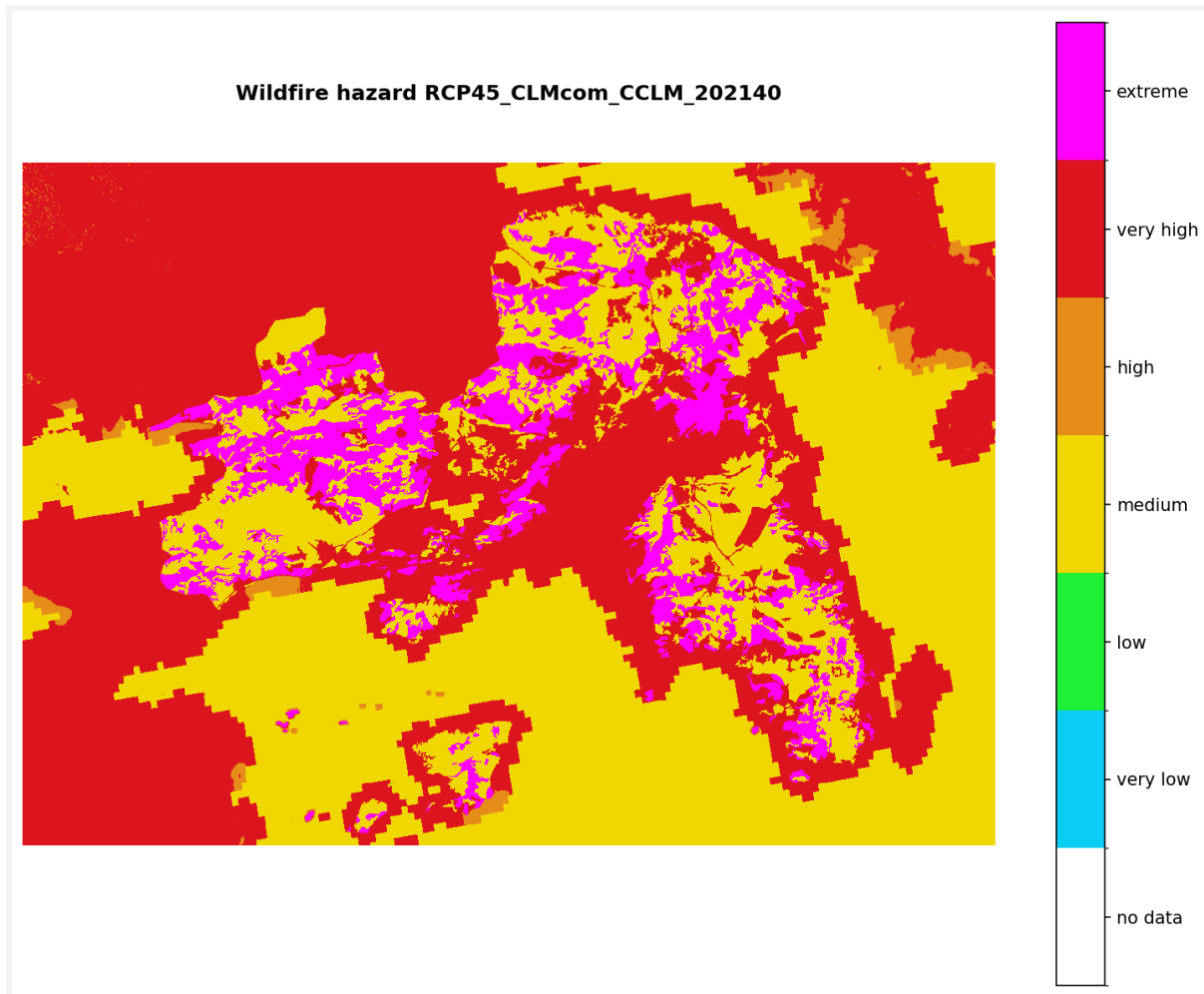


Figure 2-5: Wildfire hazard map for the Region of Attica (future period 2021 – 2040 under the RCP4.5 scenario)

The first figure (Figure 2-4) depicts the historical spatial distribution of wildfire hazard, whereas the second figure (Figure 2-5) presents the projected hazard under the RCP4.5 climate scenario for the future period. A comparative assessment of the two maps indicates a clear intensification and spatial expansion of wildfire hazard under projected climate conditions. In the historical baseline, hazard levels appear more spatially heterogeneous, with medium, high and very high classes distributed in a mosaic pattern. In contrast, the RCP4.5 scenario shows a more consolidated spatial structure, with high and very high hazard classes becoming more extensive and continuous, particularly across mountainous, forested and peri-urban areas.

More specifically, areas classified as high and very high hazard are primarily concentrated in the mountainous massifs of Attica and in transitional zones at the urban–vegetation interface, including regions such as Penteli, Hymettus and Mount Aigaleo. These areas are characterized by dense and continuous vegetation, complex topography and proximity to human activities, all of which contribute to increased wildfire susceptibility. Conversely, areas classified as low hazard are mainly located in regions such as Megara and other low-vegetation zones that are characterized by sparse fuel availability and limited adjacency to flammable biomass. It is also noteworthy that no areas are classified under the very low hazard category in the historical baseline. Under the future RCP4.5 projection, the low hazard class largely disappears, as these areas transition to higher hazard categories, predominantly high and in some cases very high, reflecting a systematic upward shift in wildfire hazard levels.

Several areas classified as medium hazard in the historical scenario shift toward high or very high categories in the future projection, while the spatial extent of low hazard classes decreases. This reflects an overall upward transition of hazard intensity and a strengthening of wildfire susceptibility under the projected climatic regime. The results are consistent with the expected influence of warmer and drier conditions on fuel moisture dynamics, fire weather severity and potential fire spread.

It should also be noted that certain coastal and marine areas appear classified as medium hazard in both maps. This is most likely attributable to artefacts introduced during land-use classification or raster processing, where water bodies were not fully masked and therefore received a default hazard value. From a physical and operational standpoint, marine areas should be considered as no data rather than as active hazard classes.

2.3.1.2 Risk assessment

The risk assessment builds directly on the hazard layers produced in the previous subsection and combines them with information on exposure and vulnerability in order to identify where wildfires may have the greatest impact in the Region of Attica. In line with the CLIMAAX framework, risk is conceptualized as a function of three elements:

$$Risk = f(Hazard, Exposure, Vulnerability)$$

In this context, risk reflects the spatial pattern of wildfire hazard, the presence of people and assets that can be affected (exposure) and the degree to which those people and assets are susceptible to damage (vulnerability). Two complementary risk formulations were implemented. The first focuses on population risk and combines categorized vulnerability with categorized hazard (“Risk method 1”). The second focuses on transport infrastructure and combines the hazard with a classified road network (“Risk method 2”). Both methods are applied for the historical hazard configuration (1991–2010) and for the selected future climate scenario (2021 – 2040), which allows a qualitative comparison of how risk patterns may evolve under climate change.

Vulnerability

The first risk formulation concentrates on population vulnerability. As input, the workflow uses gridded vulnerability rasters stored under `./data/vulnerability`, which follow the CLIMAAX structure. These include a population-based vulnerability index, an economic vulnerability index, an ecological vulnerability index and a combined ecological–economic index, all originally developed by JRC at European scale. For the Attica application, the emphasis was placed on the population vulnerability layer, since locally validated ecological and economic data at regional level are still pending; the other layers were processed and visualized for reference but not used as primary drivers in this iteration.

The JRC vulnerability rasters were first inspected visually to confirm that they cover the whole of Attica and that values lie in the expected 0–1 range. They were then clipped and resampled to the Attica DEM grid using `gdal.Warp` with bilinear resampling. This ensured that the vulnerability rasters share exactly the same projection (EPSG:3035), resolution (100 m) and extent as the hazard rasters and the DEM. The clipped files were written into a region-specific vulnerability subdirectory under `data_Attica`, so that the original pan-European rasters remain unchanged, and all risk computations use the Attica-specific copies.

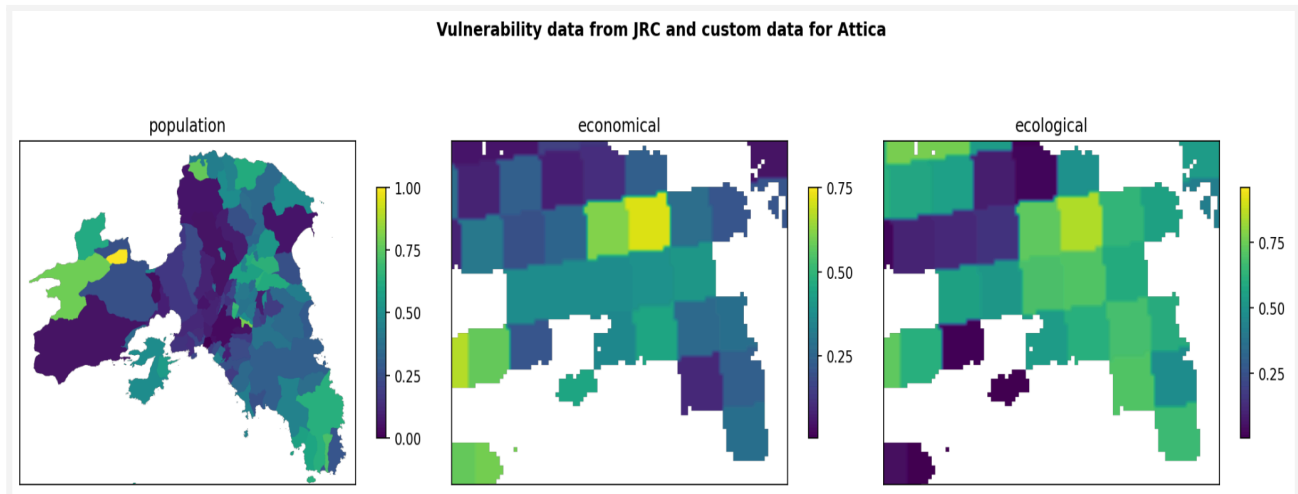


Figure 2-6: Spatial distribution of the vulnerability components used in the wildfire hazard assessment for the Region of Attica. The maps represent normalised indices (0–1) for population vulnerability (left), economic vulnerability (centre), and ecological vulnerability (right), derived from regional and national datasets. These layers were used as vulnerability inputs in the wildfire susceptibility and hazard modelling workflow.

For the risk calculation, vulnerability needs to be expressed in categorical form. Two categorization strategies were implemented: a quantile-based method, which divides the vulnerability distribution into three classes using the 25th, 50th and 75th percentiles, and a fixed-threshold method, which uses absolute thresholds (for example below 0.30, between 0.30 and 0.60, and above 0.60) on the 0–1 vulnerability scale. For Attica, the fixed-threshold option was selected, as it provides a more interpretable classification in terms of low, medium and high vulnerability. A categorization function reads each clipped vulnerability raster, masks nodata and zero values, applies the chosen thresholds and assigns each pixel to class 1, 2 or 3, representing low, medium and high vulnerability respectively. Diagnostic maps of categorized vulnerability for the population, economic and ecological layers were produced for Attica to verify that the classification behaves as expected.

In line with the data limitations described earlier, the subsequent population-based risk analysis uses primarily the categorized population vulnerability layer. The economic, ecological and combined indices from JRC remain available and have been processed to the same standard, so they can be incorporated in future iterations once regional experts confirm their suitability for Attica.

Exposure

Exposure information enters the risk analysis in two ways: through population (implicitly in the vulnerability layer) and through explicit elements of risk represented by vector layers. A set of exposure shapefiles was installed under `data_Attica/exposure`, including points corresponding to hospitals, schools, nursing homes and other relevant facilities, as well as line features representing the road network and shelters. These files refer to the reference year 2023 and were provided by the National Observatory of Athens, and were harmonized into a common CRS to ensure spatial consistency within the risk assessment framework.

The notebook reads all exposure shapefiles into a dictionary of GeoDataFrames. The Attica regional boundary shapefile is opened in parallel to provide geographic context. Because exposure datasets may come with heterogeneous coordinate systems, a short loop checks the CRS of each GeoDataFrame and reprojects it to the Attica boundary CRS where necessary. A first visualization plots all exposure layers against the

regional boundary, allowing a quick check that the elements are correctly located and fall within the area of interest.

For raster-based risk analysis, the vector exposure layers are then rasterized to the 100 m grid of the DEM using a `rasterize_numerical_feature` helper function. This function takes each point or line layer, burns it into the grid as a presence/absence raster (1 where the element is present, 0 elsewhere) and writes the result as a GeoTIFF aligned to the DEM. This produces a set of binary exposure rasters for each element type. On this basis, the workflow can later compute risk either by overlaying hazard with population vulnerability (method 1) or by overlaying hazard with a road-based vulnerability classification (method 2).

A specific challenge in the Attica case was the road network. The CLIMAAX workflow recommends using three separate road layers (primary, secondary and tertiary), each assigned a different vulnerability level. For Attica, only a single, aggregated road layer was available. As a result, it was not possible to distinguish between primary, secondary and tertiary roads in a robust way. In the current implementation, this aggregated layer is used as a generic representation of the road network, and any classification into “primary”, “secondary” and “tertiary” for risk method 2 is understood as a relative, not literal, hierarchy. This limitation is explicitly noted and will be revisited if more detailed road data become available.

Risk maps

Two complementary risk calculation methods were implemented in the Attica wildfire workflow.

Risk Method 1

The first method focuses on population risk and combines categorized vulnerability with categorized hazard at pixel level. The input consists of the three-class vulnerability raster (for example population vulnerability) and the six-class hazard raster for the chosen climate configuration (historical or future). Risk is then computed using a 3×6 contingency matrix. The matrix encodes how combinations of vulnerability level (rows) and hazard level (columns) map to a four-level risk scale. For example, a pixel with low vulnerability and low hazard may be assigned risk level 1, while a pixel with high vulnerability and very high or extreme hazard may be assigned risk level 4. Intermediate combinations fall in between, with the matrix designed such that risk increases monotonically in both vulnerability and hazard. A dedicated `contingency_matrix_on_array` function applies this matrix to the vulnerability and hazard arrays, producing a categorical risk raster where nodata in either input propagates to nodata in the output and non-burnable areas remain at zero.

