CLIMAAX
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Deliverable Phase 2 – Climate risk assessment

Methodical Climate Risk Assessment for the Cluj Metropolitan Area (MECRA-Cluj)

Romania, Cluj-Napoca Metropolitan Area

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Abbreviations and acronyms

Abbreviation / acronym	Description
CLIMAAX	CLIMAte risk and vulnerability Assessment framework and toolboX
CMA	Cluj Metropolitan Area
CRA	Climate Risk Assessment
CRM	Climate Risk Management
EHF	Extreme Heat Factor
ET-SCI	Expert Team on Sector-Specific Climate Indices
GCM	Global Climate Model
HW	Heatwave
HWA	Heatwave amplitude
HWD	Heatwave duration
HWF	Heatwave frequency
HWI	Heatwave index
HWL	Heatwave length
HWM	Heatwave magnitude
HWN	Heatwave number
INHGA	National Institute of Hydrology and Water Management
JRC	Joint Research Centre
LAU	Local Administrative Unit
LST	Land Surface Temperature
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RNMA	Romanian National Meteorological Administration
SMHI	The Swedish Meteorological and Hydrological Institute
SSP	Shared Socioeconomic Pathway
SUHI	Surface Urban Heat Island
TN	Daily minimum temperature
TX	Daily maximum temperature
WMO	World Meteorological Organization

Executive summary (1-2 pages)

This deliverable presents the outcomes of Phase 2 of the Climate Risk Assessment (CRA) for the Cluj Metropolitan Area (CMA), developed within the CLIMAAX framework. Building on Phase 1 scoping and screening results, Phase 2 aimed to refine the understanding of climate risks, improve their spatial and temporal representation, and establish a transparent prioritisation of key risks to support evidence-based decision-making and climate adaptation planning.

Phase 2 focused on heatwaves (HW) and floods, identified as the most relevant climate-related hazards for the CMA due to their increasing frequency, intensity, and impacts on public health, infrastructure, ecosystems, and socio-economic activities. The assessment integrates higher-resolution hazard datasets, locally adapted analytical methods, and structured stakeholder input to deliver a comprehensive, regionally relevant risk assessment.

The main actions undertaken included regionalising of hazard analyses, assessing current and future risk severity, evaluating urgency, and appraising resilience capacity, following the CLIMAAX Key Risk Assessment Protocol. These components were synthesised through an evaluation dashboard to determine overall risk priorities.

For HWs, the improved spatial resolution enabled a detailed spatial characterization of results and the clear identification of HW hotspot areas within the CMA. Lower-lying areas were shown to experience more frequent and intense events, while hill and low-mountain neighbourhoods are less exposed. This analysis revealed pronounced intra-urban differences in heat exposure that are not visible at coarser spatial scales and demonstrated the value of fine-scale data for targeted adaptation planning. Notably, results also indicate that certain rural areas may be more exposed to heat-related hazards than certain urban areas, highlighting the need for adaptation measures beyond the city core. The improved resolution enabled the calculation of HW indicators at the Local Administrative Unit (LAU) scale, thereby increasing policy relevance. Temporal analysis based on gridded data derived from observations shows that the increase in the Heatwave Index (HWI) is **more rapid than modelled data indicate, suggesting** that current systems may already be insufficient to cope with present and future heat extremes. Consequently, HWs were classified as a **very high priority risk**.

For **floods**, the assessment revealed a spatially differentiated risk profile. While riverine flood risk within the urban core has been reduced through existing hydrotechnical measures, pluvial and flash flooding remains a major concern in densely built-up areas. In peri-urban and rural zones, riverine flooding continues to affect floodplains, residential areas, and agricultural land. Flood risk was classified as a **moderate risk priority** due to substantial severity and urgency, and uneven resilience capacity, particularly in urban drainage and retention.

Overall, Phase 2 significantly improved spatial **detail, analytical robustness, and policy relevance** of the CRA for the CMA. Remaining challenges relate mainly to limited availability of fine-scale socio-economic, land-use, and health data, constraining the assessment of compound and cascading impacts.

Key takeaway messages:

- HWs and floods are the dominant climate risks in the CMA.
- Fine-scale analysis revealed strong intra-urban and rural–urban contrasts.
- HWs show rapidly increasing severity and require urgent action.
- Flood risk remains moderate and spatially heterogeneous.
- Improved risk communication and awareness are critical for resilience.

Plans for the final phase

Phase 3 will translate identified risk priorities into **concrete CRM actions**, including a set of recommendations for adaptation measures and stakeholder validation to support climate-resilient development in the CMA.

1 Introduction (2-3 pages)

1.1 Background

The Cluj Metropolitan Area (CMA) Intercommunity Development Association, established in 2008, is a public utility entity and associative structure governed by the Metropolitan Zones Law. Chaired by the Mayor of Cluj-Napoca, it includes Cluj-Napoca City, second largest city in Romania, and 18 communes, with a population of approximately 421,000. CMA is mandated to undertake climate adaptation planning and participates in the Climate City Contract Coalition. The association has experience in national and international research projects focused on climate mitigation, environmental protection, circular economy, and heritage preservation, collaborating with a wide network of public and private stakeholders.

1.2 Main objectives of the project

The overarching objective of the project is to develop a robust, transparent, and policy-relevant CRA for the CMA, supporting informed decision-making and long-term climate adaptation planning at metropolitan and local levels. Within this framework, Phase 2 represents a critical step, focusing on the regionalisation, refinement, and prioritisation of climate-related risks, building on the scoping and screening outcomes established in Phase 1.

The primary objective of Phase 2 is to enhance the spatial resolution of climate risk information for the CMA, with a specific focus on HWs and floods, identified as the most significant hazards for the region. By integrating higher-resolution hazard datasets and locally adapted analytical approaches, Phase 2 aims to move beyond generalized risk characterisation and provide actionable insights at urban, peri-urban, and rural scales.

A key objective of this phase is the application of the CLIMAAX Handbook and associated workflows to structure the assessment of risk severity, urgency, and resilience capacity in a consistent and transparent manner. The use of the CLIMAAX methodology ensures methodological coherence with European standards while allowing flexibility for adaptation to the CMA-specific geographic, socio-economic, and governance context. This approach facilitates comparability with other European regions while maintaining local relevance.

Another central objective of Phase 2 is to integrate local and regional data and models into the CRA process. Local climate gridded data derived from observations, high-resolution hazard maps, and region-specific hydrological and climatological analyses were incorporated to improve the accuracy and credibility of the risk assessment. The inclusion of locally developed methodologies and expert knowledge enabled the identification of intra-urban and inter-settlement differences in hazard, exposure and vulnerability, which are essential for targeted adaptation planning and prioritisation of interventions.

Overall, the significance of Phase 2 for the CMA lies in its contribution to transforming CRA from a diagnostic exercise into a strategic decision-support tool. The results provide a clear evidence base for identifying priority risks, highlighting spatial hotspots, and revealing gaps in current resilience capacity.

These outcomes directly support Phase 3 of the project, which will focus on translating prioritised risks into concrete CRM actions and adaptation pathways, thereby enhancing the CMA climate resilience.

1.3 Project team

The project is implemented through a multidisciplinary partnership combining **metropolitan governance, international research expertise, and local scientific capacity**. The CMA Intercommunity Development Association (IDA) leads the project, ensuring strategic coordination, implementation, procurement, and financial management. The Austrian Institute of Technology GmbH contributes advanced expertise in digital tools, decision-support systems, and CRA methodologies. Babeș-Bolyai University provides scientific and technical support, integrating local and regional climate data, conducting hazard-specific analyses for HWs and floods, and ensuring methodological rigour through advanced GIS, data science, and climate expertise. The consortium ensures strong alignment among CMA policy needs, scientific evidence, and practical climate adaptation planning.

1.4 Outline of the document's structure

This document, structured in accordance with the CLIMAAX framework and the provided template, presents the CRA for the CMA in a clear and logical sequence. Following the introduction, the report describes the scoping phase, including objectives, context, stakeholder engagement, and governance aspects. It then details the risk exploration and regionalized risk analysis, focusing on the two priority climate hazards, HWs and floods, and the methodologies applied for their assessment. The subsequent section presents the key risk assessment findings, including severity, urgency, resilience capacity, and risk prioritisation for both hazards. The document concludes with the monitoring and evaluation framework, the work plan for the final project phase, and a synthesis of conclusions relevant to CRM and adaptation planning.

2 Climate risk assessment – phase 2 (15-25 pages)

This section describes the methodological steps undertaken to conduct the initial CRA using the CLIMAAX framework and to evaluate the resulting preliminary findings.

2.1 Scoping

In the Cluj Metropolitan Area, the scoping phase of the CRA focused on applying the CLIMAAX methodology at a finer, locally informed spatial scale, building on the regional-scale analyses conducted in Deliverable 1 and incorporating datasets provided by local and regional institutions. The process aimed to integrate modelled climate information with operational experience and local contextual knowledge, while explicitly acknowledging constraints related to data availability, institutional responsibilities, and multi-level governance coordination.

Key stakeholders involved in the scoping process included national and regional government agencies, the National Meteorological Administration, the Someș–Tisa Water Basin Administration, Someș Water Company, and local municipalities. Academic expertise was provided by Babeș-Bolyai University (Faculty of Geography) and the Technical University of Cluj-Napoca (TREC), ensuring scientific rigor and technical support throughout the assessment.

2.1.1 Objectives

The main objective of the Climate Risk Assessment (CRA) for the Cluj Metropolitan Area (CMA) in Phase 2 was to build on the results of Deliverable 1 by downscaling available hazard data and applying the CLIMAAX framework at a finer, locally informed spatial resolution. This objective was achieved through the integration of datasets and expertise provided by local and regional institutions, enabling a more accurate and context-sensitive assessment of climate risks on a metropolitan scale.

Specifically, Phase 2 of the CRA aimed to:

- integrate locally available, higher-resolution datasets into the CLIMAAX analytical workflows;
- refine and extend the Phase 1 assessment, which relied primarily on regional-scale European datasets available through the CLIMAAX toolbox;
- compare modelled hazard outputs with the operational experience and empirical knowledge of local and regional authorities;
- improve the spatial representation and differentiation of heatwave and pluvial flood risks across urban, peri-urban, and rural areas of the CMA;
- foster a shared, technically grounded understanding of climate risks among key stakeholders involved in planning, infrastructure management, and emergency response.

The expected outcome of the Phase 2 CRA was the development of an enhanced and spatially detailed evidence base, on climate hazards and risks at metropolitan and local administrative unit levels. By combining model-based analyses with institutional knowledge, the assessment provides a robust reference for risk prioritisation and adaptation planning, serving as a foundation for the identification and evaluation of Climate Risk Management measures in Phase 3.

Although Phase 2 of the CRA was primarily methodological and data-driven, rather than prescriptive or policy-led, its results are directly relevant for ongoing and future planning and decision-making processes at local and metropolitan scale. In particular, the outcomes can inform:

- the preparation and implementation of the Pluvial and Stormwater Management Plan (PMAP) for Cluj-Napoca, by offering improved spatial insights into pluvial flood hazard and infrastructure pressure points;
- the integration of heat mitigation measures and blue–green infrastructure solutions into urban planning, public space design, and regeneration projects;
- enhanced coordination between Cluj-Napoca and surrounding communes on climate adaptation, especially in relation to shared risks and interdependent infrastructure;
- future strategic planning instruments, including the General Metropolitan Urban Plan.

Limitations, Challenges, and Boundaries

The CRA was subject to several limitations and boundary conditions. While the availability of higher-resolution hazard data represented a major improvement compared to Phase 1, fine-scale socio-economic, health, and vulnerability data remained limited or unevenly available across the metropolitan area. This constrained the full quantification of compound, cascading, and socially differentiated impacts. Institutional challenges included differences in data formats, access conditions, and responsibilities across sectors and administrative levels. These challenges were addressed through iterative data harmonisation, close collaboration with data providers, and continuous stakeholder engagement to validate assumptions and interpret results within the local context. Overall, Phase 2 was designed with clearly defined methodological and spatial boundaries, focusing on risk characterisation and prioritisation rather than the implementation of adaptation measures. These boundaries ensure coherence with the CLIMAAX framework and provide a solid, realistic basis for the action-oriented work to be carried out in Phase 3.

2.1.2 Context

To date, the assessment and management of climate hazards, impacts, and risks in the Cluj Metropolitan Area (CMA) have been addressed primarily through sector-specific and hazard-specific instruments, rather than through an integrated, metropolitan-scale climate risk framework. Among climate hazards, flood risk has been the most systematically assessed, within the national framework for the implementation of the EU Floods Directive (2007/60/EC). This process is coordinated at national level by the National Administration “Apele Române”, and implemented regionally through the Someș–Tisa Water Basin Administration (ABA) and its local unit, SGA Cluj. While these assessments provide strategic flood hazard maps and probabilistic scenarios at river basin scale, their translation into local urban planning, land-use regulation, and infrastructure investment remains limited.

In contrast, pluvial flooding has received considerably less systematic attention at local level. Although Cluj-Napoca is officially designated as an Area with Potentially Significant Flood Risk (APSFR) for pluvial flooding, a dedicated and integrated planning instrument has so far been lacking. In accordance with national obligations and formal requirements issued by SGA Cluj, the municipality is required to elaborate a Stormwater Management Plan (PMAP) by 2027. This regulatory requirement constitutes a key contextual driver for Phase 2 of the CLIMAAX project and strongly influences the prioritisation of climate risks addressed in the current assessment.

The core problem addressed by this project is the absence of a shared, evidence-based understanding of climate risks at metropolitan scale, in a context characterized by strong spatial contrasts in exposure and vulnerability. Climate risks differ substantially between the dense urban core of Cluj-Napoca and the surrounding peri-urban and rural communes. A significant portion of the sewerage system—estimated at around 85%—is old and combined, collecting both domestic wastewater and stormwater, which substantially limits drainage capacity during intense rainfall events. In addition, the presence of uncadastralized watercourses and torrents (e.g. Canalul Morii) creates further challenges for integrated water management, maintenance responsibilities, and institutional coordination.

From a governance perspective, climate risk management responsibilities in the CMA are distributed across multiple administrative and institutional levels. ABA Someș–Tisa is responsible for basin-scale flood risk assessment and planning; SGA Cluj provides operational and technical support at county level; Cluj-Napoca City Hall manages urban infrastructure and will serve as the lead authority for the PMAP; ISU Cluj is responsible for emergency preparedness and response; and Someș Water Company operates water supply and sewerage infrastructure. This multi-level governance structure underscores the need for coordination mechanisms and shared analytical frameworks, such as those provided by CLIMAAX.

Several sectors in the CMA are particularly sensitive to climate change impacts, including water management and drainage infrastructure, urban planning and public space design (notably in relation to urban heat island effects), public health (especially heatwaves), peri-urban and rural agriculture, and ecosystem protection and management. Climate change is expected to exacerbate existing pressures in these sectors, increasing the relevance of integrated risk assessment and adaptation planning.

External influences shaping the context of the CRA include the national implementation of the Floods Directive, the mandatory preparation of the PMAP, national climate adaptation strategies, and broader EU-funded climate resilience initiatives. In addition, Cluj-Napoca's participation in the Net Zero Cities initiative creates further incentives for coherent and forward-looking climate risk management approaches aligned with European policy objectives.

Within this context, potential adaptation interventions relevant to the objectives of the CRA include infrastructure upgrades (e.g. sewer system modernisation, sustainable urban drainage systems, stormwater retention), nature-based solutions (urban greening, permeable surfaces, restoration of natural retention areas), improved early-warning and communication systems, risk-informed urban planning and regulatory measures, and strengthened institutional coordination to support climate adaptation planning at metropolitan scale.

2.1.3 Participation and risk ownership

Stakeholder engagement in Phase 2 of the CLIMAAX project focused on the joint development and validation of the climate risk assessment, with particular emphasis on interpreting technical results in light of operational experience and institutional responsibilities. Rather than a consultative-only approach, stakeholder participation aimed to ensure that hazard analyses, maps, and indicators reflect both model-based evidence and field-based knowledge, thereby strengthening the relevance and credibility of the assessment.

During Phase 2, technical results—such as hazard maps, exposure analyses, and risk indicators—were presented, discussed, and jointly interpreted with key institutions. This process supported a shared understanding of climate risks at metropolitan scale and facilitated consensus on risk prioritisation and areas requiring further action.

Stakeholder Involvement

The following institutions participated in Phase 2 activities and confirmed their willingness to continue collaboration within the CLIMAAX framework:

- Public authorities
  - Cluj-Napoca City Hall
  - Intercommunity Development Association Cluj Metropolitan Area
  - Municipalities within the metropolitan area
- Technical and emergency institutions
  - Inspectorate for Emergency Situations Cluj (ISU Cluj)
  - SGA Cluj
  - Someș–Tisa Water Basin Administration (ABA)
  - Someș Water Company S.A.
- Scientific and expert bodies
  - National Meteorological Administration (ANM)
  - Babeș-Bolyai University, Faculty of Geography
  - Metapolis
- Civil society and private sector representatives
  - Sustainable Cluj
  - Rebel Dot
  - Metapolis Architects

An organigram mapping institutional roles, responsibilities, and interconnections is provided to illustrate the governance structure and information flows supporting the CRA process.

Roles and Functional Responsibilities

From a functional perspective, stakeholder roles within Phase 2 were structured as follows:

- The Cluj Metropolitan Area (CMA) acted as metropolitan coordinator and facilitator, ensuring cross-sectoral dialogue and alignment.
- Cluj-Napoca City Hall led considerations related to local implementation and urban infrastructure, particularly for pluvial flooding and heat adaptation.
- ANM and ABA/SGA Cluj provided technical expertise, monitoring data, and hazard-related information for heatwaves and floods.
- ISU Cluj contributed the emergency management and response perspective, informing the urgency assessment.
- Babeș-Bolyai University ensured methodological consistency and scientific rigor.
- Metapolis contributed to linking risk assessment results with spatial planning and the metropolitan blue–green infrastructure strategy.

