Deliverable Phase 1 – Climate risk assessment

Initiative for Climate-Proof Future of Banská Bystrica Region CLIMAAXInsight

Slovakia, Banská Bystrica Self-Governing Region

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

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Abbreviations and acronyms

Abbreviation / acronym	Description
CRA	Climate Risk Assessment
BBSGR	Banská Bystrica Self-Governing Region
BBR	Banská Bystrica Region
DRMKC	Disaster Risk Management Knowledge Centre
ECLIPS	European Climate Index Projections
FWI	Fire Weather Index
GDP	Gross Domestic Product
GHS	Global Human Settlement
CHELSA	Climatologies at High Resolution for Earth's Land Surface Areas
JRC	Joint Research Centre
KPI	Key Performance Indicators
LUISA	Land Use-based Integrated Sustainability Assessment
OSM	Open Street Maps
RCP	Representative Concentration Pathway
WUI	Wildland Urban Interface

Executive summary

This deliverable evaluates and implements the structured CLIMAAX methodology for climate risk analysis, focusing on its application in the Banská Bystrica region. The document summarizes the experience and outputs from the first 5 months of the project, including testing and implementing the CLIMAAX framework, handbook, and toolbox. It covers Phase 1, which involved risk identification, selection of climate scenarios, and validation of the methodology through four workflows for flood and wildfire hazards. It also highlights the interaction between the CLIMAAX project and the CLIMAAX Insights cascading project team. This information provides an overview of the potential and challenges of climate risk assessments in the regional context and outlines next steps to achieve practical outputs integration into the regional development and risk management.

Key Findings:

- ✓ **Methodology Validation** - The proposed climate risk assessment framework was successfully tested, demonstrating its applicability. However, some issues and areas for improvement were identified, particularly in workflows and results interpretation.
- ✓ **Risk and Vulnerability Identification** - The Banská Bystrica region faces high flood risk, particularly in the river basins of Hron and Slaná rivers basins. Projections indicate increasing flood frequency and intensity, which may cause significant damage to infrastructure, agriculture, and community operations. For wildfires, the region faces a moderate to high risk due to rising temperatures, prolonged dry periods, and forest health issues. The preliminary results confirmed our hypothesis that the most vulnerable areas in the near future will include those with monoculture spruce stands, which are already currently affected by abiotic and biotic factors.
- ✓ **Stakeholder Engagement and Challenges** - The initial stakeholders feedback was positive. However, the use of climate risk assessment outputs in decision-making and risk management will require intensive effort - continuous stakeholder engagement in future project phases, as well as improvement of the communication of the CLIMAAX outcomes.

Future Directions:

- ✓ **Data Availability and Standardization** - Limited availability and poor quality of climate data were identified as main potential constraint for next phases. Thus, phase 2 will focus on collaboration with national and regional data providers.
- ✓ **Continuous Methodology Improvement** - Further refinement of workflows is expected in Phase 2, particularly with respect to regional data specifics and availability.
- ✓ **Strengthening Stakeholder Engagement** - Ongoing engagement with data providers, municipalities, local authorities, and risk management actors is essential. The third phase of the project will focus on advocacy at the political and decision-making levels to ensure climate risks are recognized as critical political issues.

This project is expected to contribute to evaluating the application of the CLIMAAX methodology and toolbox, providing valuable insights that will help assess their broader applicability across different regions in Europe and support the standardization of climate risk assessment tools.

1 Introduction

1.1 Background

The Banská Bystrica Region (BBR) is Slovakia's largest by area (9,500 km²) but has the lowest population density, with 650,000 inhabitants across 516 municipalities and 24 towns. It is administratively managed by the Banská Bystrica Self-Governing Region (BBSGR), which oversees regional development, infrastructure, education, healthcare, and social services, while also serving as the project leader and grant beneficiary of this project.

BBR faces demographic challenges, including an ageing population and youth outmigration. By 2035, for every 100 young people, there will be 191 seniors, increasing demand for senior care. The average age will rise from 42 to 46 years. The region also struggles with high unemployment (over 10% in some districts), poverty, and energy poverty, particularly in rural and marginalized Roma communities. Its GDP accounts for only 8.8% of Slovakia's total, with GDP per capita among the country's lowest.

The economy is dominated by energy-intensive industries and public administration, with low climate resilience. Four districts rank among Slovakia's least developed, reaching just 57% of the EU-27 GDP per capita average. Spatial disparities in education, employment, and income further challenge regional development.

BBR's climate is shifting, with rising temperatures, drier conditions, and more extreme weather events. Studies link increasing temperatures to higher mortality rates, yet adaptation remains uncoordinated—only two cities have partial strategies, and community awareness is low. The DRMKC Vulnerability Index ranks BBR at 5.3 (above the national average of 4.4), with high physical (6.8) and economic (5.4) vulnerability.

In 2022, BBSGR joined the Mission Adaptation to Climate Change, committing to regional adaptation and supporting municipalities in their climate resilience efforts.

1.2 Main objectives of the project

We designed this project to establish enabling conditions at the regional level for climate adaptation. By conducting a risk assessment and integrating its findings into regional strategies and policies, we aim to create a solid framework upon which municipalities, local governments, and other regional development actors can build their own adaptation pathways and improve decision-making, based on reliable scientific data driven evidence. Additionally, this project will help us establish collaboration with key stakeholders, a crucial step toward the effective identification and implementation of relevant adaptation measures. To ensure broad accessibility and usability, we plan to share the project output as open data and make them publicly available. 3 main applications of project outputs are as follows:

1. **Refining Regional Policies**: the outcomes will play a pivotal role in refining regional policies, specifically the economic and social development program and environmental strategy of the region. While these policies address climate change, mitigation, and adaptation measures, they lack specific data for investment prioritisation and spatial planning. Importantly, it will contribute to elevating political will, emphasising the significance of climate change adaptation in regional strategies, and identifying specific locations and communities requiring targeted support and investments.

2. **Enhancing Civil Protection Preparedness**: used to bolster civil protection preparedness for climate-related hazards. Collaborating with the Regional Directorate of the Fire and Rescue Service and as a member of the Regional Security Council, the project aims to provide data enabling optimalization of intervention capabilities of firefighters. This includes recommendations for refining technical equipment, improving knowledge and skills, developing process maps, and implementing a tactical usability system.

3. **Raising Awareness and Cooperation**: Project outputs will be employed to communicate the seriousness of climate risks to local and regional self-government representatives, stakeholders, and residents. Given the low awareness of climate change risks in the region and the lack of relevant documents hindering local community resilience enhancement, these outputs aim to motivate entities to actively cooperate, prioritise investments, and enhance capacities in issues related to climate change.

The CLIMAAX Handbook is already showing several benefits, with more to emerge in the coming phases. It enhances comparability and knowledge exchange by facilitating regional comparisons and collaboration, which will strengthen informed decision-making as the project progresses. The open-access tools ensure long-term usability, allowing for continuous updates and improving risk assessments. This is expected to be particularly useful as methodologies are refined in later phases. The stakeholder-oriented approach, which integrates technical analysis with local engagement, fosters support and will improve over time. Climate scenarios play a crucial role in shaping adaptation strategies, with their full potential in policy alignment to be explored further. Accessible tools are strengthening local expertise, while standardized, evidence-based methodologies improve science-policy integration, transparency, and data-driven policymaking. The common framework enhances credibility and trust, supporting clearer communication with policymakers. The adaptable nature of the approach ensures scalability across governance levels, with further exploration of its flexibility in future phases. The improved risk assessment framework also increases eligibility for climate resilience funding. Finally, the project fosters innovation and collaboration, facilitating partnerships between public institutions, the private sector, and research organizations, with more expected in upcoming phases.

1.3 Project team

The project's core team was assembled based on the requirements of the call. In phase1, it consists of three core members. A detailed description of their roles and skills can be found in Table 1. In addition to the core team, which is directly responsible for executing tasks according to the project plan, we have a financial manager who ensures the proper implementation and compliance of the financial plan. Additionally, we collaborate - or we plan to collaborate in next phases — with other experts within our organization, including participation coordinators, urban planning specialists, a risk management specialist, and the communications department.

Table 1-1 Core team members, their skills and responsibilities.

Name	Position	Skills and previous experience	Framework assessment	Climate hazards	Climate risk assessment	Data handling	Programming
Andrea Rúfusová	Strategic planning specialist	Knowledge on the governance, stakeholders, objectives, and general understanding of climate risk in the region, along with expertise in the strategic framework and policies gained through experience in the development and implementation of strategic documents, particularly the environmental strategy.	x	x			
Martin Tuchyňa		Previous experience in climate risk assessments, geospatial and environmental infrastructures; knowledge how to handle datasets, on different levels, both local and global, knowledge of GIS and how to handle datasets in different projections; project management skills.		x	x	x	
Martin Jančovič		Previous experience in climate risk assessments; knowledge how to handle datasets, on different levels, both local and global, knowledge of GIS and how to handle datasets in different projections; data analysis skills that can modify and write scripts in the Python programming language.			x	x	x

1.4 Outline of the document's structure

This document is structured to provide a comprehensive overview of the Phase 1 Climate Risk Assessment for the Banská Bystrica Region. It begins with an introduction outlining the project's background, objectives, and team composition. The core of the document is dedicated to the climate risk assessment process, covering scoping, risk exploration, and analysis, followed by preliminary findings and recommendations. The final sections present conclusions, an evaluation of progress, and guidance for future project phases. Supporting materials, including references and relevant documentation, are provided at the end.

2 Climate risk assessment - phase 1

Climate risk assessment (CRA) of the CLIMAAXInsight project was prepared and executed, following CLIMAAX Framework, taking into the consideration specific requirements and conditions of the Banska Bystrica region. First set of the activities was focused on understanding and getting common interpretation of the CRA framework, key domain concepts, expectations towards the relevant stakeholders. Important role plays conceptual background, clarifying main principles to be considered in transformative adaptation deployment, technical choices and limitations, as well as importance of interaction with relevant stakeholders via participatory processes.

2.1 Scoping

During this initial step of CRA framework CLIMAAXInsight project team confirmed originally proposed selected climate-related hazards (floods and wildfires), based on information shared by the CLIMAAX project team, as well as analysis considering the conditions for implementation in the region. Based on that following objectives, context, participation and risk ownership aspects were addressed.

2.1.1 Objectives

The objective of the CRA directly feeds into policy and decision-making by providing a solid evidence base for regional climate adaptation planning. The risk assessment outcomes will be instrumental in shaping adaptation policies, prioritizing investments, strengthening cooperation among regional stakeholders, and enhancing communication and awareness of climate change issues. The following table outlines the objective, purpose, and expected outcomes of our CRA.

Table 2-1 Objective, purpose and expected outcomes of our CRA.

Objective of CRA	Purpose of CRA	Expected outcome of CRA
Identify, analyse, and evaluate the potential risks and vulnerability posed by climate change—specifically wildfires and floods—to our region, sector, and vulnerable groups.	**To establish a knowledge base** on the impacts of climate change on our territory, supporting informed and practical decision-making by regional and local governments, businesses, and communities. **To refine regional strategies and to enhance civil protection preparedness;** and improve evidence-based decision-making and projects prioritization. **To communicate the seriousness of climate risks** to local and regional self-government representatives, stakeholders, and residents, **and motivate them to action.**	A risk profile and scenario analysis outlining specific climate hazards and high-risk areas, with map **data available online as open data** for public use. **Recommendations and evidence-based solutions for refining regional policies and risk management strategies** that better address climate-related challenges. **Increased awareness and understanding of climate risks** among local and regional self-government representatives, stakeholders, and residents, leading to stronger engagement, informed decision-making, and proactive measures to enhance climate resilience.

The objective of the CRA directly feeds into policy and decision-making by providing a solid evidence base for regional climate adaptation planning. The risk assessment outcomes will be instrumental in shaping adaptation policies, prioritizing investments, strengthening cooperation among regional stakeholders, and enhancing communication and awareness of climate change issues.

The following table outlines the limitations and boundaries considered in our climate risk assessment, defining the responsibilities and measures to minimize risks.

Table 2-2 Limitations and boundaries for our climate risk assessment (CRA).

Risk and Constraints	*Responsibility*	*Risk Management*
Limited data availability and quality (limited data may affect the accuracy of risk projections)	Project team	We will conduct an analysis to identify available data sources, data providers, and assess data quality. We will actively engage with data providers to obtain necessary datasets, identify gaps (null data), and communicate our data needs to relevant institutions responsible for data provision.
Insufficient stakeholder involvement and public awareness	Project team	We will utilize various communication channels and create a dedicated webpage within the Open Data Portal of BBSGR - to publish open data but also provide interactive visualizations to effectively engage stakeholders and enhance accessibility to project insights. Additionally, we will create a space for feedback. Furthermore, even before submitting the project proposal, we had already discussed collaboration with the Regional Directorate of the Fire and Rescue Corps, ensuring early stakeholder involvement and support for project activities.
Limited Relevance of Outputs for Selected Hazards (Fires and Floods)	Project team	Despite our efforts, there is a risk that the project may not achieve sufficiently relevant outputs for the selected hazards. To mitigate this, we will strictly follow the established methodology and utilize the provided tools. Additionally, we will continuously consult any emerging issues with the support team/helpdesk to ensure the quality and relevance of our results.

2.1.2 Context

Our region is at a critical point in developing a structured approach to climate adaptation. Until now, our region has not developed a comprehensive climate risk assessment. Instead, we have relied on an existing national-level study (Adaptation measurement, 2023) - however, it categorizes the risk levels of individual municipalities only at the cadastral level. In addition, several partial studies and models exist, but they are not publicly accessible, often focusing on specific sectors without providing a holistic regional perspective.

Municipalities in our region face financial and technical constraints that hinder systematic climate adaptation. At the regional level, we have recognized the urgent need for a structured climate risk assessment as part of our smart governance initiatives (BBSGR Smart Strategy). While we have integrated climate adaptation into our Environmental Strategy (BBSGR Environmental Strategy) as a key principle, the lack of a structured risk assessment limits data-driven prioritization of adaptation measures. Most local actions remain ad hoc, driven by immediate needs rather than long-term strategy, emphasizing the need for a shared knowledge base for all stakeholders. Moreover, investments and actions aimed at mitigating climate impacts are not systematically monitored.