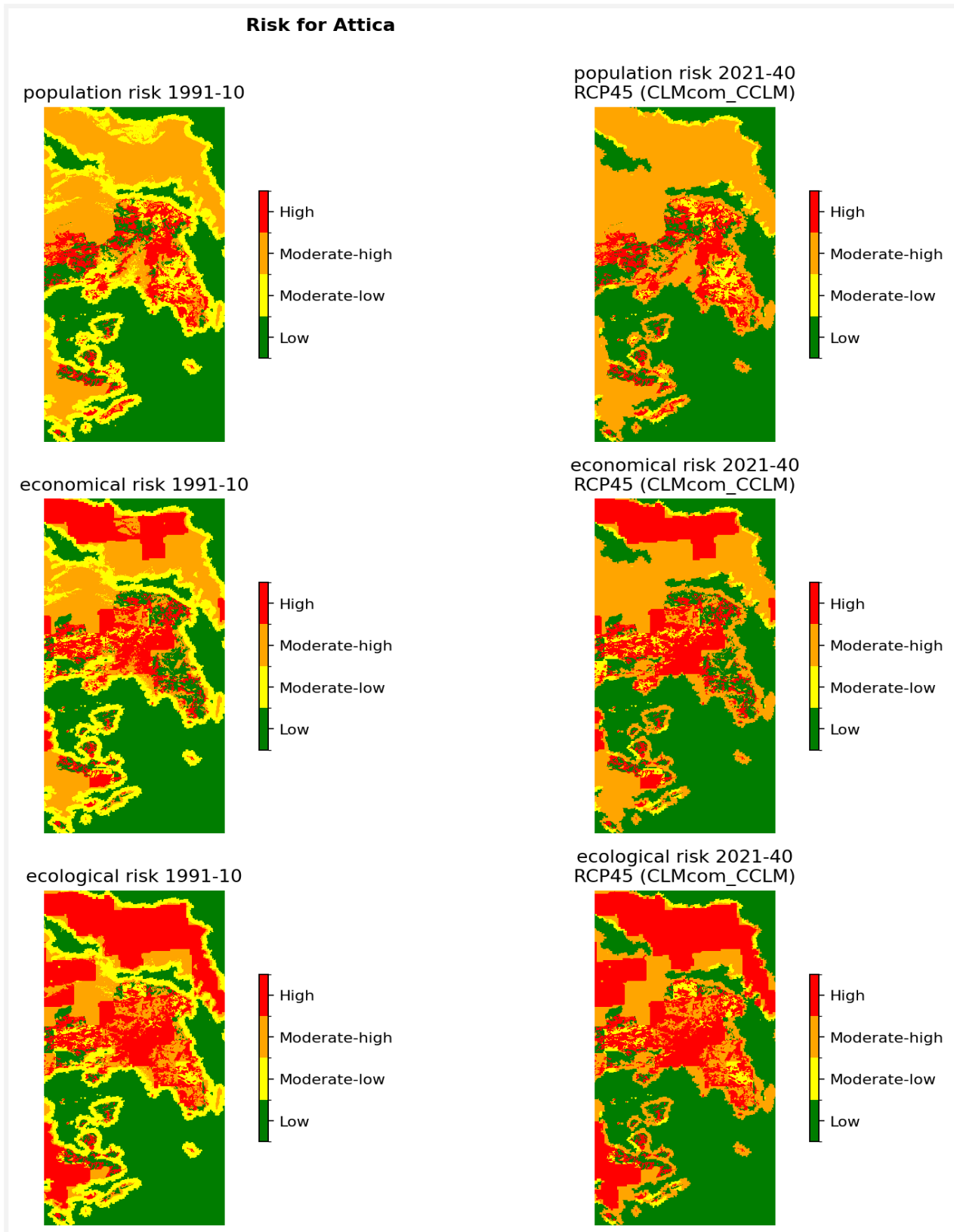


Figure 2-7: Wildfire risk maps for the Region of Attica, disaggregated by population, economic, and ecological risk components. The left column shows risk levels under historical climate conditions (1991–2010), while the right column presents projected risk under the RCP4.5 climate scenario for the period 2021–2040 (CLMcom-CCLM). Risk classes (low to high) were derived by combining wildfire hazard, exposure, and vulnerability layers using a consistent classification scheme across both time periods.

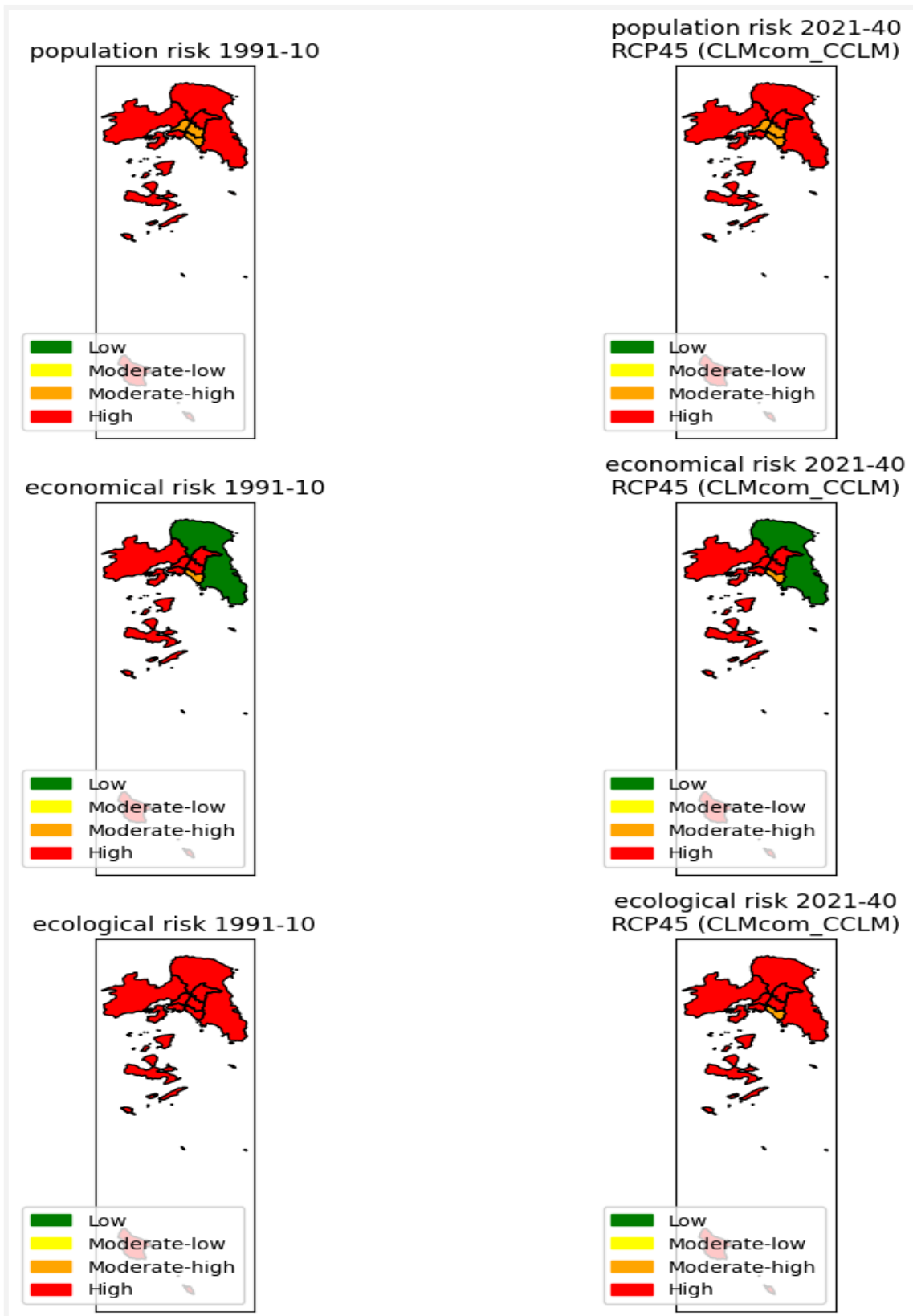


Figure 2-8: Aggregated wildfire risk levels at NUTS3 administrative level for the Region of Attica. Population, economic, and ecological wildfire risk are shown for historical climate conditions (1991–2010, left column) and for future climate conditions under the RCP4.5 scenario (2021–2040, right column). NUTS3-level risk classes were derived by spatially aggregating raster risk outputs and assigning a dominant risk class per administrative unit to provide a simplified, policy-oriented representation of wildfire risk.

The above figures (Figure 2-7, Figure 2-8) present the spatial distribution of population, economic and ecological wildfire risk for the historical period (1991–2010) and the future period (2021–2040) under the RCP4.5 climate scenario. Overall, the results indicate a consistently high level of wildfire risk across the Region of Attica, with further spatial consolidation and intensification under projected future climatic conditions.

With respect to population risk, high-risk areas are predominantly concentrated in the northern, northeastern and eastern parts of Attica, corresponding to densely populated zones that are located in close proximity to forested and peri-urban vegetation. These areas include the foothills and major mountain systems such as Penteli where the urban–wildland interface significantly increases exposure. Moderate-high and moderate-low risk classes are limited in spatial extent and mainly occur in transitional zones between highly urbanized and less vegetated areas. Under the RCP4.5 projection, the spatial pattern of population risk remains largely similar, but with a tendency toward further consolidation of the high-risk class and a reduction in lower-risk transitional zones, indicating increased exposure of human populations to wildfire hazard.

Economic risk exhibits a comparable spatial structure, with high-risk areas concentrated in regions characterized by dense infrastructure, economic activity and built assets. In the historical period, some localized areas in the northeastern part of Attica appear as low-risk zones, likely reflecting lower economic asset density or different land-use characteristics. However, in the future projection, high economic risk becomes more spatially extensive and continuous, while low-risk areas remain limited and fragmented. This pattern suggests an increasing vulnerability of economically important areas under projected climate conditions.

Ecological risk shows the most extensive spatial dominance of the high-risk class among the three categories. Both the historical and projected maps indicate that the majority of Attica’s natural and semi-natural ecosystems are classified as high risk, particularly in mountainous regions as well as in forest ecosystems across eastern and western Attica. The future projection under RCP4.5 indicates a continuation and slight expansion of this pattern, reflecting the increasing susceptibility of ecosystems to wildfire due to projected climatic conditions favoring fuel dryness and fire spread.

It is important to note that the level of spatial detail differs substantially between Figure 2-7 and Figure 2-8, which affects the visibility of differences between the historical and projected risk conditions. In Figure 2-7, wildfire risk is presented at the original raster resolution, allowing for the identification of fine-scale spatial variability and localized transitions between risk classes. At this level of analysis, spatial differences between the historical period (1991–2010) and the future projection (2021–2040, RCP4.5) are clearly observable, including the expansion and consolidation of higher-risk zones and the reduction of lower-risk areas.

In contrast, Figure 2-8 presents wildfire risk aggregated at the NUTS3 administrative level, where risk values were spatially summarized and a dominant risk class was assigned to each administrative unit. This aggregation process inherently reduces spatial resolution and masks local-scale variability, resulting in a more generalized and homogeneous representation of risk. As a consequence, the differences between the historical and future scenarios appear less pronounced at the NUTS3 level, and both time periods show similar overall risk classifications for several administrative units.

One interesting observation is that one NUTS3 subregion shifts from the high ecological risk class in the historical period to the moderate-high class under the future RCP4.5 scenario. Specifically, this change is observed in the South Athens Regional Unit. This transition is hypothesized to be primarily attributable to the aggregation methodology rather than indicating an actual reduction in ecological vulnerability. The NUTS3 classification is based on the dominant risk class within each administrative unit, which reflects the

proportional spatial distribution of raster-level risk classes. As such, relatively small changes in the relative extent of high and moderate-high risk cells may lead to a shift in the dominant class assignment. This suggests that ecological risk within the South Athens Regional Unit likely remains high overall, despite the apparent change in the aggregated administrative-level classification.

Lastly, it should be noted that in Figure 2-7 coastal and marine areas appear to be classified under the low risk category. This is likely the result of artefacts introduced during raster processing or masking procedures, where water bodies were not fully excluded from the analysis and were therefore assigned a default low-risk value. From a methodological and physical perspective, these areas should be interpreted as no-data rather than as valid wildfire risk classes.

Risk Method 2

The second method focuses on the road network as an exposed element. Here, the exposure raster is created from the road network and, under ideal conditions, would differentiate primary, secondary and tertiary roads into vulnerability levels 1, 2 and 3 respectively. In Attica, due to the absence of separate road classes, the roads are effectively treated as a single infrastructure layer and classified into vulnerability levels in a simplified way. The same 3×6 risk matrix used in Risk Method 1 is then applied to the combination of road vulnerability classes and hazard classes, resulting in a risk-along-roads raster that highlights segments of the road network traversing high-hazard areas.

In both methods, the computations are performed twice: once using the historical hazard map and once using the future hazard map for the selected RCP4.5 scenario. This produces a pair of risk maps (historical and future) for each vulnerability or exposure layer considered.

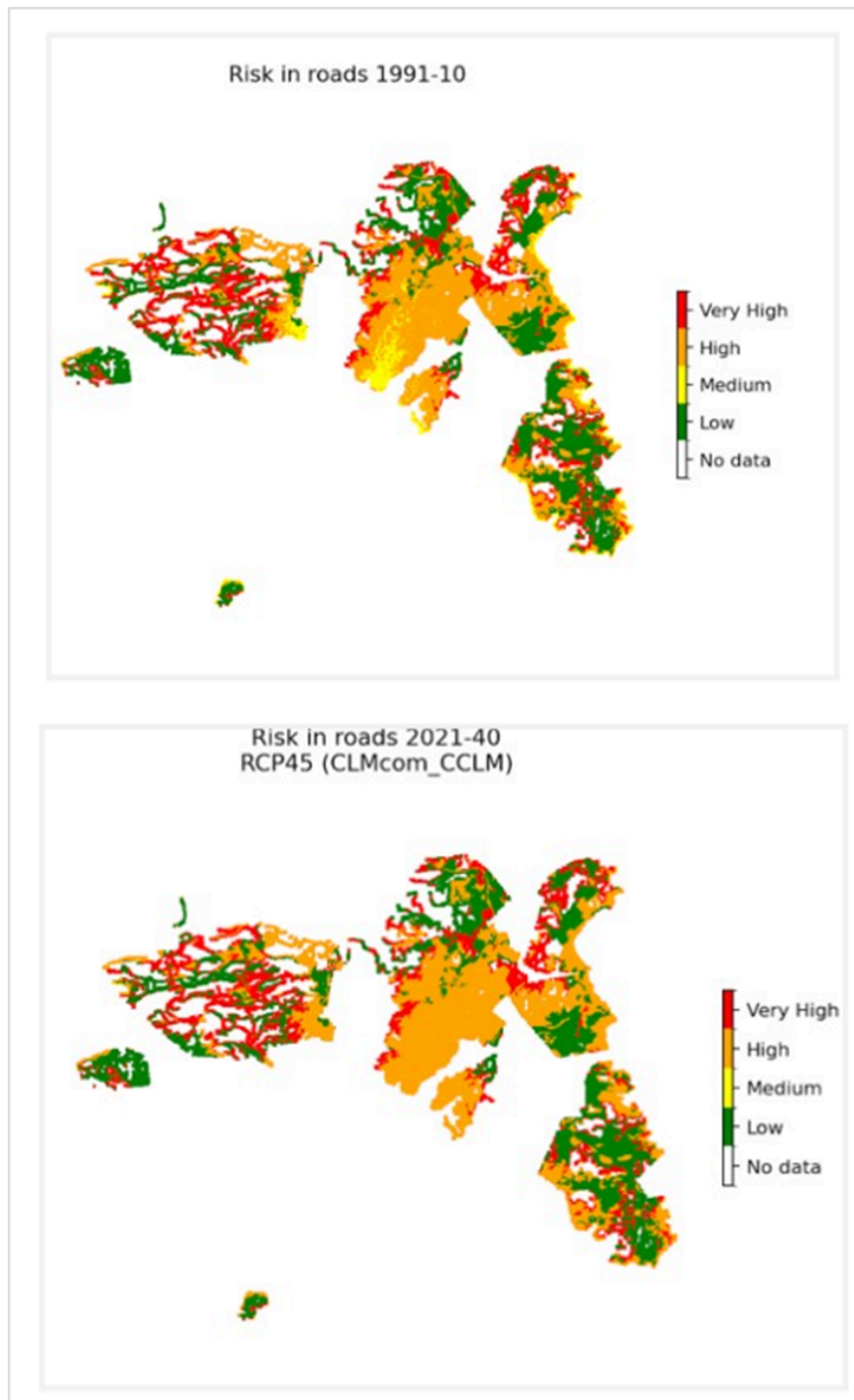


Figure 2-9: Wildfire risk affecting the road network in the Region of Attica under historical (1991–2010, up) and future climate conditions (2021–2040, RCP4.5; CLMcom-CCLM, down). Road risk classes (low to very high) were derived by intersecting raster-based wildfire hazard and risk outputs with the road network exposure layer, providing a focused representation of wildfire-related risk to critical transport infrastructure

The spatial distribution of wildfire risk affecting the road network in the Region of Attica for the historical period (1991–2010) and the future projection period (2021–2040) under the RCP4.5 scenario indicates a clear predominance of medium to high risk conditions across large portions of the transportation infrastructure. In the historical period, high risk constitutes the most widespread class, particularly across the central and southern parts of Attica, while very high risk segments appear in more spatially fragmented patterns. High-risk road segments are primarily concentrated within the central urban fabric and in areas

located near mountainous and vegetated zones, reflecting the strong influence of the wildland–urban interface on wildfire exposure. Conversely, several low-risk segments are observed in areas where the road network is relatively sparse and less exposed to continuous vegetation, such as regions located southeast of Mount Hymettus. In addition, medium-risk segments are present in the southern parts of Attica, including areas within the Piraeus and South Athens Regional Units, likely reflecting intermediate levels of hazard and exposure. Overall, low-risk road segments tend to occur in areas with reduced vegetation density or more urbanized surroundings, where fuel availability is comparatively limited.

