climate ready regions

Deliverable Phase 2 – Climate risk assessment

"ClimateREADY Ruse: Planning for Resilience and Sustainability" Bulgaria, District of Ruse/Ruse Municipality

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

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1. Document Information

Deliverable Title	Phase 2 – Climate risk assessment
Brief Description	The project aims to advance the local Climate Risk Assessment (CRA) by applying the CLIMAAX Common Methodology Framework to assess, quantify, and prioritize key climate-related risks affecting the municipality. Building on the outcomes of Phase 1, the project refines the multi-risk assessment through the integration of high-resolution local data, and climate scenarios, with a focus on the most relevant hazards such as river flooding, heavy rainfall and wildfire. The project combines scientific data, local knowledge, and stakeholder engagement to analyze hazard, exposure, and vulnerability, enabling a comprehensive understanding of current and future climate risks. Using the CLIMAAX Toolbox and event-based climate storylines, the project evaluates risk dynamics under different climate scenarios and identifies critical hotspots and vulnerable sectors.
Project name	„ClimateREADY Ruse: Planning for Resilience and Sustainability"
Country	Bulgaria
Region/Municipality	District of Ruse/Ruse Municipality
Leading Institution	Ruse Municipality
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5.0	30.04.2026	Ruse Municipality	Revised Deliverable as per reviewers comments
	…		Final version to be submitted

2. Table of contents

Contents

3. List of figures

4. List of tables

5. Abbreviations and acronyms

Abbreviation / acronym	Description
BAS	Bulgarian Academy of Sciences
BG32	North Central Planning Region (NUTS 2), Bulgaria
C3S	Copernicus Climate Change Service
CAWRI	Climate, Atmosphere and Water Research Institute
CDS	Copernicus Climate Data Store
CEMS	Copernicus Emergency Management Service
CLIMAAX	Climate Risk Assessment Framework and Toolbox (project name)
CRA	Climate Risk Assessment
CPI	Consumer Price Index
DRBD	Danube River Basin Directorate
EAD	Expected Annual Damage
EAPE	Expected Annual Population Exposed
EAPD	Expected Annual Population Displaced
EEA	European Environment Agency
EFAS	European Flood Awareness System
EFFIS	European Forest Fire Information System
EPI	Extreme Precipitation Indicator
EURO-CORDEX	European Coordinated Regional Climate Downscaling Experiment
FSTP	Financial Support to Third Parties
FWI	Fire Weather Index
GCM	Global Climate Model
GEV	Generalized Extreme Value distribution
GIS	Geographic Information System
IDF	Intensity–Duration–Frequency
JRC	Joint Research Centre (European Commission)
NIMH	National Institute of Meteorology and Hydrology (Bulgaria)
NSI	National Statistical Institute (Bulgaria)
NUTS	Nomenclature of Territorial Units for Statistics
OSM	OpenStreetMap
PFRA	Preliminary Flood Risk Assessment
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RP	Return Period
SSP	Shared Socioeconomic Pathway
WUI	Wildland–Urban Interface

6. Executive summary

This deliverable presents the Phase 2 Climate Risk Assessment for Ruse Municipality, prepared within the CLIMAAX project. It builds on the Phase 1 screening and prioritization and provides a more regionalized, quantitative, and decision-relevant assessment of the municipality's priority climate risks: **river floods, heavy rainfall, and wildfires**.

Compared to Phase 1, this assessment moves beyond broad hazard screening by combining CLIMAAX workflows with local and regional evidence. The analysis integrates official flood hazard and risk maps, historical hydrological information, local wildfire records, observational precipitation data, spatial exposure information, scientific studies, and stakeholder feedback. These sources are used to validate, contextualize, and interpret the workflow outputs, strengthening the local relevance of the assessment.

For **river floods**, the assessment confirms that flood risk remains a very high-priority climate risk for Ruse Municipality. The analysis explicitly distinguishes between the large-scale fluvial influence of the **Danube River** and the faster, rainfall-responsive dynamics of the **Rusenski Lom** system. Building damage, population exposure, displacement, and critical infrastructure exposure are quantified across multiple return periods. Expected Annual Damage (EAD), Expected Annual Population Exposed (EAPE), and Expected Annual Population Displaced (EAPD) provide a concrete basis for flood risk management, infrastructure protection, emergency preparedness, and investment prioritization.

For **heavy rainfall**, the assessment shows a clear increase in both frequency and intensity of extreme 24-hour precipitation events. A locally justified threshold of **50 mm/24h** is applied as an impact-relevant indicator for disruptive rainfall, supported by Bulgarian climatological evidence and local observations. Events of this magnitude, historically associated with return periods of approximately **10–25 years**, are projected to occur every **5–10 years** by mid-century. This confirms heavy rainfall as a high-priority, municipality-wide risk affecting drainage capacity, pluvial flooding, transport systems, public services, and emergency response.