Risk Ownership in the CMA

Risk ownership in the CMA is distributed across multiple institutions, depending on the type of hazard:

- Riverine flooding
  - Risk identification and assessment are coordinated at strategic level by ABA Someș–Tisa, with SGA Cluj responsible for operational implementation.
  - Emergency preparedness and response fall under the responsibility of ISU Cluj.
- Urban pluvial flooding
  - Detailed assessment and implementation of mitigation measures are primarily the responsibility of Cluj-Napoca City Hall, supported technically by SGA Cluj and Someș Water Company S.A., particularly in relation to drainage infrastructure.

- Heatwaves
    - Monitoring and warning services are provided by ANM, while adaptation and mitigation measures are primarily the responsibility of local authorities, including municipalities and metropolitan governance structures.

Vulnerable Groups and Risk Tolerance
The representation of vulnerable or highly exposed groups in Phase 2 was largely indirect, mainly through civil society organisations such as Sustainable Cluj and through municipal identification of heatwave and flood hotspots in densely built-up areas. Direct engagement with vulnerable populations is recognised as an important area for further development in Phase 3.
Regarding acceptable or tolerable risk levels, clear regulatory thresholds exist for riverine flooding within the national Floods Directive framework, and for HWs they are part of the national early warning system. While operational warning thresholds exist for flash floods and heatwaves, explicit locally defined tolerance thresholds to guide urban planning, investment decisions, and adaptation priorities are not yet clearly established. As a result, responses to these risks remain predominantly reactive and emergency-driven, rather than guided by predefined and agreed-upon risk acceptance criteria. Addressing this gap constitutes a key motivation for advancing toward more structured and anticipatory climate risk management in the next project phase.

2.1.4 Application of principles

The CRA for the CMA was conducted in line with the core principles of the CLIMAAX Framework, ensuring that the analysis is not only technically robust, but also socially relevant, precautionary, and transparent. The manner in which each principle was applied is outlined below.
Social Justice, Equity, and Inclusivity
The principle of social justice and equity was addressed by explicitly recognizing that climate risks are unevenly distributed across space and population groups. The analysis demonstrated that heatwave risk varies significantly within the urban fabric, with dense, highly built-up neighbourhoods—often characterized by limited green space and reduced adaptive capacity—experiencing higher exposure. By combining high-resolution spatial hazard data with available socio-demographic information and hotspot identification, the assessment prioritised areas of highest vulnerability and exposure, rather than focusing solely on economically or politically central zones.
Although direct representation of vulnerable groups was limited at this stage, the CRA incorporated proxy indicators of vulnerability (e.g. urban density, land use, heat exposure patterns) and stakeholder input from civil society organisations and local authorities. This approach ensures that the assessment lays the groundwork for more inclusive, targeted adaptation measures to be developed in subsequent phases.
Quality, Rigour, and Transparency
Quality and scientific rigour were ensured through the systematic application of the CLIMAAX framework, combined with the integration of high-resolution local datasets and peer-reviewed analytical methods. The use of refined spatial data allowed the CRA to move beyond municipality-level averages and to identify intra-urban, peri-urban, and rural differences in risk, particularly for heatwaves and pluvial flooding.
Transparency was maintained by clearly documenting:

- data sources and their limitations,

- methodological assumptions,
- processing steps and analytical choices,
- and the role of expert judgment and stakeholder interpretation.

Results were validated through dialogue with technical institutions and academic partners, reinforcing confidence in the findings and supporting reproducibility and comparability with other CLIMAAX case studies.

Precautionary Approach

The precautionary principle was applied by treating heatwave risk as a priority hazard, even in the absence of comprehensive structural adaptation measures currently in place. Observed trends and projections indicate a clear increase in heatwave intensity, frequency, and duration, suggesting that delaying action until impacts become critical would substantially increase social and economic costs.

Accordingly, the CRA emphasised proactive and anticipatory planning, supporting early consideration of adaptation options such as urban green and blue infrastructure, shading, improved urban ventilation, and enhanced heat early-warning and public awareness systems. This approach aligns with the objective of reducing future vulnerability and avoiding maladaptation by embedding climate risk considerations into current planning and investment decisions.

2.1.5 Stakeholder engagement

Stakeholder engagement in Phase 2 of the CLIMAAX project focused on the joint interpretation, validation, and discussion of the climate risk assessment results, with particular emphasis on translating technical analyses into planning- and decision-relevant insights. Engagement activities were designed to support dialogue between technical institutions, decision-makers, experts, and civil society representatives, ensuring that the CRA reflects both analytical evidence and practical perspectives.

Engagement Methods and Meetings

Engagement methods applied during Phase 2 included technical presentations, data-sharing sessions, and structured discussions with key institutions involved in climate risk management and urban development. These activities allowed participants to explore hazard maps, understand the methodological approach, and assess implications for ongoing and future planning processes.

The main Phase 2 stakeholder meeting took place on 15 January 2026 and was attended by representatives from ISU Cluj, SGA Cluj, ABA Someș–Tisa, Someș Water Company S.A., National Meteorological Administration (ANM), Babeș-Bolyai University (UBB), Cluj-Napoca City Hall, Cluj Metropolitan Area (CMA), Metapolis, Sustainable Cluj, and Rebel Dot.

Communication of Project Goals and Results

Project objectives and intermediate results were communicated through:

- the presentation of CLIMAAX-based hazard and risk maps for heatwaves and floods;
- a clear explanation of the applied methodology and data sources, including limitations;
- facilitated discussions on the implications of results for metropolitan planning, infrastructure management, and adaptation policies.

Visual outputs and maps were used extensively to support understanding and enable constructive feedback.

Stakeholder Feedback and Reception

Overall, participants welcomed the increased level of spatial detail and analytical depth compared to previous assessments. SGA Someș–Tisa highlighted the relevance of the findings, confirming

Cluj-Napoca Municipality as one of the 17 nationally identified areas with significant pluvial flood risk. Representatives of Someș Water Company S.A. and SGA Cluj emphasized the structural limitations of the existing outdated combined sewer system and stressed the need for modernization and capacity expansion to cope with extreme rainfall events.
Urban planning stakeholders underlined the importance of integrating climate risk information into building regulations, public investment planning, and projects related to the metropolitan Green–Blue Belt, while civil society representatives highlighted the need for improved public awareness and accessibility of climate risk information.

Use of Project Outcomes and Next Steps

Project outcomes from Phase 2 are expected to be actively used by Cluj-Napoca City Hall and the CMA to inform climate adaptation investments and support alignment with the forthcoming Stormwater Management Plan (PMAP). Metapolis intends to integrate the identified flood-prone areas and heat exposure patterns into metropolitan spatial planning and blue–green infrastructure strategies. These anticipated uses confirm the practical relevance and uptake potential of the CRA results.

Challenges Encountered

Key challenges encountered during stakeholder engagement included:

- data gaps, particularly in socio-economic and health-related exposure information, which limited the ability to fully quantify vulnerability;
- an awareness gap between advanced technical risk analyses and broader societal understanding of long-term climate risks and adaptation needs.

Despite these challenges, the Phase 2 engagement process supported a qualitative alignment of risk perceptions among stakeholders and strengthened the shared understanding of priority climate risks at metropolitan scale.

2.2 Risk Exploration

Risk exploration for CMA began with a screening of the primary climate-related risks. Based on regional historical data and climate projections, HWs and floods were identified as the most relevant ones (see Phase 1 Deliverable).
HWs have been increasingly frequent and intense, significantly impacting public health (Toma and Croitoru, 2025), urban infrastructure, energy demand, and ecosystem services. HWs are strongly associated with the urban heat island effect, which can exacerbate their intensity. For this second stage, we used a finer spatial resolution to calculate HW parameters. We additionally improved the methodology for the hazard analysis by applying the new indices existing in the Climpact Indices list developed by the WMO ET-SCI), and introduced a new methodology for SUHI hotspot detection in urban areas (Magyari-Saska et al., 2024).
Flooding represents a significant climate-related risk in the CMA, arising from the interaction between regional geomorphology, hydrological processes, urban expansion, and climate-driven extreme precipitation. Flood events can affect critical infrastructure, transportation networks, residential areas, and agricultural land, with direct and indirect socio-economic consequences.
Within the urban core of Cluj-Napoca, the probability of large-scale riverine flooding along the Someșul Mic River has been substantially reduced due to upstream hydrotechnical works and in-channel regulation measures. Consequently, flood risk within the city is increasingly dominated by pluvial and urban flash-flood processes, which are closely linked to high impervious surface coverage, limited infiltration capacity, and intense short-duration rainfall events (Sampson et al.

2024). For this reason, urban flash floods constitute a key focus of the current risk exploration at the city scale.

At the metropolitan scale, however, riverine flooding remains a relevant and recurring hazard, particularly in the surrounding communes located along the Someșul Mic River, such as Apahida, Jucu, and Bonțida. In these areas, flood risk is driven by a combination of lower channel capacity, local geomorphological constraints, and extensive floodplain exposure, affecting both built-up areas and agricultural land (https://inundatii.ro/).

In addition, flood hazards are evident along the main tributaries of the Someșul Mic River within the CMA, notably the Nadăș and Gădălin streams. These tributaries are characterised by rapid runoff response, limited retention capacity, and increasing hydrological pressure due to land-use change and urban expansion in their catchments. As a result, both pluvial and fluvial flooding processes may occur, often with short lead times and elevated damage potential.

In this second stage of the risk exploration, high-resolution flood mapping was employed to capture areas exposed to both pluvial flash flooding and riverine flooding. The analysis highlights persistent flood-prone zones in downslope urban areas and in peri-urban and rural floodplains, even when considering existing grey flood-protection measures along the Someșul Mic River. This broad screening confirms flooding, across both urban and rural contexts, as a key climate risk requiring further detailed assessment, stakeholder engagement, and prioritisation within the Cluj-Napoca Metropolitan Area.

2.2.1. Screen risks (selection of main hazards)

For Phase 2, we retained the same hazards as those identified in Phase 1, HWs and floods, because they were identified as the most impactful in the focus region. Their criticality is further highlighted by the general urban sprawl specific to the main city, Cluj-Napoca, the urbanization of the surrounding rural settlements, and the increasing share of the elderly population.

The HWs are extreme events that affect most of the socio-economic sectors, and thus they become highly relevant in the context of this project. Additionally, a generalized increase in the parameters of the HWs (frequency, duration, intensity, and magnitude) identified based on different definitions was previously detected in scientific studies conducted over the last decade (Croitoru et al., 2016, Piticar et al., 2018, Ionita, 2024), with the Cluj-Napoca city area identified as affected by the most intense change in frequency and duration of the HWs during the 1993-2023 period compared with the period 1961-1990 (Ionita, 2024).

Although a new database containing extreme temperature datasets (TX and TN) was recently released by the Romanian National Meteorological Administration (RNMA), with a considerably improved spatial resolution of 1 km (Fig. 2-1) compared to the previously existing database, which is of utmost importance for local-level analysis, projection data at a comparable resolution are not yet available. This limitation constrains the accurate identification of high-risk hotspots in small regions. Additionally, population data, including health indicators (mortality and morbidity), are still not available at a lower than LAU-scale resolution.

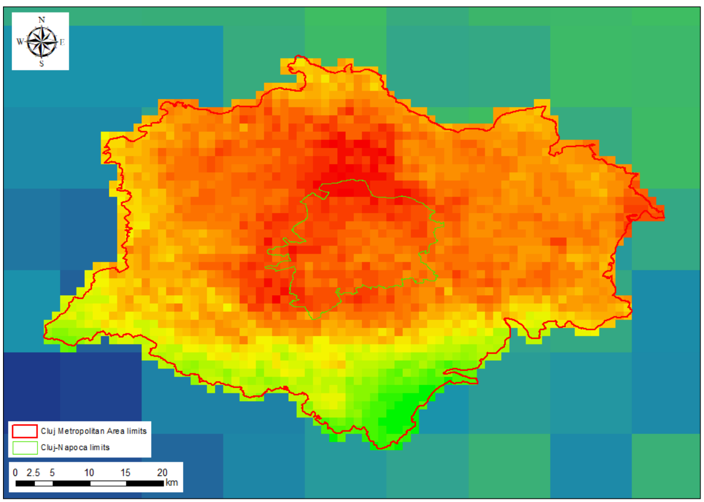


Fig. 2-1. Improved spatial resolution of the gridded data for HW detection (0.11x0.11° background compared to 1x1 km foreground)

Flood risk in the area is driven by the combined effects of intense precipitation events, increasing impervious surface coverage, modified drainage pathways, and exposure of both urban and peri-urban areas. Consequently, floods can affect multiple socio-economic sectors, including housing, transportation, public utilities, and agriculture, making them highly relevant to this project.

At the level of Cluj-Napoca municipality, the effectiveness of upstream hydrotechnical works has considerably reduced the probability of large-scale riverine flooding along the Someșul Mic River. However, flood risk within the urban core is increasingly dominated by **pluvial and urban flash floods**, which occur during short-duration, high-intensity rainfall events and are amplified by limited infiltration capacity and constrained urban drainage systems. In contrast, in the surrounding communes of the Cluj-Napoca Metropolitan Area, particularly along the Someșul Mic River and its main tributaries (Nadăș and Gădălin), **riverine flooding remains a recurring hazard**, affecting floodplains, residential areas, and agricultural land.

Previous studies and recent hydrological analyses conducted in the region indicate an increase in flood-related hazards, particularly those associated with extreme precipitation and rapid runoff generation, over the past few decades (Wypych & Ustrnul, 2024). These trends suggest a growing relevance of flood risk under current and projected climate conditions, particularly when combined with land-use change and increasing exposure in peri-urban areas (Zoccatelli et. al 2010, Croitoru et al, 2016).

2.2.2. Choose Scenario

For HWs, as Europe is the region experiencing the most accelerated warming, we identified as the most relevant climate change scenarios, for the medium- and long-term, depending on the data availability in the datasets selected. For this second deliverable, we considered the RoCLIB database developed by the RNMA. It contains bias-corrected CORDEX RCM datasets over Romania for four variables derived from ten combinations of GCMs, dynamically downscaled in the EURO-CORDEX initiative by several RCMs and adjusted over Romania, for the period 1971–2100. Two climate change scenarios were selected, namely the moderate (RCP4.5) and business-as-usual scenario (RCP8.5). The multivariate bias correction by the N-dimensional probability density method (MBCn) was applied to bias-correct the RCM outputs, using the ROCADA gridded dataset as the reference (Dumitrescu and Amihaiesei, 2021). The next RCM and GCM Driving models were used:

- CCLM4-8-17/CNRM-CERFACSCNRM-CM5
- RACMO22E/CNRM-CERFACS CNRM-CM5
- RCA4CNRM-CERFACS/CNRM-CM5
- CCLM4-8-17/ICHECEC-EARTH
- RCA4I/CHECEC-EARTH
- RACMO22E/ICHECEC-EARTH
- HIRHAM5/ICHECEC-EARTH
- CCLM4-8-17/MPI-MMPI-ESM-LR
- RCA4/MPI-MMPI-ESM-LR
- REMO2015/NCC NorESM1-M

The time horizons considered in the analysis were short-term (2026-2040), medium-term (2041-2070), and long-term (2071-2100).

For vulnerability and exposure data for the recent historical period, we used World Population datasets with temporal coverage from 2000 to 2020. For future periods, we employed SSP2 population growth with 1 km spatial resolution and 5-year temporal resolution for 2025-2100.
For the assessment of river flood hazard, we analyzed flood inundation scenarios corresponding to multiple return periods (10-, 100-, and 1000-year events), combined with future climate projections for the near-term (2011–2040), mid-term (2041–2070), and long-term (2071–2100) horizons. These temporal intervals are consistent with those implemented in the river floods (discharge) assessment toolbox, ensuring methodological compatibility and direct comparability of results across scenarios.
The selection of these specific return periods was guided by established practice and regulatory standards, as they are officially adopted by the National Water Administration for flood hazard and risk assessment in Romania. Moreover, to ensure institutional coherence and data reliability, we employed the climate change scenario already integrated within the national hydrological datasets, thereby aligning our analysis with the assumptions, boundary conditions, and modelling framework used by the responsible water management authorities.
In addition to riverine flooding, we also incorporated pluvial flood hazard into the analysis. Specifically, we developed pluvial flood extent maps for a 100-year return period, as well as 100-year pluvial flood scenarios that account for climate change impacts. This integrated approach enables a more comprehensive representation of flood hazards, particularly in urban and peri-urban areas where intense precipitation events and surface runoff can generate significant flooding independently of river overflow.
Climate change is accounted for by including an additional scenario applied to the 1 % annual exceedance probability (100-year return period) flood event, representing future hydro-climatic conditions. This scenario is based on modified design discharges and synthetic flood hydrographs reflecting projected climatic conditions around the mid-21st century (approximately 2050), as provided by the INHGA (World Bank, 2021, 2024). The adjusted hydrological inputs are subsequently used in hydraulic modelling to delineate climate-change-affected flood extents.

2.3 Regionalized Risk Analysis

The next step was to apply the dedicated workflows and scenario decisions to estimate risk in our focus region (CMA) using improved spatial-resolution data. The risk workflows consider four main steps to calculate a region’s individual Climate Risk: (i) preparation of the application in R (based on researchers' expertise), (ii) choosing and accessing data, (iii) estimating the hazard, and (iv) combining it with exposure and vulnerability data. The data used are presented in detail in the dedicated tables in each workflow section.

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

The new data we used for HWs are presented in Table 2-1.