Under the future climate projection (2021–2040, RCP4.5), the spatial pattern of road network wildfire risk remains broadly similar in its overall structure; however, a systematic upward shift in risk classes is observed. Specifically, several road segments previously classified as medium risk appear to transition to high risk, while a number of low-risk segments shift toward medium risk. This results in an overall increase in the spatial extent and continuity of medium and high-risk classes. This pattern is particularly evident in peri-urban and mountainous regions, where projected climatic conditions are expected to enhance wildfire hazard through increased fuel dryness and more favorable fire weather conditions.

2.3.2 Heatwave Workflow

Table 2-2 Data overview for the heatwave workflow

Hazard data	Vulnerability data	Exposure data	Impact metrics/Risk output
Land Surface Temperature (LST) rasters derived from MODIS MOD11A1.061 (Daytime and Night-time, ~1 km resolution), provided by the National Observatory of Athens (NOA) for the period June–October 2023. Original data delivered in sinusoidal projection and reprocessed (GeoTIFF conversion, reprojection to WGS84/EPSSG:4326, clipping to Region of Attica).	Age-structure–based vulnerability indicators derived from 2021 census data at municipal level. Indicators include elderly ratio, dependency ratio ((children + elderly) / working-age population) and composite vulnerability indices, normalized to the [0,1] range after rasterisation and alignment to the LST grid.	Population distribution rasters at 1 km resolution, derived from official 2021 population statistics aggregated by municipality (total population, children 0–19, working-age population, elderly 65+). Municipal polygons were dissolved, joined to census tables and rasterised onto the common analysis grid.	Heatwave risk surfaces combining LST-based hazard indicators with population exposure and normalized vulnerability indices. Outputs include continuous risk maps and categorical risk classes, as well as aggregated indicators (e.g. exposed population in high-risk areas) at municipal and NUTS levels via zonal statistics.
Aggregated LST indicators, including mean and maximum LST over the June–October 2023 period, computed per pixel from the multi-temporal LST stack with consistent handling of NoData values.	Normalized vulnerability raster layers, ensuring comparability with hazard and exposure components and suitability for composite index calculation within the CLIMAAX framework.	Age-specific exposure layers, allowing identification of exposed vulnerable groups (children and elderly) in overheated areas.	Overheated area maps, based on reclassification of maximum LST into ten numeric classes and five qualitative overheating categories (Very Low to Very High), supporting spatial prioritisation of heat mitigation measures.
L8 Raster Stack			

2.3.2.1 Hazard assessment

As part of the Phase 2 heatwave hazard assessment for AtticaReady, a xclim-based workflow was successfully executed to derive annual heatwave indicators from EURO-CORDEX daily climate projections. The workflow uses daily 2m maximum temperature (tasmax) and 2m minimum temperature (tasmin) and computes heatwave indices for both a historical period and future climate scenarios (RCP4.5 and RCP8.5) at $\sim 0.11^\circ$ (~ 12 km) resolution.

A practical challenge encountered during implementation was that some CDS downloads did not complete reliably due to the large dataset size (multi-decade daily data). To overcome this, the data retrieval step was adapted so that the datasets were downloaded in smaller chunks, i.e., per year or per date-range window (e.g., multi-year blocks), separately for each variable and scenario. Each chunk was then extracted locally and later combined for analysis (using multi-file loading) so that the workflow could run end-to-end without download timeouts or storage bottlenecks.

After retrieval, the workflow: assigns the EURO-CORDEX rotated pole CRS and clips the data to a selected bounding box covering the Attica area of interest, computes annual (yearly) indicators using xclim, exports the computed indices as GeoTIFF rasters (multi-band, one band per year), reprojects outputs to WGS84 for visualization and for extracting time series at selected points, provides an interactive map step to select a location and plot yearly indicator values.

It is noted that the temperature thresholds applied in the analysis were selected on the basis of authoritative sources, including official guidance and publications from the Hellenic National Meteorological Service (HNMS). This approach ensures that the adopted thresholds are consistent with nationally recognized definitions and are representative of the climatic conditions and heatwave characteristics of the Attica region.

Indicators computed

Heatwave Index (HWI)

Computed as the number of days per year that belong to a heatwave, defined as 3 or more consecutive days above a threshold of 38°C (yearly aggregation).

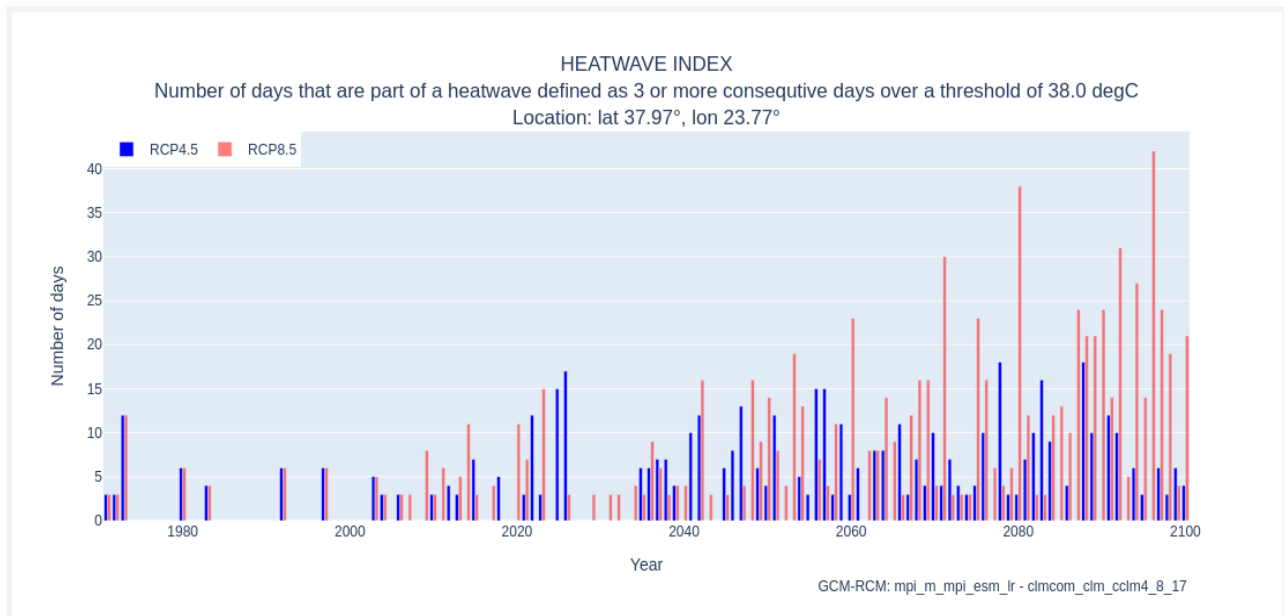


Figure 2-10: Time series of the Heatwave Index (HWI), defined as the annual number of days belonging to heatwave events (≥ 3 consecutive days with daily maximum temperature above $38\text{ }^{\circ}\text{C}$). The figure illustrates the temporal evolution of the HWI under historical and future climate conditions (RCP4.5 and RCP8.5) at a representative grid point in the Region of Attica

Heatwave Frequency (HWF)

Computed as the number of heatwave events per year, where a heatwave event is defined as a period of at least three consecutive days during which daily maximum temperatures exceed $38\text{ }^{\circ}\text{C}$ and night-time minimum temperatures exceed $26\text{ }^{\circ}\text{C}$.

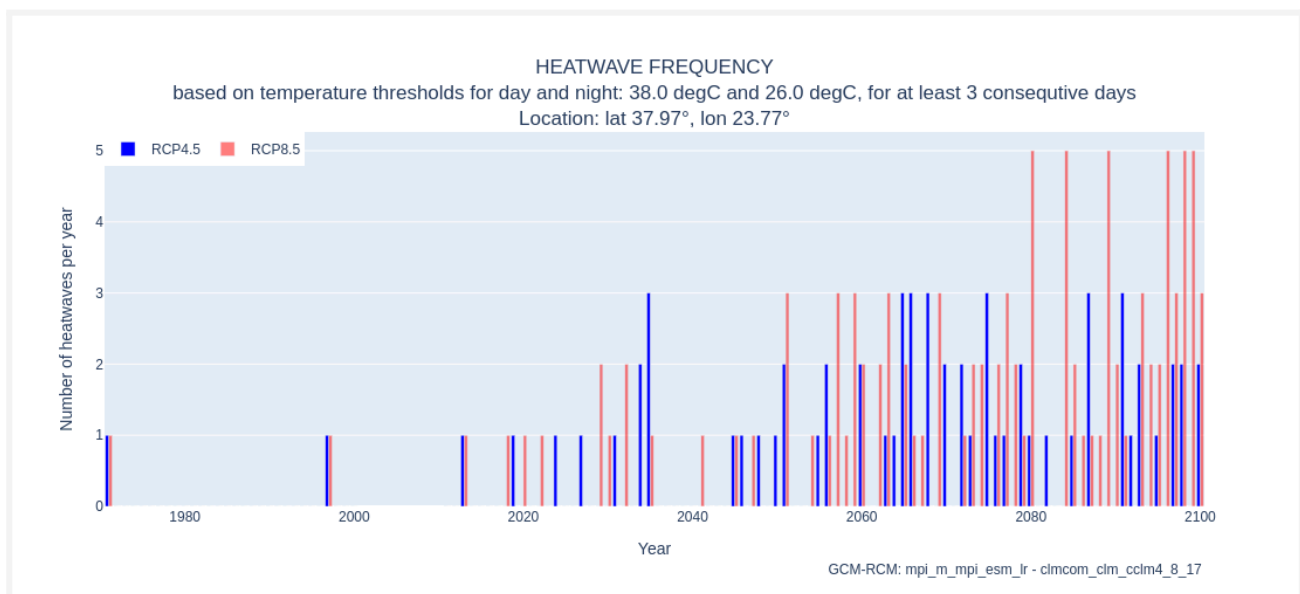


Figure 2-11: Time series of Heatwave Frequency, defined as the annual number of heatwave events meeting combined daytime and nighttime temperature thresholds (daily maximum temperature $> 38\text{ }^{\circ}\text{C}$ and daily minimum temperature $> 26\text{ }^{\circ}\text{C}$, sustained for at least 3 consecutive days). The figure illustrates the temporal evolution of heatwave frequency under historical and future climate conditions (RCP4.5 and RCP8.5) at a representative grid point in the Region of Attica.

Heatwave Total Length (HWTL)

Computed as the total number of heatwave days per year, defined as the sum of all days that are part of heatwave events, where a heatwave event consists of at least three consecutive days with daily maximum temperatures above 38 °C and night-time minimum temperatures above 26 °C.

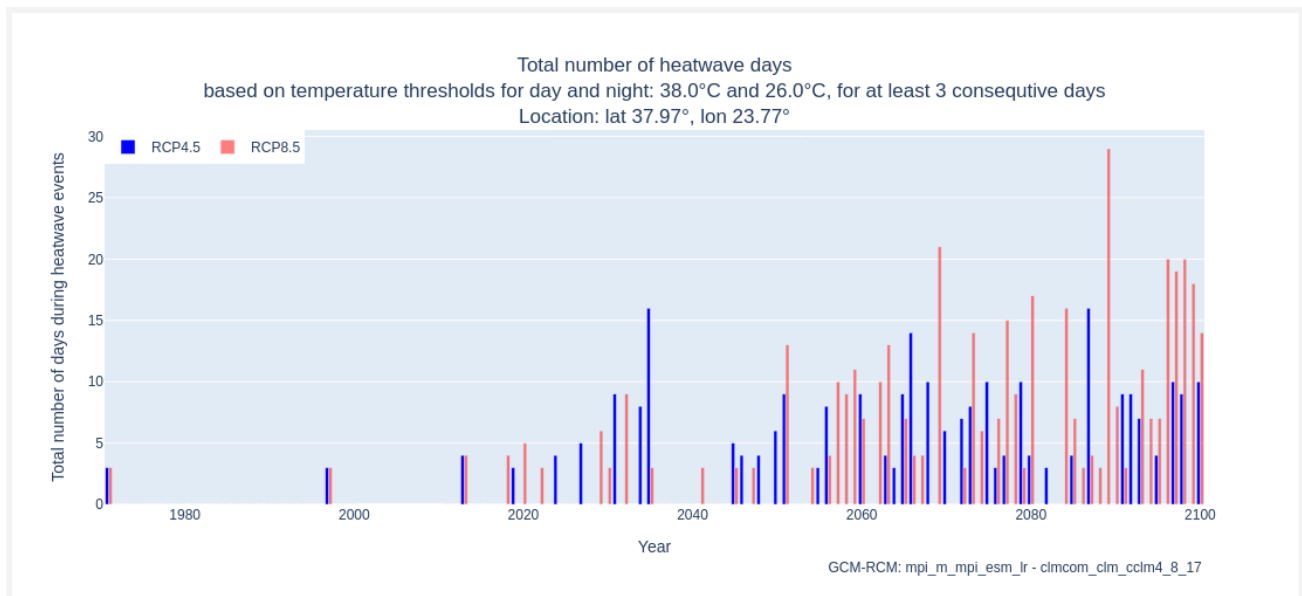


Figure 2-12: Time series of Heatwave Total Length (HWTL), defined as the annual total number of days belonging to heatwave events (daily maximum temperature > 38 °C and daily minimum temperature > 26 °C, sustained for at least 3 consecutive days). The figure illustrates the temporal evolution of cumulative heatwave duration under historical and future climate conditions (RCP4.5 and RCP8.5) at a representative grid point in the Region of Attica and is provided for indicator definition and interpretation purposes.

Results summary

The notebook visualizes the computed indicators as yearly bar charts for a representative selected point in Attica (shown on the figures as lat 38.06°, lon 23.79°) and compares RCP4.5 vs RCP8.5 for the same location. The charts show clear interannual variability in all indicators and, importantly, the future scenarios generally exhibit higher heatwave burden than the historical period, with RCP8.5 typically producing higher values than RCP4.5 in the later decades (both in number of heatwave events and total heatwave days). The plots also include the GCM-RCM combination used in this run (as displayed on the figures), which is important because the magnitude of indicators can vary depending on the selected model chain.

Because these indicators are threshold-based, interpretation should always be linked to the chosen thresholds (38°C for HWI; 38°C/26°C for HWF & HWTL) and to comparisons across multi-year periods (e.g., comparing a historical baseline window to a future window) rather than over-interpreting single-year spikes.

The projected increase in heatwave frequency and duration under future climate scenarios confirms the growing importance of heatwaves as a priority climate hazard for the Region of Attica and supports their inclusion as a core component of the Climate Risk Assessment.

2.3.2.2 Risk assessment

It is important to clarify that the heatwave hazard assessment presented in section 2.3.2.1 is complementary to the risk analysis and is used exclusively to explore, quantify and visualize trends in the three heatwave

indicators (HWI, HWF, HWTL). For the purpose of the risk assessment, a different hazard representation is adopted. Specifically, the hazard component used in the risk formulation is based on Land Surface Temperature (LST), which allows a spatially explicit and impact-oriented representation of heat exposure across the study area.

For the AtticaReAdy pilot, LST data covering the period June to October 2023 were obtained from the National Observatory of Athens (NOA), based on the MODIS MOD11A1.061 satellite product, with a spatial resolution of approximately 1 km. Both daytime and night-time LST observations were considered, allowing the analysis to capture heat accumulation during the day as well as limited nocturnal cooling.

All LST datasets were pre-processed to ensure full consistency with the other spatial layers used in the CLIMAAX workflow. This included reprojection to a common coordinate system, spatial alignment with the Region of Attica, and harmonization of spatial resolution and extent. The resulting LST layers therefore share the same grid as the exposure and vulnerability datasets, enabling direct spatial combination in the risk analysis.