Our region also lacks a dedicated institutional framework for climate impact assessment. Although district offices play a key role in adaptation through crisis management, land-use planning, and environmental policies, strengthening their capacities and coordination would enhance preparedness. The Regional Security Council, operating under Act No. 387/2002 Coll. on Crisis Management, oversees disaster prevention, emergency response, and recovery, while rescue services ensure rapid intervention in climate-related disasters. The Regional Directorate of the Fire and Rescue Service in Banská Bystrica coordinates responses to extreme weather events such as floods, wildfires, and landslides. Additionally, most municipalities are required to establish Voluntary Fire Brigades under Act No. 314/2001 Coll., categorized by fire risk levels as per Decree No. 611/2006 Coll.

The main sectors vulnerable to climate change in our region are:

- Forestry and agriculture: These sectors have already experienced economic losses due to droughts, wildfires, flash floods, and related biotic and abiotic factors. Climate change exacerbates soil degradation, reduced crop yields, and forest health decline.
- Water Management: Irregular precipitation patterns, extreme droughts, and sudden floods create challenges for water availability, quality, and infrastructure resilience.
- Biodiversity and Ecosystems - Changing climates disrupt habitats and reduce ecosystem services.
- Disaster Response Organizations: These organizations, including fire and rescue services, face increased operational demands due to the rising frequency and intensity of climate-related disasters, which can challenge their effectiveness in protecting communities.
- Transport Infrastructure: Roads and bridges are increasingly affected by flooding, extreme heat, and landslides, leading to higher maintenance costs and safety concerns.
- Housing and Urban Development: Climate change increases risks to communities and property, particularly in flood-prone areas. Strengthening building regulations and urban resilience strategies is crucial.
- Tourism - affected are mainly ski resorts and water-dependent tourism destinations.
- Human and Animal health - Rising temperatures and extreme weather events increase heat-related illnesses, vector-borne diseases, and air pollution-related health issues.

Slovakia engages in international initiatives and EU-funded programs to support climate adaptation through knowledge exchange and best practices. However, regional efforts face several challenges. The absence of a strong legislative framework, due to the failure to pass the proposed Climate Law, slows progress in climate resilience. Unresolved conflicts between forestry management and ecosystem conservation, particularly regarding protected zones in national parks, hinder effective adaptation measures. Additionally, efforts to restore river basins and wetlands, which are crucial for climate resilience, suffer from insufficient financial and policy support, leading to degraded water ecosystems and heightened flood risks. A lack of cross-sectoral collaboration further complicates adaptation efforts, as academic institutions, public bodies, private stakeholders, and NGOs remain disconnected, with no established platform for regional knowledge-sharing.

2.1.3 Participation and risk ownership

As a first step, we conducted a stakeholder analysis and identified the following key stakeholders and their roles in adaptation process:

Table 2-3 Stakeholder analysis.

Stakeholder	Strategic planning	Decision-maker	Implementation of adaptation measures	Legislative and Regulatory Authority	Risk Management	Crisis Response and Emergency Management	Monitoring and Reporting	Data Providers	Environmentally responsible behavior	Public pressure and advocacy	Environmental education
Banská Bystrica Self-Governing Region	x	x	x	x	x		x				
Council BBSGR		x									
Municipalities and Cities	x	x	x	x	x	x	x	x			
Association of Towns and Communities										x	
District Offices		x		x	x		x	x			
The Regional Security Council					x	x					
Regional Directorate of the Fire and Rescue Corps	x					x	x	x			
Voluntary Fire Protection of Slovakia	x					x	x	x			x
Private and State Forest Managers	x		x				x	x		x	
Slovak Water Management Enterprise	x		x				x	x		x	
Agricultural Sector	x		x				x	x		x	
State Nature Conservation and National Park Administrations	x	x	x	x			x	x		x	x
Regional Tourism Organization	x	x						x		x	
National Forest Centre	x						x	x			x
National Agricultural and Food Center							x	x			
Slovak Hydrometeorological Institute							x	x			
Water Research Institute							x	x			
NGOs in Social and Environmental Sectors		x								x	x
Environmental Education Coordinators in Secondary Schools											x
General Public		x							x	x	

We have identified vulnerable population groups whose risk exposure is increased by socioeconomic, demographic, and environmental factors, limiting access to resources for prevention and response - please find detailed analysis in Table 2-6.

Many municipalities face high risks from wildfires and floods but lack sufficient prevention and preparedness efforts. To raise awareness of climate risks, we have planned activities to communicate outcomes, with specific objectives and target audiences outlined in Table 2-4.

Table 2-4 Communication objectives, target audiences, and communication channels.

Communication Objectives	Target audience	Communication Channel
Increase general awarness about project	all stakeholders	1 article in regional media (Phase 3), 4 posts on social media (Phase 2,3), 1 press release (Phase 3), **participation at conference Strengthening Disaster Risk Resilience of Communities and Regions in Slovakia (Phase 1)**
Improve data accessibility and ensure that climate risk assessments are available to decision-makers and practitioners	all stakeholders	Project outcomes published at OPEN DATA PORTAL BBSGR (Phase 3) + information in media and email directly
Support evidence-based policymaking by providing clear and actionable insights from the project's findings	decision-makers	*Project outcomes published at OPEN DATA PORTAL BBSGR (Phase 3) + information in media and email directly*
Secure political support for climate change adaptation efforts	BBSGR Council	1 policy brief document for BBSGR Council (Phase 3) + presentation
Support the implementation of adaptation within the competence of BBSGR	internal capacities at BBSGR (relevant divisions and departments)	2 internal workshops (Phase 3), 4 **posts on internal social network Viva engage** (Phase 1,2,3), 1 Recommendation document for strategic integration and adaptive strategy development (Phase 3)
Enhance preparedness of intervention capacities in risk management	Security Council of BBSGR, Regional Directorate of the Fire and Rescue Corps, Voluntary Fire Protection of Slovakia, municipalities (as responsible establishing voluntery firefighting corps), Association of towns and municipalities	2 collaboration events (Phase 2,3), 1 policy brief document addressed to the Security Council of BBSGR (Phase 3), 1 recommendation for optimization of intervention capacities in risk management (Phase 3)
Raise awareness of climate risks and their potential impacts	all stakeholders	1 public event (Phase 3) + event medialization
Encourage action by relevant stakeholders to implement adaptation measures	all stakeholders	1 public event (Phase 3) + event medialization
Promote collaboration and establish new partnerships for innovation in climate adaptation	potential R&D institutions and academy sector, other regions and subjects willing collaborate in this agenda	1 public event (Phase 3) + event medialization

Table note: Activities written in grey indicate those that are repeated multiple times, while those in green represent activities that have already been completed in this phase.

2.2 Risk Exploration

Risk exploration starts with a broad screening of the most significant risks in the Banská Bystrica region, evaluating the underlying hazards, exposures, and vulnerabilities that are of major concern to both key stakeholders and the wider public. In prioritizing risks, we considered the availability of data and the vulnerability of local communities. A critical factor in this process was the substantial forest coverage in the region, accounting for nearly 50% of the land area (454,121 ha), which is crucial to the region's ecosystem and economy.

The Banská Bystrica region faces challenges related to the degradation of non-native spruce monocultures, especially in areas where these species were introduced. This degradation poses both economic and ecological consequences, such as increased unscheduled logging. The primary reason for the low resilience of forests to climate change and other stressors is the unbalanced age structure of the forest, which makes them more susceptible to pests, disease, and climate-induced calamities. The collapse of spruce forests, particularly in the Horehronie area, driven by these stressors, is one of the most significant risks we face.

Similarly, in water management, the region is grappling with the challenges of complying with the European Water Framework Directive (2000/60/EC). Many watercourses have been altered over the years, affecting their natural ecosystem functions. The historical hydromelioration of small streams and wetlands has led to long stretches of watercourses with altered hydrological, hydromorphological, hydraulic, and biological parameters. This alteration is most evident in the Slaná River basin, where 28% of the watercourses have been human-modified. Reduced space for watercourses, groundwater depletion, and diminished water retention capacity have all contributed to increasing risks of floods and droughts in the region.

Both the forest and water management systems are currently facing ideological conflicts, which must be addressed to effectively adapt to the changing climate. We are at a point where a paradigm shift in our approach is necessary, guided by the latest scientific knowledge. Climate change is one of the key drivers behind this shift, emphasizing the need for new solutions that consider the complex, interrelated nature of these risks.

As part of this pilot climate risk assessment, a crucial aspect of our decision-making has been identifying which risks would allow us to establish practical adaptation strategies and collaborations, considering our competencies and communication capabilities. We are exploring how municipalities can leverage the expertise of voluntary fire brigades to enhance climate change awareness. Firefighters, who are often on the front lines during emergencies, could play a key role in communicating climate risks to the public, though the specifics of this collaboration are still under discussion. This approach aims to integrate local risk management with broader community adaptation efforts.

Table 2-5 Climate Hazard priorisation matrix.

Hazard	Relevance in the Region	Data Availability	Impact on the Community	Connection to Other Projects	Existing Collaboration
River floods	TRUE	medium	high	TRUE	TRUE
Drought	TRUE	low	medium	FALSE	FALSE
Heatwaves	TRUE	medium	medium	FALSE	FALSE
Wildfires	TRUE	medium	medium	TRUE	TRUE
Windstorms	TRUE	low	low	TRUE	TRUE
Snow	TRUE	medium	medium	FALSE	FALSE

2.2.1 Screen risks (selection of main hazards)

In our climate risk assessment, we have prioritized two main climate-related hazards for the Banská Bystrica region: floods and wildfires. These hazards were selected based on their significant impact on local communities, infrastructure, and livelihoods, as well as the availability of data that supports effective risk management.

Current Situation and Affected Areas: Flooding is a recurring and severe issue in the Banská Bystrica region, particularly in low-lying areas along major rivers and tributaries, including the Slaná and Hron rivers. Heavy rainfall, rapid snowmelt, and insufficient flood management infrastructure contribute to frequent flooding events. Settlements, agricultural land, and critical infrastructure such as roads and bridges are particularly vulnerable. Climate change is expected to increase both the frequency and intensity of floods, exacerbating risks for urban and rural communities. Additionally, areas with altered watercourses and reduced natural water retention capacity, such as the Slaná River basin, are especially susceptible. Wildfires pose an escalating threat, particularly in forested and agricultural areas during prolonged periods of drought and heatwaves. The Banská Bystrica region, with almost 50% of its land covered by forests, faces increasing wildfire risks, especially in areas dominated by non-native spruce monocultures, which are highly vulnerable to climate-induced stress, pest outbreaks, and fires. The Horehronie area, known for its extensive spruce forests, is particularly at risk. Rising temperatures, prolonged dry spells, and land mismanagement contribute to the accumulation of dry biomass, further fuelling wildfire outbreaks. Occasional human negligence also increases the likelihood of fires, making effective monitoring and early warning systems critical to mitigating this hazard.

Expected Hazards: Both flooding and wildfires are expected to become more frequent and severe due to climate change. Flooding is likely to intensify, occurring more suddenly because of shifting precipitation patterns, extreme weather events, and insufficient flood prevention measures. At the same time, rising temperatures and prolonged dry periods will lead to more frequent and intense wildfires, especially in forested areas vulnerable to drought stress.

Vulnerable groups: The following table presents an analysis of the vulnerable groups identified in relation to the risks of wildfires and floods, highlighting the key factors that contribute to their increased vulnerability.

Table 2-6 Vulnerable groups analysis.

Category	Vulnerable Group	Risk - River Floods	Risk - Wildfires
Residents	**Elderly and disabled populations**	Limited mobility, higher health risks	Higher vulnerability to smoke inhalation and evacuation challenges
Residents	**Low-income households**	Limited financial means to recover from flood damage	Limited ability to recover from fire-related losses
Residents	**Children**	Higher health risks, dependent on caregivers	More susceptible to smoke inhalation and health issues
Visitors	**Tourists and hikers**	Unfamiliar with local risks and evacuation routes	At risk when visiting fire-prone areas
Local Government	**Municipalities in floodplains and near forests**	Responsible for risk management and local response planning	Responsible for fire prevention strategies and emergency coordination
Business Sector	**Farmers in flood-prone areas**	Crops and livestock losses, economic damage	Crops, land, and infrastructure at risk of fire damage
Business Sector	**Forestry and agricultural workers near fire-prone regions**	Risk of losing resources and work facilities	Increased risk due to proximity to flammable materials

Emergency Services	**Firefighters and rescue teams**	High exposure during rescue operations	Direct exposure to hazardous conditions
Infrastructure & Critical Services	**Critical infrastructure (roads, bridges, water supply)**	Damage to transport, utilities, and emergency response	Damage to energy, water, and communication networks

Existing Data and Knowledge: Historical flood data, hydrological models, and land use patterns provide insights into flood risks, though more precise climate projections and local vulnerability assessments are needed to refine risk mitigation strategies. Fire records, satellite data, and climate projections indicate a growing wildfire threat, but further research is needed on fire spread dynamics, community preparedness, and the effectiveness of early warning systems.

Additional Data Needs. To further refine our understanding and improve risk assessment, additional data is required. You can find the preliminary analysis of data suitable for refining the analysis in data inventory (Zenodo ClimaaxInsight Phase 1).

2.2.2 Workflow selection

In order to execute the climate risk assessment for selected hazards, following workflows were selected:

River floods:

- 1.1. River Floods - River flooding
- 1.2 River floods - Flood building damage and population exposure

Wildfires

- 2.1. Wildfire (ML approach)
- 2.2 Wildfire FWI

2.2.3 Choose Scenario

For assessing climate risks in Banská Bystrica, the RCP4.5 and RCP8.5 scenarios are most relevant. This choice reflects the current pace of climate policy implementation and emission reduction efforts in countries like Slovakia, indicating that climate goals are not being met effectively enough. As a result, focusing on scenarios that account for negative climate impacts, such as RCP4.5 and RCP8.5, is necessary, as optimistic scenarios like RCP2.6 could underestimate the risks.

The RCP4.5 scenario is suitable for our short- and medium-term planning. It assumes moderate emission reductions over the medium term and transformation in energy and industry sectors, also emphasizes enhancing adaptation capacities, which is crucial for our region, where flexibility is needed across different sectors.

The RCP8.5 scenario should also be considered, particularly as a warning scenario for the most vulnerable areas. It reflects a more severe reality, helping us prepare for worsening conditions, such as more frequent and intense extreme weather events.