Table 2-1 Data overview workflow #1 for phase 2

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
• *1 km – resolution daily minimum temperature data https://opendata.meteoromania.ro/data/daily/tmin/d*	Category: Population; • Dataset: WorldPop; Spatial resolution: 3 arcsec, 30 arcsec; Temporal resolution: 2000-2020;	Category: Population; Dataset: WorldPop; Spatial resolution: 3 arcsec, 30 arcsec; Temporal resolution: 2000-2020;	HW risk level

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
aily_tmin_synop_2025.nc • *1 km – resolution daily maximum temperature data https://opendata.meteoromania.ro/data/daily/tmax/daily_tmax_synop_2025.nc* • *RoCliB - Bias corrected CORDEX RCM dataset over Romania https://zenodo.org/records/4642464* • *Mean temperature reclassified according to the Toolbox, obtained from Landsat LST, over the period 2021-2024 for summer months (JJA).*	References: Pezzulo et al., 2017. Available at: https://hub.worldpop.org/doi/10.5258/SOTON/WP00646 • Population over 65, reclassified according to the Climaax Toolbox, derived from WorldPop for the year 2025; https://hub.worldpop.org/doi/10.5258/SOTON/WP00841; https://hub.worldpop.org/geodata/summary?id=106095 • https://hub.worldpop.org/geodata/summary?id=110984	References: Pezzulo et al., 2017 Available at: https://hub.worldpop.org/doi/10.5258/SOTON/WP00646 Population over 65, reclassified according to the Climaax Toolbox, derived from WorldPop for the year 2025; https://hub.worldpop.org/doi/10.5258/SOTON/WP00841; https://hub.worldpop.org/geodata/summary?id=106095 https://hub.worldpop.org/geodata/summary?id=110984	

2.3.1.1 Hazard assessment

For the HW hazard assessment, we employed a methodology similar to that used in Phase 1, but applied to he national database available at 1 km spatial resolution for historical data (1961-2024). Based on the researchers' expertise, we used R scripts for data processing. Compared to phase 1, the increase of the spatial resolution allowed more detailed mapping representation of the specific indices/parameters and emphasizing the critical areas with a much higher accuracy:

- HW Index (HWI) – number of events calculated based on TX when it exceeds 25 °C for at least 3 consecutive days;
- HW length (HWL) – duration of HW events (days);
- HW frequency (HWF) – total HW events duration in a year (days);

HWF and HWL were calculated for events identified using fixed thresholds for TN (18°C) and TX (25°C), considering 2-day and 3-day events.

The improved spatial resolution of the available data enabled a more detailed spatialization of the results, which in turn allowed for the clear identification of HW hotspot areas within the CMA. As expected, lower areas experienced more events, whereas neighbourhoods located on hills or low mountains are less exposed. This enhanced spatial insight is particularly important for climate change adaptation planning, as it reveals significant intra-urban differences in heat exposure that would not be visible at coarser scales of analysis. From an adaptation perspective, the ability to locate and delineate these hotspot areas provides a strong basis for evidence-based decision-making, supporting the prioritization and targeting interventions at a smaller spatial scale within the metropolitan region. Such fine-scale prioritization is especially relevant at the city and neighborhood levels, where tailored measures, such as increasing urban green infrastructure, modifying the built environment, or improving access to cooling resources, can be implemented more efficiently and equitably to reduce heat-related risks. However, this analysis shows that rural areas appear to be more exposed to heat-related hazards than urban areas. The results are presented in Figs. 2-2, 2-3, and 2-4.

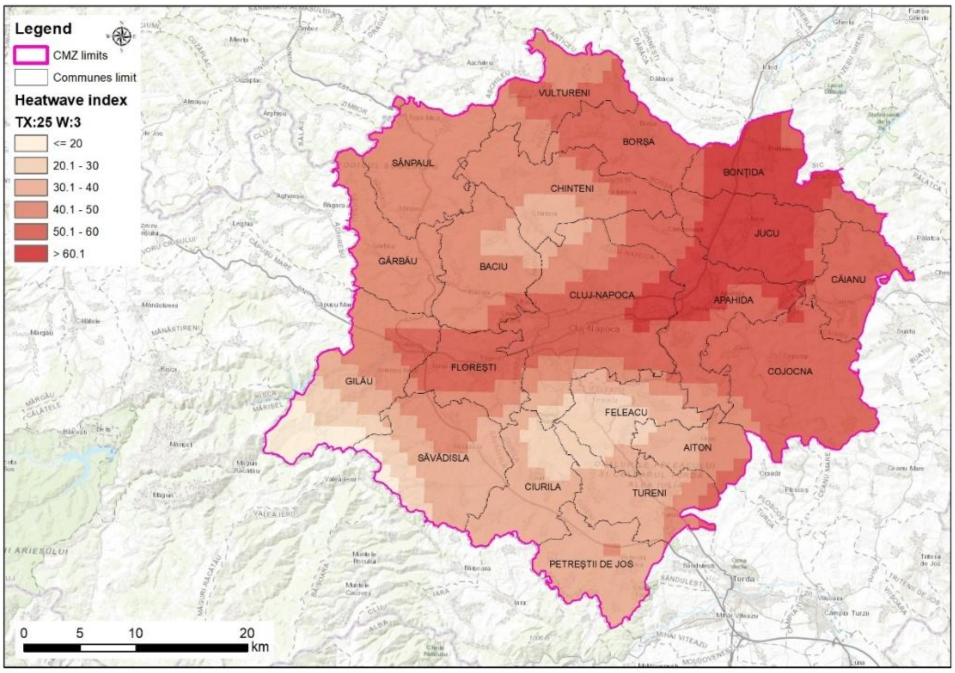


Fig. 2-2. Heatwave index in CMA over the period 1961-2024 (based on NMA dataset)

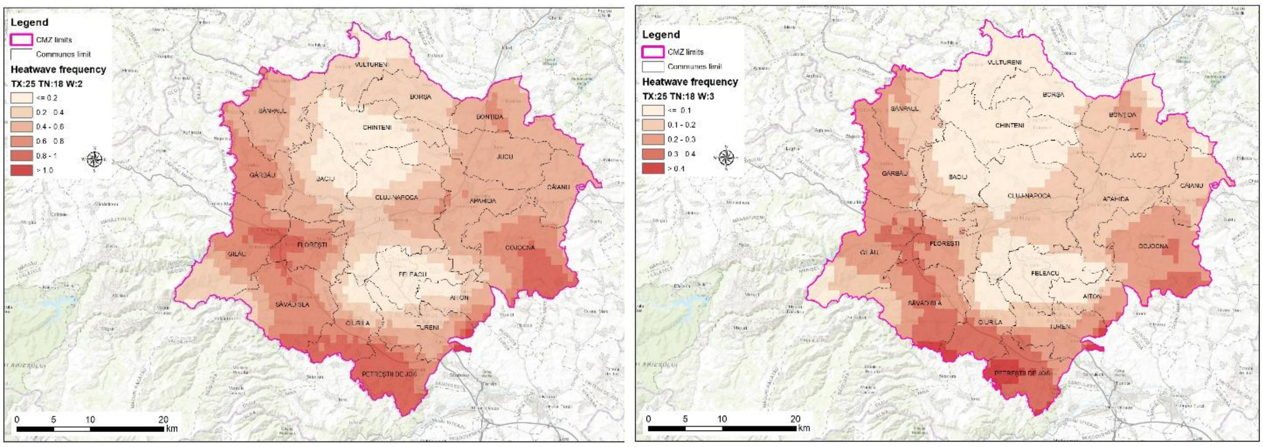


Fig. 2-3. Heatwave frequency for 2-day events (left) and 3-day events (right) in CMA over the period 1961-2024 (based on NMA dataset)

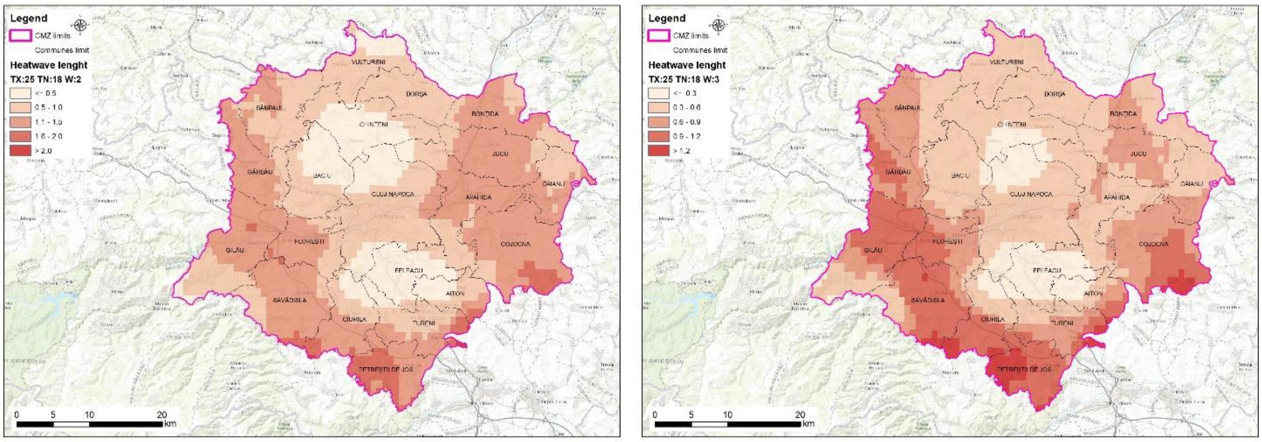


Fig. 2-4. Heatwave length for 2-day events (left) and 3-day events (right) in CMA over the period 1961-2024 (based on NMA dataset)

Moreover, the improved spatial resolution allowed us to calculate each index/parameter at the local administrative unit level (Supplementary material 1).

Also, the temporal evolution derived from observation data indicated an increase in the HWI much more accelerated compared to the modeled data for most of the grid points in the focus region (Fig. 2-5).

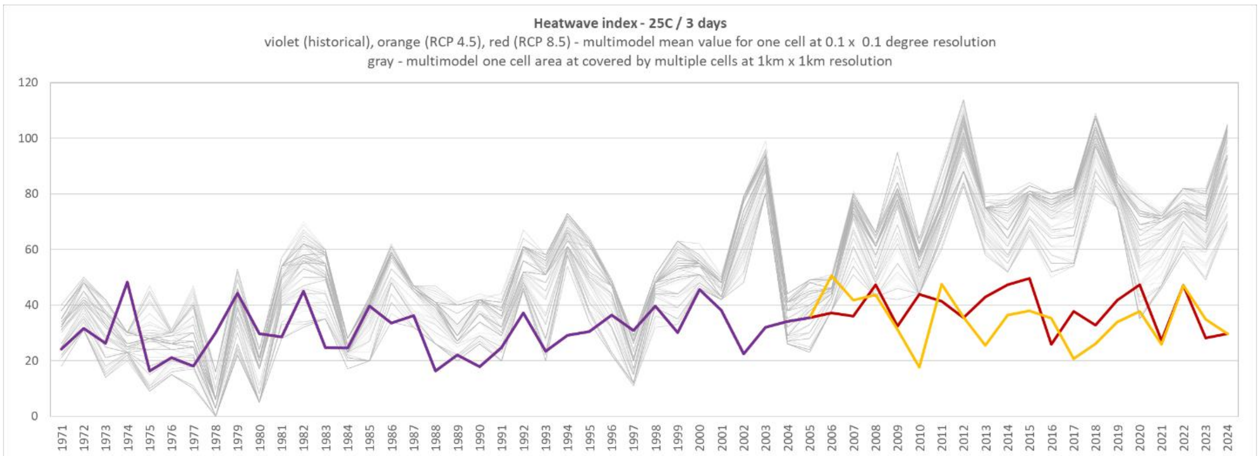


Fig. 2-5. Heatwave index temporal evolution derived from historical (violet line) modeled and projected data (red and orange lines), and from gridded data derived from observations (grey lines).

2.3.1.2 Risk assessment

Based on the HWI, the spatial distribution of risk remains heterogeneous, with very high risk in Cluj-Napoca, medium risk in the eastern, northeastern, and western parts of the region, and low risk in the southern, southwestern, and northwestern areas (Fig. 2-6).

The risk assessment derived from HWF (Fig. 2-7) and HWL (Fig. 2-8) shows medium to high risk levels in Cluj-Napoca and in the villages located west of the city for 2-day events, while low risk characterizes the western and eastern sectors, and very low risk is observed in the northern and central southern regions. For 3-day heat events, the overall risk pattern remains similar but slightly reduced in magnitude, likely reflecting the lower occurrence of longer-duration (3-day) HWs.

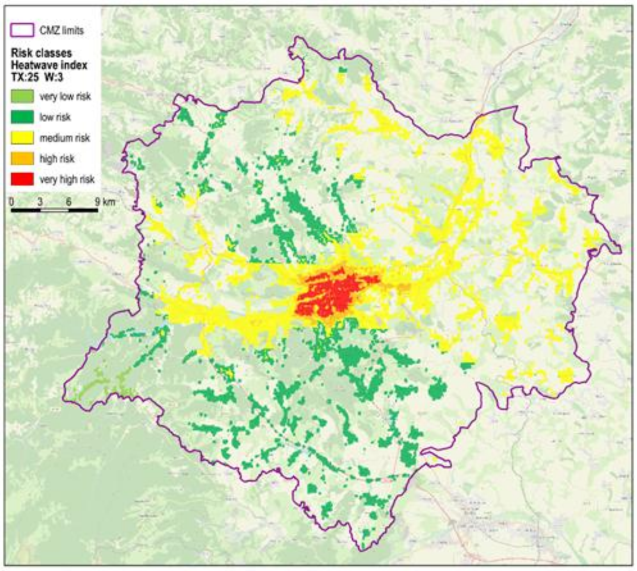


Fig. 2-6. Risk assessment based on HWI

The pronounced heat-related risk identified in Cluj-Napoca underscores an urgent need for targeted heat adaptation interventions. As a densely built-up urban area, the city is particularly vulnerable to elevated temperatures due to the urban heat island effect, high population density, and extensive impervious surfaces, which exacerbate both the frequency and intensity of heat stress.

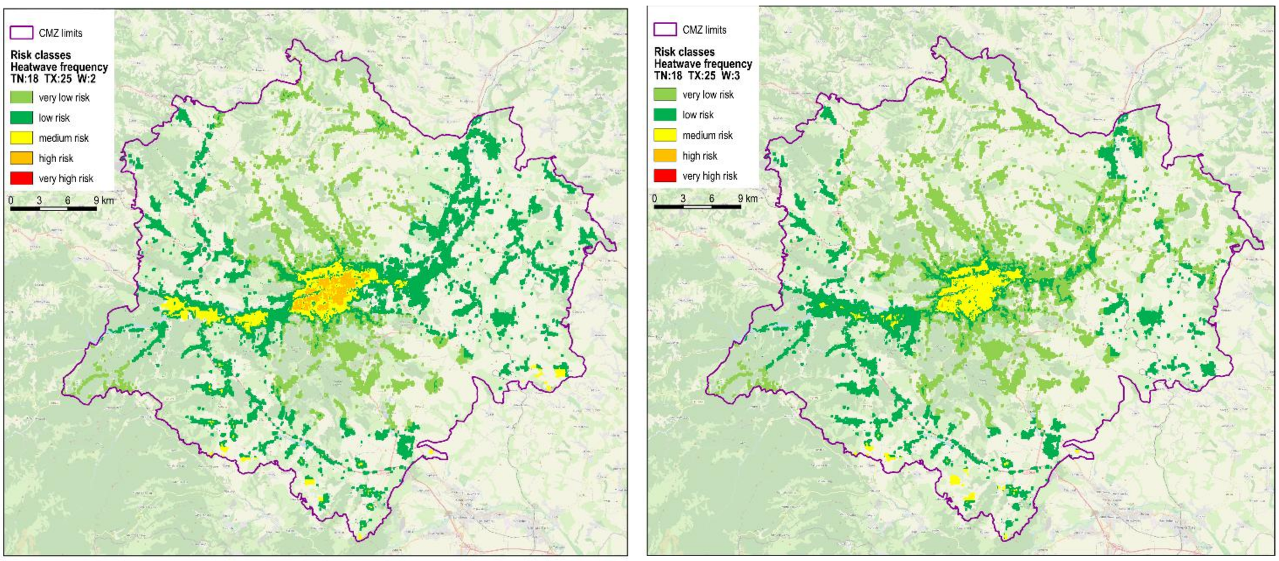


Fig. 2-7. Risk assessment based on HWF

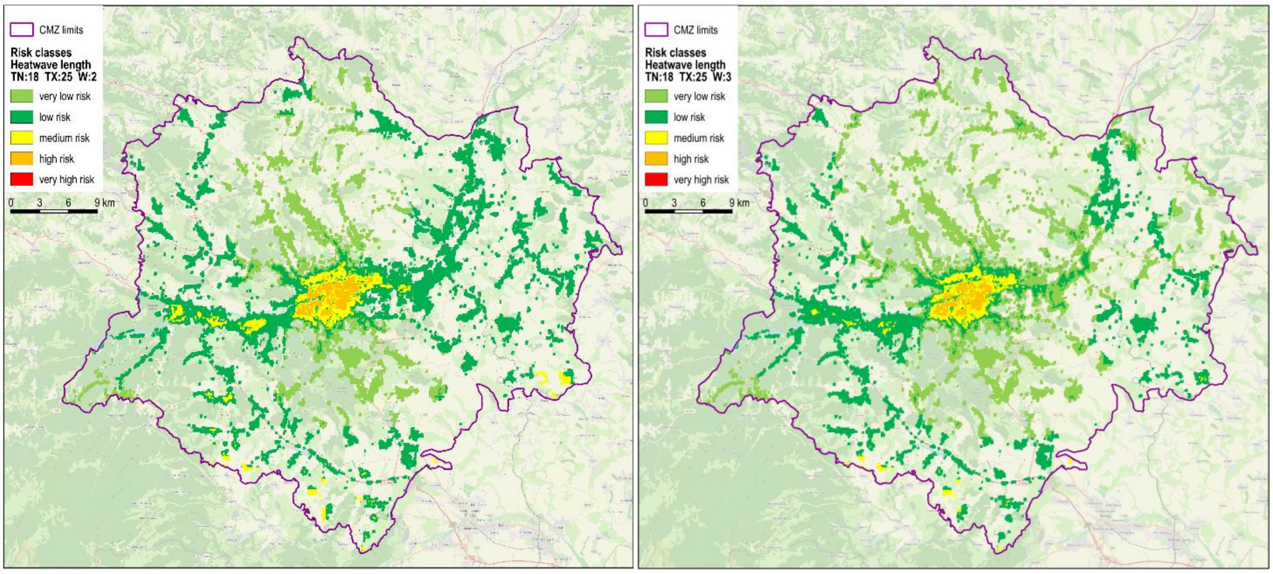


Fig. 2-8. Risk assessment based on HWL

The consistently high-risk levels indicated by multiple heat indicators suggest that current urban and social systems may be insufficient to cope with present and future heat extremes. Therefore, integrated adaptation measures (e.g., increasing urban green and blue infrastructure, improving building thermal performance, expanding shaded public spaces, and enhancing the early-warning system for heat and public awareness) are essential to reduce population exposure and vulnerability. Proactive heat adaptation in Cluj-Napoca is crucial not only to protect public health but also to enhance urban resilience in the context of ongoing climate change.