From the processed daily LST data, a set of aggregated heat hazard indicators was derived. In particular, mean LST over the warm season was used to represent average thermal conditions, while maximum LST was used to identify areas exposed to extreme surface temperatures. These indicators provide complementary information on both persistent and peak heat stress across the region.

To support an intuitive interpretation of overheating patterns, the maximum LST values were further classified into relative thermal stress categories. A data-driven, quantile-based approach was applied, dividing the study area into classes that represent increasing levels of surface overheating, from Very Low to Very High. Specifically, the class boundaries were defined by the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th and 90th percentiles of the LST distribution, resulting in ten numeric classes (1–10), each containing approximately 10 % of all pixels in the study area. For the Attica region, the derived decile thresholds were:

40.81 °C, 42.43 °C, 43.50 °C, 44.36 °C, 45.10 °C, 45.95 °C, 46.75 °C, 47.43 °C and 48.36 °C.

In a second step, these ten numeric classes were aggregated into five qualitative overheating categories: Very Low (classes 1–2), Low (classes 3–4), Medium (classes 5–6), High (classes 7–8) and Very High (classes 9–10).

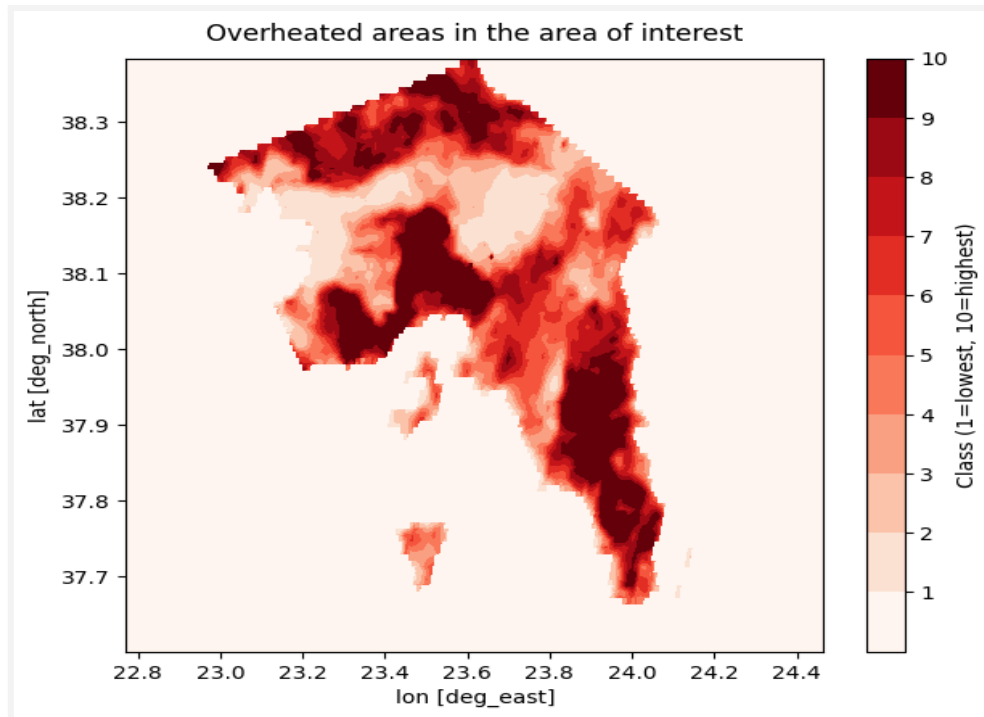


Figure 2-13: Spatial distribution of overheated areas in the Region of Attica, derived from custom processing of land surface temperature data. Grid cells were classified into ten relative heat-intensity classes (1 = lowest, 10 = highest) based on their relative thermal anomaly within the study area. The map highlights areas consistently exhibiting higher land surface temperatures during the warm season and is used to support the spatial heatwave hazard assessment.

The figure above (Figure 2-13) illustrates the spatial distribution of overheated areas within the study region, expressed through a classified index ranging from 1 (lowest intensity) to 10 (highest intensity). The results indicate a clear concentration of higher overheating classes (8–10) across densely urbanised and coastal zones, as well as along major built-up corridors. These areas form relatively continuous hotspots, suggesting strong surface heat accumulation and limited thermal dissipation.

Three major spatial clusters of elevated overheating intensity can be identified. The first cluster is located in eastern Attica, particularly across the coastal and peri-urban zones of the Mesogeia and Lavreotiki areas. This includes settlements such as Rafina, Artemida, Keratea, Lavrio, and surrounding coastal and inland areas. These locations are characterized by a combination of built-up surfaces, limited dense vegetation cover, and strong solar exposure, which contribute to increased surface heat storage and reduced cooling potential. The continuity of high overheating classes along this eastern coastal corridor suggests a structurally elevated susceptibility to heat stress, particularly in low-elevation coastal and suburban environments.

A second major hotspot is observed in western Attica, particularly across the Thriasio Plain, including the areas of Elefsina, Aspropyrgos, and Megara. This zone exhibits extensive high overheating classes, forming one of the most pronounced overheating regions within the study area. The observed pattern is likely associated with the combined effects of industrial land use, extensive impervious surfaces, sparse vegetation cover, and basin-like geomorphological conditions that limit ventilation and enhance heat accumulation.

A third cluster is identified in northern Attica, particularly in lowland and coastal areas north of Mount Parnitha, including the broader Oropos area and adjacent settlements. These areas show elevated overheating classes, likely reflecting the combined influence of coastal exposure, low elevation, limited vegetation cover

in built-up zones, and geomorphological conditions that favor heat accumulation. Although less spatially extensive than the eastern and western clusters, this northern hotspot represents an additional area of increased thermal stress within the regional context.

In contrast, lower overheating classes are primarily observed in less urbanised, mountainous, or vegetated areas, where higher vegetation density and elevation contribute to more effective heat dissipation and lower surface temperatures.

It should be noted that LST represents surface temperature rather than air temperature. While absolute values therefore differ from standard meteorological measurements, LST is a key determinant of the urban thermal environment and is well suited for identifying areas where heat exposure and heat-related impacts are likely to be highest.

The final outcome of this process is a harmonized set of LST-based hazard layers and overheating maps for the Region of Attica, which are used as the hazard input in the overall heatwave risk assessment, in combination with the exposure and vulnerability components described in the following sections.

Exposure & vulnerability

The exposure and vulnerability components of the heatwave risk assessment are based on population data, with a particular focus on age-related vulnerability, which is widely recognized as a key driver of heat-related impacts.

Official 2021 population statistics at municipal level were used as the primary data source. These data include the total population as well as a breakdown by age groups for each municipality in the Region of Attica. The population information was spatially linked to municipal boundaries and subsequently transformed into spatial layers that are fully compatible with the Land Surface Temperature (LST) grid used in the hazard assessment.

For the purposes of the analysis, the population data were organized into three main age categories:

- Children,
- Working-age population, and
- Elderly population.

This grouping allows a clear distinction between population segments with different levels of susceptibility to heat stress, with particular emphasis on the elderly and dependent age groups.

The municipal-level population information was then converted into gridded population layers at approximately 1 km spatial resolution, matching the resolution and spatial reference of the hazard data. This step ensures that population exposure can be evaluated consistently across space and directly combined with the LST-based heat hazard layers.

Based on these gridded population datasets, a set of demographic vulnerability indicators was derived to capture differences in sensitivity to heat across the region. Specifically, three indicators were considered:

- (i) the share of elderly population per grid cell,
- (ii) a dependency ratio, defined as the combined share of children and elderly relative to the working-age population, and
- (iii) a composite demographic vulnerability indicator reflecting the proportion of dependent age groups (children and elderly) within the total population.

These indicators quantify the relative concentration of population groups that are more susceptible to heat-related impacts. The resulting vulnerability values were subsequently normalized and combined into a single composite demographic vulnerability layer, allowing direct comparison and consistent integration with the hazard and exposure components of the risk assessment.

All exposure and vulnerability layers, including the composite demographic vulnerability layer, were spatially aligned with the LST hazard grid, ensuring a one-to-one correspondence between hazard, exposure and vulnerability at the pixel level. This alignment enables the identification of areas where high surface temperatures coincide with high population exposure and increased demographic vulnerability.

The outcome of this process is a harmonized, spatially explicit set of population exposure and composite demographic vulnerability layers for the Region of Attica, which are used as the exposure and vulnerability inputs in the overall heatwave risk assessment framework.

It should be noted that population data are aggregated at municipal level and subsequently rasterized to a 1 km grid, which may not fully capture intra-urban variability at neighbourhood scale. Nevertheless, this approach ensures consistency with available official statistics and provides a reliable basis for regional-scale climate risk assessment.

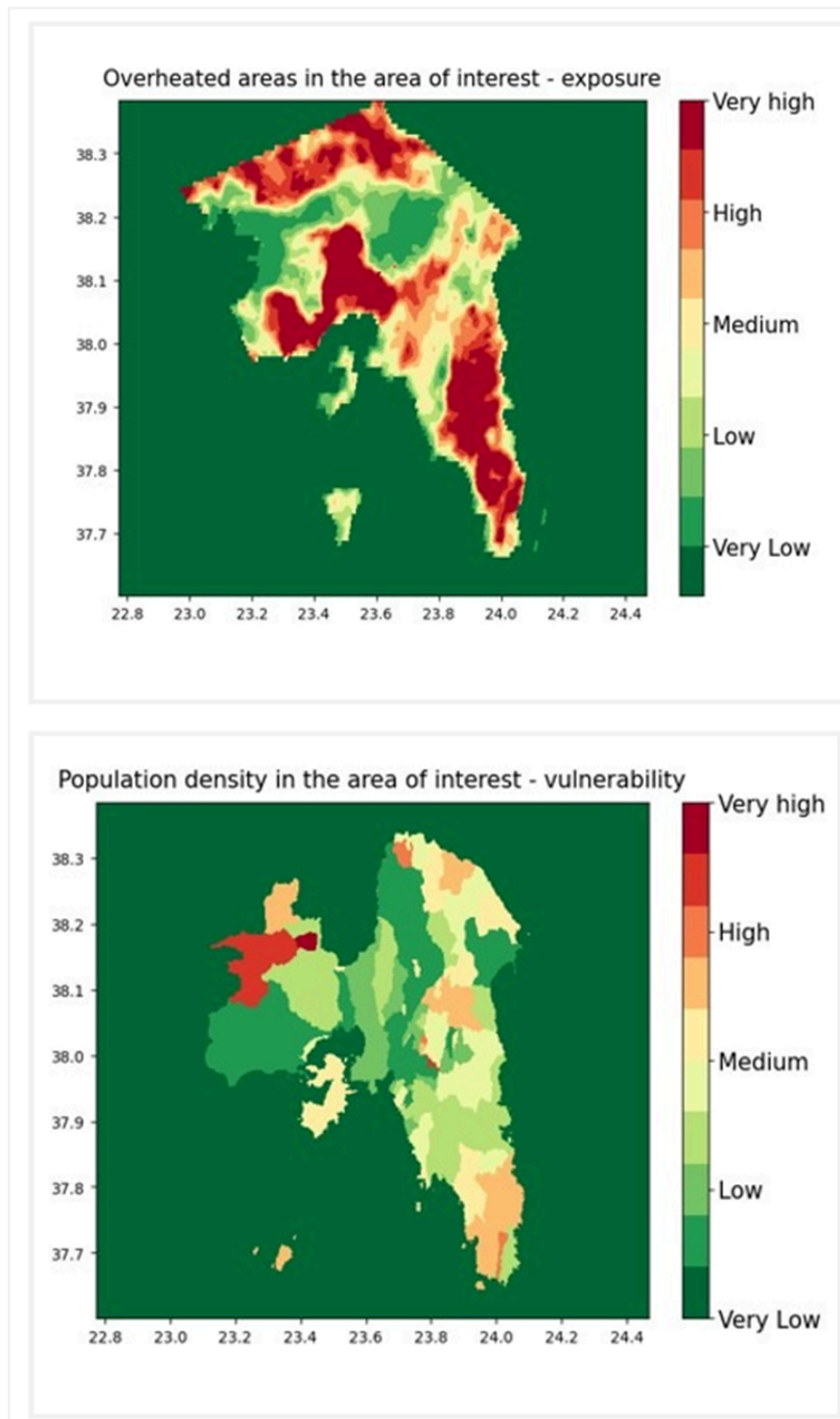


Figure 2-14: Categorized heatwave exposure and vulnerability layers for the Region of Attica. The top panel shows relative heat-intensity classes derived from land surface temperature data and used as a proxy for heatwave exposure, while the bottom panel presents population density-based classes used as a proxy for vulnerability. In both cases, values were classified into five relative categories (very low to very high) to support the subsequent heatwave risk assessment.

The top figure presents the spatial distribution of overheating exposure, while the bottom figure illustrates population density as a proxy for vulnerability. The exposure map indicates that very high and high overheating levels are concentrated primarily in densely built and coastal urban zones, forming extended hotspots across central and southern parts of the area of interest. In contrast, peripheral and more vegetated

areas exhibit predominantly low to very low exposure levels, reflecting the moderating effect of lower building density and increased green cover.

The population density map reveals a different but partially overlapping spatial pattern. Very high and high vulnerability levels are concentrated in specific urban cores, whereas several overheated zones correspond to areas of moderate or even low population density. This spatial mismatch suggests that exposure to extreme heat does not uniformly coincide with the highest concentrations of population, although certain central urban areas experience both elevated overheating and high demographic vulnerability.

Risk map

Following the preparation of the hazard, exposure and vulnerability layers described in the previous sections, these components were integrated within the CLIMAAX heatwave workflow to produce spatially explicit heatwave risk maps for the Region of Attica.

Risk is assessed at the grid-cell level by combining surface heat conditions (LST-based hazard) with population exposure and demographic vulnerability indicators, resulting in a composite representation of potential heat-related impacts. Higher risk values therefore correspond to locations where elevated surface temperatures coincide with both high population density and increased demographic vulnerability.

The resulting risk assessment provides a relative spatial indication of heat-related risk to vulnerable population groups across the Region of Attica. Because all calculations are performed on a common spatial grid, the risk layers can be directly aggregated over administrative units such as NUTS regions or municipalities by means of zonal statistics (summation, averaging or extraction of maxima).

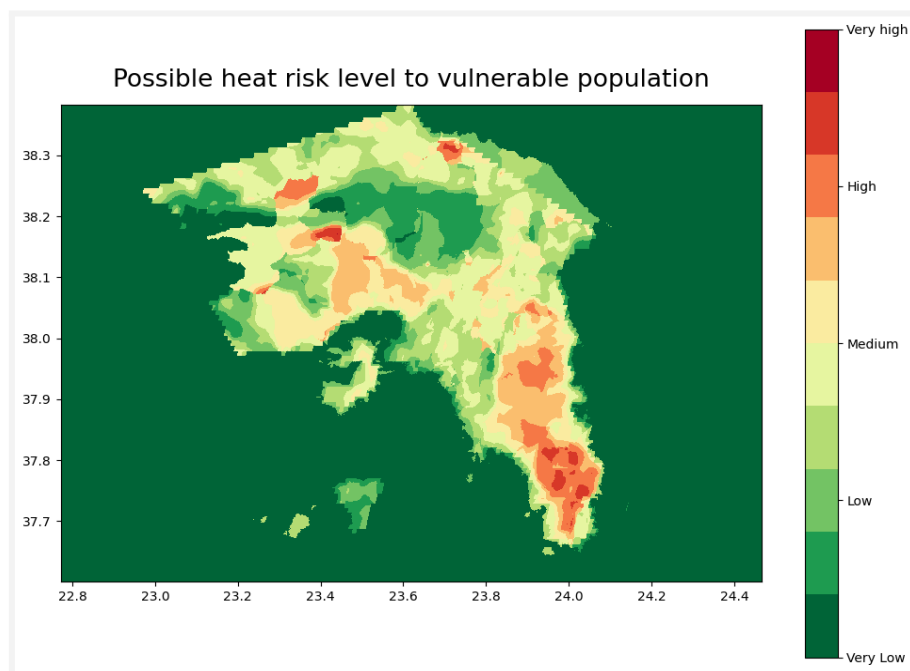


Figure 2-15: Spatial heatwave risk to vulnerable population groups in the Region of Attica. Heatwave risk was derived by combining classified heat exposure (based on relative land surface temperature intensity) with population-based vulnerability classes. The resulting risk levels are expressed in five relative categories (very low to very high), highlighting areas where elevated heat intensity coincides with higher population vulnerability.