Geographical and sectoral differences within the region require careful consideration when selecting climate risk scenarios. The northern districts, dominated by forests, are at risk of forest degradation due to extreme drought and changes in precipitation, while the southern agricultural districts are particularly vulnerable to drought, threatening agricultural production. Furthermore, local factors like socio-economic status and adaptation capacity play a role. The region's low adaptation capacity could exacerbate the impacts of climate change.

2.3 Risk Analysis

For this initial phase of CRA selected workflows were applied utilising the data resources made available by default setting of the CLIMAAX Handbook with minimal customisations. In general workflows were executed on local infrastructure and occasionally tested on provided ECMWF cloud Jupyter Hub infrastructure. Similarly, datasets were downloaded and processed locally. Following section provides an overview of the datasets used for particular workflows.

2.3.1 Workflow #1.1 River Floods - River flooding

Table 2-7 Data overview workflow #1.1.

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
JRC high-resolution flood hazard maps for Europe in historical climate, Aqueduct Floods coarse-resolution flood maps	Damage Curves for land use	LUISA - Different land use classes	Comparison of flood depth maps between the future and historical climates under two climate scenarios (RCP4.5 and RCP8.5) for different return periods derived from a coarse-resolution global dataset, Flood damage maps, expressed in economic value, for extreme events with different return periods based on available flood maps for the historical climate.

2.3.1.1 Hazard assessment

The flood hazard assessment workflow in the CLIMAAX Toolbox utilizes multiple datasets to evaluate flood risks across various return periods and under different climate change scenarios.

This workflow integrates JRC's high-resolution flood maps[1] and Aqueduct Floods climate projections to provide insights into the likelihood and severity of river flooding.

JRC High-Resolution Flood Maps provides flood extents for extreme hydrological events with return periods of 10, 20, 30, 40, 50, 75, 100, 200, and 500 years.

[1] https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81

The difference between a 10-year and a 500-year flood return period lies in how often such floods are statistically expected to occur and how severe they might be.

1. **Return period meaning:**
- A **10-year flood** has a **1 in 10 (10%)** chance of happening in any given year.
- A **500-year flood** has a **1 in 500 (0.2%)** chance of happening in any given year.
2. **Severity:**
- The **10-year flood** is less severe — it typically covers a smaller area and has lower water levels compared to rarer events.
- The **500-year flood** is much more severe, with higher water levels and more extensive flooding. It represents an extreme event, but it **can still happen in any year** — the return period is just a statistical average, not a schedule.
3. **Misconception alert:**
 A "500-year flood" doesn't mean it happens exactly every 500 years. It could happen twice in a decade — or not for a thousand years. The return period describes **probability, not timing**.

We selected 10, 50, 100, 200, 500 return periods. Uses historical hydrological data and flood modelling techniques to estimate the areas affected under different flood magnitudes (figure 2-1).

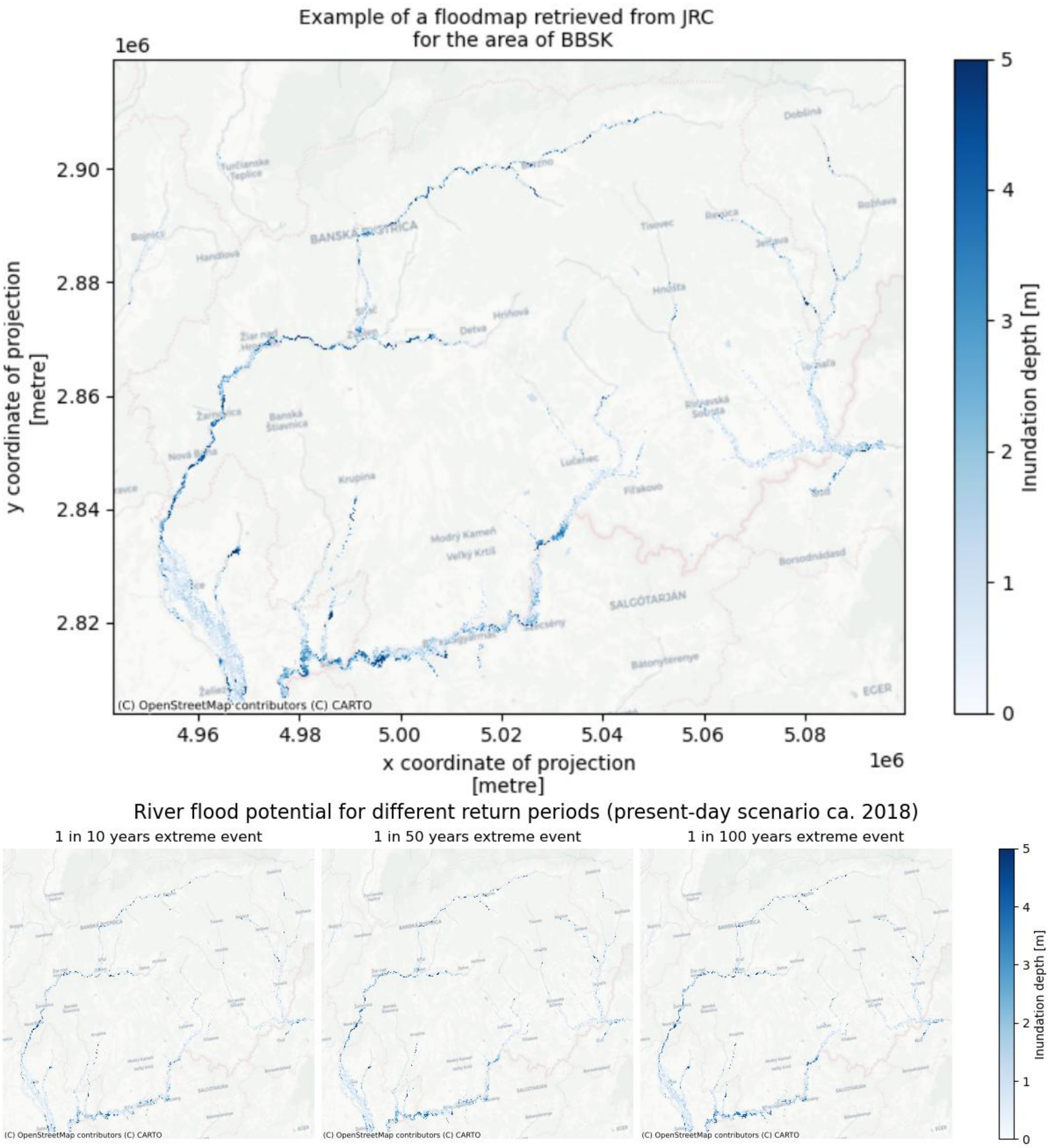

Figure 2-1 Potential River flood maps for return periods 500, 100, 50 and 10 years

Figure source: CLIMAAX Insight phase 1

The figure 2-1 provides comparison for the maps of flood potential in different return periods, including detailed plot of the region representing the return period 1 in 500 years extreme event.

Aqueduct Floods Climate Projections evaluates potential changes in flood frequency and severity under different climate scenarios. We used RCP 4.5 (moderate emissions) and 8.5 (high emissions) (figure 2-2)

Aiming to estimate the effect of climate scenarios on the river flood hazard, assesses how future **river discharges** may shift due to **climate-induced precipitation and hydrological changes**.

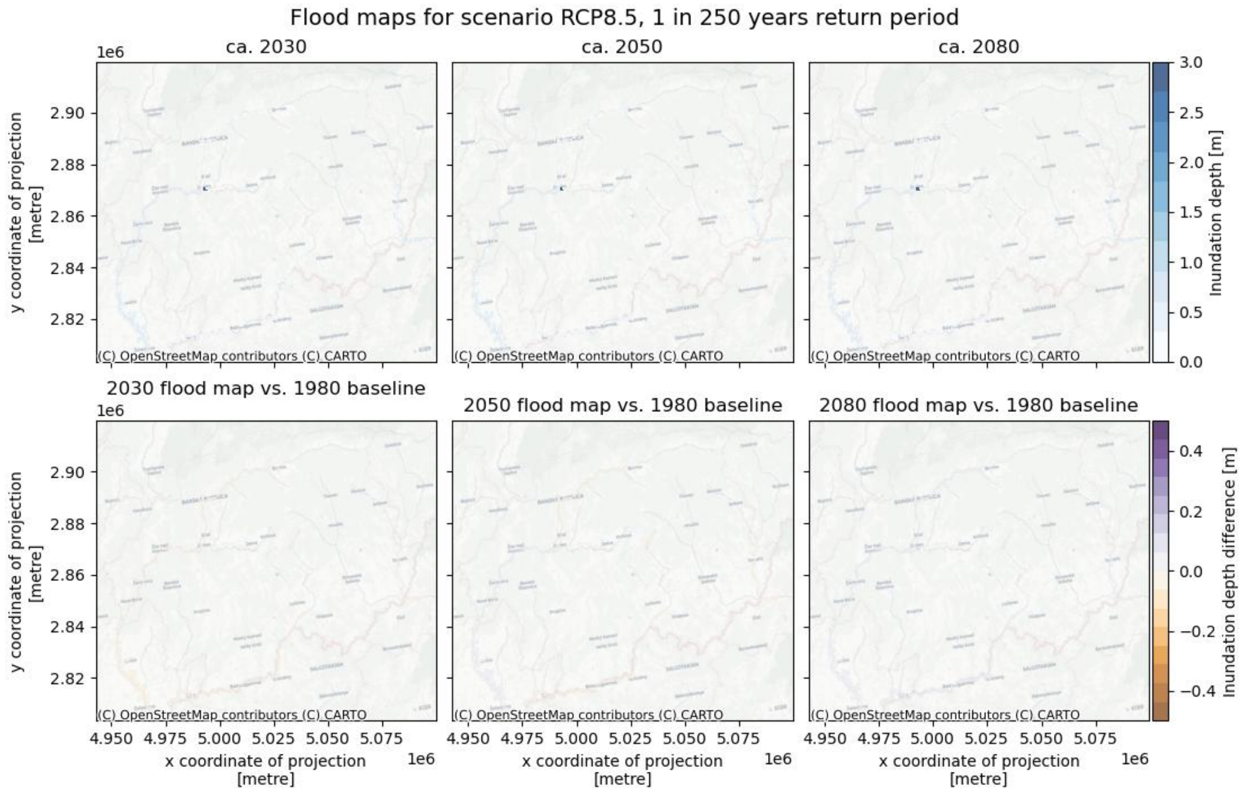

Figure 2-2 Estimating the effect of climate scenarios on the river flood hazard

Figure source: CLIMAAX Insight phase 1

Figure 2-2 provides comparison of flood maps inundation depth for different year timestamps (2030, 2050 and 2082)" according the RCP8.5 High emission release scenario - first three higher plots. Difference in inundation depth for floods in the same timestamps, comparing to the base line timestamp in 1980 - second three lover plots.

The Hron, Ipeľ, Rimava, and Slaná rivers represent key areas of concern for potential flooding in the Banská Bystrica region, as they are among the largest rivers in this area. The Hron River, with its extensive floodplains, poses a significant hazard, especially in its middle and lower reaches, affecting towns such as Banská Bystrica, Zvolen, and Žiar nad Hronom. The Ipeľ River, which forms a natural border between Slovakia and Hungary, frequently floods in the border areas, particularly affecting Šahy. The Rimava River is particularly prone to flash floods, impacting Rimavská Sobota and nearby settlements, while the Slaná River presents flood risks in lowland regions in the eastern part of the area.

In addition to these major rivers, several smaller watercourses in the region also contribute to flood hazards. Muráň, Čierny Hron, Slatina and Suchá etc. are smaller rivers that can cause localized flooding, particularly during heavy rainfall events. Bystrica, flowing through the city of Banská Bystrica, poses a potential flood hazard in urban areas during extreme precipitation. The flood hazard in the region is influenced not only by river size but also by local topography, precipitation patterns, and hydrological conditions, emphasizing the need for targeted flood management strategies.

These observations largely align with the data from the Slovak Water Management Enterprise (SVP), even though JRC data, which lacks the same level of detail, was used.

2.3.1.2 Risk assessment

The risk assessment for river flooding in the Banská Bystrica region (BBSK) focuses on quantifying the potential economic damage caused by fluvial flooding to building infrastructure. This analysis integrates flood hazard maps, land use data, and economic vulnerability models to estimate financial risks associated with extreme river discharge events.

The flood risk assessment integrated multiple modelling components for a comprehensive analysis. Flood return periods (RP10, RP50, RP100, RP200, RP500) captured both frequent and extreme events. Climate scenarios included RCP 4.5 and RCP 8.5, with projections for 2030, 2050, and 2080 to assess future risk trends. GDP was set at 16 000€ per capita.

Flood hazard maps were resampled to 100 m resolution for consistency with land-use data. Economic losses were estimated using JRC depth-damage curves, linking flood depth to infrastructure vulnerability. This structured approach ensured a comprehensive assessment of flood risk to support effective flood management. The results can be seen in Figures 2-3 and 2-4.