2.3.2 Hazard #2 - finetuning to local context

The new data we used for flood hazard are presented in Table 2-2.

Table 2-2 Data overview workflow #2

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
National-scale river flood hazard maps derived from hydraulic modelling that accounts for local flood defence and hydrotechnical measures, provided at a high spatial resolution (~2 m) corresponding to multiple return periods (10-, 100-, and 1000-year events) that take in consideration also climate change.	• The land use map available from the Copernicus Land Monitoring Service; • Population density • Available at:GHS-POP R2023A dataset (Carioli et al., 2023) • Building data. Available at: OpenStreetMap	• Flood-damage curves for infrastructure expressed as relative damage percentage, available from JRC. • The economic value for different types of land use, which can be country/location specific.	• Flood inundation maps for the area of interest with different return periods based on European JRC dataset. • Flood damage maps, expressed in economic value, for extreme events with different return periods based on available flood maps for the historical climate. • Maps of exposed population and estimated annual exposed / displaced population graph.

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
National-scale pluvial flood hazard maps at 100 year return period that take in consideration also climate change (based on modified design discharges and synthetic flood hydrographs reflecting projected climatic conditions around the mid-21st century) …	• The land use map available from the Available at: Copernicus Land Monitoring Service. • Population density • Available at: GHS-POP R2023A dataset (Carioli et al., 2023) • Building data. Available at: OpenStreetMap	• Flood-damage curves for infrastructure expressed as relative damage percentage, available from JRC. • The economic value for different types of land use, which can be country/location specific.	Flood inundation maps for the area of interest with different return periods
Catchment-level discharge data for the historical period and for future periods of 2011-2040, 2041-2070 and 2071-2100:			• Daily time series of river discharges based on the historical model period • Flow duration curves • Seasonal variations of river discharges • Monthly mean river discharges for different GCM-RCM combinations and averaged across the hydrological multi-model ensemble • Extreme river discharges • Relative change in extreme river discharge

2.3.2.1 Hazard assessment

For the assessment of riverine and pluvial flood hazards, we applied a methodology conceptually consistent with that used in Phase 1, while adapting it to national-scale hazard datasets with a spatial resolution of approximately 2 m. Due to the very large size of the raster datasets, standard GIS-based processing workflows proved computationally inefficient. Consequently, data processing and analysis were carried out using custom R scripts, which preserved the analytical logic and core methodological steps implemented in the official hazard assessment toolboxes.

Compared to Phase 1, the substantially higher spatial resolution of the input data enabled a more precise delineation of flood-prone areas within the CMA, thereby allowing a more accurate assessment of exposed elements and associated potential damage and risks. The improved level of spatial detail facilitated a more detailed spatialization of the results and enabled the clear identification of localised hotspots of flood hazard across the metropolitan territory.

This enhanced spatial resolution is particularly relevant for climate change adaptation planning, as it highlights pronounced intra-urban variability in flood hazard that would not be detectable at coarser resolutions. In the case of riverine flooding, the results indicate that the most affected areas are predominantly located in the peri-urban and rural sectors adjacent to the Someșul Mic river channel, as well as along selected reaches of the Nadăș and Gădălin rivers (Fig. 2-9, upper).

By contrast, pluvial flooding associated with intense, short-duration rainfall events (usually summer shower rains) is mainly concentrated within the urban area of the CMA. This spatial pattern reflects the design of the hydrological modelling framework, which focuses on surface runoff generation and drainage capacity in built-up areas. As a result, the modelled pluvial flood extents are more pronounced in densely urbanised zones, where impervious surfaces and limited infiltration capacity enhance flood generation under extreme precipitation scenarios (Fig. 2-9, down).

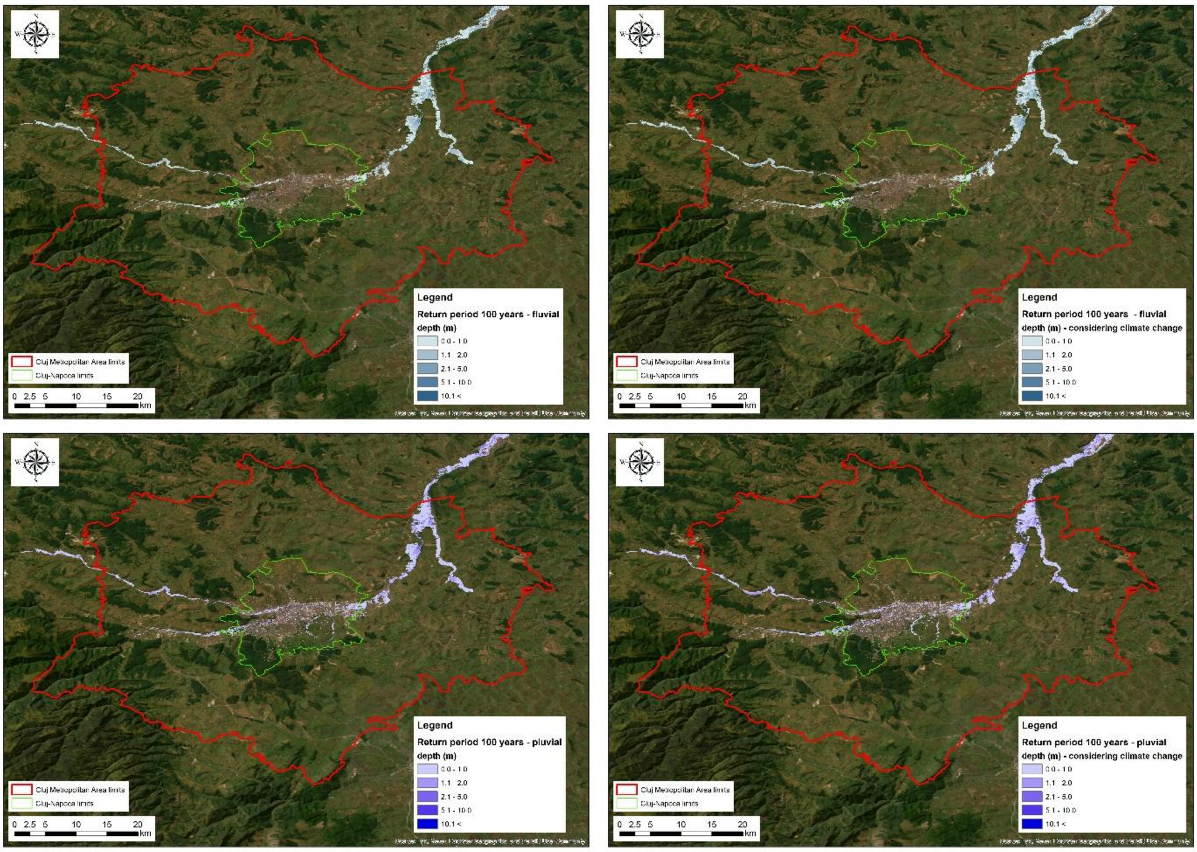


Fig. 2-9. Riverine (upper) and pluvial (down) flood hazard maps, assessed with and without climate change impact

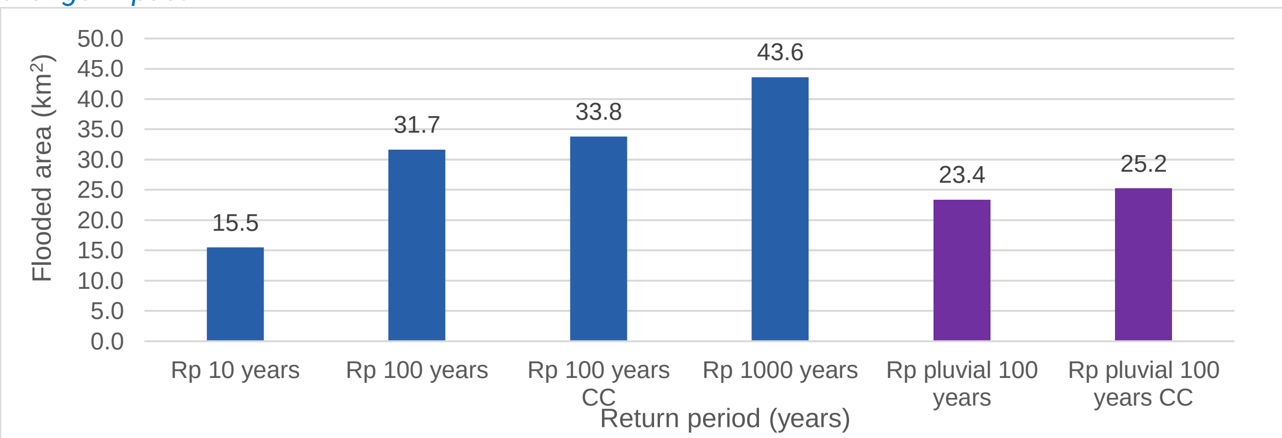


Fig. 2-10. Riverine (in blue) and pluvial (in purple) flooded areas for different return periods

Figure 2-10 compares riverine (blue) and pluvial (purple) flooded areas across different return periods. For riverine flooding, the flooded area increases substantially with increasing return period, reflecting the greater spatial extent of rare, high-magnitude flood events. Pluvial flooded areas are smaller, as these scenarios were modelled only for the urban area, but they still represent a significant proportion of the built-up zone. In both riverine and pluvial cases, climate change scenarios lead to larger flooded areas, indicating an intensification of flood hazard under future climate conditions.

2.3.2.2 Risk assessment

The analysis focused on risks to the built environment, with flood risk expressed primarily in terms of potential economic damages. Economic losses were estimated through the integration of flood extent and inundation depth data with exposure and vulnerability information. This approach relies on the application of depth–damage curves, which relate inundation depth to the proportion of damage for specific land-use categories. These curves were combined with country-specific economic parameters to approximate the monetary value of potential damages associated with different types of built infrastructure.

Compared to the first deliverable, both the depth-damage functions and the resulting economic damage estimates were recalculated using the updated hazard data at higher spatial resolution, allowing for a more refined representation of flood impacts. The recalculated depth-damage relationships (Fig. 2-11) and the corresponding economic damage estimates by land-use category (Fig. 2-12) reflect this enhanced spatial detail and are provided in the accompanying Zenodo archive (Flood_Phase2.zip).

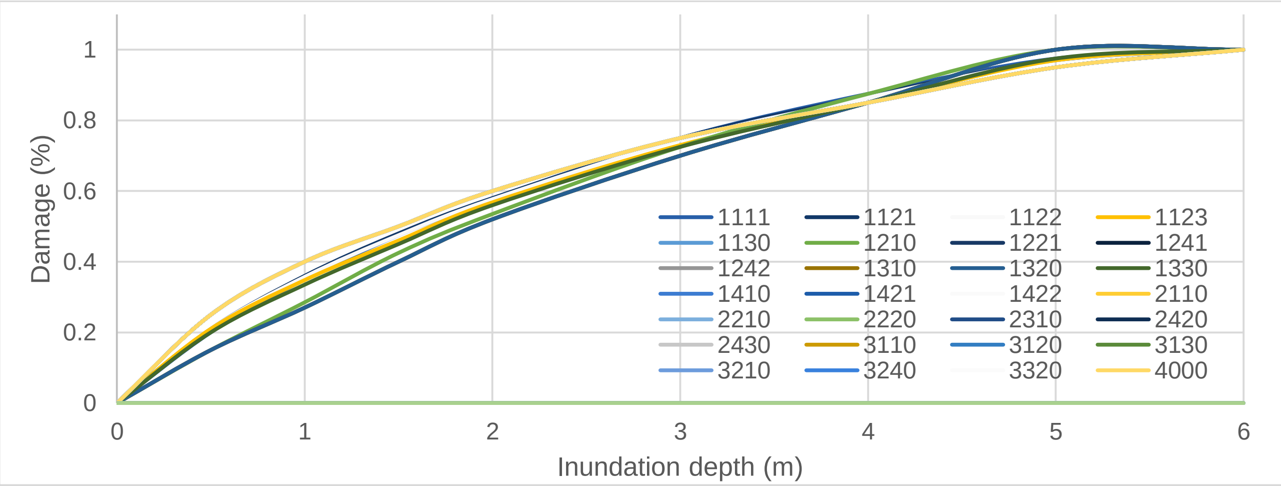


Figure 2-1. Vulnerability - damage curves for land use (CMA area) 100 years return period pluvial flood

By spatially overlaying flood inundation depth, land-use classifications, and economic vulnerability indicators, we generated detailed spatial outputs identifying hotspots of potential economic damage across the study area for multiple flood scenarios corresponding to distinct river discharge return periods, as well as pluvial flooding scenarios (Fig. 2-12). These outputs capture both exposed assets and expected damage intensity, enabling a differentiated assessment of flood risk across urban, peri-urban, and rural zones.

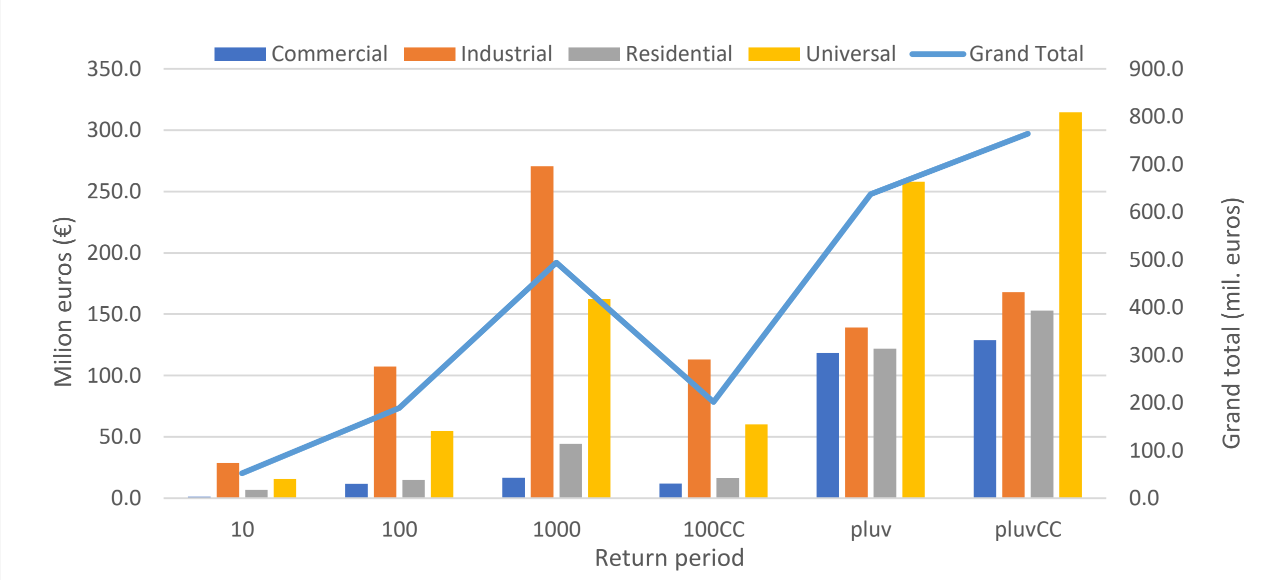


Figure 2-2. Economic damage estimates by land-use category

The resulting maps and summary statistics effectively highlight spatial variations in flood risk, clearly delineating areas most likely to experience significant economic losses under different flood magnitudes. This enhanced level of spatial detail is particularly relevant for climate change adaptation and flood risk management, as it supports the identification of priority intervention areas and provides a robust evidence base for targeted mitigation measures, land-use planning, and strategic investment decisions by stakeholders and decision-makers.

Both exposed and displaced populations increase with flood severity. For riverine floods, impacts increase with increasing return periods, with the 1000-year event affecting most people. In contrast, pluvial floods generate substantially higher exposure and displacement than fluvial floods, highlighting the dominant impact of intense rainfall events in urban areas (Fig. 2-13).

Figure 2-3. Exposed and displaced population numbers corresponding to different return periods

2.3.3 Additional assessments based on local models and data

As additional analysis, we considered two approaches for heat-related analysis:

(1) The use of **WMO-recommended HW indices**, calculated based on the methodology available from https://climpact-sci.org/indices/): number (HWN), duration (HWD), cumulated duration/frequency (HWF), magnitude (HWM), and amplitude (HWA); all indices were calculated based on **two definitions**, with events lasting at least 3 consecutive days:

- Daily TX exceeding the 90th percentile;
- Extreme Heat Factor (EHF) based definition, which is considered one of the most complex and comprehensive ones, developed based on two subindices: acclimatization and significance (Perkins and Alexander, 2013);

HWs identified using the EHF are widely considered as more meaningful than those defined only by TX thresholds or by simple combinations of TX and TN, because EHF better reflects how heat is experienced and its potential impacts and provides a HW definition that more closely tracks actual health impacts than simple fixed temperature thresholds or TX-only indices. Rather than relying on fixed temperature limits, EHF evaluates heat in relation to local climate conditions, allowing extreme events to be identified based on what is unusually hot for a given location. This relative approach makes EHF particularly effective for comparing heat stress across regions with different climatic backgrounds and for capturing locally relevant extremes (Nain et al, 2009; Scalley et al., 2015).