The figure above presents the spatial distribution of heat risk to vulnerable populations, integrating overheating intensity with exposure and vulnerability components. The observed pattern is broadly consistent with the overheating hotspots identified in Figure 2-13, although the final risk distribution reflects additional modulation by the spatial distribution of vulnerable population groups.

In western Attica, elevated heat risk is observed in the broader Thriasio Plain, particularly in the areas of Elefsina and Aspropyrgos and their surrounding areas, where high to very high risk levels are present. These areas correspond to zones of intense overheating combined with significant residential and occupational exposure. In contrast, nearby areas such as Megara exhibit predominantly medium risk levels, reflecting comparatively lower exposure or vulnerability despite the presence of elevated overheating intensity.

In eastern Attica, a clear south-to-north gradient in risk levels is observed. The southern coastal zone of Lavreotiki, including Lavrio, Keratea, and surrounding settlements, exhibits extensive high to very high risk classes, indicating the combined effect of strong overheating conditions and exposed populations. Further north along the eastern coastal corridor, including Rafina and Artemida, risk levels are generally moderate to high, suggesting that while overheating conditions remain significant, differences in population distribution and vulnerability influence the final risk classification.

In northern Attica, elevated heat risk appears more spatially concentrated, particularly in the coastal and lowland areas near Oropos, where localized high to very high risk zones are observed. Surrounding areas, which are generally less densely populated and include more vegetated or rural landscapes, exhibit predominantly medium risk levels. This pattern highlights the role of population distribution and local land use in shaping the final risk profile, even within areas exposed to similar overheating conditions.

2.3.3 River Flooding Workflow

Study Area

The Cephissus River basin was selected as the study area due to its strategic hydrological role within the Attica region and its documented exposure to flood events. The Cephissus constitutes the main drainage axis of the Attica basin, flowing from the northern mountainous areas (Parnitha and Penteli foothills) southwards through the Athens metropolitan area before discharging into Phalerum Bay.

The hydrological catchment covers approximately 364 km² and includes densely urbanised municipalities such as Athens, Peristeri, Aigaleo, Nikaia, Moschato-Tavros, Nea Filadelfeia and Acharnes, among others. The downstream section of the river is heavily engineered and partly covered, while numerous tributaries drain highly impervious urban areas.

Given its large drainage area, high degree of urbanisation, hydraulic modifications, and history of significant flood events, the Cephissus basin represents one of the most critical flood-prone systems in the Region of Attica.

Table 2-3 Data overview for the river flooding workflow

Hazard data	Vulnerability data	Exposure data	Impact metrics/Risk output
Gridded river flood inundation depth maps for Cephissus river, for 50-, 100-, and 1000-year return periods, provided by the National Observatory of Athens (NOA).	Depth–damage curves (JRC) for residential, commercial, and industrial buildings, translated to LUISA land-use classes using a building-type mix and maximum damage values (EUR/m ²), scaled by GDP per capita.	LUISA baseline land-use raster (2018), 100 m resolution, EPSG:3035, clipped to the AOI. LUISA classes used as exposure categories and linked to vulnerability functions.	Damage maps per return period.

2.3.3.1 Hazard assessment

For the representation of river flood hazard in the Cephissus basin, gridded maximum inundation depth maps corresponding to return periods of 50, 100, and 1000 years were utilized. The datasets originate from the publicly funded project “*Assessment of earthquake, wildfire and flood risk in the Region of Attica*”, implemented under a formal Programmatic Agreement between the Region of Attica and the National Observatory of Athens (NOA). Specifically, the data were produced within Deliverable P1.5(a) – 5th Interim Progress Report (Phase 5, 02/2024), which focuses on flood risk assessment in the Cephissus River basin.

According to Deliverable P1.5(a), the flood assessment followed an integrated hydrological–hydraulic modelling workflow. The analysis was based on a 2 m resolution Digital Elevation Model (DEM) from the National Cadastre, land-use classification derived from Copernicus Urban Atlas data (enhanced with post-fire burned area mapping by NOA/FireHub), and rainfall time series from national meteorological stations used to derive locally calibrated IDF relationships. Design storm hyetographs were developed for the 50-, 100- and 1000-year return periods and applied under conservative antecedent soil moisture conditions.

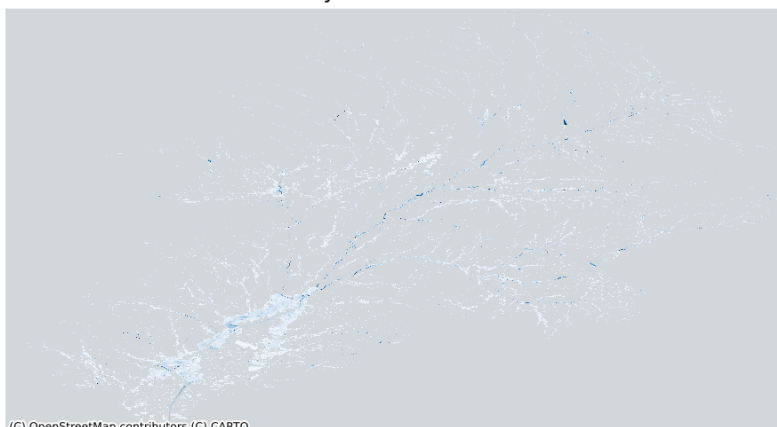
Rainfall–runoff processes were simulated at sub-basin scale and coupled with two-dimensional hydraulic simulations using HEC-RAS 2D, applying a spatially distributed rain-on-grid approach. Manning roughness coefficients were assigned according to land-use classes, and appropriate hydraulic boundary conditions were incorporated along the river network. The simulations produced spatially distributed outputs including maximum inundation depth (raster format), flow velocity fields, and flood extent for each return period.

The dataset provided to the present study consisted exclusively of the gridded maximum water depth rasters for the three return periods. In this assessment, flood hazard is therefore represented directly through simulated maximum water depth. Although the hydraulic simulations were not reproduced within the present assessment, the adopted inundation datasets originate from a structured two-dimensional hydrodynamic modelling workflow implemented by a national research institution under a formally commissioned regional project, and are therefore considered suitable for quantitative flood risk assessment.

The figure below illustrates the spatial distribution of the modeled inundation depths for the selected return periods.

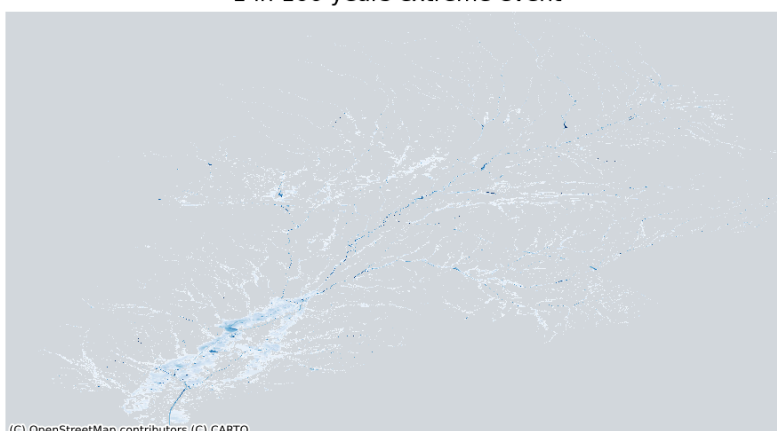
River flood potential for different return periods (present-day scenario ca. 2018)

1 in 50 years extreme event



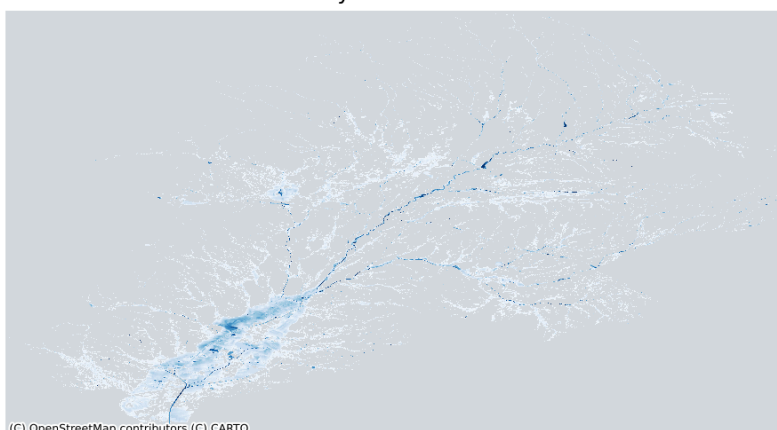
(C) OpenStreetMap contributors (C) CARTO

1 in 100 years extreme event



(C) OpenStreetMap contributors (C) CARTO

1 in 1000 years extreme event



(C) OpenStreetMap contributors (C) CARTO

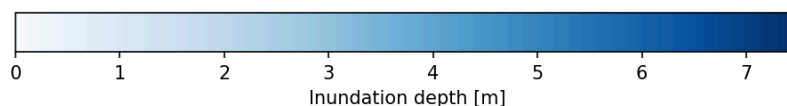


Figure 2-16: Comparison of river flood hazard (inundation depth) for RP50, RP100, and RP1000 for the same Cephissus AOI extent

According to the result rasters for all return periods, flooding of urban areas is observed alongside the engineered stream part, mainly on its western side, while it can also be concluded that overflows cannot easily return to the main riverbed, resulting in areas at a distance from it being affected. The significant escapes from the main channel occur approximately 10 km from its outlet to the sea.

The spatial distribution maps further confirm a progressive increase in both the extent and intensity of inundation with increasing return period. Under the 50-year scenario, flooding remains largely confined within or close to the main river corridor, whereas under the 100-year scenario floodwaters extend into adjacent urbanized areas, indicating exceedance of channel conveyance capacity. The 1000-year return period scenario exhibits the most extensive and severe inundation pattern, with deeper and more spatially continuous flooded areas affecting a wider portion of the floodplain. This progression highlights the increasing hydraulic stress on the river system under extreme events and the growing exposure of urban areas located near or beyond the engineered river channel.

It should be noted that the DEM used did not include elevation and volumetric data of the building blocks, including information on the existence of buildings and facilities in the flooded areas. This theoretically leads to smaller estimated flood depths on the surface of urban streets and at the same time incorrectly presents greater flood depths (in some cases over 3 meters) in areas where there are existing tall buildings.

2.3.3.2 Risk assessment

The river flood risk assessment for the Cephissus AOI is based on the combined evaluation of hazard, exposure, and vulnerability within a consistent spatial framework. Flood hazard is represented by inundation depth maps for multiple return periods. Exposure is approximated through the LUISA 2018 land-use baseline, which defines the spatial distribution of land-cover classes within the study area.

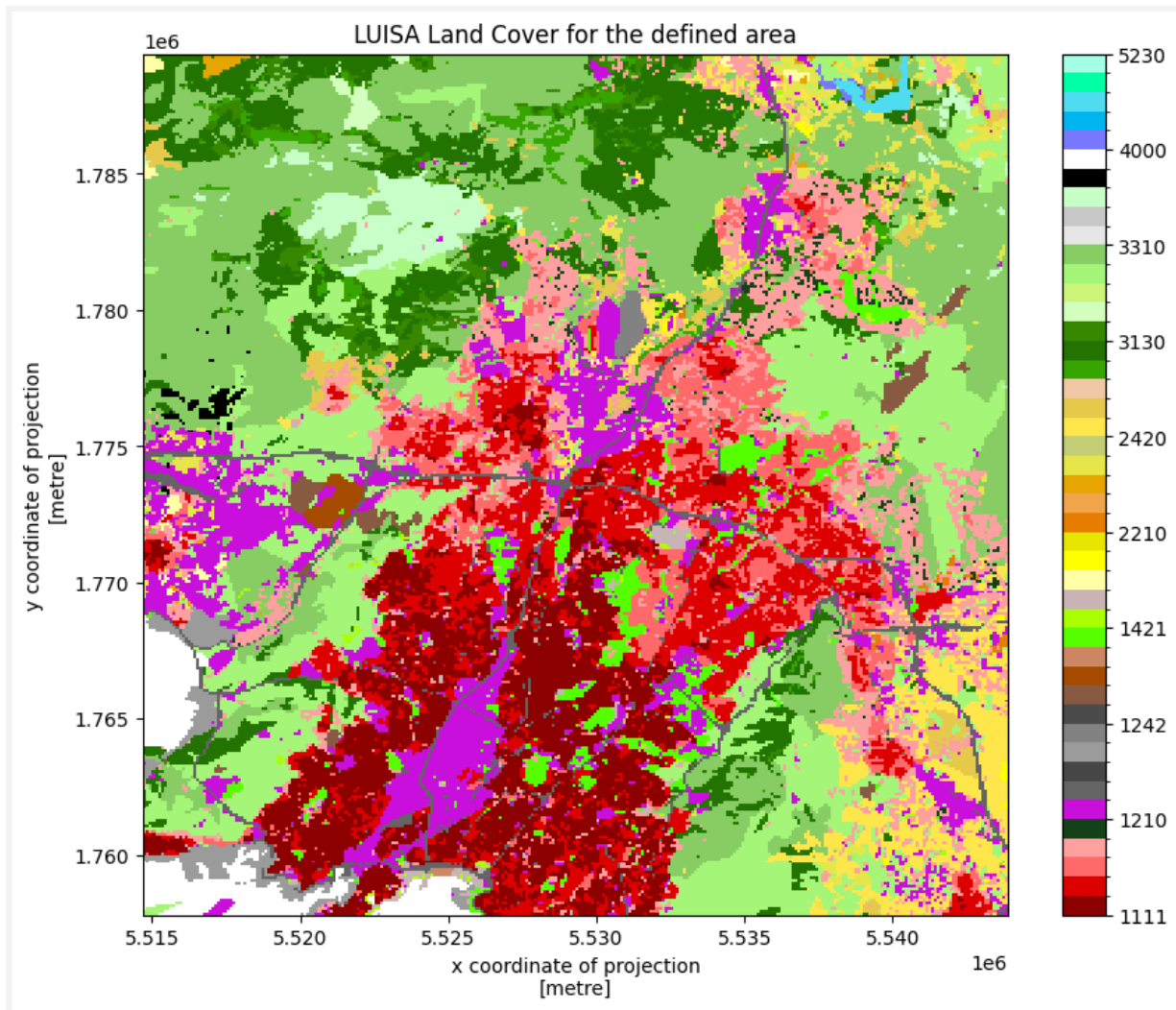


Figure 2-17: LUISA land-cover classification for the defined study area. The map depicts the spatial distribution of land-cover classes as provided by the LUISA dataset, shown in a projected coordinate system (meters). Distinct colours represent different land-cover categories (e.g. artificial surfaces, agricultural areas, forest and semi-natural areas, and other land-use types), as indicated by the legend.

The LUISA dataset provides a consistent and spatially explicit representation of land use across Europe, allowing direct linkage between land-use classes and corresponding vulnerability functions. Its spatial resolution ensures compatibility with the hazard datasets and enables robust spatial quantification of flood exposure within the study area.

As illustrated in Figure 2-17, high-density urban fabric (class 1111), medium-density urban fabric (1121), and industrial and commercial units (1210) are strongly concentrated along the central and downstream sections of the Cephissus corridor. These areas coincide spatially with the main flood-prone zones identified in the hazard assessment, indicating a high degree of exposure of economically valuable assets and critical infrastructure. In contrast, upstream and peripheral areas are characterized by lower-density urban development, agricultural land, and semi-natural land cover, which generally correspond to lower exposure values in terms of potential economic losses.