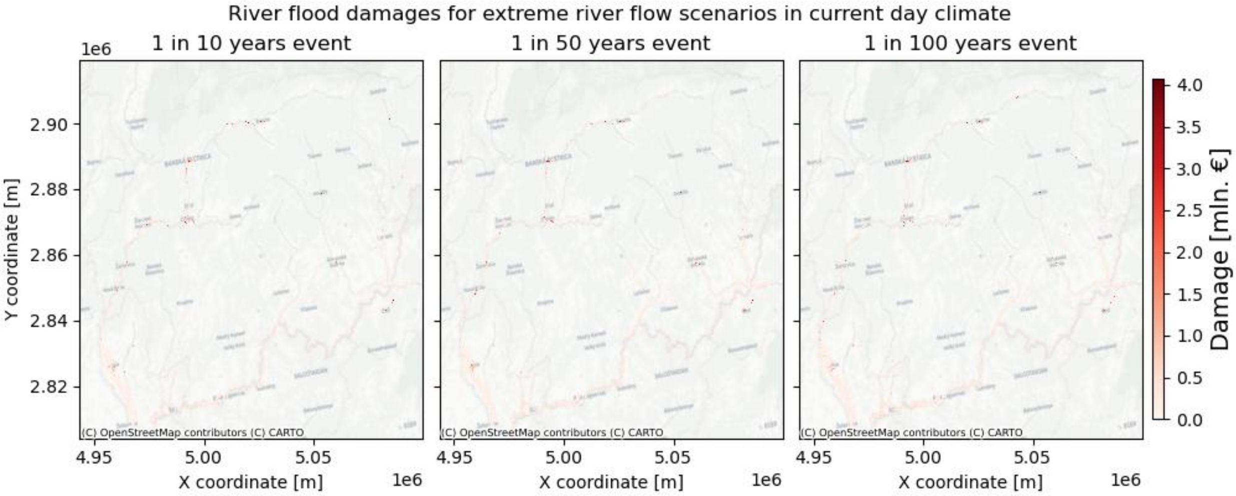

Figure 2-3 Visual for estimated river flood damages for return periods 10, 50 and 100 years

Figure source: CLIMAAX Insight phase 1

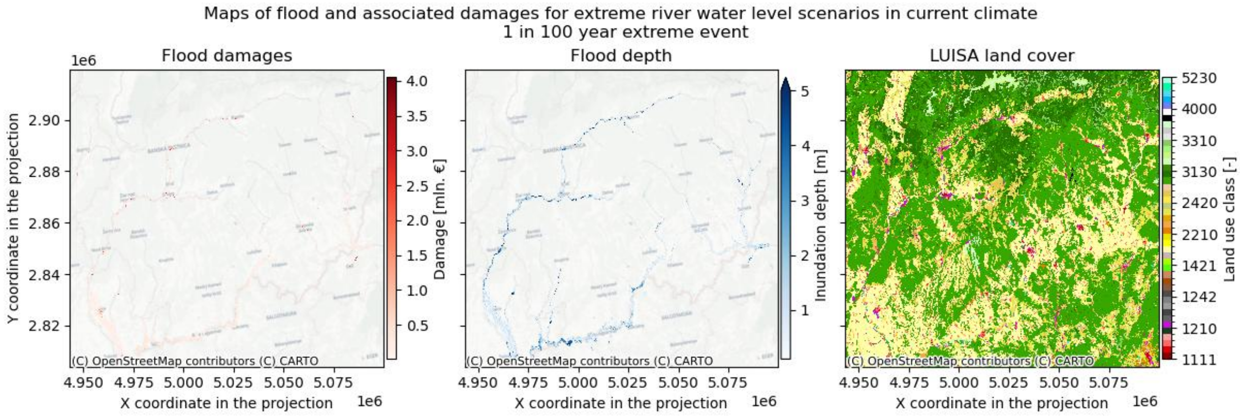

Figure 2-4 Flood damages, flood map depths and land cover for the return period 100 years.

Figure source: CLIMAAX Insight phase 1

Above maps in figure 2-4 provides better indication, why certain areas are damaged more than the others for a given return period, with aim to help to see, which areas carry the most economic risk under the flooding scenarios.

Table 2-8 Damage calculations for selected return periods and relevant land cover types.

Risk_assessment_FLOOD_RIVER

	Description	RP10	RP50	RP100	RP200	RP500
2110	Non irrigated arable land	4012.177325	4967.331782	5297.183071	5591.344333	5940.859109
1210	Industrial or commercial units	1356.503125	1627.076529	1729.689712	1810.305956	1916.161514
2310	Pastures	853.191097	1001.596281	1047.798654	1089.091142	1136.031044
2430	Land principally occupied by agriculture	686.330382	789.394808	822.211747	848.718429	881.534839
1122	Low density urban fabric	545.681755	703.227158	766.019319	818.656364	874.364377
1123	Isolated or very low density urban fabric	226.759401	277.012132	292.978144	308.810242	326.722081
3210	Natural grassland	212.442107	250.950487	262.908397	273.551656	284.247103
1221	Road and rail networks and associated land	154.206913	186.707165	199.114967	209.008843	222.437999
1121	Medium density urban fabric	105.724063	139.429272	152.335722	164.663972	179.286927
4000	Wetlands	86.226330	101.826745	107.649238	111.557524	116.453303

The highest economic damages occur in areas with the largest river flows, as identified in the hazard analysis. These regions are most vulnerable due to the combination of extensive floodplains, high population density, and significant infrastructure exposure. The analysis confirms that major river basins, where water accumulation is highest, experience the greatest financial impact from flooding events.

A critical component of the assessment is the consideration of climate change impacts on future flood risks. Using projections from coarse-resolution flood models, the analysis evaluates how changes in precipitation and river discharge could influence flood patterns in the coming decades. The results suggest that in certain areas, flood depths are expected to increase, heightening economic risks and the need for adaptive flood management strategies.

These findings underscore the importance of targeted flood mitigation measures, including enhanced flood defences, improved land-use planning, and early warning systems. The assessment provides essential data to inform regional flood preparedness efforts, ensuring that decision-makers have the necessary tools to develop resilient infrastructure and minimize future damages.

The greatest added value of this workflow is its ability to analyse damages in millions of euros for each relevant land use category across different return periods. In a use case with more detailed hazard maps, we can achieve highly accurate results.

2.3.2 Workflow #1.2 River floods - Flood building damage and population exposure

Table 2-9 Data overview workflow #1.2

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
JRC high-resolution flood hazard maps for Europe in historical climate,	Damage Curves	Open Street Maps (OSM), Population density GHS-POP R2023A	Building flood exposure maps, Building damage maps and estimated annual building damage graph, Critical infrastructure map combined with the flooded area, Maps of exposed population and estimated annual exposed population graph, Maps of displaced population and estimated annual displaced population graph.

2.3.2.1 Hazard assessment

Hazard assessment was the same one as in previous workflow 1.1

2.3.2.2 Risk assessment

This risk assessment evaluates economic damage to buildings (Figure 2-6), exposure of critical infrastructure (Figure 2-7), and population exposure due to river flooding (Figure 2-9) in the Banská Bystrica region. The analysis integrates flood hazard maps, land use data, and economic vulnerability models to estimate financial risks for different flood return periods. We selected 10, 50, 100 and 500 return periods.

Flood hazard maps from the Joint Research Centre (JRC), with a resolution of 3 arc-seconds, were used to assess flood depth and extent. Building data from OpenStreetMap (OSM) provided information on building types and footprints, while economic losses were estimated using JRC depth-damage curves, linking flood depth to structural vulnerability. The workflow also incorporated population exposure and displacement, using global population datasets to estimate the number of people affected by floods exceeding critical depth thresholds. GDP was set at 16 000€ per capita.

After calculating the estimated damage to buildings based on the mean flood depth per building, we obtained a mean expected annual damage of €173.14 million in the Banská Bystrica region.

The total estimated damage varies significantly depending on the severity of the flood event. For a 10-year flood (RP10), the damage is approximately €1,500 million, reflecting the impact of more frequent but less severe floods. As the flood intensity increases, the damage becomes more extensive, with a 50-year flood (RP50) causing almost €2,000 million in losses. A 100-year flood (RP100) results in damage of around €2,000 million, demonstrating the significant destruction that such an event can bring. In the case of an extreme 500-year flood (RP500), the estimated damage rises sharply to nearly €2,250 million, indicating catastrophic impacts on buildings and infrastructure (Figure 2-5). These figures highlight the substantial economic risks posed by severe floods and underscore the necessity of robust flood prevention and mitigation measures in the region.

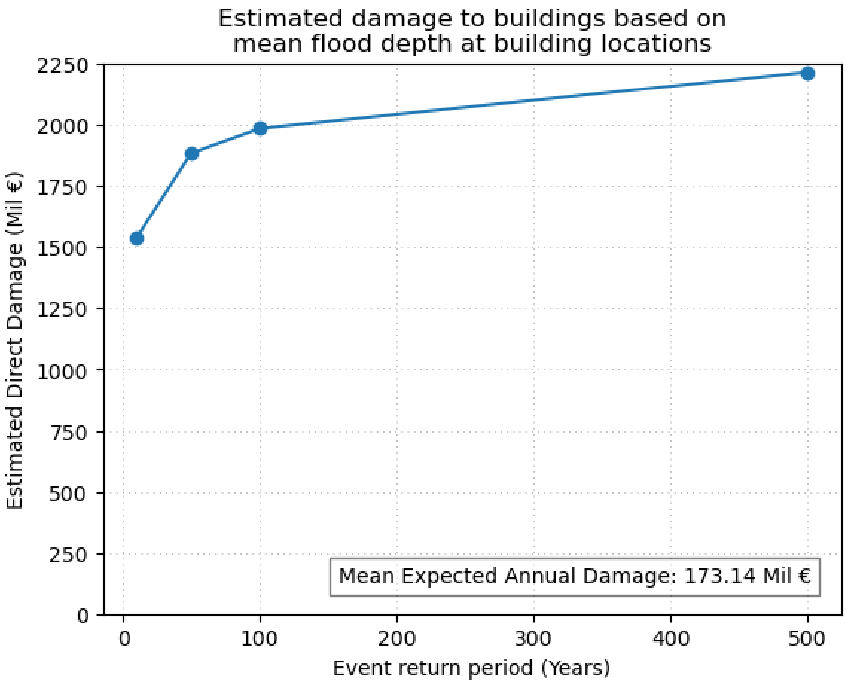

Figure 2-5 Plot of building damages vs return periods of the flood maps

Figure source: CLIMAAX Insight phase 1

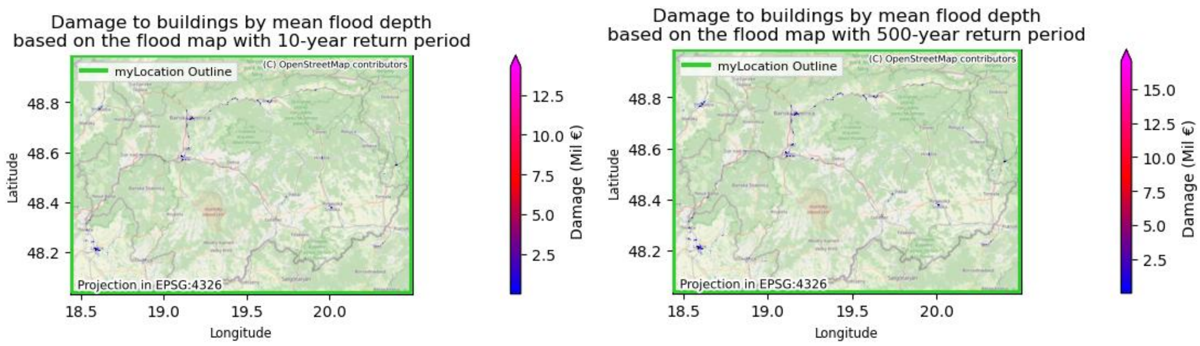

Figure 2-6 Map visualisation of the outcomes for calculating economic damage to buildings

Figure source: CLIMAAX Insight phase 1

For critical infrastructure, the workflow mapped key facilities such as hospitals, police stations, and transportation hubs, identifying those most vulnerable to flooding. The population exposure analysis revealed that thousands of residents in the region are at risk, with expected annual population exposure and expected annual displaced population increasing sharply with flood magnitude.

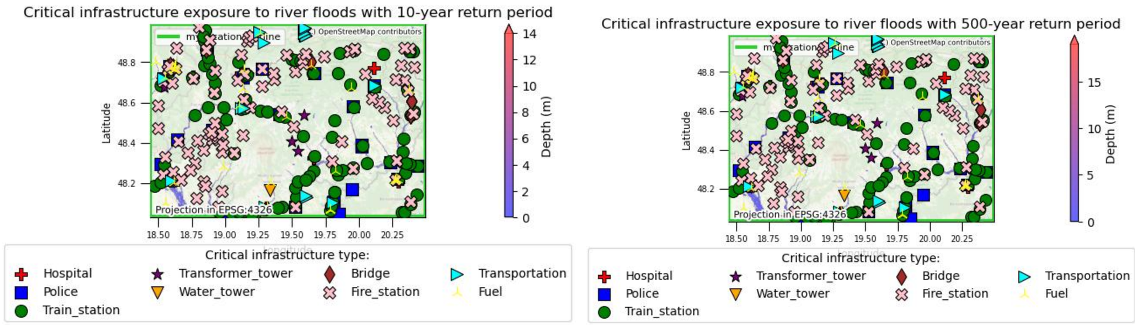

Figure 2-7 Exposure of critical infrastructure for the area of interest

Figure source: CLIMAAX Insight phase 1

Exposed population refers to residents living in areas affected by floodwaters, even at shallow depths. For RP10, the number of exposed people is approximately above 80,000. At RP50 and RP100, this number rises sharply to almost 100,000, particularly in low-lying urban districts. At RP500, flooding extends further into residential zones, putting a significantly higher number of people at risk, well above 100,000 people. Expected annual population exposed is 8954 people.

The displaced population represents individuals whose homes are affected by floods, making their residences temporarily or permanently uninhabitable. The analysis shows that while moderate events, RP10 - almost 40,000 people, RP50 - approximately 48,000 people, cause localized displacement, RP100 affects around 50,000 people, and RP500 displaces well over 50,000 people, leading to large-scale relocation. The expected annual displaced population follows a similar trend, highlighting the need for emergency shelters and long-term relocation planning in high-risk areas. Expected annual population displaces is 4315 people.