Methodologically, EHF strength lies in combining short-term excess heat with an acclimatization component and using both TX and TN, so it can detect intense, health-relevant events across very different climates on a common scale. Another key advantage of EHF is that it accounts for short-term thermal acclimatization by comparing current temperatures with those of the preceding weeks. This feature is important because the health and societal impacts of heat are often more pronounced when high temperatures occur suddenly after cooler periods, when people and infrastructure have not yet had time to adapt. Metrics based solely on TX and TN do not capture this temporal dimension of heat stress or the cumulative burden of sustained warmth. Moreover, EHF emphasizes the persistence and intensity of heat over multiple consecutive days, which better corresponds to observed impacts on human health, such as increased morbidity and mortality during prolonged hot spells. By integrating information on intensity, duration, and local climatic context, EHF-based HW definitions provide a more impact-oriented and reliable basis for risk assessment, early warning systems, and climate adaptation planning than simpler temperature-based indicators (Nairn et al., 2018; Nairn and Fawcett, 2014).

For the historical period, the indices have been calculated based on the extreme temperature national datasets at 1 km spatial resolution, and for the future decades, RoCLIB datasets were used, using Climpact online application.

(2) A **new approach for SUHI hotspots,** recently developed by the BBU researchers involved in this project, and which allows **ranking the hotspots in an urban area based on their intensity and persistence** (Magyari-Saska et al., 2024).

This approach represents an innovative method for detecting SUHI hotspots, providing a comprehensive assessment of the SUHI phenomenon and generating new insights into the spatial and temporal patterns of heat distribution within urban environments. By systematically analysing where heat repeatedly accumulates, the method enables the identification and ranking of the city's most critical hot areas based on their severity (measured by persistence and intensity), highlighting locations where elevated temperatures pose the greatest risk (Magyari-Saska et al., 2024).

The proposed method offers several key advantages. First, it allows users to flexibly adapt intensity thresholds and the number of identified hotspots to reflect local conditions and specific planning or policy objectives. Second, by using multi-image processing, it produces a synthetic overview of SUHI hotspots over extended time periods, ranking them by severity, calculated from persistence and intensity, thereby supporting the prioritisation of intervention areas. Furthermore, the method supports both single-image and multi-image analyses, enabling the derivation of aggregated results and the systematic ranking of SUHI hotspots. As such, it constitutes a valuable decision-support tool for urban planners and policymakers, clearly identifying the most critical locations requiring urgent action to improve urban resilience and adaptation to heat-related stress (Magyari-Saska et al., 2024).

This analysis covered the CMA's main city, Cluj-Napoca, and used 74 Landsat images spanning 2021-2023.

2.3.3.1 Hazard assessment

(1)The hazard assessment for HW indices calculated as mean values for the period 1991-2024 indicates considerably higher values for most indicators for the HWs identified based on EHF than for pair indices calculated based on the TX 90th percentile. Also, the spatial patterns differ across definitions for some indices (Fig. 2-14). The spatial pattern of indices calculated based on EHF differs slightly from that obtained using Climaax's proposed methodology. Only for HWA and HWM, the spatial pattern is similar to that of HI, HL, or HF.

(2) The hazard assessment, conducted through the detection of SUHI hotspots using high-resolution satellite imagery, revealed the most severe hotspots (in red on the hazard map), which are classified as high in both intensity and persistence. These critical areas are primarily concentrated in the northeastern and northern parts of Cluj-Napoca city, which largely correspond to brownfield sites formerly occupied by industrial facilities. The lack of vegetation and the presence of impervious surfaces in these areas contribute to the accumulation and persistence of elevated surface temperatures. In addition to these former industrial zones, the analysis identified densely built-up residential areas in the eastern neighbourhood of the city (Marasti), dominated by 11-storey concrete blocks of flats, as one of the city's hottest locations (Fig. 2-15).

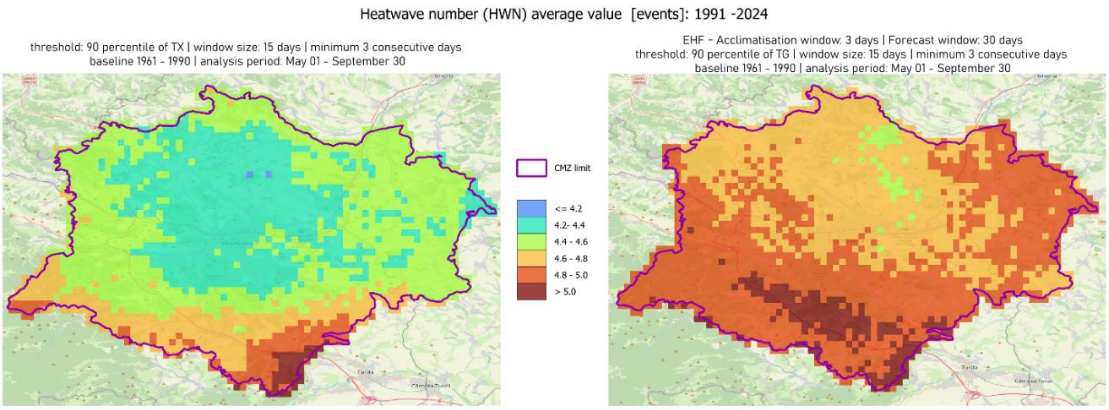


Fig. 2-14. HW indices calculated based on daily TX 90th percentile (left) and based on EHF (right) for the period 1991-2024

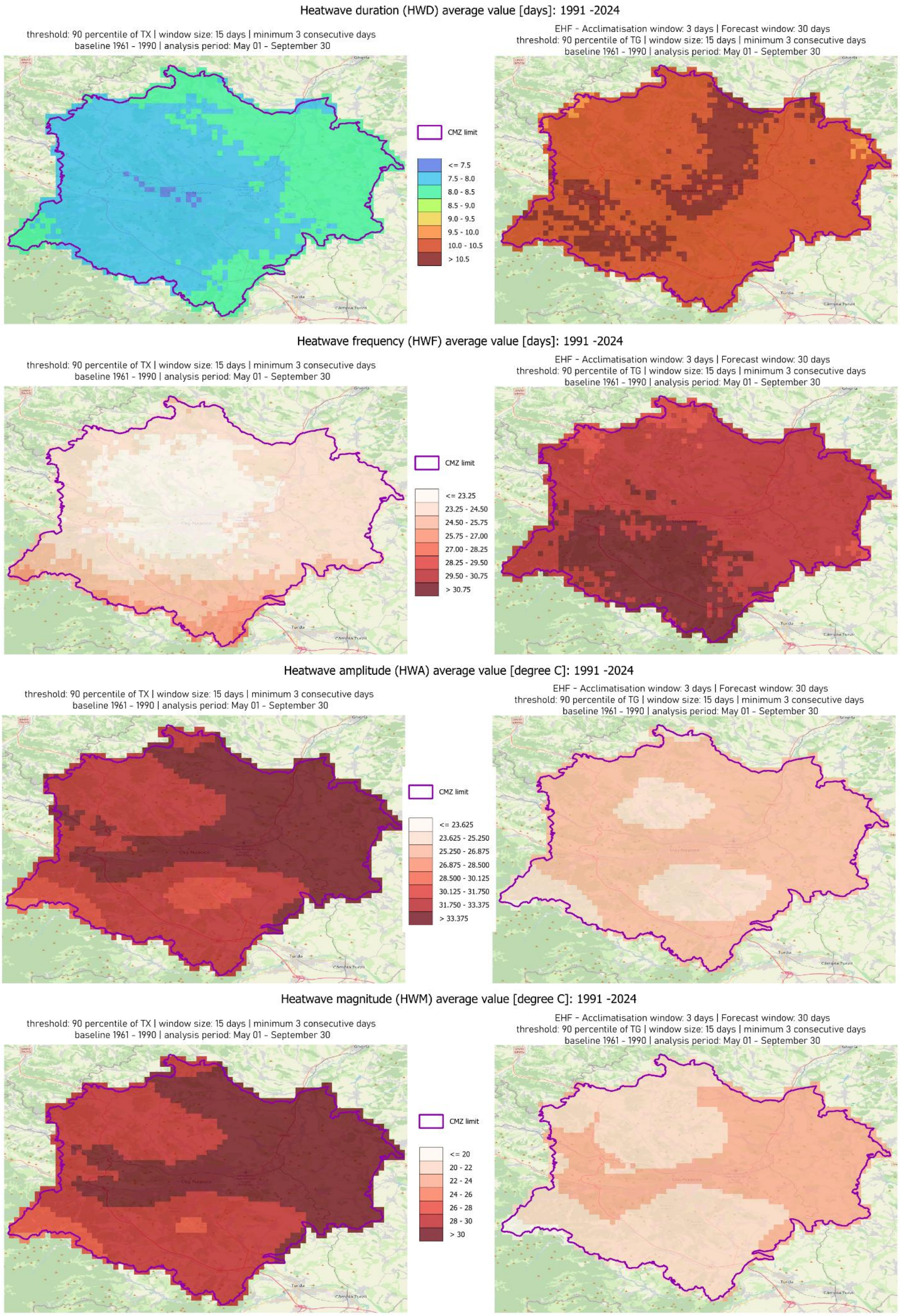


Fig. 2-14. HW indices calculated based on daily TX 90th percentile (left) and based on EHF (right) for the period 1991-2024 (continued)

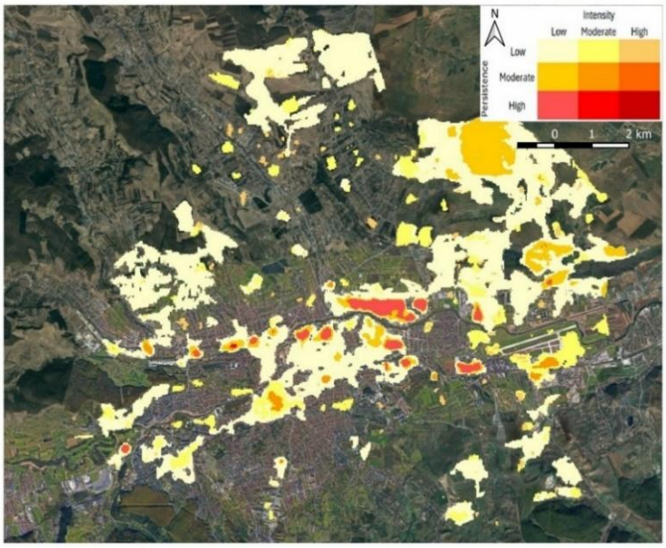


Fig. 2-15. Severity SUHI hotspots map (2021-2023)

The combination of high building density, minimal green space, and heat-retaining construction materials in this neighbourhood exacerbates local thermal stress, making it a key target for heat-mitigation measures. Overall, the SUHI-based hazard assessment provides a spatially detailed understanding of the city's most thermally stressed areas, offering critical insights for urban planning and climate adaptation strategies.

2.3.3.2 Risk assessment

(a) Risk assessment based on HW indices.

For the HW risk assessment, risk values were calculated annually and subsequently aggregated across three future periods: 2025–2040, 2041–2070, and 2071–2100. The assessment followed the methodology of the original toolbox, which classifies both hazard and population into ten classes, ultimately producing a five-class risk matrix. To estimate the population at risk, the SSP2 scenario was employed, providing data at a spatial resolution of 1 km and a temporal resolution of five years.

The analysis indicates a consistent increase in HW risk over time, in both intensity and spatial coverage, across all indices considered. For illustrative purposes, we present risk estimates for the HWF index, calculated using the two HW definitions, based on the TX 90th percentile and the one based on EHF, under the RCP4.5 and RCP8.5 climate scenarios. The analysis shows that HW risk is generally higher when defined using EHF, reflecting the method's sensitivity to extreme and persistent heat events (Fig. 2-16, 2-17, 2-18, and 2-19). Risk maps based on the other HW indices (HWN, HWD, HWA, and HWM) are provided in Supplementary Material 2.

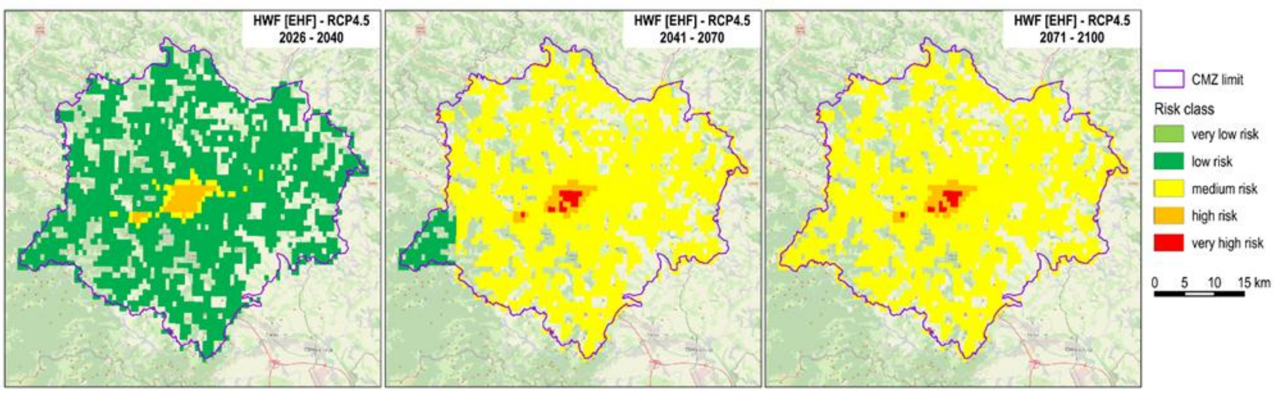


Fig. 2-16. Risk calculated for HWF for HW-EHF for RCP4.5

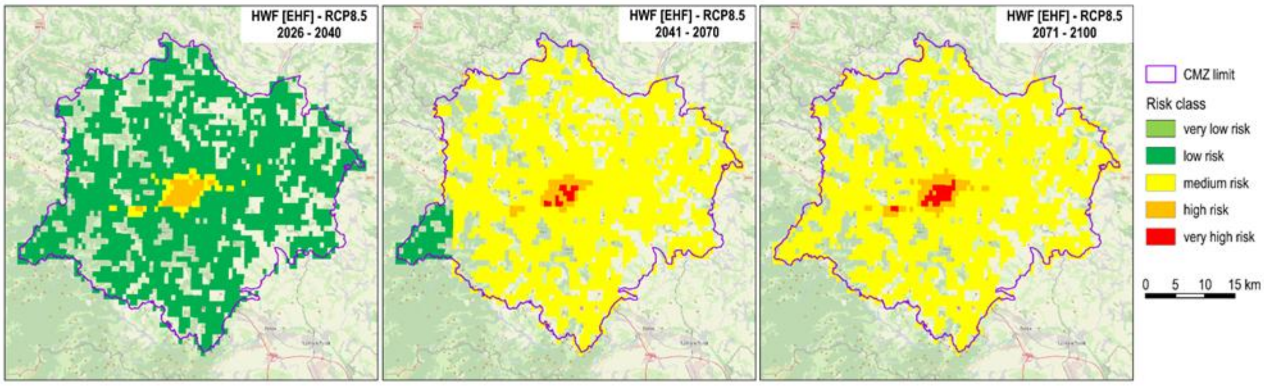


Fig. 2-17. Risk calculated for HWF for HW-EHF for RCP8.5

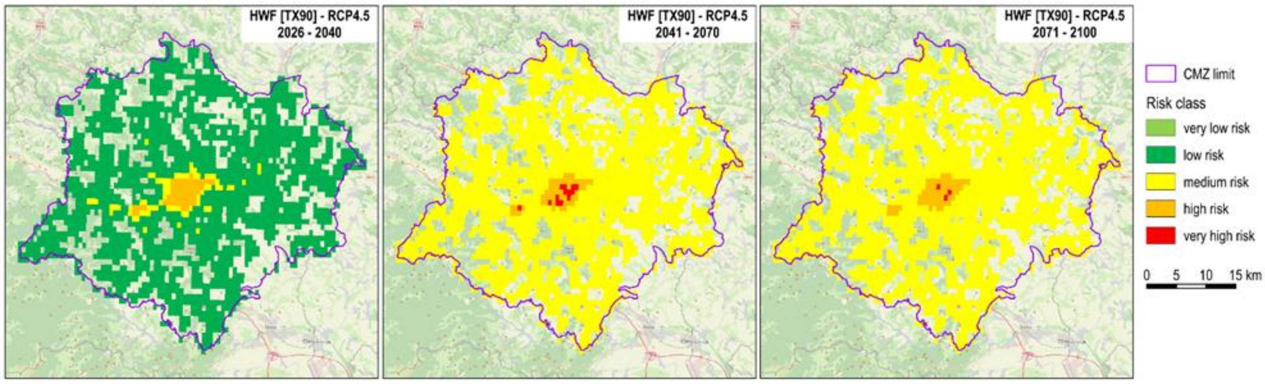


Fig. 2-18. Risk calculated for HWF for HW-TX90p for RCP4.5

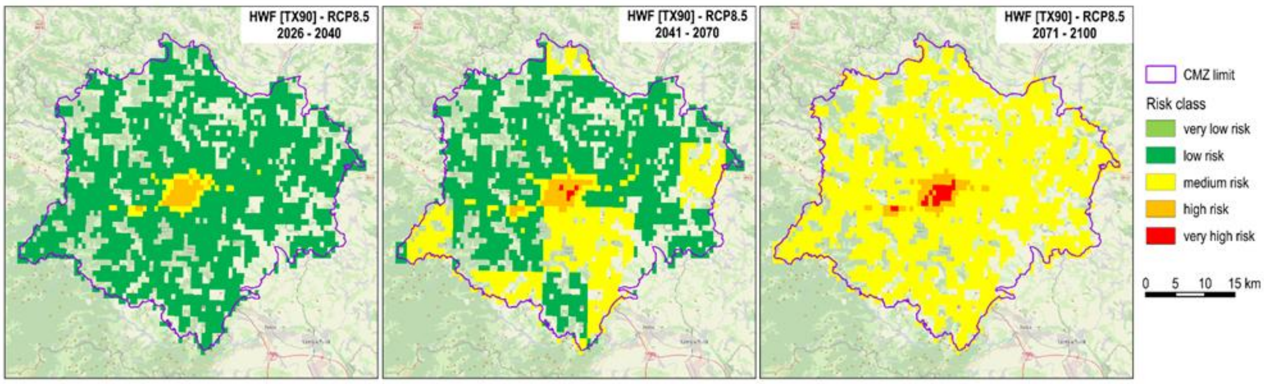


Fig. 2-19. Risk calculated for HWF for HW-TX90p for RCP8.5

These results highlight not only the projected temporal escalation of HW risk in CMA, but also the influence of the choice of HW definition and climate scenario on the magnitude and spatial distribution of future risk.