The land-use classes applied in the analysis, together with their corresponding codes and descriptions, are presented in Table 2-4.

Table 2-4 LUISA Base Map 2018 - Land Cover Class Codes and Descriptions

Code	Label	Code	Label
1111	High density urban fabric	2310	Pastures
1121	Medium density urban fabric	2410	Annual crops associated with permanent crops
1122	Low density urban fabric	2420	Complex cultivation patterns
1123	Isolated or very low density urban fabric	2430	Land principally occupied by agriculture
1130	Urban vegetation	2440	Agro-forestry areas
1210	Industrial or commercial units	3110	Broad-leaved forest
1221	Road and rail networks and associated land	3120	Coniferous forest
1222	Major stations	3130	Mixed forest
1230	Port areas	3210	Natural grassland
1241	Airport areas	3220	Moors and heathland
1242	Airport terminals	3230	Sclerophyllous vegetation
1310	Mineral extraction sites	3240	Transitional woodland shrub
1320	Dump sites	3310	Beaches, dunes and sand plains
1330	Construction sites	3320	Bare rock
1410	Green urban areas	3330	Sparsely vegetated areas
1421	Sport and leisure green	3340	Burnt areas
1422	Sport and leisure built-up	3350	Glaciers and perpetual snow
2110	Non irrigated arable land	4000	Wetlands
2120	Permanently irrigated land	5110	Water courses
2130	Rice fields	5120	Water bodies
2210	Vineyards	5210	Coastal lagoons
2220	Fruit trees and berry plantations	5220	Estuaries
2230	Olive groves	5230	Sea and ocean

Vulnerability is expressed through depth–damage functions assigned to each LUISA land-use class, together with class-specific maximum damage values reflecting reconstruction costs.

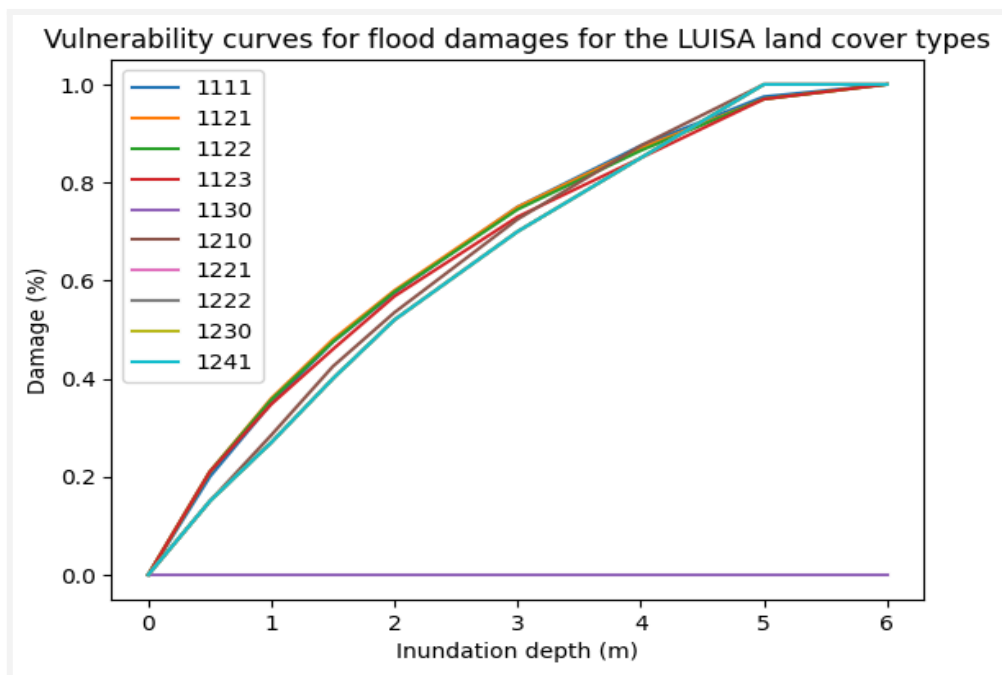


Figure 2-18: Vulnerability (inundation depth–damage) curves used to estimate flood damages for the LUISA land-cover classes. The curves express the relationship between flood inundation depth (m) and relative damage (%) for each LUISA class

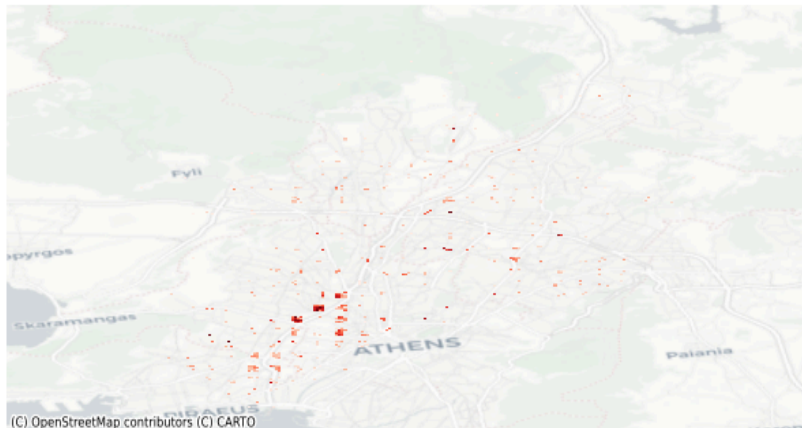
Figure 2-18 shows a clear non-linear relationship between inundation depth and expected damage. Damage increases rapidly at relatively low flood depths (0–2 m), where vulnerability is highest and a large proportion of total damage occurs, reaching approximately 40–60% of maximum damage depending on land-use class, and continues to rise progressively toward near-total damage at depths exceeding approximately 5–6 m. Urban and industrial land-use classes exhibit particularly high damage sensitivity, reflecting the higher economic value and structural vulnerability of built-up areas. These vulnerability curves confirm that flood depth is a critical determinant of economic loss magnitude and justify the use of inundation depth as the primary hazard indicator in the risk assessment framework.

For each return period, inundation depth is overlaid with the land-use raster to estimate direct economic losses at pixel level. Damage is calculated by applying the appropriate depth–damage function to the modeled flood depth and scaling the resulting damage fraction by the maximum reconstruction cost (EUR/m²), adjusted to the local economic context. The results are presented as spatially explicit damage maps, as illustrated in the figures below.

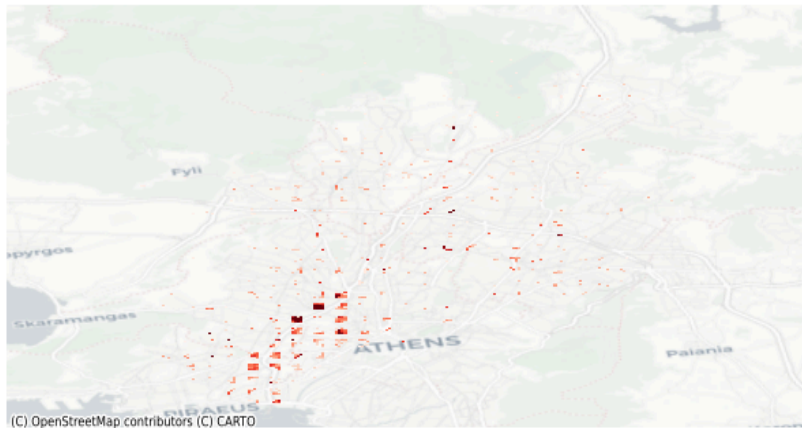
This approach ensures that vulnerability is represented through physically meaningful relationships between flood depth and expected economic damage, consistent with internationally recognised methodologies developed by the Joint Research Centre (JRC) and widely applied in European flood risk assessments.

River flood damages for extreme river flow scenarios in current day climate

1 in 50 years event



1 in 100 years event



1 in 1000 years event

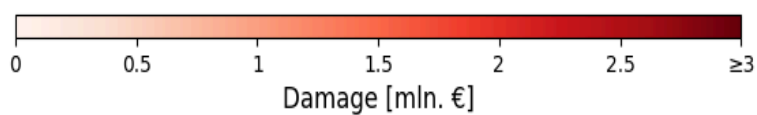
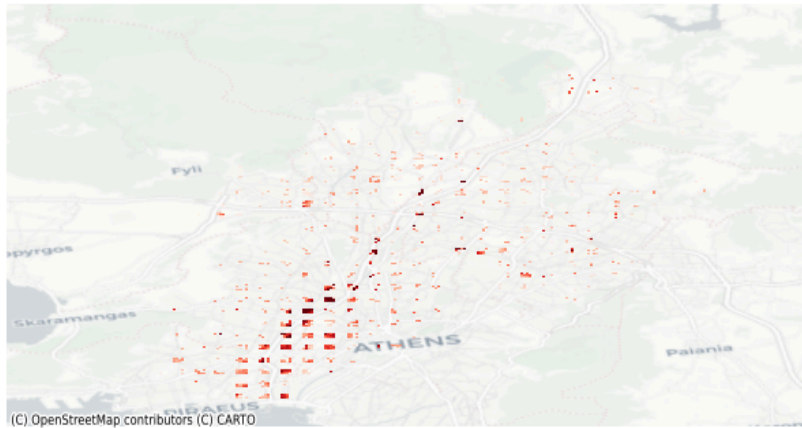


Figure 2-19: Spatial distribution of estimated river flood damages for extreme river flow events under current climate conditions, shown for 1-in-50-year, 1-in-100-year, and 1-in-1000-year return periods. Damages are expressed in million euros (€).

Based on the final risk maps, the estimated flood damages are primarily concentrated in areas characterized by medium to high-density urban fabric and the presence of critical infrastructure, including major road and rail networks.

As illustrated in Figure 2-19, damage hotspots are clearly concentrated along the main river corridor and downstream urban sections, where high inundation depths coincide with densely built urban and industrial land uses. Under the 50-year return period scenario, damages remain relatively localized and confined to areas immediately adjacent to the river channel. In the 100-year return period scenario, both the spatial extent and intensity of damages increase significantly, with additional affected zones extending into adjacent urban districts. The 1000-year return period scenario exhibits the most extensive and severe damage pattern, with larger contiguous damage clusters and higher economic losses, reflecting the combined effect of increased inundation depth and expanded flood extent.

The results further indicate that the magnitude of damages is more strongly associated with inundation depth than with land use type, which appears relatively homogeneous across the zones experiencing the highest losses. Flood impacts intensify clearly with increasing return period.

This progression confirms the expected escalation of flood risk under more extreme hydrological conditions, with both exposure and vulnerability contributing to the amplification of potential economic losses.

The 1-in-50-year event remains largely confined to the river corridor, resulting in relatively limited and localized damages. The 1-in-100-year scenario extends further into urban areas, increasing both exposure and losses due to greater inundation depths. Under the 1-in-1000-year event, flood extent and depths expand substantially, affecting broader urban zones and causing a disproportionate escalation in potential economic and infrastructure damages. Overall, higher return periods lead to both wider spatial exposure and significantly higher losses.

Moreover, the input layer provided by NOA was delivered at a very high spatial resolution (approximately 2×2 m), while the other layers used in the analysis were available only at a coarser spatial scale, specifically at a resolution of 100×100 m, which imposed a constraint on the effective resolution of the analysis. As a result, all subsequent processing and the resulting map outputs were harmonised to the 100 m grid to ensure spatial consistency and to avoid introducing artificial precision that would not be supported by the underlying hazard data.

The primary enhancement introduced in Phase 2 concerns the hazard component, through the use of updated inundation depth maps based on higher-resolution local data.

This refinement of the hazard input proved to be particularly meaningful. Given the central role of flood depth in the damage calculation process, the improved spatial detail and local representativeness of the hazard maps directly influenced the spatial distribution and magnitude of estimated losses. As a result, the analysis identified more clearly defined and spatially coherent hotspots within the Area of Interest.

In particular, the refined hazard inputs enabled more precise identification of localized high-risk zones along the urban river corridor, improving the reliability of spatial risk prioritization and supporting more targeted flood risk management and adaptation planning.

For reference, the figure below approximately shows the geospatial positioning and alignment of the analysis layers in relation to a base map of the Athens metropolitan area. It illustrates the approximate location of the Area of Interest (Cephissus basin) and the spatial correspondence between the inundation depth rasters, the LUISA land-use dataset, and the resulting damage maps within the broader urban context, providing general geographic orientation for the analysis.

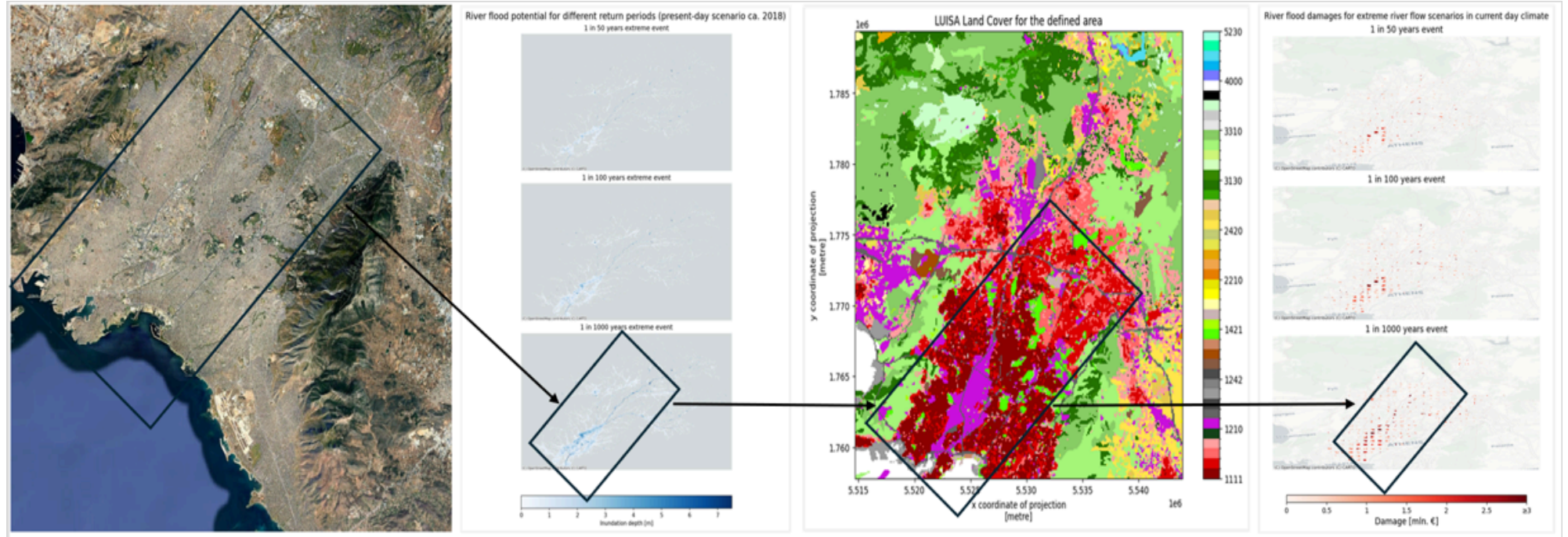


Figure 2-20: Spatial linkage between hazard, exposure, and risk outputs for the Cephissus River basin. On the left, a broader view of the Region of Attica is presented, with the highlighted polygon indicating the specific part of the region that corresponds to the Area of Interest (AOI) of the present study, focusing on the Cephissus River basin.

2.4 Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

The CLIMAAX Key Risk Assessment (KRA) is intended to be conducted jointly with stakeholders, experts and priority groups using the evaluation dashboard (severity–urgency–resilience capacity). In the Attica context, the core participation structure remains the Community of Practice (CoP) established in Phase 1, complemented by sectoral contacts within the Region of Attica and municipal administrations (e.g., civil protection, environment/climate adaptation, transport, health and social care, and spatial planning). In Phase 2, engagement activities were primarily preparatory and technical, reflecting the focus of this phase on implementing and regionalizing the heatwave wildfire and river flooding workflows and producing aggregation-ready outputs (maps and indicators) that can be meaningfully evaluated through the dashboard. Risk outputs were shared and discussed in ongoing exchanges with regional and municipal counterparts to ensure (i) alignment with operational needs (DRM planning, RCCAP update processes), and (ii) clarity on what each output represents, its limitations, and how it should (and should not) be interpreted in decision-making contexts.