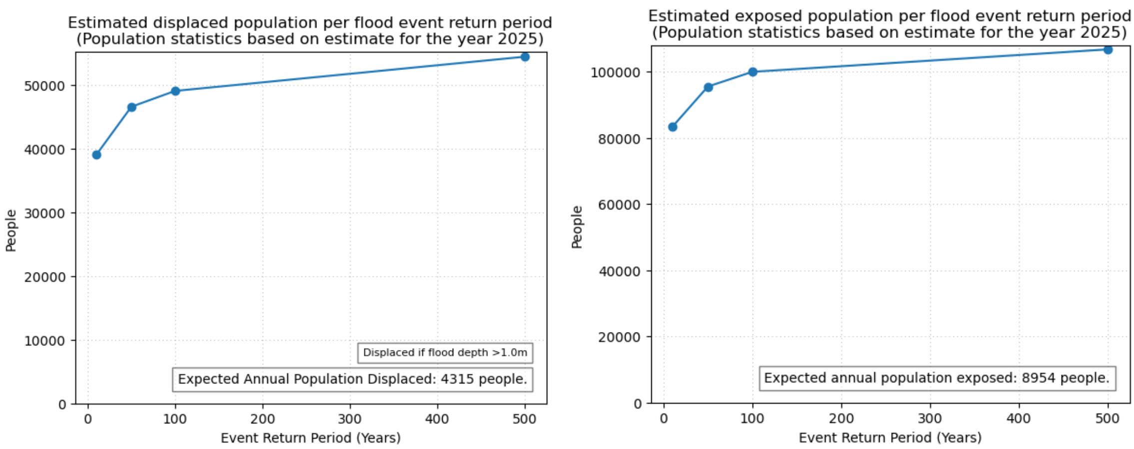

Figure 2-8 Plot of displaced population vs flood map return period

Figure source: CLIMAAX Insight phase 1

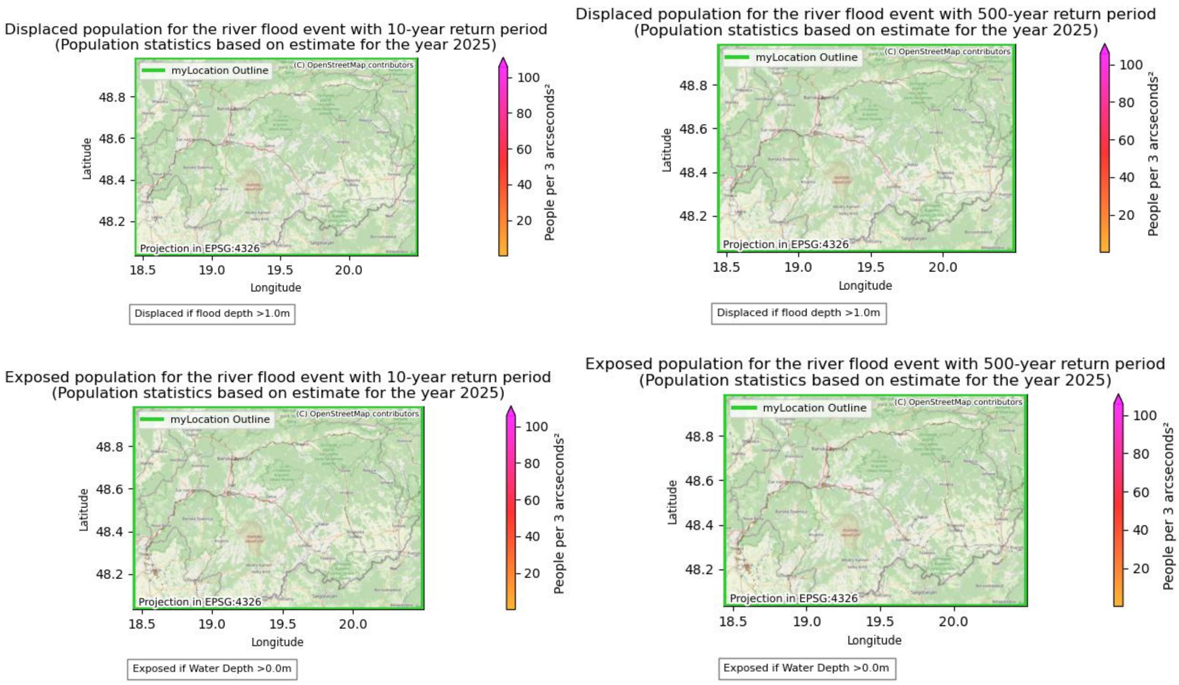

Figure 2-9 Map of displaced population

Figure source: CLIMAAX Insight phase 1

The workflow emphasizes that climate change and increasing flood depths will likely heighten both economic risks and human displacement in the coming decades. Adaptive flood management strategies such as strengthening flood defence, optimizing land-use planning, and enhancing early warning systems are essential to mitigate economic losses and protect communities.

The key contribution of this analysis is its ability to quantify financial damages in millions of euros and estimate the population at risk, providing valuable data for evidence-based flood preparedness efforts in the Banská Bystrica region. Similarly to the previous case, better local data will be needed.

2.3.3 Workflow #2.1 Wildfires (ML approach)

Table 2-10 Data overview workflow #2.1

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
ECLIPS/CHELSA, Corine Land Cover, historical EFFIS, DEM, NUTS	JRC data - population, economic, ecological and ecological-economic vulnerability indicators	Open Street Maps - roads, hospitals, hotels, schools, shelters, Wildland Urban interface (WUI)	Population, economic and ecological risk for reference period and RCP 4.5 2021-40, Risk in roads for reference period and RCP4.5 2021-40

2.3.3.1 Hazard assessment

ECLIPS and CHELSA

Hazard Assessment for Wildfire using a Machine Learning Approach is based on the ECLIPS and CHELSA datasets. The analysis focuses on computing a wildfire hazard map for a Banská Bystrica region using inputs such as Digital Elevation Model (DEM), Corine land cover, fire data (EFFIS), and administrative levels (NUTS). This method builds on a structured approach that includes data gathering and preprocessing, training a machine learning model for wildfire susceptibility under present climate conditions, projecting susceptibility to future climate scenarios, and evolving susceptibility into hazard by considering vegetation types as proxies for fire intensity.

From the results of the model using data from ECLIPS or CHELSA, we can observe relatively similar outcomes. The highest wildfire hazard is mainly concentrated in the northern parts of the region, where the terrain is mountainous and there are extensive forested areas. Additionally, fragmented hazard zones appear throughout the area, particularly in locations where there is an available fuel source for burning. Looking at the RCP 4.5 ECLIPS 2021-2040 scenario, the situation slightly worsens, with medium-risk areas expanding across the entire studied region. In contrast, when examining the RCP 4.5 scenario with CHELSA data for 2021-2040, a significant deterioration is visible in the mountainous and forested areas.

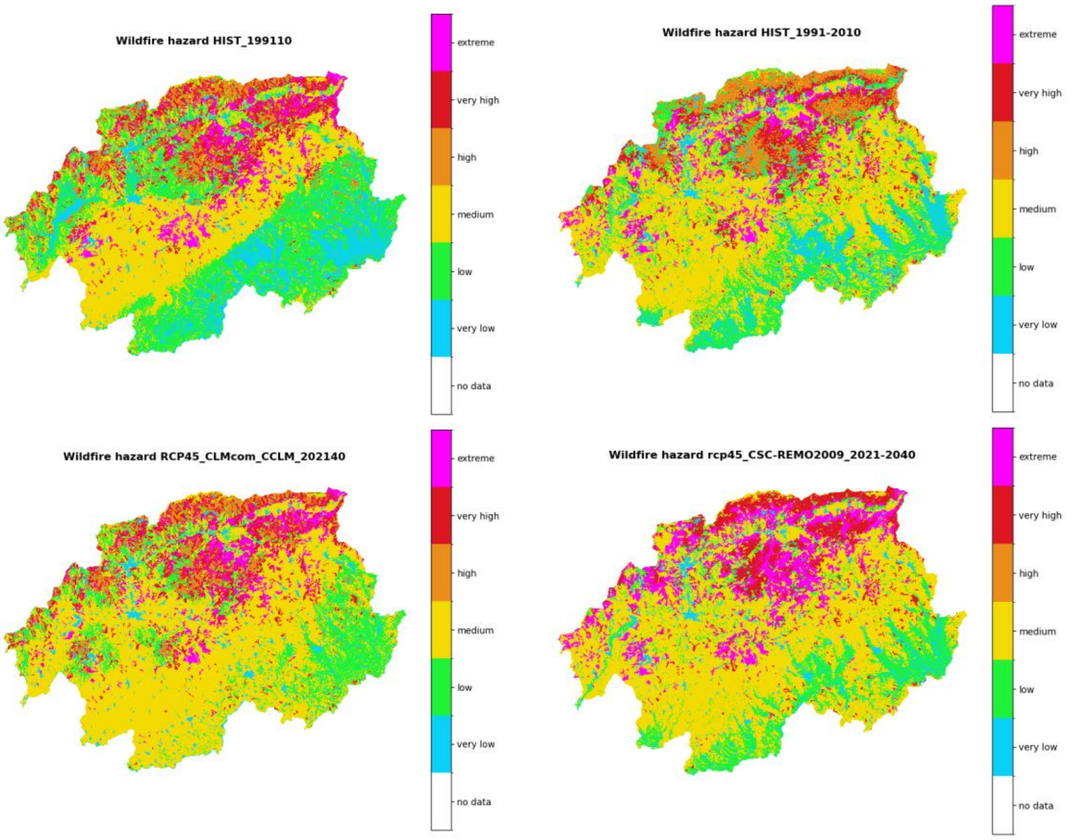

Figure 2-10 Comparison of the wildfire hazard assessment between ECLIPSE (Left side) and CHELSEA datasets.

Figure source: CLIMAAX Insight phase 1

2.3.3.2 Risk assessment

ECLIPS and CHELSA

This risk assessment evaluates wildfire risk by integrating hazard intensities (ECLIPS or CHELSA) calculated through a Machine Learning algorithm with vulnerability and exposure datasets. Vulnerability data include population, ecological, economic, and combined ecological-economic indicators provided by the Joint Research Centre (JRC), visualized across the study region (Figure 2-11). Exposure data, including critical infrastructure such as hospitals, hotels, schools, shelters, and key road networks, were sourced from OpenStreetMap and rasterized to align spatially with hazard and vulnerability data. The resulting integrated risk maps depict current and future wildfire risks at a municipal level, clearly illustrating regions of varying risk intensities under different climate scenarios.

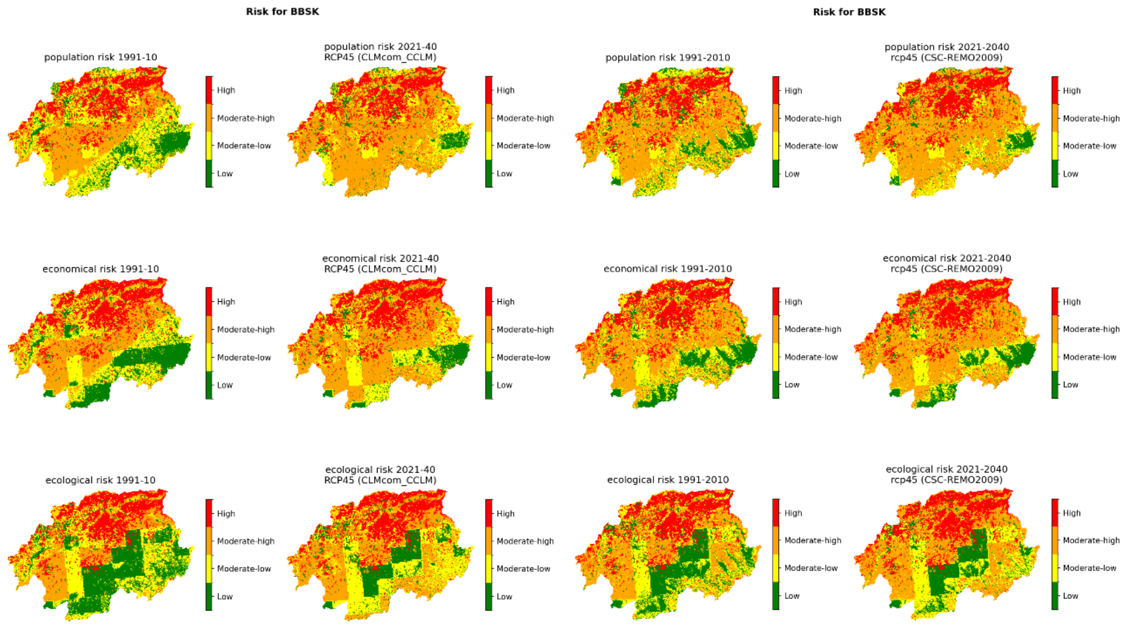

Figure 2-11 Visualisation of risk maps for ECLIPSE (left two columns) and CHELSEA datasets.

Figure source: CLIMAAX Insight phase 1

Figure 2-11 shows the differences between the ECLIPS and CHELSA datasets for various vulnerabilities. Visually, conditions slightly deteriorate under the RCP 4.5 scenario; however, it is noteworthy that certain areas depicted in the maps show improvements under this scenario.

For a more generalized overview, a clearer representation is provided by the aggregated district-level output shown in Figure 2-12, highlighting the variability across individual districts within the Banská Bystrica region. For example, we present the output based on the ECLIPS dataset. The analysis reveals that northern districts of the region consistently demonstrate higher risk across economic, ecological, and population dimensions. In contrast, southern districts initially display lower risk levels. However, it is noteworthy that under the RCP 4.5 scenario, conditions in these southern districts significantly deteriorate—frequently by two risk classes, shifting from low to moderately significant risk. This clearly illustrates how climate projections can substantially alter local risk profiles, emphasizing the importance of adaptive measures tailored to the specific needs of these districts.