(2) Risk assessment using SUHI

Based on LST and population data, spatially explicit maps of vulnerability, exposure, and overall heat-related risk were developed for Cluj-Napoca city. The resulting vulnerability map reveals a predominance of high-to-very-high vulnerability levels across most of the urban area, reflecting the combined effects of elevated thermal conditions and sensitive population groups. By contrast, lower vulnerability values are mainly observed in peripheral zones of the city (Fig. 2-20), which are largely characterised by newer residential developments and a comparatively younger population structure. These areas generally benefit from improved building standards, greater availability of open spaces, and reduced cumulative heat stress, all of which contribute to lower susceptibility to extreme heat. The spatial patterns highlighted by the vulnerability map underscore pronounced intra-urban disparities in heat-related vulnerability (with higher values in the city centre) and provide an essential basis for identifying priority areas for targeted adaptation and risk-reduction measures.

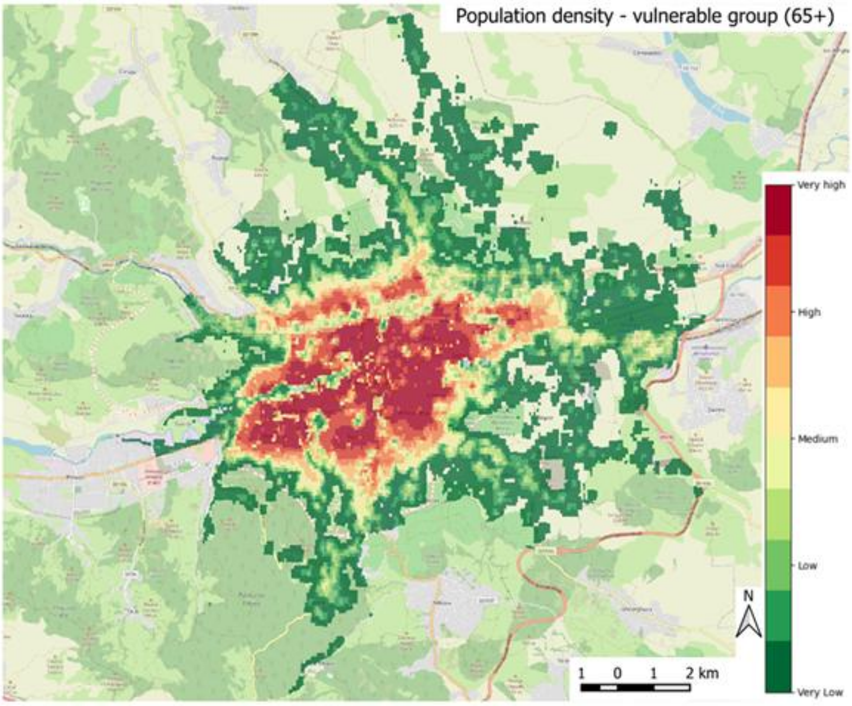
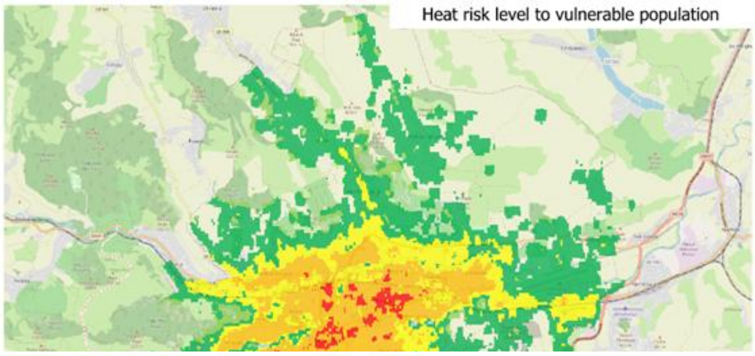


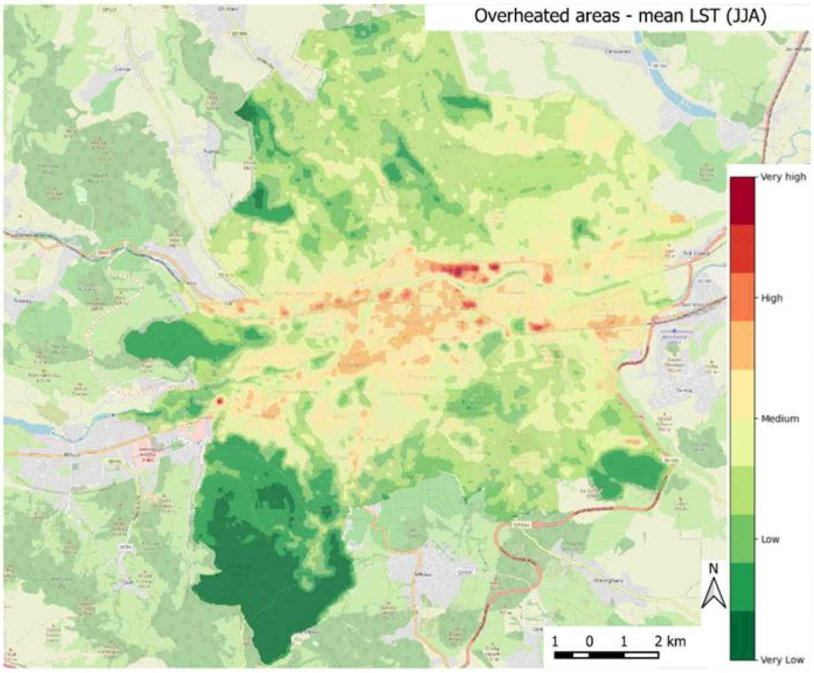
Fig. 2-20. Vulnerability map for Cluj-Napoca city.

The exposure map closely mirrors the overall spatial distribution of SUHI hotspots across Cluj-Napoca, highlighting clear spatial contrasts in heat exposure within the urban area. The highest exposure levels are concentrated mainly in the northeastern, northern, and eastern parts of the city, where exposure values range from high to very high. These areas are generally characterized by dense former industrial environments (brown fields) or newly built-up commercial areas, extensive impervious surfaces, and limited green infrastructure, which contribute to the accumulation and persistence of elevated surface temperatures. By contrast, the central part of the city, corresponding largely to the historic core (old city), exhibits medium to high levels of heat exposure (Fig. 2-21). Although this area benefits from some shading and urban morphology that can locally moderate temperatures, high building density and intense human activity still result in considerable exposure to elevated thermal conditions. Overall, the exposure map emphasizes the strong influence of urban form and land use on spatial patterns of heat exposure and provides critical information for identifying areas where heat mitigation measures may be most urgently needed.

Fig. 2-21. Exposure map for Cluj-Napoca city.

The risk map highlights pronounced spatial differences in heat-related risk across Cluj-Napoca, revealing areas exhibiting high to very high vulnerability, typically associated with older, more densely built neighbourhoods and more sensitive population groups, tend to coincide with elevated risk levels. Very high risk levels were identified in the central and eastern parts of the city, along with several localized high-risk hotspots in the western extremity (Fig. 2-22). These patterns emerge from the combined influence of the hazard, vulnerability, and exposure components, reflecting their cumulative effect on overall risk. In particular, the spatial configuration of the risk map shows a stronger correspondence with the vulnerability distribution, as areas characterised by high to very high vulnerability, often associated with older, denser neighbourhoods and more sensitive population groups, tend to exhibit the highest risk levels. This effect is further reinforced in the eastern and central zones by elevated exposure to SUHI hotspots, where persistent high LST





amplifies thermal stress. By contrast, peripheral areas with lower vulnerability and, in some cases, reduced exposure generally display lower risk values. The resulting risk map underscores the critical role of population sensitivity in shaping heat-related risk patterns and provides a robust basis for prioritising adaptation and mitigation measures in the most affected urban areas.

Fig. 2-22. Heat-related risk for Cluj-Napoca city.

2.3.3.3. Hazard assessment for river flooding using river discharge statistics

Due to the limited availability of scenario-based projections within the local hydrological datasets, an additional assessment was performed using the Flood River Discharge Analysis workflow. This analysis focused on the hydrometric station located in Cluj-Napoca. River discharge projections were evaluated using outputs from six GCM–RCM combinations under RCP4.5 and RCP8.5 scenarios for three future time horizons: early century (2011–2040), mid-century (2041–2070), and end-century (2071–2100).

Model performance was validated against observed multiannual monthly discharge values recorded at the hydrometric station. The comparison between measured and modeled discharges indicates a strong agreement, with a Pearson correlation coefficient of $r = 0.86$ ($p < 0.001$), an RMSE of 4.45, a mean bias of −1.15, and a Nash–Sutcliffe Efficiency of 0.72, demonstrating the model's ability to reproduce the observed seasonal discharge dynamics with satisfactory accuracy.

The analysis is based on the SMHI hydrological climate impact indicators dataset, accessed via the Copernicus Climate Data Store, which provides discharge projections derived from a European-scale hydrological model forced by multiple climate model combinations. This ensemble-based framework enables a robust assessment of both changes in mean seasonal discharge and alterations in extreme flow conditions under future climate scenarios.

Results indicate a progressive modification of the seasonal flow regime relative to the historical reference period (1971–2000). While the overall seasonal pattern is preserved, winter and early spring discharges are projected to increase under both scenarios, particularly toward the end of the century and under RCP8.5, whereas late summer and early autumn flows tend to remain stable or decrease slightly. Increasing divergence among individual GCM–RCM simulations in the long-term highlights growing uncertainty, underscoring the importance of ensemble interpretation (Fig. 2-23).

Extreme discharge analysis for 10-year and 50-year return periods reveals a general intensification of high-flow events across all future periods. Increases are more pronounced for higher return periods and later time horizons, with ensemble median projections under RCP8.5 indicating increases exceeding 30–40% by the end of the century for the 50-year event. These findings suggest a non-linear amplification of flood extremes in response to climate forcing.

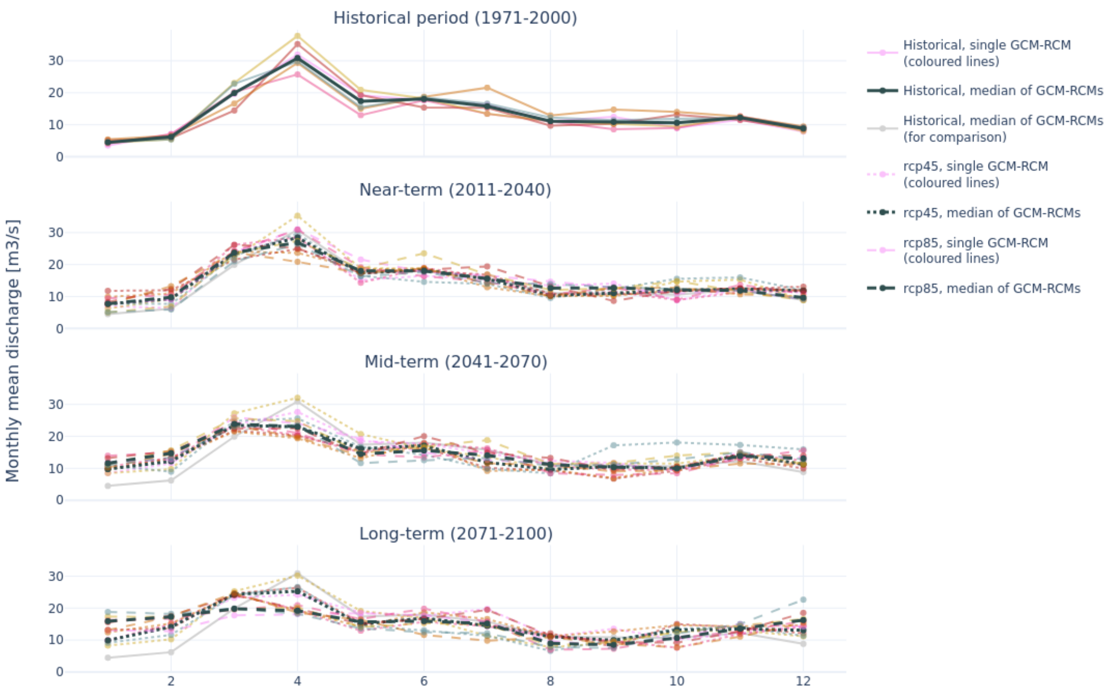


Fig. 2-23. Monthly mean river discharges for different GCM-RCM combinations.

The analysis indicates a progressive increase in extreme river discharges from the historical period toward future time slices for both the 10-year and 50-year return periods (Fig. 2-24). Median projections under RCP4.5 and RCP8.5 show higher discharge values compared to the historical reference, with the largest increases generally occurring toward the late-century period (2071–2100). The spread among individual climate model simulations highlights uncertainty, but the overall signal suggests a strengthening of flood-generating flows under future climate conditions, particularly for higher return periods.

Overall, the combined changes in seasonal discharge and extreme flow magnitude indicate an increasing flood hazard, particularly during winter and spring. The results provide a robust quantitative basis for climate-informed flood hazard and risk assessments, supporting the integration of future discharge projections into floodplain management, infrastructure planning, and long-term climate adaptation strategies, while explicitly accounting for scenario-related uncertainty.

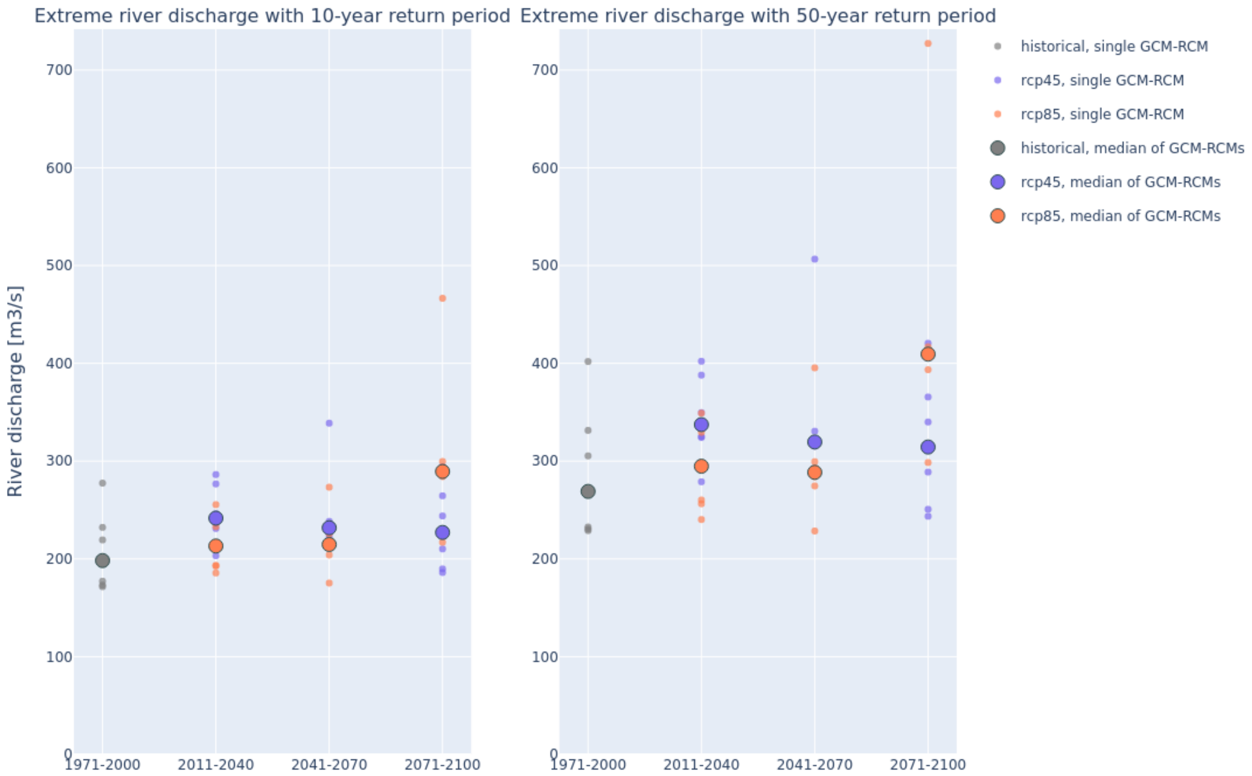


Fig. 2-24. Extreme river discharges for different GCM-RCM combinations.

2.4. Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

Stakeholder engagement for risk evaluation in Phase 2 builds on the participatory processes described in Section 2.1.5 and focuses specifically on the feedback gathered in relation to the climate risk assessment results and prioritisation. Engagement activities enabled stakeholders, experts, and representatives of priority groups to reflect on the assessed severity, urgency, and implications of the identified climate risks.

Feedback collected during stakeholder consultations largely validates the findings of the risk assessment and provides valuable insights into operational constraints, governance challenges, and opportunities for strengthening climate risk management within the Cluj Metropolitan Area. Stakeholders emphasized both the relevance of the identified priority risks and the need for targeted interventions and capacity building.