These exchanges ensured that the spatial risk products generated in Phase 2 are suitable for structured evaluation within the KRA dashboard, including severity, urgency, and resilience capacity scoring at municipal and regional level.

Feedback gathered during Phase 1 remains highly relevant for the risk evaluation step. Stakeholders emphasized: (a) the need to maintain a multi-hazard perspective (floods–wildfires–heatwaves), (b) the importance of clearer communication of results to support municipal uptake, and (c) the need to strengthen the link between technical assessments and formal planning instruments and prioritization processes. Phase 2 responds to this feedback by providing more standardized, spatially explicit products (e.g., overheating classes, population-based wildfire risk, and road exposure/risk layers) that can be directly discussed and scored in a structured way through the KRA dashboard at municipal and regional scales.

Priority groups (e.g., elderly and dependent populations, overheated urban districts, and communities in wildland–urban interface areas) are currently represented mainly through municipal/regional governance and social-service structures, and their sensitivities are embedded in the vulnerability indicators used in the workflows.

2.4.2 Gather output from Risk Analysis step

The risk evaluation in Step 2.4 draws directly on the core spatial outputs and aggregated indicators produced in the Phase 2 Risk Analysis for heatwaves, wildfires and river flooding, ensuring that severity, urgency and response capacity can be discussed using consistent evidence at municipal and regional level. For heatwaves, the evaluation uses the harmonized hazard–exposure–vulnerability layers generated by the heatwave workflow: (i) the Land Surface Temperature (LST) derivatives (mean and maximum) for the warm season, (ii) the categorical “overheating” classes (from very low to very high thermal stress), and (iii) the gridded population exposure and vulnerability layers (including age-structured population, elderly ratio, dependency ratio and composite vulnerability indices). These are combined into a heatwave risk map, allowing the dashboard discussion to focus on where overheated areas coincide with high concentrations of vulnerable population groups.

For wildfires, the evaluation uses both hazard products and risk formulations derived from the wildfire ML workflow. Hazard evidence includes the continuous susceptibility maps and the six-class categorical wildfire

hazard maps produced for a historical reference and a near-term future climate configuration (RCP4.5, 2021–2040), enabling comparative discussion of intensification patterns. Risk evaluation then relies on the two complementary risk outputs described in the report: (a) the population-based risk maps, generated by coupling categorical hazard with categorical vulnerability through a contingency-matrix approach (resulting in four risk levels), and (b) the infrastructure-focused outputs, where wildfire hazard is overlaid with the regional road network exposure (and associated summaries) to identify transport corridors likely to face disruption under high-hazard conditions. These outputs are also aggregated into NUTS3 summaries, which are the primary inputs used in the Key Risk Assessment dashboard discussions.

For river flooding, the evaluation draws on the integrated hazard–exposure–vulnerability framework developed for the Cephissus AOI within the river flood workflow. Hazard evidence is provided by the high-resolution inundation depth grids for the 50, 100, and 1000-year return periods, which constitute the core physical driver of loss estimation. These layers are combined with the LUISA 2018 land-use baseline serving as the spatial proxy for exposed assets, and with class-specific depth–damage functions linked to each land-use category and parameterized using reconstruction cost values adjusted to local economic conditions. By intersecting modeled flood depth with land-use-based exposure and applying the corresponding vulnerability functions, the workflow produces spatially explicit damage maps for each return period, which serve as the basis of the evaluation.

These damage maps provide quantitative estimates of potential economic losses and enable direct comparison of severity across return periods, forming the primary evidence used for severity and urgency assessment in the KRA dashboard.

2.4.3 Assess Severity

Severity was assessed by translating the Phase 2 risk analysis outputs into the four protocol categories (limited, moderate, substantial, critical).

The assessment considers:

- (i) the spatial extent of high-risk areas,
- (ii) the concentration of exposed and vulnerable population and critical assets, and
- (iii) the potential for cascading or irreversible impacts.

Wildfires

For wildfires, current severity is assessed as “**substantial**”, based on ML-derived hazard and risk layers that highlight concentrated high-risk zones in wildland–urban interface areas and along critical transport corridors. Wildfires in Attica are associated with potentially irreversible impacts, including loss of life, ecosystem degradation, long recovery times, and cascading disruptions to transport, power, telecommunications and emergency response.

Future severity is assessed as “**critical**” in the near term, where the RCP4.5 (2021–2040) configuration indicates intensification or spatial expansion of high-hazard patterns, increasing the likelihood of repeated or more severe disruption in already vulnerable areas.

- o Severity: Current: Substantial | Future: Critical

Heatwaves

For heatwaves, current severity is assessed as “**substantial**” for most large parts of metropolitan Attica, and “critical” in specific urban hotspots where very high overheating conditions coincide with high population density and elevated demographic vulnerability (notably elderly and dependent population groups). This reflects the persistent warm-season heat stress captured by the LST-based indicators and the known sensitivity of vulnerable populations in dense urban environments. Heatwave impacts include severe health effects (up to excess mortality), pressure on health and social services, reduced labor productivity, and compounding effects when heat coincides with other hazards such as wildfire smoke.

As Phase 2 does not include projection-based heatwave scenarios, future severity is treated as an indicative continuation or escalation of current spatial patterns, with existing hotspots remaining priority areas. This limitation will be addressed in Phase 3 through the integration of scenario-based heat indicators.

- o Severity: Current: Substantial | Future: Critical

River Flooding

For river flooding, current severity is assessed as “**substantial**”, as the integrated analysis of inundation depth, land-use exposure, and depth–damage vulnerability indicates clearly defined flood-prone zones where significant economic losses and infrastructure disruption may occur, particularly along developed sections of the Cephissus floodplain. Although the spatial extent of high-risk areas is relatively limited compared with other hazards, the concentration of valuable urban assets within these zones, combined with the potential for service interruptions and localized cascading effects, supports a substantial severity classification under present conditions.

Based on future climate projections, the return periods of flood events are expected to shorten, meaning that events historically associated with lower probability (e.g., a 1-in-100-year flood) may occur more frequently (e.g., closer to a 1-in-75-year event). This shift implies a systematic increase in the likelihood of damaging flood conditions within the planning horizon, even if hazard intensity remains similar. Consequently, future severity is assessed as “**critical**”, reflecting the anticipated rise in event frequency, the increased probability of repeated impacts in already exposed areas, and the heightened risk of cumulative economic and infrastructure disruption.

- o Severity: Current: Substantial | Future: Critical

Stakeholder perspectives—particularly civil protection and municipal services—tend to elevate perceived severity due to operational constraints (evacuation complexity, limited local capacity, and interdependencies across transport and emergency response).

2.4.4 Assess Urgency

Urgency reflects the need for action in the near term and combines:

- (i) Current severity
- (ii) evidence of change in hazard or risk patterns, and
- (iii) the lead time required for effective risk reduction.

Wildfires

For wildfires, urgency is assessed as “**immediate action needed**”, particularly because high-risk zones are already clearly identified in wildland–urban interface areas and along critical transport corridors, and the near-term climate configuration (RCP4.5, 2021–2040) indicates likely intensification within a planning horizon that overlaps directly with current DRM and adaptation cycles. Wildfires combine sudden-onset dynamics with strong seasonal drivers, meaning that damaging events can occur with little warning while remaining a structural and recurring threat. The preparation time required to strengthen prevention, readiness, evacuation planning, and corridor protection further supports an immediate urgency classification.

- o Urgency: Immediate action needed

Heatwaves

For heatwaves, urgency is assessed as “**more action needed**”, as recurrent warm-season thermal stress already affects large parts of metropolitan Attica and repeatedly places pressure on health and social services. Even though Phase 2 relies on present-day LST indicators rather than scenario-based projections, the combination of widespread exposure, demographic vulnerability, and the broader climate context indicating increasing heat stress justifies sustained and scaled-up intervention. Stakeholder input—particularly from civil protection, municipalities, and social services—reinforces this urgency due to implementation constraints, uneven preparedness, and the need to translate hotspot identification into targeted measures before upcoming warm seasons.

- o Urgency: More action needed

River Flooding

For river flooding, urgency is assessed as “**more action needed**”, since current results identify specific flood-prone zones where damaging impacts on infrastructure, transport, and urban assets could occur, while future projections suggest that flood return periods may shorten, increasing the likelihood of events within standard planning horizons. Although flood impacts are spatially localized compared with other hazards, their potential consequences can be significant where exposure is concentrated, and preparedness measures—such as drainage improvements, protection of critical assets, and emergency planning—require lead time for design and implementation. This combination of localized but potentially high consequences and increasing probability supports a proactive but not emergency-level urgency classification.

- o Urgency: More action needed

Stakeholder perspectives—particularly civil protection, municipalities, and services dealing with vulnerable groups—typically raise urgency because they experience the constraints of implementation capacity, uneven preparedness across municipalities, and the operational need to translate hotspot maps into targeted measures and procedures before the next warm seasons.

2.4.5 Understand Resilience Capacity

Resilience capacity was assessed by reviewing the existing governance and operational arrangements described for Attica (regional and municipal mandates, planning instruments, and civil protection structures) alongside the gaps and constraints identified in Phase 1–2 (data resolution limitations, uneven municipal capacity, participatory and resource constraints). In practice, the categorization (low / medium / substantial / high) reflects whether current financial, human, physical, social and natural capacities are sufficient to (a) anticipate and reduce risk, (b) respond during events, and (c) sustain recovery and learning. For Attica, the baseline is strengthened by the existence of established policy instruments and responsibilities (e.g., Regional Climate Change Adaptation Plan and Civil Protection planning under the relevant legal/administrative frameworks) but constrained by persistent bottlenecks in local capabilities and resources across the 66 municipalities.

Wildfires

For wildfires, resilience capacity is assessed as “medium” overall, reflecting the presence of established civil protection structures, formal emergency planning frameworks, and operational coordination mechanisms at regional and municipal levels that provide a functional foundation for preparedness and response. Existing capabilities can be further strengthened through the application of high-resolution hazard and risk outputs, which support prioritization of wildland–urban interface areas and protection of critical corridors. However, important constraints remain, including uneven technical and operational capacity across municipalities, limited sustained engagement bandwidth, and gaps in key exposure datasets that affect the translation of hotspot identification into differentiated, implementable measures. The combination of high operational complexity during fast-onset wildfire events and variability in local resources supports a medium rating at regional scale.

- o Resilience capacity: Medium

Heatwaves

For heatwaves, resilience capacity is assessed as “**medium**”, as the hazard is institutionally recognized and partially addressed through existing planning frameworks, routine service delivery, and sectoral responsibilities in health, civil protection, and social services. Current governance structures—such as regional adaptation planning mechanisms and municipal preparedness arrangements—provide a basis for targeted intervention in identified vulnerability hotspots. Nevertheless, structural constraints persist, including gaps in participatory governance, limitations in technical and financial resources, and challenges in ensuring consistent implementation across municipalities. Planned capacity-building actions in subsequent phases are expected to strengthen resilience over time, but under present conditions overall capacity remains at a medium level.

- o Resilience capacity: Medium

River Flooding

For river flooding, resilience capacity is assessed as “**medium**”, as institutional mechanisms for flood risk management, emergency response, and infrastructure maintenance are already in place and provide a functional baseline for addressing localized flood hazards. Existing planning instruments, drainage and flood-protection works, and civil protection procedures support response capability in identified flood-prone

zones. However, resilience is constrained by spatial variability in municipal technical capacity, limited availability of high-resolution exposure and asset data, and the need for further integration of risk information into land-use planning, infrastructure design, and preparedness protocols. Because flood impacts can be locally severe while response effectiveness depends strongly on site-specific preparedness and infrastructure condition, overall resilience remains moderate rather than high.

- o Resilience capacity: Medium

2.4.6 Decide on Risk Priority

The definition of risk priorities for the Region of Attica results from the synthesis of quantitative evidence derived from the Phase 2 risk analysis (hazard patterns, exposure and vulnerability hotspots) and the qualitative assessment of resilience capacity, as informed by stakeholder input and operational considerations. The process follows the Key Risk Assessment protocol, providing a transparent and structured basis for prioritizing Phase 3 interventions. Based on this synthesis, the following risk priorities are established:

Wildfires

Wildfire risk is classified as “**very high**” priority due to its potential for catastrophic and irreversible impacts, particularly in wildland–urban interface zones and along critical transport and evacuation corridors. The analysis indicates substantial to critical current severity, with near-term escalation under the RCP4.5 (2021–2040) scenario, increasing the likelihood of repeated high-impact events. Urgency is assessed as immediate in priority zones, reflecting the sudden-onset nature of wildfire events, rapid fire spread under extreme conditions and the limited lead time available for effective response. Although established civil protection and coordination structures provide an essential baseline, uneven local capacity, operational complexity and cascading effects (e.g. smoke exposure, access constraints and service disruption) constrain resilience. Taken together, the combination of critical severity, immediate urgency and constrained resilience capacity supports the classification of wildfires as a very high priority risk for the Region of Attica.

- o Risk Priority: Very High

Heatwaves

Heatwaves are also classified as “**very high**” priority, reflecting their widespread spatial extent, recurrent seasonal nature and significant impacts on vulnerable population groups. The technical analysis highlights extensive urban areas where high surface temperatures coincide with dense population and elevated demographic vulnerability, particularly among elderly and dependent groups. Severity is assessed as substantial to critical in urban hotspots, while urgency is immediate in these areas and more action needed at regional scale, due to the recurrent and multi-day character of heatwave events. Although institutional capacity and planning frameworks are in place, uneven municipal resources and implementation constraints limit effective risk reduction, reinforcing the need for prioritized action in Phase 3. Key intervention needs include targeted heat mitigation measures, protection of vulnerable groups and the operational use of heat-risk hotspots in preparedness and response planning.

- o Risk Priority: Very High

River Flooding

River flooding is classified as **“high” priority**, reflecting its capacity to generate significant localized impacts where flood-prone zones intersect with densely developed urban land uses and critical infrastructure. The analysis indicates substantial current severity in identified hotspots, with the potential for escalation in future conditions as projected shortening of return periods increases the likelihood of damaging events within standard planning horizons. Urgency is considered elevated due to the need for proactive mitigation, infrastructure adaptation and preparedness measures that require planning and implementation lead time, even though events are spatially concentrated rather than region-wide. Existing institutional arrangements and flood management mechanisms provide a functional baseline for response, but variability in municipal capacity, infrastructure condition and data availability constrains overall resilience. Taken together, the combination of substantial localized severity, forward-looking urgency and moderate resilience capacity supports the classification of river flooding as a high priority risk for the Region of Attica.

- o Risk Priority: High

These priorities provide a clear and actionable framework for Phase 3, guiding the allocation of resources, the sequencing of interventions and the targeting of measures across the Region of Attica. By assigning very high priority to both wildfires and urban heatwaves, and high priority to river flooding, the assessment reflects the combined challenge faced by the region: managing fast-onset, high-impact wildfire events, recurrent, population-wide heat stress, and spatially concentrated but potentially severe flood impacts, all of which require sustained and coordinated risk reduction efforts grounded in the spatial evidence generated by the risk assessment.

Risk Workflow	Severity		Urgency	Capacity	Risk Priority
	C	F		Resilience/ CRM	
River flooding	3	4	3	2	High
Heatwaves	3	4	3	2	Very high
Fire	3	4	4	2	Very high













Severity  Critical  Substantial  Moderate  Limited	Urgency  Immediate action needed  More action needed  Watching brief  No action needed	Resilience Capacity  High  Substantial  Medium  Low	Risk Ranking Very high High Moderate Low
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Figure 2-20: Summary evaluation of key risks as derived from the Key Risk Assessment Excel tool

2.5 Monitoring and Evaluation

Phase 2 provided clear learning on what is required to operationalize a harmonized CRA at regional scale and what the main constraints are. The strongest lesson is that the move from Phase 1 scoping/results to Phase 2 implementation depends heavily on disciplined data management and repeatable workflows: consistent folder structures, naming conventions, CRS/grid alignment and transparent script-based processing were essential to produce aggregation-ready risk outputs for all municipalities. Practical implementation challenges (e.g., inconsistent directory names, raster misalignment, and incomplete infrastructure classification) required robust fixes that can now be reused in future updates, improving maintainability and transferability of the analysis.