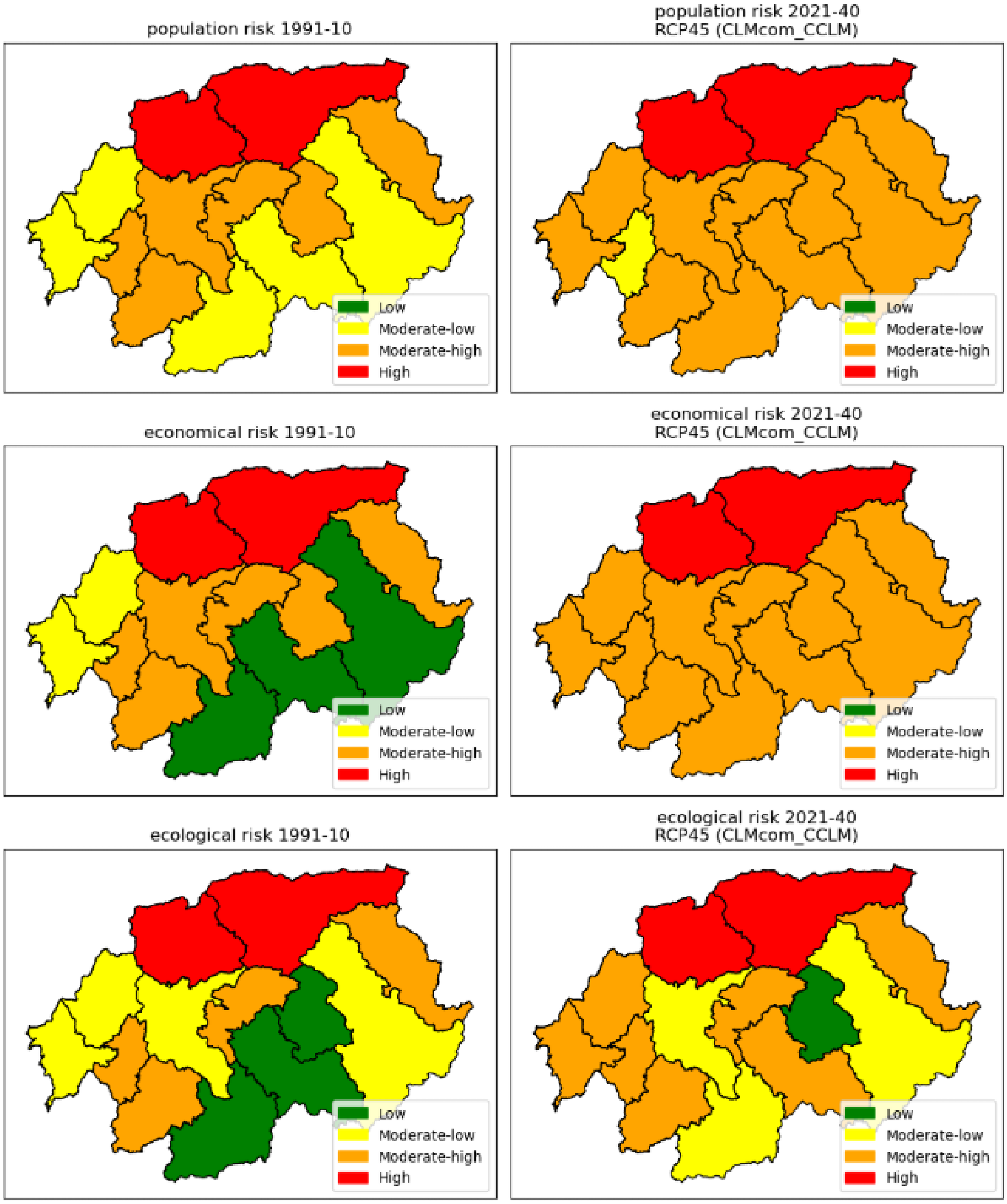

Figure 2-12 Risk assessment on districts level based on the ECLIPS dataset.

Figure source: CLIMAAX Insight phase 1

In the final part of the workflow, we generated the "risk roads" map, presenting the risk for the reference period and for the RCP 4.5 scenario. As in the previous cases, we observe an increase in risk under the RCP 4.5 scenario, enabling us to identify critical areas (Figure 2-13). This identification can help us better prepare for and mitigate future wildfire risks.

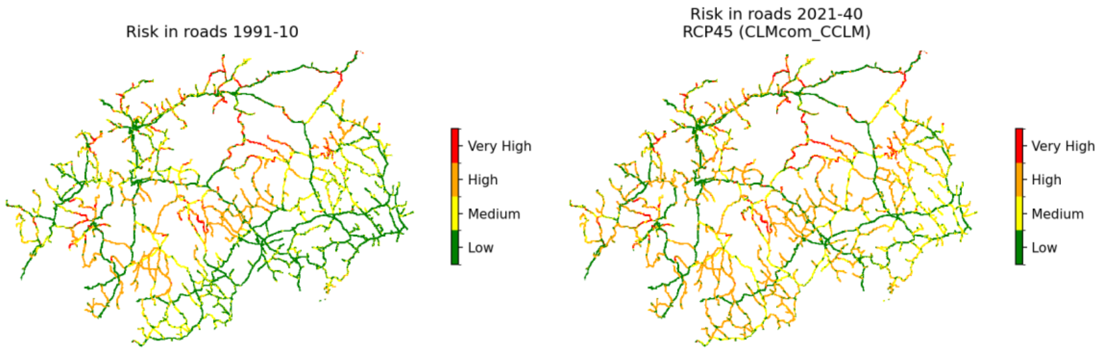

Figure 2-13 Visualisation of the risk in roads based on the ECLIPS dataset.

Figure source: CLIMAAX Insight phase 1

The resulting maps were aggregated at municipal or provincial levels, providing clear visual representations of current and projected wildfire risks. This approach is directly applicable to policy implementation, aiding decision-makers in prioritizing wildfire risk mitigation, targeted resource allocation, and strategic planning, especially in vulnerable urban interfaces and critical infrastructure areas.

2.3.3.3 Change assessment

ECLIPS and CHELSA

This workflow supplements the previously conducted Hazard and Risk assessments by visualizing differences between historical and future wildfire susceptibility, hazard, and risk (ECLIPS or CHELSA). These visualizations provide crucial context for interpreting changes driven by projected climate scenarios and machine learning model parameters.

The analysis comparing historical data with future projections under the RCP 4.5 scenario.

Susceptibility maps indicate areas with changing degrees of susceptibility between historical and future scenarios. Similarly, hazard maps visualize shifts in wildfire hazard intensity, highlighting increased risks under the RCP 4.5 scenario.

Risk assessments are further detailed for economic factors, population, and road infrastructure. Each risk category demonstrates clear differences between historical and projected conditions, with significant risk increases observed in certain areas, particularly affecting economic stability, population safety, and critical transportation networks.

Finally, changes in climate input variables used in the model are visualized, helping to interpret the driving factors behind shifts in susceptibility, hazard, and risk. Examples at figure 2-14.

This comprehensive visualization approach supports strategic decision-making for wildfire preparedness and adaptive planning under changing climate conditions.

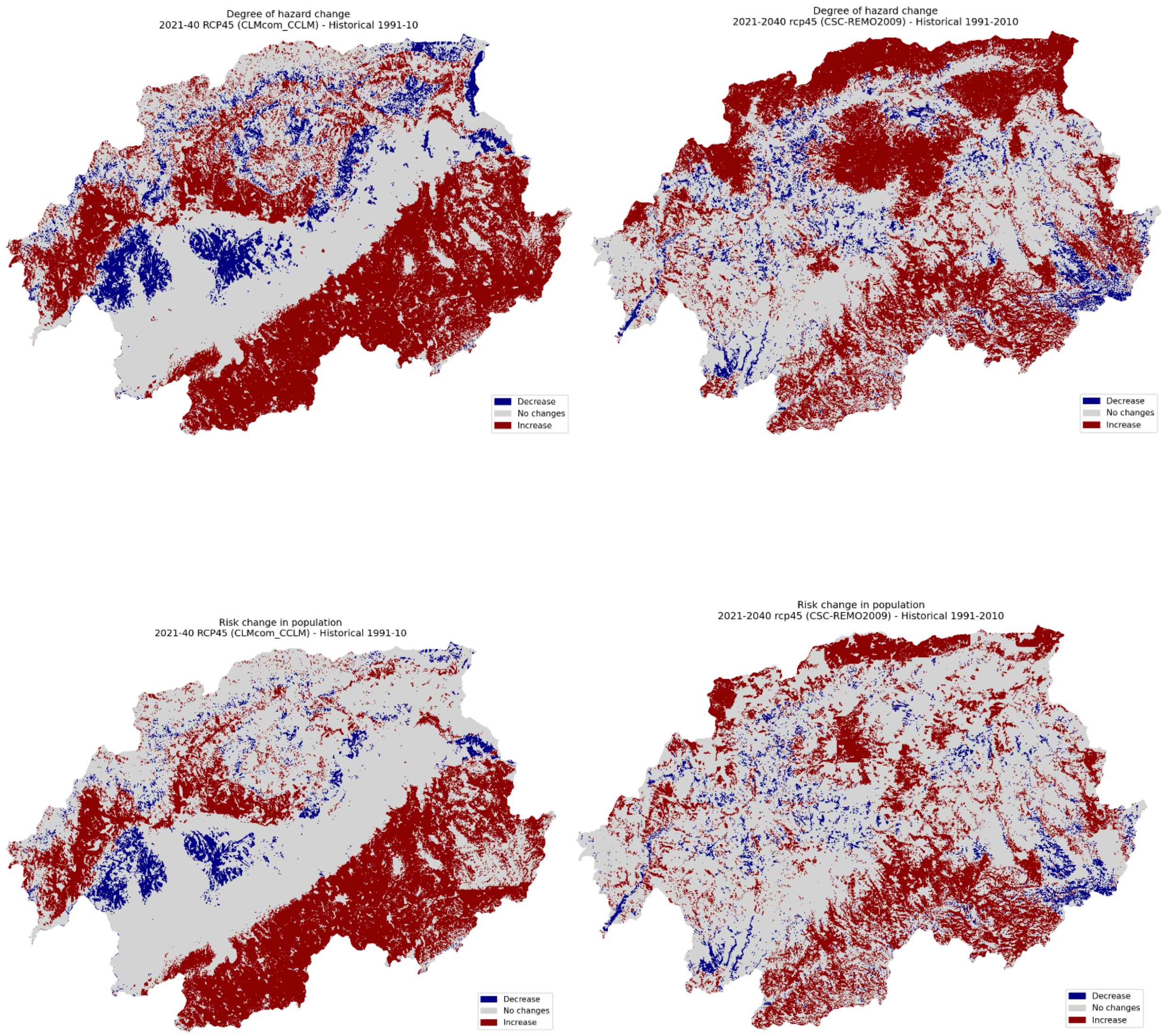

Figure 2-14 Change assessments for hazard and population for ECLIPSE (left) and CHELSEA datasets.

Figure source: CLIMAAX Insight phase 1

2.3.4 Workflow #2.2 Wildfire FWI

Table 2-11 Data overview workflow #2.2

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
CDS - seasonal and daily Weather Index Data, EFFIS - Burnable vegetation	EFFIS - Population, Protected Areas, Ecosystem Irreplaceability Index, Population density, Ecosystem Restoration Cost		Fire Risk RCP 2.6 2045 - 2050

2.3.4.1 Hazard assessment

Seasonal FWI (part 1: „Changes in seasonal FWI intensity ")

Hazard Assessment for Wildfire using the Fire Weather Index (FWI) Approach utilizes data from the Copernicus Climate Data Store (CDS) and EURO-CORDEX projections. The analysis focuses on quantifying wildfire hazard in the Banská Bystrica region based on the Fire Weather Index (FWI), a compound indicator integrating surface temperature, humidity, wind speed, and precipitation. This index reflects how favourable the climate conditions are for wildfire occurrence and spread.

The methodology involves downloading and processing seasonal and daily FWI data under historical and projected RCP scenarios (e.g. RCP4.5, RCP8.5). Seasonal FWI values represent average danger levels during the peak fire season (June-September), while daily data are used to determine the length of the fire weather season—defined as the number of days exceeding a user-defined FWI threshold (e.g. FWI > 30).

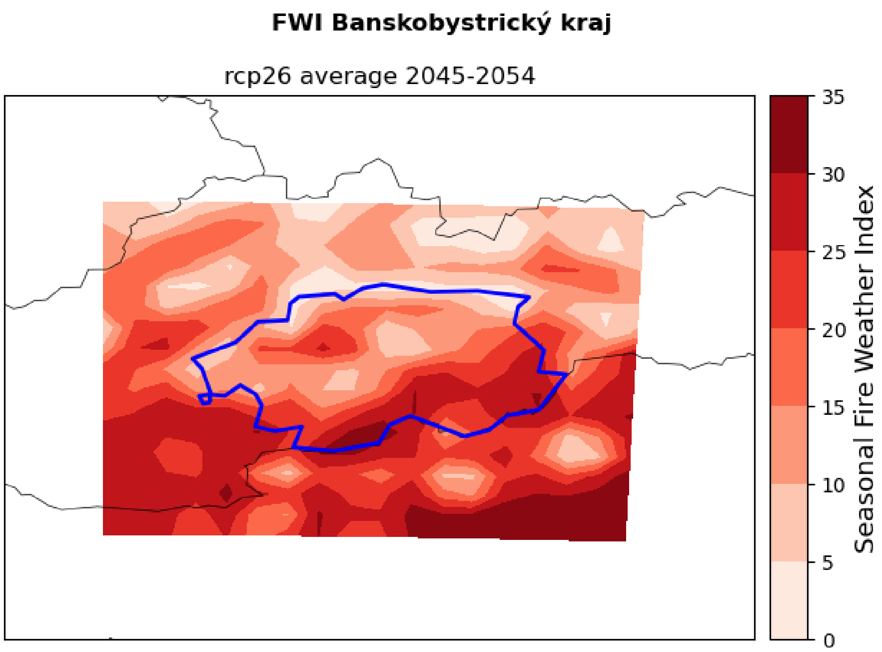

Figure 2-15 Seasonal Fire Weather Index averaged over the selected period

Figure source: CLIMAAX Insight phase 1

Daily FWI (part 2: „Fire Season Length“)