Synthesis of Stakeholder Feedback on Risk Assessment Findings

- **Pluvial Flood Risk and Infrastructure Gaps.** Stakeholders expressed a high level of concern regarding pluvial (stormwater) flooding, particularly due to its sudden onset and increasing frequency. Existing urban drainage infrastructure was widely recognized as aging and undersized, leading to limited capacity during intense precipitation events. This feedback aligns with the assessment results, which indicate that flood risk within the urban core is increasingly dominated by pluvial processes linked to high imperviousness. The need for a dedicated Stormwater Management Plan (PMAP) emerged as a recurring priority, with an emphasis on strengthening both the technical and physical capacity to manage pluvial flood hazards.

- **Mainstreaming Nature-Based Solutions (NBS).** Planning and environmental experts strongly advocated for the systematic integration of blue–green infrastructure and peri-urban sponge solutions to improve stormwater retention and delay runoff generation. Stakeholders emphasized that a continued reliance on conventional grey infrastructure alone leaves critical gaps in resilience and supported the project's objective to promote nature-based solutions as complementary adaptation measures.
- **Knowledge Transfer and Public Awareness.** Representatives from public authorities and emergency management institutions highlighted a persistent gap in public awareness and effective risk communication, particularly regarding long-term climate risks and adaptation needs. The development of targeted education and awareness programmes was identified as essential for strengthening human and social adaptive capacity to both heatwaves and floods.
- **Cross-Sectoral Coordination and Governance.** Stakeholder discussions revealed the need for clearer allocation of responsibilities and improved coordination mechanisms among institutions managing interconnected climate risks. Participants from the private sector expressed interest in contributing to preventive measures, pointing to opportunities for broader stakeholder engagement and resource mobilisation in subsequent project phases.

Overall, stakeholders confirmed heatwaves and floods as high-priority climate risks for the Cluj Metropolitan Area, while simultaneously highlighting key challenges related to implementation capacity, governance structures, and societal awareness. This feedback reinforces the relevance of the Phase 2 prioritisation and provides important guidance for the action-oriented work planned in Phase 3.

2.4.2 Gather output from Risk Analysis step

The risk evaluation in Phase 2 is based on a comprehensive set of outputs generated during the Risk Analysis step, which combined hazard characterization, exposure assessment, and interpretation of future climate projections. These outputs provide the analytical foundation for assessing risk severity, urgency, resilience capacity, and overall risk priority.

2.4.3 Assess Severity

The severity of climate-related risks in the CMA was assessed for both current and future conditions, in accordance with the CLIMAAX Key Risk Assessment Protocol. Severity was evaluated qualitatively and categorized as limited, moderate, substantial, or critical, based on the interpretation of quantitative risk analysis outputs, observed historical trends, projected climate impacts, and contextual information relevant to the regional socio-economic and environmental setting.

Heatwaves

Under current climate conditions, HWs in the CMA are assessed as posing a substantial to critical severity risk (Fig. 2-25). Observational evidence indicates an increase in the frequency, duration, and intensity of HW events over recent decades, with pronounced impacts in densely built-up urban areas due to the SUHI effect. Current impacts include increased heat-related health stress, particularly among elderly populations, children, and individuals with pre-existing conditions; elevated energy demand for cooling; and reduced thermal comfort in public spaces. While these impacts are largely manageable under present conditions, they already exert measurable pressure on public health services and urban infrastructure.

For future climate conditions, HW severity is assessed as critical, as well (Fig. 2-25). Climate projections for the region indicate continued intensification of extreme temperature events, with more frequent and prolonged HWs expected during the summer season. The combination of rising background temperatures, urban expansion, and demographic ageing significantly increases the potential for high human impacts, including excess mortality during extreme events, reduced labour productivity, and heightened stress on energy and healthcare systems. Potential cascading effects include disruption of critical services, amplification of air pollution episodes, and increased social vulnerability in disadvantaged neighbourhoods. From this perspective, future HW risk in the CMA will reach critical severity, particularly in the absence of effective adaptation measures.

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

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

Fig. 2-25 The evaluation dashboard

Floods (Fluvial and Pluvial)

Flood risk in the CMA exhibits a spatially differentiated severity profile, reflecting the coexistence of riverine and pluvial flooding processes across urban, peri-urban, and rural areas.

Under current conditions, flood severity is assessed as moderate to substantial (Fig. 2-25). Within the urban core of Cluj-Napoca, large-scale riverine flooding along the Someșul Mic River has been substantially reduced through hydrotechnical regulation; however, pluvial and urban flash floods driven by short-duration, high-intensity rainfall events remain a significant concern. These events frequently affect transport infrastructure, residential areas, and public utilities, leading to traffic disruptions, property damage, and localized economic losses. In peri-urban and rural settlements, particularly along the floodplain of the Someșul Mic and its tributaries (Nadăș and Gădălin), riverine flooding continues to pose significant risks to agricultural land, housing, and local infrastructure.

For future conditions, flood risk severity is assessed as substantial, with the potential to become critical in specific locations (Fig. 2-25). Projections of increased extreme precipitation intensity and seasonal discharge variability, consistent with European-scale assessments, indicate a higher likelihood of damaging flood events. The spatial extent of flooded areas, particularly during events with return periods of 100 years and above, is expected to increase, affecting a larger number of people and assets. Potential cascading effects include prolonged disruption of transportation networks, damage to critical infrastructure, loss of agricultural productivity, and degradation of floodplain ecosystems. While widespread irreversible impacts are not anticipated at the metropolitan scale, localized high-impact events with long recovery times justify a classification approaching critical severity in the most exposed zones.

Stakeholder Perspectives and Risk Perception

Stakeholder consultations and expert input played an essential role in refining the severity assessment. Local authorities, technical experts, and practitioners emphasized the underestimated social impacts of both HWs and floods, particularly for vulnerable groups and informal urban areas. Stakeholders highlighted challenges related to limited awareness, uneven access to cooling and protective infrastructure, and insufficient integration of climate risk knowledge into spatial planning processes.

Although decision makers in the CMA generally demonstrate a solid technical understanding of flood risk—largely due to existing regulatory frameworks—awareness and preparedness regarding HW impacts remain comparatively lower, especially in the context of long-term climate change projections. This disparity reinforces the assessment of increasing severity for both hazards under future conditions and underscores the need for targeted capacity-building and adaptation planning.

2.4.4 Assess Urgency

The urgency of climate-related risks in the CMA was assessed in accordance with the CLIMAAX Risk Evaluation Protocol, considering anticipated temporal evolution, rate of change, event persistence, and the time required to implement adaptation measures effectively. Urgency was evaluated qualitatively and classified into one of four categories: no action needed, watching brief, more action needed, and immediate action needed.

Heatwaves

The urgency of HW risk in the CMA is assessed as *more action is needed* (Fig. 2-25). HWs have already increased in frequency and duration over recent decades, and their impacts are becoming increasingly visible, particularly in the urban core of Cluj-Napoca. Although existing coping mechanisms (e.g., medical services, informal behavioural adaptation) mitigate some impacts, they are insufficient to address growing exposure and vulnerability. Climate projections consistently indicate a significant worsening of heat-related hazards in the near to medium term, with higher probabilities of prolonged and intense HW events. The risk severity is expected to increase substantially from current to future conditions, particularly due to demographic ageing, expanding impervious surfaces, and the amplification of the UHI effect. HWs are partly slow-onset processes (gradual temperature increase) but manifest through sudden extreme events, which can result in acute health crises and elevated mortality. Their seasonal persistence during summer months further reinforces urgency, as repeated events can erode adaptive capacity over time.

The current severity level, combined with clear upward trends, indicates that action cannot be postponed without increasing future damage.

Stakeholder and expert consultations emphasized that decision-makers and vulnerable groups often underestimate the urgency of HW risk compared to more visible hazards such as floods. Public health experts highlighted the limited lead time available during extreme heat events and the long planning horizon required to implement structural adaptation measures (e.g. urban greening, building retrofitting). These perspectives support the classification of future HW risk as requiring immediate action, including both short-term preparedness and long-term structural interventions.

Floods (Riverine and Pluvial)

For current conditions, flood risk urgency in the CMA is assessed as *more action needed* (Fig. 2-25). Flooding is already a recurring hazard, with pluvial and flash floods occurring during short-duration, high-intensity rainfall events, and riverine flooding continuing to affect peri-urban and rural areas. The sudden-onset nature of these events, combined with limited lead times, means that delayed action can result in immediate damages to infrastructure, housing, and economic activities. Although existing flood protection and emergency response mechanisms reduce impacts, observed trends and recent events indicate that the current level of preparedness is insufficient to address increasing exposure.

Under future conditions, flood urgency approaches immediate action needed, particularly for pluvial flooding in urban areas and riverine flooding in floodplain zones. Climate projections suggest an increase in the intensity and variability of extreme precipitation and seasonal discharges, leading to higher probabilities of damaging flood events in the near to medium term. The risk severity is therefore expected to increase from current to future conditions, with a shortening window for effective intervention.

Flood hazards in the CMA are predominantly sudden-onset events, especially pluvial and flash floods, which significantly raise urgency due to limited warning time and the potential for cascading impacts (e.g., traffic disruption, utility damage, emergency service overload). At the same time, flood risk exhibits some persistence, as repeated events may affect the same vulnerable areas, gradually degrading infrastructure and increasing long-term vulnerability.

Stakeholder input highlighted that while technical capacity for flood response is relatively strong, long-term preventive and adaptive measures often require extended planning, coordination, and investment. Experts stressed that without timely action—particularly regarding nature-based solutions, improved drainage, and spatial planning controls—future flood risks may escalate beyond manageable levels. These considerations reinforce the classification of future flood risk urgency as immediate action needed in the most exposed areas of the CMA.

Overall, both HWs and floods demonstrate a clear escalation in urgency from current to future conditions in the CMA. The combination of increasing hazard intensity, high exposure, limited adaptation lead time, and potential persistence of impacts justifies moving from reactive management toward proactive and anticipatory CRM. Stakeholder and expert perspectives consistently support the need for accelerated action, particularly in integrating climate risk considerations into urban planning, public health preparedness, and infrastructure investment strategies.

2.4.5 Understand Resilience Capacity

Resilience capacity in the CMA was assessed qualitatively in accordance with the CLIMAAX Risk Evaluation Protocol, considering the *financial, human, social, physical,* and *natural dimensions* of capacity relevant to CRM. The assessment focused on the extent to which existing measures, institutional arrangements, and resources can reduce current and future impacts, as well as on the presence of gaps or limitations that may constrain effective adaptation. Based on this evaluation, resilience capacity is classified as low, medium, substantial, or high, separately for HWs and floods.

The evaluation draws on outputs from the regionalized risk analysis, a review of existing policies and technical measures, and insights obtained through stakeholder and expert engagement.

Heatwaves

The overall resilience capacity of the CMA to HW risk is assessed as *high* (Fig. 2-25).

From a *human and social capacity perspective*, the region benefits from a well-developed healthcare system, academic expertise, and access to climate and public health knowledge through local universities and national institutions. However, awareness of heat-related risks among the general population remains uneven, and targeted preparedness measures for vulnerable groups (e.g. elderly people, children, outdoor workers) are still limited. Formal HW action plans and systematic early-warning response protocols are not yet fully institutionalized at the metropolitan scale.

In terms of *physical capacity*, basic meteorological monitoring and forecasting systems are in place at national level, enabling advance warnings for extreme temperature events. However, the translation of these warnings into locally coordinated response actions—such as the activation of cooling shelters, public advisories, and emergency response protocols—remains fragmented. Operational measures aimed at protecting the population from heat stress, with particular attention to vulnerable groups, are implemented during periods of extreme heat. These include the provision of free drinking water at designated points in highly frequented public areas, as well as the installation of temporary shading structures or tents in public squares, pedestrian zones, and other exposed locations. Such measures are intended to reduce direct heat exposure and mitigate immediate health risks during heatwave events. In addition, the municipality collaborates with local pharmacies, which function as community support points during heatwaves. Pharmacies provide access to drinking water, basic guidance on preventing heat-related health effects, and in some cases temporary refuge from extreme temperatures. This cooperation extends the local heat-response network and improves the accessibility of support services, particularly for elderly residents and other heat-sensitive groups.

Despite these measures, urban infrastructure remains highly exposed to heat stress, as limited shading, insufficient green–blue infrastructure, and a high proportion of impervious surfaces continue to intensify UHI effects..

Natural capacity is constrained by ongoing urban expansion and limited continuity of green corridors, despite the presence of parks and peri-urban green areas. While these areas provide some mitigation of heat stress, their distribution is uneven, and ecosystem-based cooling services are not yet systematically integrated into urban planning.

Regarding *financial and policy capacity*, the CMA has access to national and European funding instruments for adaptation, but heat-specific measures compete with other development priorities. Although strategic documents increasingly acknowledge heat-related risks, concrete, enforceable regulations targeting heat adaptation (e.g. building standards, urban design requirements) are still at an early stage.

Overall, while the CMA demonstrates a moderate ability to cope with current HW impacts, existing capacities are insufficient to effectively manage the current and projected increase in HW severity and frequency, justifying a classification of medium resilience capacity, with clear scope for improvement through targeted interventions.

Floods (Riverine and Pluvial)

The CMA's resilience capacity to flood risk is assessed as *substantial*, though with significant spatial and thematic disparities.

From a *physical and technical capacity* standpoint, significant flood protection infrastructure is already in place, particularly along the Someșul Mic River, including channel regulation works and flood defence structures that have substantially reduced the likelihood of large-scale riverine flooding within the urban core of Cluj-Napoca. In addition, flood hazard maps, the early-warning system, and established emergency response mechanisms are available through national institutions, providing a solid foundation for flood risk management.

Institutional and human capacity for flood response is relatively strong, supported by clear legal responsibilities, technical expertise within water management authorities, and experience with past flood events. Emergency services and local authorities are familiar with flood response procedures, and coordination mechanisms are generally functional.

However, pluvial and flash flooding represent a much more complex challenge. Urban drainage systems are often undersized for extreme rainfall events, and adaptation measures targeting surface runoff management (e.g. sustainable drainage systems, retention areas) are not yet widespread, or they become ineffective due to the severe rain showers' intensity, leading to soil erosion and massive solid mass transportation (soil, leaves, tree branches, other solid materials) and pluvial sewage system clogging. This represents a key weak spot in the current resilience framework, particularly in rapidly urbanizing areas.

From a *natural capacity* perspective, floodplains along the Someșul Mic and its tributaries retain some buffering capacity, but past land-use changes and ongoing development pressures have reduced their effectiveness in certain locations. Nature-based solutions, such as floodplain restoration or enhanced retention areas, are recognized in strategic planning documents but are only partially implemented.

In terms of *financial and policy capacity*, flood risk management benefits from stronger regulatory backing and dedicated funding channels than HWs do. Insurance mechanisms, hazard mapping, and legally defined protection zones further reduce residual risk. Nevertheless, long-term financing for transformative measures, particularly those addressing climate change-driven increases in flood magnitude, remains uncertain.

Overall, while the CMA demonstrates a substantial capacity to manage current flood risks, especially riverine flooding, this capacity is unevenly distributed and less effective for pluvial flooding under future climate conditions.

In summary, the CMA's resilience capacity differs between the two assessed hazards. Flood risk management benefits from a relatively strong institutional, technical, and regulatory framework, supporting a classification of substantial resilience capacity, albeit with notable gaps related to urban pluvial flooding and ecosystem-based solutions.

By contrast, HWs resilience capacity remains moderate, constrained by limited targeted measures, insufficient integration into spatial planning, and uneven awareness and preparedness among vulnerable groups.

Stakeholder and expert input consistently emphasized the need to move beyond reactive responses and to strengthen anticipatory and preventive capacities, particularly through integrated urban planning, nature-based solutions, enhanced public awareness, and improved cross-sectoral coordination. A recurrent concern highlighted during consultations was the insufficient dissemination of climate risk information to the wider society, including limited understanding of risk severity, early warning messages, and individual preparedness measures. Strengthening risk communication and knowledge transfer was therefore identified as a key prerequisite for effective climate adaptation, alongside technical and infrastructural interventions. These findings highlight resilience capacity as a critical factor influencing overall risk prioritization and underscore the importance of targeted investments not only in physical measures, but also in education, communication, and stakeholder engagement, in order to address identified weaknesses under current and future climate change scenarios.

2.4.6 Decide on Risk Priority

Risk priority in the CMA was determined through an integrated qualitative evaluation of severity, urgency, and resilience capacity, in accordance with the *CLIMAAX Risk Evaluation Protocol* and using the standardized evaluation dashboard as a synthesis tool (Fig. 2-25). This step represents the final stage of the Key Risk Assessment and aims to identify climate risks that require immediate and strategic intervention, as well as those that warrant continued monitoring.
The prioritization process followed three consecutive steps:

1. Integration of severity (current and future)
2. Combination with urgency assessment
3. Modulation by resilience capacity

Applying this framework through the evaluation dashboard led to the following prioritization outcomes:
HWa were classified as a *very high priority risk*, driven by critical severity under both current and future conditions, high urgency, and medium resilience capacity. The combination of escalating health impacts, strong urban amplification effects, and insufficient targeted adaptation measures makes HWs a top priority for immediate and long-term CRM in the CMA.
River flooding was classified as a *moderate risk*. Although resilience capacity is assessed as substantial due to existing flood protection infrastructure and institutional arrangements, high current and future severity combined with elevated urgency justify its prioritization. Particular attention is required for peri-urban and rural floodplains and for managing future climate-induced increases in flood magnitude.
The evaluation dashboard (Figure 2-25) provides a transparent and reproducible visual summary of this prioritization logic, clearly illustrating how the interaction between severity, urgency, and resilience capacity leads to differentiated risk priorities. This integrated approach ensures that prioritization is not driven by hazard occurrence alone, but by a balanced consideration of impacts, time pressure, and adaptive capacity, consistent with the objectives of the CLIMAAX framework.
The resulting risk priorities serve as a robust basis for guiding CRM actions in Phase 3, supporting informed decision-making on where adaptation efforts, investments, and stakeholder engagement should be concentrated to maximize long-term resilience under climate change.