The most persistent difficulties encountered were data and scenario limitations that constrain interpretability and “future-proofing” of results. High-resolution, locally validated datasets for ecological and economic vulnerability and detailed infrastructure attributes were not consistently available, which limited the granularity and realism of the risk analysis (e.g., road exposure was available as an aggregated layer rather than a hierarchy of primary/secondary/tertiary links). In addition, the absence of explicit socio-economic scenarios means that future risk products currently reflect changes in hazard (e.g., wildfire hazard under RCP4.5 2021–2040) while keeping exposure and vulnerability largely static, reducing the ability to explore how demographic or land-use change may shift risk patterns.

Stakeholders have played an important role in the Monitoring and Evaluation framework, primarily through interpretation, validation, and feedback on the Climate Risk Assessment outputs. During the assessment process, stakeholders contributed contextual and local knowledge that supported the interpretation of identified risk hotspots, helped identify inconsistencies with operational experience, and informed the identification of additional local datasets for potential future iterations.

Feedback collected during Phase 1 highlighted the need for clearer communication of results and stronger links between the CRA and policy and planning processes. This feedback has informed the Phase 2 approach, which focuses on the production of standardized, aggregation-ready indicators designed to facilitate integration into existing regional planning and monitoring routines. While systematic tracking of policy uptake is at an early stage, the CRA outputs provide a structured basis for future monitoring of policy-relevant indicators, such as the use of CRA results in municipal planning and prioritization processes.

Learning is ensured through the way the CRA has been implemented: workflows are script-based and reproducible, with documented preprocessing steps and harmonized data organization (e.g., the region-specific data structure and alignment procedures). This creates a basis for iterative improvement, where new data can be integrated without redesigning the process from scratch, and where outputs can be re-generated to support periodic reviews (e.g., during RCCAP and municipal DRM revision cycles). However, to strengthen learning further, additional competencies and resources are needed, especially at municipal level, to consistently interpret outputs, maintain datasets, and translate results into actions.

Regarding data needs, Phase 2 identifies several priorities for improving future iterations: (i) more detailed road-network classification and criticality attributes, (ii) locally validated ecological vulnerability layers and improved economic/asset exposure proxies, and (iii) socio-economic scenario layers (population change, urban expansion/land-use, and sectoral exposure) to complement the climate-driven hazard scenarios. Communication of final outcomes will use multiple channels: inclusion in AtticaReAdy and Horizon Europe reporting, presentation and discussion in CoP meetings and sectoral workshops, and—where feasible—integration of risk layers into regional GIS platforms and decision-support tools used by planners and civil-protection staff; dissemination via the Climate Adaptation Observatory and policy-oriented materials (policy briefs/info packages) is also foreseen.

A dedicated monitoring system for climate risk and adaptation in Attica is not yet documented, but Phase 2 outputs are structured to enable such a system (e.g., tracking changes over time in hazard classes, exposed population and vulnerable groups, and infrastructure segments falling within high hazard/risk zones). What worked well was the efficient reuse of CLIMAAX workflows combined with targeted localization and automation, which improved consistency and reduced manual effort in repeated processing; what did not work well was the time cost of resolving data inconsistencies and the limits imposed by missing high-resolution local vulnerability/infrastructure data and socio-economic scenarios. Overall, resource use (time/staff/cost) was efficient for producing harmonized outputs, but the same efficiency trade-off likely reduced the amount of time available for structured stakeholder scoring sessions and deeper validation.

2.6 Work plan Phase 3

Phase 3 of the AtticaReAdy project will focus on translating the evidence generated by the Phase-2 climate risk assessment into concrete, prioritized adaptation measures and improved disaster risk management practices for the Attica Region. Building on the high-resolution heatwave, wildfire and river flooding risk maps, Phase-3 activities will concentrate on the co-development, prioritization and integration of targeted adaptation and preparedness measures within existing regional and municipal planning instruments.

The primary focus will be on high-priority risk zones identified in Phase 2, including overheated urban neighborhoods, wildland–urban interface areas, critical transport corridors exposed to elevated wildfire risk, and flood-prone zones where river flooding intersects with densely developed urban areas and critical infrastructure. Using the CRA outputs, the project will support the refinement of Regional Climate Change Adaptation Plan (RCCAP) measures, the revision of municipal Disaster Risk Management Plans and the prioritization of early-warning, evacuation planning and risk-reduction interventions.

3 Conclusions Phase 2- Climate risk assessment

Phase 2 of the AtticaReAdy Climate Risk Assessment (CRA) successfully advanced the project from the exploratory scoping and prioritization stage of Phase 1 to a more operational and spatially explicit implementation focused on three priority climate hazards: heatwaves, wildfires and river flooding. Using the CLIMAAX Framework and Toolbox, this phase delivered harmonized, reproducible, high-resolution hazard and risk outputs in the form of maps and indicators. These outputs can be consistently aggregated at municipal and NUTS3 level, providing a robust and transparent evidence base to support regional planning, civil protection preparedness, and the establishment of future monitoring and update cycles.

For heatwaves under current climatic conditions, the assessment shows that risk is widespread across metropolitan Attica, with particularly critical hotspots in dense urban areas where extreme overheating coincides with high population density and elevated social vulnerability, especially among elderly and dependent population groups. These hotspots clearly emerge as priority areas for targeted heat-risk reduction measures and the protection of vulnerable citizens. Heatwave impacts include severe health effects, pressure on health and social services, reduced labor productivity, and compounding effects when heat coincides with other hazards.

For wildfires, the analysis highlights substantial to critical risk levels, driven by the concentration of high-hazard zones in wildland–urban interface areas and along key transport corridors that are essential for emergency access and evacuation. The machine-learning-based hazard modelling, combined with population and infrastructure overlays, identifies areas where operational disruption and cascading impacts are most likely. Under the near-future climate configuration (RCP4.5, 2021–2040), wildfire patterns indicate persistence or intensification of high-hazard zones within the planning horizon.

For river flooding, the assessment indicates spatially concentrated but potentially significant risk, primarily affecting areas located along the Cephissus floodplain where modeled inundation depths intersect with dense urban land uses and critical infrastructure. The results show that while flood risk is not uniformly distributed across Attica, clearly defined hotspots emerge where exposure and asset values are high, leading to substantial potential economic losses and localized service disruption during high-return-period events. Future projections suggesting shortening flood return periods reinforce the need for forward-looking adaptation, as events historically considered rare may become more frequent within planning horizons.

A key cross-cutting outcome of Phase 2 is the enablement of a more transparent and stakeholder-oriented Key Risk Assessment (KRA) process. By structuring outputs as a coherent “risk evidence pack” consisting of spatial hazard maps, hotspot patterns, and municipal summaries, the results can be systematically scored using the CLIMAAX evaluation dashboard across severity, urgency, and resilience capacity dimensions. This approach supports the derivation of clear, actionable priorities by hazard type and geographic area. Within this framework, heatwaves are assessed as having substantial current severity across most of metropolitan Attica and critical severity in specific urban hotspots where extreme overheating coincides with high population density and elevated demographic vulnerability; in the absence of scenario-based projections in Phase 2, future severity is aligned with a critical classification in persistent hotspot areas. Wildfires are assessed as having substantial current severity and critical future severity under the near-term climate configuration (RCP4.5, 2021–2040), reflecting the projected persistence or intensification of high-hazard patterns within existing planning horizons. River flooding is assessed as substantial under current conditions and critical under future projections, given the anticipated shortening of return periods and the increased likelihood of repeated damaging events in already exposed zones. In terms of urgency, wildfires are classified as immediate action needed due to the concentration of high-risk areas in wildland–urban interface zones and critical corridors combined with near-term climate intensification, while heatwaves and river flooding are classified as more action needed, reflecting widespread or localized but significant impacts that

require proactive and sustained intervention within current planning cycles. Resilience capacity across all three hazards is assessed as medium, acknowledging the presence of established institutional frameworks, civil protection mechanisms, and planning instruments at regional and municipal levels, while also recognizing persistent constraints related to uneven municipal capacity, technical and financial limitations, data gaps, and implementation challenges across the Region of Attica.

Several important challenges were successfully addressed during this phase. A primary challenge was the operationalization and reproducibility of the analytical workflows, including consistent data organization, naming conventions, coordinate reference systems, grid alignment, and script-based processing. This foundational work significantly reduces the effort required for future updates and improves the transferability of the methodology. In addition, Phase 2 improved localization by integrating national and local datasets where available, such as land surface temperature products and detailed municipal population structures, thereby increasing relevance for Attica-specific decision-making and more accurately representing vulnerable groups.

Despite these advances, some limitations remain. Data gaps continue to constrain the granularity and realism of certain vulnerability dimensions, particularly ecological, economic and detailed infrastructure attributes. For example, the use of an aggregated road network restricts differentiation of road criticality and limits the realism of transport vulnerability assessments, while similar data constraints affect the level of detail that can be incorporated into river flooding exposure and impact analyses. In addition, future risk representation is only partially developed: wildfire projections primarily capture climate-driven hazard changes, whereas exposure and vulnerability are treated as static due to the absence of socio-economic scenario data. Likewise, forward-looking heatwave risk projections have not been implemented, limiting the quantitative assessment of future severity. These constraints should be considered when interpreting the results and in the design and communication of outputs in Phase 3.

4 Progress evaluation

Table 4-1 Overview of key performance indicators

<i>Key performance indicators</i>	<i>Progress</i>
At least 2 workflows successfully applied during Phase 1	1. River Flood Workflow 2. Wildfire Workflow successfully applied
At least 2 workflows successfully applied during Phase 2	1. River Flood Workflow 2. Wildfire Workflow successfully applied 3. Heatwave Workflow
CoP with at least 5 key institutions/authorities/associations participating in the core group and a list of stakeholders to be updated	CoP with 5 key institutions/authorities/associations participating in the core group and a list of stakeholders partially updated
Workshop targeted to administration, policy makers	Phase 3 (presentation of the results of Phase 2)
Info package (150 copies)	Phase 3 as planned
Note for policy makers (100 copies)	Phase 3 as planned
3 Articles on the website of the region and the Climate Adaptation Observatory of Attica (1 to announce the project start, targets and potentialities; 1 with the first results; 1 with the final results and workshop attendance)	1 Article on the website of the region to announce the project start, targets and potentialities. 1 Article on the website of the region with the results of Phase 1: (link)
2 Newsletters informing the 66 municipalities of the region about the results of the project	Phase 3 (one at the beginning with the results of phase 2 and one at the end with the results of questionnaires etc).

Table 4-2 Overview of milestones

<i>Milestones</i>	<i>Progress</i>
Mil 1: Report on scoping	Achieved by the end of 2024
Mil 2: Stakeholder meeting	Achieved (bilateral meetings)
Mil 3: Attend the CLIMAAX workshop mid 2025	Achieved
Mil 4: Production of policy brief and info package	Phase 3 as planned
Mil 5: Workshop	Phase 3 as planned
Mil 6: CLIMAAX Workshop in Brussels	Phase 3 as planned

5 Supporting documentation

- Main Report (PDF)
- Datasets shared on Zenodo:

Wildfires workflow

- **DEM-derived terrain variables for hazard assessment (Attica Region)**
<https://doi.org/10.5281/zenodo.18353835>
- **Wildfire Hazard, Susceptibility and Risk Maps (GeoTiff & Png) – Historical (1991–2010) and RCP4.5 Future (2021–2040), Attica**
<https://doi.org/10.5281/zenodo.18681296>
- **Shelters of Attica (2023) – National Observatory of Athens**
<https://doi.org/10.5281/zenodo.18697435>
- **Schools of Attica (2023) – National Observatory of Athens**
<https://doi.org/10.5281/zenodo.18697405>
- **Hospitals in the Municipality of Attica (2023) - National Observatory of Athens**
<https://doi.org/10.5281/zenodo.18681098>
- **All Roads in the Municipality of Attica (2023) - National Observatory of Athens**
<https://doi.org/10.5281/zenodo.18697360>

Heatwaves workflow

- **MODIS LST File Collection and Temporal Indexing – Summer 2023 (MOD11A1 v061, 1 km)**
<https://doi.org/10.5281/zenodo.18361561>
- **Land Surface Temperature (LST) Dataset – MOD11A1 v061 (June–August 2023), Region of Attica (From National Observatory of Athens)**
<https://doi.org/10.5281/zenodo.18361309>
- **Population Data and Demographic Vulnerability Index – NUTS3 Level (ELSTAT, 2023)**
<https://doi.org/10.5281/zenodo.18361232>
- **Heatwave Risk Assessment Outputs – Region of Attica (2023)**
<https://doi.org/10.5281/zenodo.18681705>

River flooding workflow

- **Cephissus River Flood Risk Results – Damage Maps and Statistics**
<https://doi.org/10.5281/zenodo.18697771>
- **Cephissus River Flood Hazard Maps – Present and Climate Scenarios**
<https://doi.org/10.5281/zenodo.18697717>
- **Cephissus River Flood Depth and Flood Maps – Attica (NOA & Derived Products)**
<https://doi.org/10.5281/zenodo.18697598>

General dataset

- **Geographical Scope – Region of Attica Administrative Boundary (National Observatory of Athens)**
<https://doi.org/10.5281/zenodo.18360240>

6 References

Arianoutsou, M., Zerefos, C., Kalabokidis, K., Poupkou, A., Aravanopoulos, F., Eds.; Resilience of the Greek Forest Ecosystems to Climate Change; Committee for the Resilience of the Greek Forest Ecosystems to Climate Change (EADO); Academy of Athens: Athens, Greece, 2023; 547p, ISBN 978-960-404-413-9.

Arianoutsou, M.; Athanasakis, G.; Kazanis, D.; Christopoulou, A. Attica: A Hot Spot for Forest Fires in Greece. *Fire* 2024, 7, 467. <https://doi.org/10.3390/fire7120467>

Diakakis, M., Andreadakis, E., Nikolopoulos, E. I., Spyrou, N. I., Gogou, M. E., Deligiannakis, G., Katsetsiadou, N. K., Antoniadis, Z., Melaki, M., Georgakopoulos, A., Tsaprouni, K., Kalogiros, J., and Lekkas, E.: An integrated approach of ground and aerial observations in flash flood disaster investigations: The case of the 2017 Mandra flash flood in Greece, *International Journal of Disaster Risk Reduction*, Volume 33, 2019, Pages 290-309, ISSN 2212-4209, <https://doi.org/10.1016/j.ijdrr.2018.10.015>.

Efthimiou, N.; Psomiadis, E.; Panagos, P. Fire severity and soil erosion susceptibility mapping using multi-temporal Earth Observation data: The case of Mati fatal wildfire in Eastern Attica, Greece. *Catena* 2020, 187, 104320.

Galanaki, E., Lagouvardos, K., Kotroni, V., Giannaros, T., and Giannaros, C.: Implementation of WRF-Hydro at two drainage basins in the region of Attica, Greece, for operational flood forecasting, *Nat. Hazards Earth Syst. Sci.*, 21, 1983–2000, <https://doi.org/10.5194/nhess-21-1983-2021>, 2021

Giannaros C, Agathangelidis I, Papavasileiou G, et al (2023) The extreme heat wave of July–August 2021 in the Athens urban area (Greece): Atmospheric and human-biometeorological analysis exploiting ultra-high resolution numerical modeling and the local climate zone framework. *Science of The Total Environment* 857:159300. <https://doi.org/10.1016/J.SCITOTENV.2022.159300>

Santamouris, M., Paraponiaris, K. & Mihalakakou, G. Estimating the ecological footprint of the heat island effect over Athens, Greece. *Climatic Change* 80, 265–276 (2007). <https://doi.org/10.1007/s10584-006-9128-0>