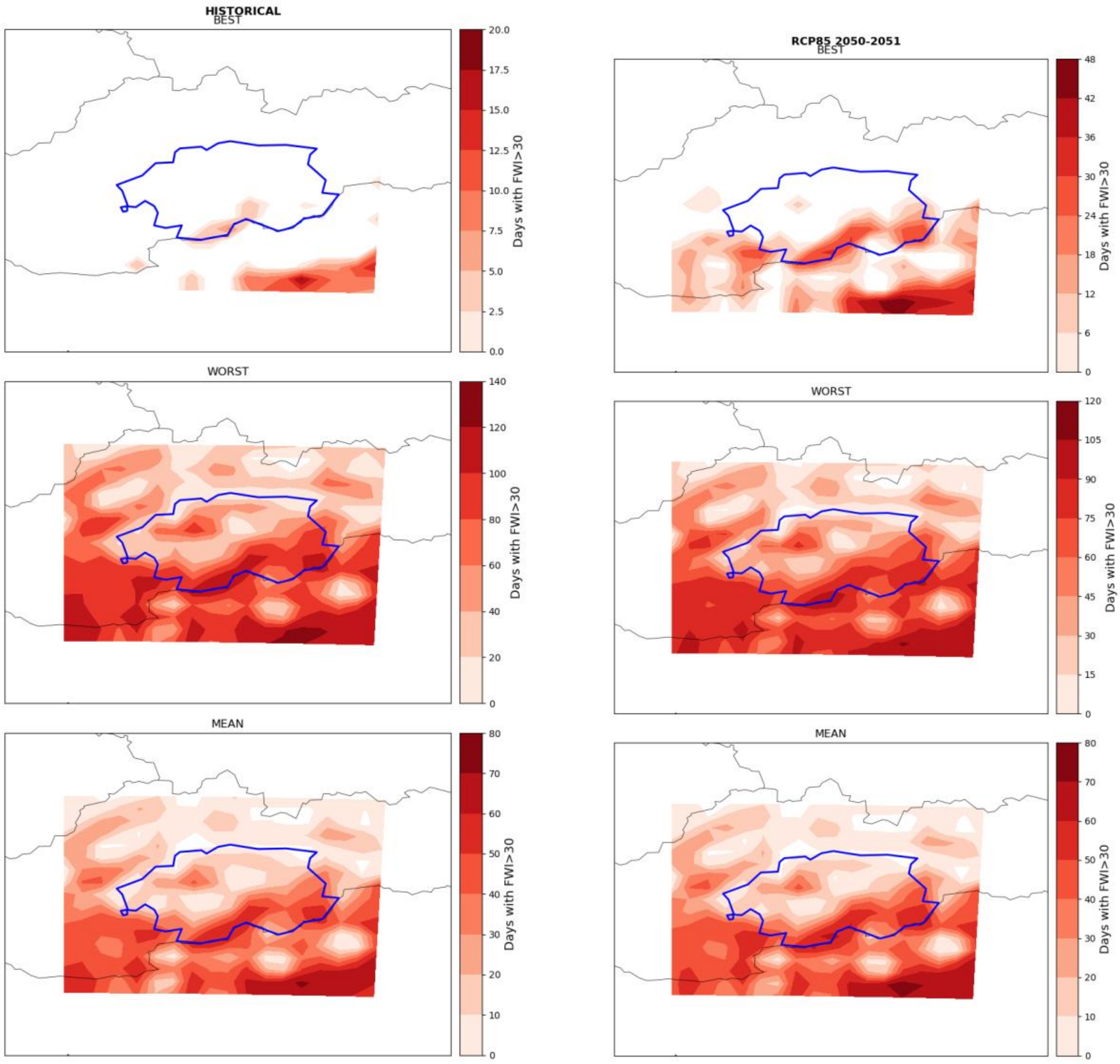

Figure 2-16 Fire weather season length map

Figure source: CLIMAAX Insight phase 1

The results reveal clear spatial patterns of fire danger within the region. Contrary to expectations, the highest FWI values are found mainly in the southern parts, where lower rainfall, higher temperatures, and the presence of flammable agricultural vegetation create suitable conditions for wildfires. These areas, despite being non-forested, consistently show high seasonal FWI intensity and a significant extension of the fire weather season.

Unlike machine learning approaches using susceptibility modelling, this method does not rely on past fire occurrence or land cover patterns. Instead, it provides a climate-driven assessment of changing fire hazard potential, useful for long-term adaptation planning and regional preparedness under worsening climatic conditions.

2.3.4.2 Risk assessment

This wildfire risk assessment is based on the CLIMAAX FWI Risk workflow, combining the seasonal Fire Weather Index (FWI) with selected vulnerability indicators to identify areas of highest risk. Unlike approaches based on past wildfire occurrences, this method synthesizes climate-driven fire danger—determined by threshold values of seasonal FWI and the presence of burnable vegetation—with multiple vulnerability layers, including the wildland-urban interface (WUI), population density, protected areas, ecosystem irreplaceability, and restoration cost.

Using multi-criteria Pareto analysis, the workflow identifies areas where climatic and socio-environmental risk factors most strongly overlap. The results show that elevated FWI values are not uniformly distributed but are instead concentrated in the southern parts of the region, and to some extent in the east and west, where fire-prone conditions coincide with high vulnerability—whether due to population exposure or ecological sensitivity. Interestingly, some areas with only moderate FWI values still show high risk due to their vulnerability characteristics.

This type of risk mapping provides a more comprehensive perspective than fire danger models alone, delivering actionable insights for regional adaptation planning. Thanks to its flexible selection of vulnerability indicators, the workflow offers a customizable tool for building resilience strategies tailored to local climate risks and the growing threat of wildfires.

Following risk map (Figure 2-17) highlights which areas in the region have the highest wildfire risk given the specified vulnerability. The map can help regional authorities understanding where wildfire risk might be the highest, guiding them towards an effective planning and allocation of resources for wildfire risk adaptation.

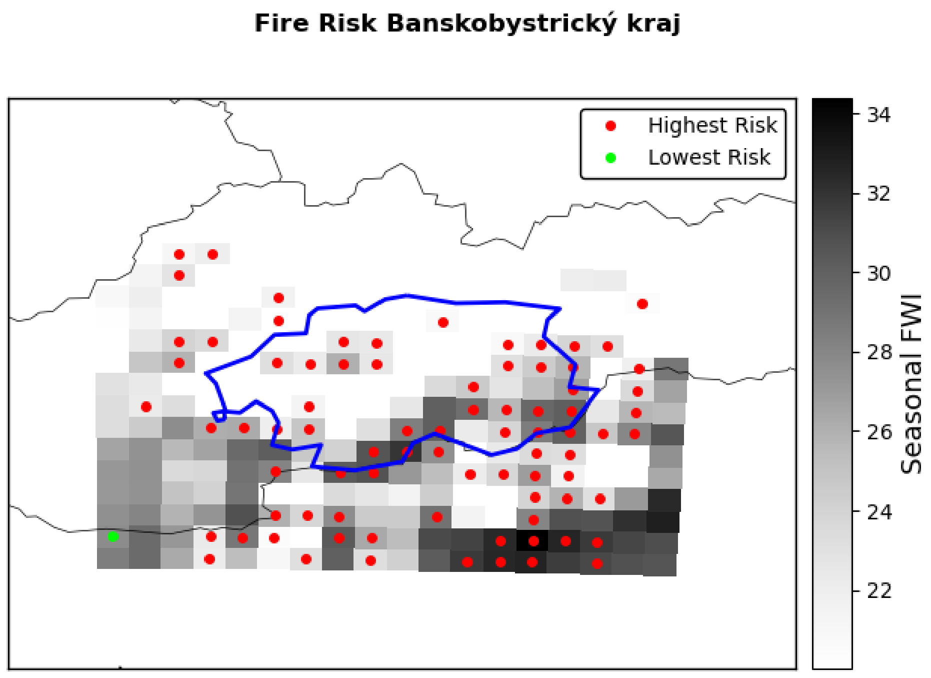

Figure 2-17 Wildfire risk map visualisation

Figure source: CLIMAAX Insight phase 1

2.4 Preliminary Key Risk Assessment Findings

2.4.1 Severity

The risk analysis confirms that the tested workflows are effective for risk management across various Representative Concentration Pathways (RCP) scenarios and different future periods. These workflows help decision-makers assess potential climate risks and develop adaptation strategies.

Flood risk in Banská Bystrica is highly susceptible to flooding due to its river network, including the Hron, Slatina, and other tributaries. Climate change projections indicate an increasing frequency and intensity of extreme rainfall events, leading to higher flood risks. Historically, severe flash floods, triggered by intense precipitation and snowmelt, have caused infrastructure damage, agricultural losses, and disruptions to local communities.

Urban expansion along floodplains further amplifies exposure, while deforestation and land-use changes reduce natural water retention, increasing runoff and worsening floods. The potential impacts include damage to roads, bridges, and water systems, economic disruptions, and a growing need for improved flood defence, land-use planning, and early warning systems. The severity of flood risk is classified as high due to its widespread effects and increasing trend under climate change.

The region's vulnerability to wildfires is driven not only by its dense forest cover but also by increasing temperatures, changing vegetation, and human-induced ignition sources such as tourism and agriculture. Although historically less frequent, climate variability has shown periodic increases in fire danger. Projected climate trends suggest a longer fire season, requiring better forest management and prevention strategies. The potential impacts of wildfires include forest ecosystem degradation, threats to human settlements, and deterioration of air quality, affecting public health. The severity of wildfire risk is classified as moderate to high, depending on seasonal climate conditions and human intervention.

The tested workflows provide a structured approach to assess and mitigate these risks under future climate scenarios. Key adaptation strategies include improved water management, afforestation, and early warning systems to enhance resilience. Effective risk management also requires collaboration between authorities, environmental agencies, and local communities to ensure long-term preparedness and disaster prevention.

2.4.2 Urgency

The major impacts of these risks will intensify over the coming decades, depending on climate change progression and human interventions. Our analysis tested two periods: the historical period (1991-2010) and the near-future period (2021-2040) under the RCP 4.5 scenario. The results indicate that flood risk is expected to increase in frequency and intensity due to more extreme rainfall events. Similarly, wildfire risk is projected to escalate, driven by rising temperatures and prolonged dry periods.

Action is needed immediately to implement flood defence, land-use planning, and reforestation efforts to mitigate future impacts. Early warning systems, improved water management, and fire prevention strategies should be prioritized now to prevent escalating damages.

In the next phase of the analysis, the plan is to test different time period variations and assess the risk under the RCP 8.5 scenario, which represents a higher-emission pathway and could reveal even more severe climate impacts.

The risks in Banská Bystrica include both slow- and sudden-onset hazards, with different levels of urgency:

Flooding is a sudden-onset hazard, triggered by extreme rainfall, flash floods, or snowmelt. Based on the 1991-2010 and 2021-2040 analysis under RCP 4.5, the likelihood of intense floods is increasing. Urgency is high, as rapid response mechanisms (early warning systems, emergency planning) are crucial to minimize immediate damages.

Wildfires develop gradually under dry conditions but can spread rapidly once ignited. The tested periods show a trend toward drier conditions, increasing the risk of fire outbreaks in many areas. Urgency depends on seasonal conditions, requiring continuous monitoring and proactive prevention measures to reduce long-term impacts.

In future research, we will analyse the impact of climate change under RCP 8.5, which assumes higher greenhouse gas emissions and stronger warming trends. This will help further refine adaptation strategies and improve long-term risk management planning.

2.4.3 Capacity

Flood risk management in the BBSGR includes essential infrastructure and legislative measures, but key areas need strengthening. Technical measures such as dams, levees, and early warning systems help mitigate risks, while the Flood Protection Act and land-use planning regulate development in flood-prone areas. However, better management of natural watercourses is needed to restore river retention capacity where it poses no risk to life or property.

Opportunities for improvement include enhanced risk analysis for better municipal preparedness, integration of nature-based solutions like river revitalization, and increased access to funding for innovative projects. Strengthening stakeholder collaboration can lead to an integrated flood risk management model, addressing land use, water management, and flood prevention. Raising public awareness about flood risks and harmful activities like construction in floodplains could also drive community-based prevention efforts.

Wildfire risk management relies on existing firefighting capacity and forest management but requires further investment. Fire Protection Act No. 314/2001 sets guidelines, including seasonal bans, while preventive measures focus on firebreaks, maintaining forest roads, and public awareness campaigns. A shift toward nature-based forest management is emerging, promoting ecosystem health to reduce fire risks.

Key opportunities include investing in forest health research, restoring fire-prone ecosystems through pilot projects, and improving land management by implementing fire-resistant strategies. Expanding wildfire prevention and ecosystem restoration efforts can create new jobs and enhance sustainability. Stakeholder collaboration among government agencies, forest managers, NGOs, and communities is essential for an integrated approach, combining proactive forest management, ecosystem conservation, disaster response, and public communication of fire restrictions.

Both flood and wildfire risk management can benefit from strengthened intervention capacities, improved coordination, and multi-stakeholder collaboration for a more integrated and resilient approach in risk management.

2.5 Preliminary Monitoring and Evaluation

From the first phase of the CRA, we gained valuable insights into the key vulnerabilities in our region. However, we encountered several difficulties with the actual execution of the analyses, while some of these issues subsequently complicated our ability to interpret the data. The following text describes these issues in more detail.

FLOODS: Issues:

- Problems related to the hash in the "Hazard Flood River *script" workflow were resolved with an update*.
- Graphs in the "Flood Damage and Population Exposure" workflow probably do not match annual values correctly with the Y-axis.
- It is not clear, what are the units of measurements for the values in the Table 2-7 Damage calculations for all scenarios and return periods for relevant land cover types. Is it in Millions €? Eg. For 2110 Non irrigated arable land under RP10 is total damage for all covered area in 4012.177325 million €?

Usability: The process is simple to use. However, improved custom data is require*d in the second step*.

FIRES: Issues:

- The default process is only applicable to Catalonia, so custom data must be prepared: (Boundaries: A .shp file defining the BBSK boundary; DEM: A digital elevation model at 100x100 m resolution for BBSK; Corine: Corine land cover data at 100x100 m resolution for BBSK; Historical Fire Data: Data from EFFIS appears insufficient, as there is a large gap indicating no recorded fire activity during certain periods.)
- OpenStreetMap data had to be downloaded and processed to extract information for BBSK (e.g., hotels, hospitals, roads) based on the Catalonia example.
- For calculating risk related to population, economy, ecology, and combined ecological-economic (ecol_econ) assessments, datasets from the Catalonia example (which include European-wide data) were used.
- For example, one tool (Eclipse) automatically downloads Corine data, whereas another tool (CHELSA) requires manual uploads, causing inconsistencies. This leads to problems when different versions of Corine data are downloaded.
- In shared functions, the values "NaN" had to be changed to "nan" on the local machine.
- For instance, the "Aggregate at NUTS3 level" workflow produces zonal statistics for BBSK only as an image. Note that in our case, NUTS3 covers the entire BBSK region, but calculations were performed at the NUTS4 level.
- Fire ML hazards - When comparing maps, the legend sometimes appears identical for both the historical and scenario maps—even if one map uses a scale from 0 to 1 and the other from 0 to 0.8. This can lead to misinterpretation (e.g., a value of 0.8 may appear as if it were 1).
- Fire FWI produces outputs only in .png format.

Usability: Users must understand the data structure and manually load custom datasets into the appropriate folders, which could be challenging for less experienced users. It would be helpful if data could be automatically downloaded, like the flood workflows, or at least clearly specify data sources relevant to our region.

GENERAL

Inconsistent Output Structure: Outputs are stored in various formats (.png, .tif) and in different folder structures. A unified structure for all workflows would be beneficial. Sometimes we have problem to interpret data. Support for georeferenced output datasets is important, too.

Script Issues: Some scripts get stuck on the "os.remove" command. Commenting out this line allows the scripts to run, but files are then not removed. All scripts were exported to a "support" directory, with some changes in code as necessary.

Online Environment: The online environment used for running the scripts is unreliable.