2.5. Monitoring and Evaluation

The Monitoring and Evaluation (M&E) component of Phase 2 of the CRA for the CMA focused on reflecting upon the added value, limitations, and learning outcomes of the regionalized risk analysis and the key risk assessment process. This step supports continuous learning and provides a basis for improving both the assessment methodology and future CRM actions.

2.5.1. Key Lessons Learned and Challenges Encountered

The second phase of the CRA demonstrated the significant added value of higher-resolution datasets and locally adapted methodologies for identifying climate-related risks at metropolitan and intra-urban scales. The refined spatial resolution enabled a clearer differentiation among urban, peri-urban, and rural risk profiles, particularly for HWs and floods, and improved the relevance of results for spatial planning and sectoral decision-making. Also, the refined spatial resolution in the case of HWs showed a much more critical situation than the sparse resolution provided by the RCM output.

The most significant challenges encountered during Phase 2 were related to data availability and integration. While hazard datasets showed substantial improvement in spatial resolution, limitations remained in land-use, socio-economic, and health-related exposure data, which constrained the ability to fully quantify impacts on vulnerable groups and reduced the precision of risk estimates. Additionally, the processing and harmonization of very large raster datasets required advanced technical workflows, increasing the complexity and time requirements of the analysis.

2.5.2. Role of Stakeholders in Monitoring and Evaluation

Stakeholders played a central role in the M&E process by contributing contextual interpretation, validating assumptions, and critically reflecting on the relevance of the CRA outputs for policy and practice. Their input was particularly valuable in translating technical results into practically meaningful risk narratives, especially for decision makers and local authorities.

Feedback from stakeholders emphasized the importance of:

- clearer communication of climate risks to the general public,
- stronger links between risk assessment outputs and concrete policy instruments,
- and improved coordination between sectors involved in urban planning, water management, health, and emergency response.

Stakeholders also highlighted the potential of the CRA to inform local adaptation strategies, spatial planning regulations, and funding priorities, reinforcing its relevance beyond purely analytical exercise.

2.5.3. Ensuring Learning and Adaptive Improvement

Learning is ensured through an iterative assessment approach, whereby findings from Phase 2 directly inform the prioritization of risks and the design of adaptation measures in Phase 3. Continuous learning is further supported by:

- documentation of methodological choices and limitations;
- integration of stakeholder feedback;
- and comparison of results with previous assessments and national or European reference frameworks.

This adaptive process allows the CRA to be updated as new data, tools, or policy requirements emerge.

2.5.4. Data Availability and Remaining Needs

Phase 2 benefited from the availability of improved hazard datasets for both HWs and floods. However, the assessment identified a continuous need for higher-resolution population and socio-economic vulnerability data, health impact data linked to extreme heat at the sub-municipal scale, consistent and long-term urban monitoring datasets (e.g. surface temperature, runoff and drainage performance), and further research on compound and cascading risks.

Addressing these gaps would significantly enhance future risk assessments and improve the robustness of monitoring efforts.

2.5.5. Communication of Results

Clear and accessible communication was identified as a prerequisite for ensuring uptake of results and strengthening societal resilience. The final outcomes of the CRA are intended to be communicated through a multi-level and multi-format dissemination strategy, including:

- technical reports and policy-oriented summaries for decision makers;

- visual materials and maps to support spatial planning processes;
- presentations and workshops targeting stakeholders and practitioners;
- and public-facing communication to raise awareness and improve societal understanding of climate risks.

2.5.6. Monitoring Systems and Ongoing Risk Tracking

No fully integrated metropolitan-wide monitoring system currently exists that simultaneously address all analyzed risks. The national early-warning system is already in place, and it covers floods and extreme temperatures (HWs). The CRA highlights the need to better integrate these systems and align them with long-term climate adaptation objectives, including systematic tracking of risk indicators and adaptation effectiveness.

2.5.7. Performance Reflection: What Worked Well and What Did Not

The use of the CLIMAAX Framework and standardized protocols worked well in structuring the assessment and ensuring methodological transparency and comparability. The combination of quantitative risk analysis with qualitative expert and stakeholder input proved effective in capturing both technical and social dimensions of risk. Conversely, limitations in data granularity and the time required for advanced data processing constrained the scope of certain analyses.

2.5.8. Resource Efficiency and Impact on the CRA

Available resources in terms of time, staff expertise, and financial means were used efficiently by prioritizing high-impact analyses and leveraging existing datasets and institutional knowledge. While the intensive data-processing requirements increased the workload, they also resulted in substantially improved analytical detail, positively impacting the overall quality of the CRA.

2.5.9. Overall Impact of the CRA

Overall, the CRA significantly improved the understanding of climate risks in the CMA by enhancing awareness among stakeholders and decision makers, strengthening institutional capacity to interpret and prioritize climate risks, supporting evidence-based planning and adaptation discussions, and providing a credible basis for future funding applications and investment decisions.

The assessment thus represents an important step toward more systematic, informed, and proactive CRM at metropolitan scale.

2.6. Work plan Phase 3

The final phase of the project (Phase 3) will focus on a detailed analysis of the existing strategic and planning documents at the CMA scale, conducted to assess if the considered hazards and climate risk identified in Phase 2 are addressed. Phase 3 will deliver recommendations for a coherent and policy-relevant set of adaptation measures for the CMA to be further included in strategic documents, demonstrating how CRA results can be effectively transformed into actionable guidance for climate adaptation planning and climate-resilient development. The next actions are foreseen:

(i) Operationalisation of key risk priorities: Phase 3 will start with a structured follow-up of the key risk assessment findings, using the prioritisation of HWs and floods as the analytical entry point. The objective is to ensure a clear and traceable link between assessed risk characteristics and proposed adaptation responses.

(ii) Identification and assessment of adaptation measures building on existing measures already implemented in the CMA, gaps and weaknesses identified in the resilience capacity assessment, and relevant best practices and guidance from European and national adaptation frameworks. The

analysis will consider grey, green, and soft measures, including urban planning interventions, nature-based solutions, early-warning and preparedness actions, governance and policy instruments, and awareness-raising initiatives. Measures will be assessed qualitatively in terms of effectiveness, feasibility, co-benefits, and alignment with local governance structures.

(iii) Stakeholder validation and co-design through reviewing and validating proposed adaptation measures and pathways. Engagement activities will focus on assessing practical feasibility, institutional responsibility, and social acceptability, ensuring that the final recommendations are grounded in local realities and benefit from cross-sectoral perspectives.

(iv) Linkage to policy, planning, and monitoring will consist in the final set of proposed measures will be linked to relevant local and regional planning instruments, policy processes, and funding opportunities, highlighting how Phase 3 outcomes can support implementation beyond the project. Indicative monitoring indicators will be proposed to track adaptation progress and effectiveness over time.

Phase 3 will not aim to develop new quantitative hazard models or detailed cost-benefit analyses, as these fall beyond the project's scope and available resources. Likewise, implementation of adaptation measures will not be undertaken within the project timeframe. Instead, the focus will remain on strategic prioritisation, planning relevance, and decision support, ensuring that the Phase 3 outputs are directly usable by local authorities and stakeholders.

3. Conclusions Phase 2- Climate risk assessment (1-2 pages)

The second phase of the CRA for the CMA represents a significant step forward in developing a spatially explicit, evidence-based understanding of climate-related risks at the metropolitan scale. By applying the CLIMAAX framework and integrating improved datasets, new approaches, local expertise, and stakeholder perspectives, Phase 2 has deepened the analytical foundation established in Phase 1 and provided a robust basis for risk prioritisation and subsequent CRM actions.

A central achievement of Phase 2 is the regionalisation and refinement of risk analysis for the two priority hazards identified for the CMA (HW and floods). The use of finer spatial resolution data, particularly for hazard mapping, enabled a more nuanced representation of risk patterns across urban, peri-urban, and rural areas. This refinement proved essential for identifying localised hotspots of exposure and vulnerability that remain concealed in coarser, municipality-level analyses.

For HWs, the assessment confirms a clear and consistent increase in frequency, duration, and intensity under both current and projected future climate conditions. Urban areas within the CMA, especially the densely built-up zones of Cluj-Napoca, are highly sensitive due to the UHI effect. Phase 2 demonstrates that HW risk is no longer episodic but represents a systemic and growing threat to public health, energy systems, and urban liveability, particularly for vulnerable population groups.

In the context of floods, the analysis highlights the coexistence of distinct yet interconnected risk mechanisms. While riverine flooding along the Someșul Mic River has been partially mitigated in the urban core through hydrotechnical works, flood risk persists in peri-urban and rural floodplains. At the same time, pluvial and flash flooding has emerged as a dominant risk within the urban area, driven by intense rainfall events, extensive impervious surfaces, and limited drainage capacity. Phase 2 confirms that flood risk in the CMA is spatially heterogeneous and increasingly influenced by climate-driven extremes and land-use change.

The Key Risk Assessment step, integrating severity, urgency, and resilience capacity, allowed for a transparent and structured prioritisation of risks. HWs were classified as a very high priority, reflecting critical future severity, high urgency, and moderate resilience capacity. Floods were classified as a moderate priority, combining substantial severity and urgency with uneven but generally stronger resilience capacity. This prioritisation provides clear guidance for focusing adaptation efforts in the subsequent project phase.

Key Findings:

- *Risk severity increases markedly from current to future conditions* for both HWs and floods, underlining the importance of proactive adaptation rather than reactive response.
- *Urban areas act as hotspots* for climate impacts, particularly for HWs and pluvial flooding, while peri-urban and rural floodplains remain highly exposed to riverine flooding.
- *Resilience capacity is unevenly distributed*, with stronger institutional and technical capacity for flood management compared to HWs adaptation.
- *Non-structural measures*, such as public awareness, early warning communication, and governance coordination, are currently underdeveloped relative to the magnitude of the assessed risks.

- *An existing gap between technical understanding and societal awareness* was revealed by stakeholder engagement, especially regarding HW risks and long-term climate change impacts.

Phase 2 successfully addressed several challenges encountered in earlier project stages, notably the need for greater spatial detail and a structured approach to risk prioritisation. The integration of stakeholder perspectives also enriched the interpretation of quantitative results and supported a more socially grounded assessment.

Nevertheless, certain limitations remain. Despite improvements in hazard data resolution, socio-economic and health-related exposure data remain problematic, limiting the precision of vulnerability assessments. The absence of fully harmonised datasets for future socio-economic scenarios also limits the quantification of compound and cascading impacts.

4. Progress evaluation (1-2 pages)

This section summarizes the progress achieved during Phase 2 of the MECRA-Cluj project, highlighting the connections between this deliverable, its outputs, and the planned activities for the final project phase. Phase 2 builds directly on the outcomes of Phase 1 and represents a transition from tool testing and initial validation to a regionalized, high-resolution, and decision-oriented CRA.

4.1 Connection between Phase 2 Outputs and Subsequent Project Phases

Phase 2 represents a critical consolidation and refinement phase within the overall project structure. While Phase 1 focused on assessing the applicability of CLIMAAX tools in their original configuration and validating them against existing regional risk analyses, Phase 2 advanced the assessment through integration of higher-resolution hazard datasets for HWs and floods, application of locally adapted analytical workflows, systematic assessment of severity, urgency, and resilience capacity, and formal risk prioritisation using the CLIMAAX evaluation dashboard.
The outputs of this deliverable provide a robust and spatially explicit evidence base that directly supports the objectives of Phase 3, which will focus on the identification, prioritisation, and co-design of CRM and adaptation measures.

In particular, Phase 2 results enable Phase 3 to:

- focus adaptation planning on very high and high priority risks (HWs and floods),
- target identified spatial hotspots (urban, peri-urban, and rural),
- address gaps in resilience capacity revealed during the assessment,
- support stakeholder-validated, policy-relevant adaptation pathways.

Thus, Phase 2 acts as the analytical and strategic bridge between tool validation (Phase 1) and action-oriented adaptation planning (Phase 3).

4.2 Key Achievements of Phase 2

Compared to Phase 1, Phase 2 achieved significant methodological and operational progress:

- ➢ Hazard and risk analyses were conducted at substantially improved spatial resolution, enabling intra-urban and inter-settlement differentiation;
- ➢ Pluvial flooding was explicitly included alongside riverine flooding, reflecting urban flash-flood dynamics;
- ➢ HWs indicators were refined, allowing the identification of heat hotspot areas and revealing differences between low-lying, urban, and rural zones;
- ➢ Temporal analysis demonstrated that observed HW intensification exceeds modelled trends, strengthening the urgency of adaptation action;
- A structured risk prioritisation was completed, providing a transparent basis for decision-making;
- Stakeholder engagement moved from awareness-raising to interpretation and validation of results, reinforcing policy relevance.

Table 4-1 Overview key performance indicators

Key performance indicators	*Progress*
High-resolution hazard assessment	HW and riverine and pluvial flood hazards were assessed using refined spatial datasets, significantly improving local risk identification.
Risk assessment for priority hazards	Severity, urgency, and resilience capacity were evaluated for HWs and floods under current and future conditions.
Inclusion of pluvial flood dynamics	Pluvial and flash-flood scenarios were integrated alongside riverine flooding to address key urban risks.
Risk prioritisation completed	HWs were classified as *very high priority* and floods as *high priority* using the CLIMAAX evaluation dashboard.
Methodological enhancement	CLIMAAX workflows were adapted and documented to handle higher-resolution local datasets.
30 stakeholders involved in the activities of the project	Stakeholders have been involved during the second phase both in one to one informal meetings and also trough a formal meeting with a wider participation from public authorities, emergency and technical institutions, scientific and expert bodies, civil society/private sector

Table 4-2 Overview milestones

Milestones	*Progress*
CLIMAAX workflow successfully applied Downscaling and integration of hazard data	High-resolution datasets for HWs and floods were processed and incorporated into the CRA workflows.
Regionalized risk analysis completed	Localized risk patterns were identified at metropolitan, municipal, and LAU levels.
Evaluation of severity, urgency, and capacity	All components of the CLIMAAX Key Risk Assessment Protocol were applied and documented.
Risk prioritisation finalized	Priority risks were formally classified to guide Phase 3 actions.
Stakeholders meeting realized	A stakeholder meeting was held in January 2026, bringing together representatives of public authorities (City Hall), emergency and technical institutions (ISU Cluj, SGA Cluj, water companies), scientific bodies (ANM, Babeș-Bolyai University), and civil society and private sector organisations.
Phase 2 results shared and validated	Results were communicated to key stakeholders and expert partners, and feedback was integrated into this deliverable.

4.3 Overall Progress Assessment

Phase 2 successfully fulfilled its objectives by moving beyond exploratory assessment toward decision-relevant climate risk analysis. The phase addressed key challenges identified in Phase 1, particularly limitations in spatial resolution and hazard representation, while also revealing remaining gaps related to socio-economic and health data availability.

The deliverable confirms that the project is progressing on schedule with Phase 2 outcomes providing a strong and credible foundation for the selection and prioritisation of adaptation measures in Phase 3.

5. Supporting documentation (1-2 pages)

During Phase 2 of the CRA for the CMA, a comprehensive set of analytical, visual, and communication outputs was generated. These outputs reflect the transition from tool testing and validation (Phase 1) to a regionalized, high-resolution, and decision-oriented CRA. All outputs produced during this stage have been prepared for dissemination and are shared via the *Zenodo* repository in a structured, consistent order.

5.1. Main Report

The main report consists in the *Deliverable Phase 2 – Climate Risk Assessment (MECRA-Cluj)*, which comprehensively documents the application of the CLIMAAX framework at metropolitan scale, including refined hazard analyses for HWs and floods, assessment of severity, urgency, resilience capacity, and final risk prioritisation. The report presents methodological enhancements, regionalized results, stakeholder-informed interpretations, and directions for the Phase 3 actions.

5.2. Visual Outputs (Maps, Charts, Figures)

A wide range of visual materials was produced to support interpretation, communication, and decision-making, including:

- HW analysis outputs:
  - High-resolution maps identifying HWI, frequency, length and hotspot areas across the CMA;
  - Charts showing spatial variation of HW indices (frequency, duration, magnitude) at local administrative unit level;
  - Temporal evolution plots comparing observed and modelled HW indices under current and future conditions.
- Flood analysis outputs:
  - Flood hazard maps for riverine flooding at multiple return periods, including climate change scenarios;
  - Maps and charts illustrating pluvial flood extents under current and climate change conditions;
  - Charts presenting exposed and displaced population for fluvial and pluvial floods across different return periods;
  - Figures illustrating projected changes in extreme river discharge for selected return periods based on climate model ensembles.
- Risk assessment and prioritisation visuals:
  - Evaluation dashboard summarising severity, urgency, resilience capacity, and final risk priority.

5.3. Analytical Outputs (Tables and Data Products)

- Summary tables describing:
  - Severity, urgency, and resilience capacity scores for each analysed hazard;
  - Risk prioritisation outcomes for HWs and floods;
  - Population exposure and displacement estimates for different flood scenarios.

- Processed analytical datasets supporting figures and maps used in the report.

5.4. Communication Outputs

Phase 2 results were communicated to stakeholders and the broader public ensuring transparency and uptake. Presentation materials used to communicate Phase 2 findings, key risk priorities, and methodological advancements.

5.5. Datasets Collected and Generated

- High-resolution climate and hazard datasets used and processed during Phase 2, including:
  - HW indices derived from observational and modelled climate data;
  - Landsat data collection for SUHI hotspot detection;
  - Flood hazard maps for riverine and pluvial flooding scenarios.
- Tabular datasets (Excel/CSV) containing:
  - Aggregated indices at LAU scale;
  - Inputs and outputs supporting the risk evaluation dashboard.

All datasets and supporting materials are stored in the *Zenodo* repository to ensure transparency, traceability, and reuse. Due to data ownership and licensing constraints, as well as file size limitations, raw flood hazard raster datasets are not redistributed; instead, finalized derived products (maps, figures, and aggregated outputs) generated within the project are shared. This approach ensures open access to the project results while fully respecting data ownership conditions and practical dissemination constraints.

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