The workflow descriptions are quite basic, making it difficult for newcomers to grasp the meaning of specific parts. Additionally, the partial and main outcomes are often either missing or described only superficially. Identifying which datasets are visualized in plots and maps is also challenging, as their descriptions tend to be minimal, further complicating their interpretation.

The feedback we have received from stakeholders so far has been positive. We have gathered valuable input from municipalities, local authorities, and stakeholders involved in risk management, which has been instrumental in understanding the key needs of municipalities from the perspective of strategic planning and risk management. However, as we move forward with the next phase of the analysis, we recognize the need to involve additional stakeholders. We will need to engage stakeholders from the areas of monitoring, river management, and forestry management entities. This will be crucial for obtaining more specialized insights and data relevant to these specific sectors. Additionally, including research organizations and the broader public will ensure that the analysis remains comprehensive and incorporates diverse perspectives, ultimately enhancing the robustness and applicability of the findings.

In the next phase of the project, we will focus on utilizing the most up-to-date and detailed data at the regional level, including both environmental and socio-economic data. The first draft of the planned data usage in this phase is presented in data inventory (Zenodo ClimaaxInsight Phase 1). To better understand the risks we face, we will focus on assessing risks in relation to the adaptive capacity of municipalities and cities. This will involve analysing the development of adaptation strategies, both implemented and planned measures, as well as the intervention capacities of fire brigades established by municipalities, which play a key role in risk management. To this end, we will use specific data on the intervention capacities, equipment, and skills of firefighters.

Regarding environmental data, we will preliminarily consult the results with relevant institutions in the fields of water management and forest management and research. We expect that specific data will be identified based on discussions around initial outputs.

It is possible that we will need to strengthen our expert capacities in the interpretation of climate risks in the affected sectors to ensure accurate and comprehensive assessments. Additionally, we will work to refine the data related to the population and improve our understanding of the vulnerability of different population groups within the context of our region's specific characteristics.

3 Conclusions Phase 1- Climate risk assessment

At this stage of the project, we successfully applied the provided methodology and selected workflows to the identified risks—floods and wildfires. We evaluate the use of these workflows as successful. Through our analyses, we obtained a basic overview of the issue. A key focus for us was the **user experience**—we invested time in understanding how the workflows operate, how to interact with them, and how to make them more intuitive. Equally important was the **interpretation of results**.

Technical Insights and Workflow Evolution

- The **scripts are functional and continue to evolve** over time. Some adjustments may still be necessary to further streamline the process.
- The **current data infrastructure** is highly valuable for **testing purposes**, providing a solid foundation for experimentation. However, real-world applications will require more localized and precise data in our more detailed cause. Therefore, the current assessment of the territory should be considered preliminary — even so, the outputs already help identify key hazards and risks in the area. For final outputs, it will be necessary to **reassess the granularity of outputs** based on territorial units, so that they reflect the needs of stakeholders in the areas of adaptation and risk management and adjust the granularity of input data accordingly.
- Testing further **scenarios and time periods** will be highly beneficial for improving the robustness and applicability of the workflows.

Key findings for floods in the Banská Bystrica Region

Our analyses identified a high severity of flood risk, particularly in the river basins of the Hron and Slaná rivers. Projections indicate that their frequency and intensity will increase, potentially leading to significant damage to infrastructure, agriculture, and community operations. Given the urgency of the situation, immediate implementation of flood prevention measures and improved land-use planning is necessary. However, a major challenge in our region is the lack of cross-sectoral cooperation in addressing mitigation, prevention, and management of climate risks.

While certain risk management elements are already in place, their effectiveness must be reassessed considering the growing flood threat. It is crucial to enhance discussions and planning for long-term solutions, such as nature-based approaches and adjustments in landscape and spatial planning management. Additionally, raising public awareness of floodplain risks and sharing best practices will be essential in fostering resilience at the local level.

A key limitation we observed in the analysis was the quality of available data, particularly in terms of flood line delineations, which affected the overall reliability of the outputs. As a result, the current assessment of the region should be considered preliminary. Despite this, the outputs already provide valuable insights into key hazards and risks. Moving forward, more localized and precise data will be necessary to ensure that real-world applications and interventions are based on the most accurate and detailed information available.

Key findings for Wildfire in the Banská Bystrica Region

Our analyses identified a moderate to high severity of fire risk in the region. Climate trends indicate an extended fire season, which increases the likelihood of wildfires. The primary causes of this heightened risk include rising temperatures and prolonged dry periods, as well as human activities such as tourism, forestry work, berry picking, and grassland burning.

The findings from our analyses suggest that the most vulnerable areas are those already weakened by other environmental stressors, such as windstorms, drought, or bark beetle infestations. However, obtaining more precise results will require further analysis. We observed inconsistencies in the FireWild workflows, particularly when using different models or when comparing them to the FWI and ML-based workflows, which underscores the need for additional refinement.

To mitigate fire risk, several opportunities for stakeholders' engagement improvement have been identified. Strengthening our collaboration with firefighting units will be crucial, as they can provide practical insights and propose specific measures to enhance fire prevention and response strategies. Investing in research and ecosystem restoration efforts in the context of fire resilience in Slovakia could also help us better understand the adaptation capacity of ecosystems.

During the preliminary analysis, we focused on the RCP4.5 and RCP8.5 scenarios. The RCP4.5 scenario aligns with the current pace of climate policy implementation and emission reduction efforts, making it suitable for our short- and medium-term planning. Meanwhile, we consider the RCP8.5 scenario useful for the most vulnerable areas as warning scenario.

To support communication of the Phase 1 outcomes, **dedicated web map app** (WildFires web app) been prepared, providing the possibility to visualise and compare various hazard and risk output datasets related to the wildfire's workflow.

Stakeholder engagement

During the first phase of the project, we became more aware of the need for **intensive collaboration with stakeholders**, particularly data providers, municipalities and cities as the primary entities responsible for developing and implementing adaptation measures, and voluntary firefighting corps establishment; stakeholders in forest and water management, nature conservation and risk management at regional, but as well as local level.

Next Steps

In the next phase of the project, obtaining the most detailed data possible will be crucial for refining our analyses. We will aim to incorporate higher-quality environmental data and socio-economic data; integrate preparedness of municipalities and intervention capacities in risk management data. Equally important will be maintaining intensive communication with the methodology developers, who will need to adapt workflows to our specific needs. Since our goal is to prioritize measures at the regional and local level, it is essential that the project outputs enable this. The level of granularity must be carefully chosen based on the type of risk being analysed. For floods, the ideal scale is at the level of specific flood-prone areas or sub-municipal zones, allowing for precise identification of at-risk locations and targeted flood prevention measures. In the case of forest fires, administrative boundaries do not necessarily align with risk areas, making it more appropriate to work with forest units, ecological zones, or land-use categories that account for fire history and landscape characteristics.

Beyond conducting high-quality analyses, one of the biggest challenges will be effectively communicating project results and ensuring their practical application. This also involves integrating analytical findings into political and governance processes.

4 Progress evaluation and contribution to future phases

This initial work serves as the base for the next phase of the project, enabling us to carry out more detailed analyses, engage with stakeholders, and validate our hypotheses. In Phase 2, we will refine these outputs by incorporating additional data, including not only environmental factors but also social aspects, critical infrastructure, and intervention capacities for risk management. This will involve mapping the region's readiness for implementing adaptation measures. By Phase 3, we aim to produce recommendations and informative reports for decision-makers and stakeholders, refine our policies, and design a communication campaign. This will set the stage for further steps and projects aimed at strengthening the region's long-term efforts in adapting to climate change. For detailed information see scheme below.

Next, we outline the Key Performance Indicators (KPIs), and milestones achieved during this phase, along with the actions taken to meet the targets as outlined in the Individual Following Plan. The summary tables below provide an overview of the progress made.

Table 4-1 Overview key performance indicators

Key performance indicators	***Progress***
At least 2 relevant Workflows for selected hazards documented in Deliverable 1 - Final number of workflows will be determined according to the available workflows and guidelines specified in the CLIMAAX handbook2 (Phase 1)	done
4 posts on the enterprise social platform **(**Phase 1-3)	done

Table 4-2 Overview milestones

Milestones	***Progress***
M1 Project Onboarding done - team members acquaint themselves with the project tools, methodology, and other essential resources relevant for successful project execution	Milestone achieved
M2 Executed multi risk assessment	Milestone achieved
M3 Evaluated results	Milestone achieved
M 4 Recommendations for phase 2 completed (processed in cooperation with experts and stakeholders)	Milestone achieved
M 5 Submitted deliverable 1	Milestone achieved

[2] *alternative hazard will be selected if those proposed in D1 are not available in the toolbox*

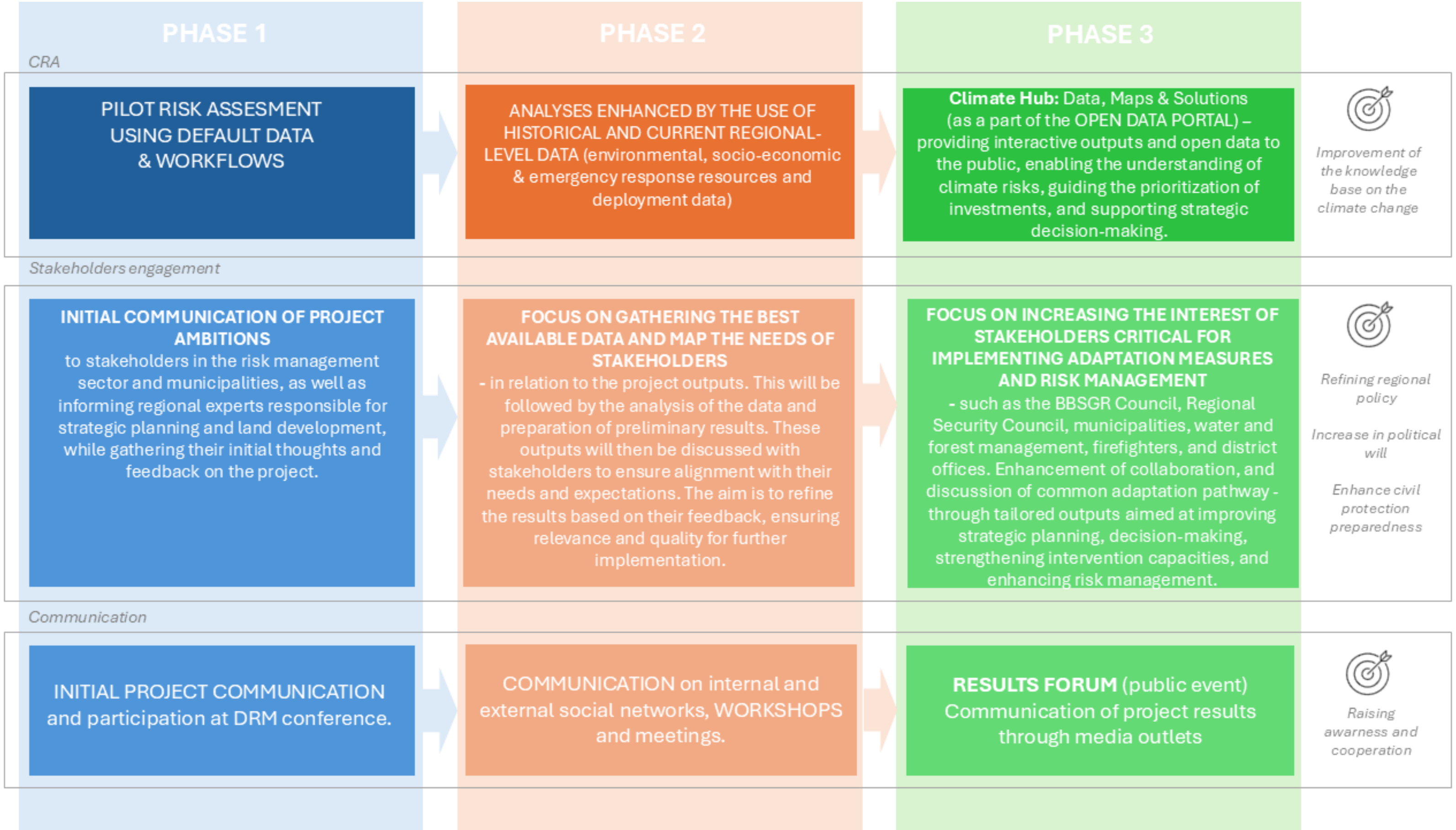

Figure 4-18 Summary of the Phase 1 main achievements

Figure source: CLIMAAX Insight phase 1

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5 Supporting documentation

In addition, set of additional supporting documentation for the Phase 1 has been prepared and uploaded into the Zenodo (Zenodo ClimaaxInsight Phase 1), including:

- **Source info for web map app**

Containing the code for webmap viewer (*fires_visualization_web_map.rar*)

Snapshot of web map app (WildFires web app)

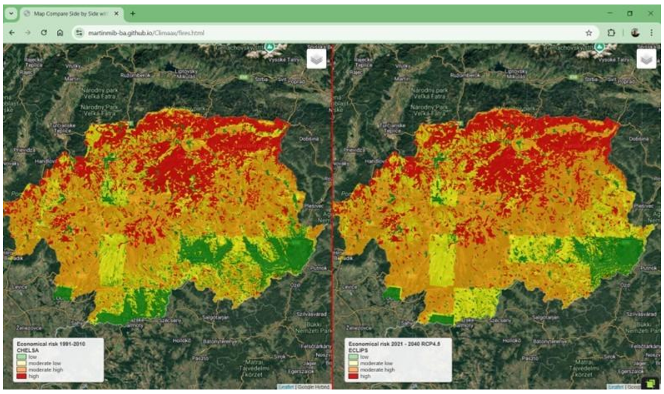

Figure 5-18 Wildfires web map app

Figure source: CLIMAAX Insight phase 1

- **Handbook/Toolbox Scripts**

These folders contain aside the original workflows, snaps of their implementation for this ClimaaxInsight cascading project (folders Support) in *.pdf or *.html reports. There are also all input and output datasets, additional graphs and plots, including QGIS *.qgz projects.

There are two archives:

  - *Fires.rar*
  - *Floods.rar*

- **Datasets inventory**

In form of simple tabular document with the initial overview of the datasets foreseen to be used (*Data_inventory-link.rtf*).

- **Communication activities**

Providing summary of the Communication activities carried out during Phase 1 of the project, both within and beyond the established KPIs (*Communication activities.rtf*).

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