For **wildfires**, the assessment shows that Ruse faces a growing climate-sensitive risk despite its historically lower wildfire profile. The analysis combines Fire Weather Index-based modelling, national wildfire risk information, and local empirical fire records for **2019–2025**. The results indicate increasing fire weather danger, a lengthening fire season, and growing exposure in peri-urban and wildland–urban interface zones. Wildfire risk remains lower than flood-related risks in the overall prioritization, but it is clearly intensifying and requires preventive land management, awareness measures, and stronger preparedness.

Overall, Phase 2 confirms that the priority risks are interconnected. Heavy rainfall can intensify river flood impacts, while drought and heat increase wildfire susceptibility. Climate risk in Ruse is therefore increasingly shaped by interacting hazards, exposed urban infrastructure, critical services, and vulnerable population groups.

The main added value of this deliverable is the translation of harmonized CLIMAAX workflows into a locally grounded evidence base for municipal decision-making. The results support the identification of risk hotspots, prioritization of adaptation needs, and integration of climate risk considerations into spatial planning, infrastructure investment, flood risk management, stormwater management, civil protection, and peri-urban land-use planning.

In Phase 3, these findings will be used to identify, assess, and prioritize adaptation options that are technically relevant, locally applicable, and aligned with the risk profile of Ruse Municipality. The Phase 2 assessment therefore provides the analytical bridge between climate risk diagnosis and practical adaptation planning.

1 Introduction

1.1 Background

Ruse Municipality is located in northern Bulgaria, on the southern bank of the Danube River, and forms part of the North Central Planning Region (NUTS 2 – BG32). Its geographical position, combined with its urban, industrial, transport, and cross-border functions, makes it one of the strategically important municipalities in northern Bulgaria. At the same time, this location exposes the municipality to multiple and interacting climate-related hazards.

The Climate Risk Assessment (CRA) process for Ruse Municipality is part of a broader transition from predominantly reactive risk management towards a structured, forward-looking, and climate-informed approach to local governance. Although Ruse has substantial experience in emergency response and sector-specific hazard management, Phase 1 of the CLIMAAX project showed that existing practices remain largely fragmented, hazard-specific, and insufficiently aligned with long-term climate change projections and integrated risk-based planning.

Phase 1 established the analytical baseline by applying the CLIMAAX Common Methodology Framework to identify the main climate hazards, exposed assets, vulnerable population groups, and institutional capacities relevant to Ruse. The assessment confirmed that river flooding, heavy rainfall, and wildfires represent the most significant climate-related risks for the municipality, due to both current impacts and expected intensification under future climate conditions. It also highlighted spatial concentrations of risk in floodplain areas, densely built urban zones with limited drainage capacity, and peri-urban areas where environmental and settlement pressures intersect.

Beyond hazard identification, Phase 1 identified systemic vulnerabilities and governance challenges, including ageing infrastructure, fragmented data availability, limited integration of climate risk information into spatial and sectoral planning, and constrained financial and technical capacity at municipal level. At the same time, it pointed to opportunities for strengthening resilience through improved data use, inter-institutional coordination, and the application of harmonized European methodologies and tools such as those provided by CLIMAAX.

As one of Bulgaria's largest urban centres and a key Danube port, Ruse plays a major administrative, economic, transport, and cultural role, including strong cross-border connections with Romania. The municipality's setting — combining river floodplains, urbanized territory, loess plateaus, agricultural land, and peri-urban forested areas — creates a complex climate risk profile. This makes Ruse an appropriate case for advancing from broad risk screening towards a more detailed, locally grounded, and decision-relevant climate risk assessment.

1.2 Main objectives of the project

In accordance with the CLIMAAX Common Methodology Framework, the main objective of Phase 2 is to refine the Climate Risk Assessment for Ruse Municipality by moving from broad risk scoping and screening towards a more regionalized, quantitative, and scenario-based analysis of the priority climate risks identified in Phase 1.

Building on the previous phase, Phase 2 focuses on three priority hazards — river flooding, heavy rainfall, and wildfires — and examines them through an integrated analysis of hazard, exposure, and vulnerability. The aim is to produce a spatially explicit and locally relevant understanding of risk that can support current risk management and future adaptation planning.

A key purpose of Phase 2 is to generate decision-relevant risk information. By applying CLIMAAX workflows and evaluating risks in terms of severity, urgency, and resilience capacity, the assessment helps distinguish between risks requiring immediate action and those suitable for medium- or long-term adaptation planning. In this way, Phase 2 supports the transition from general risk awareness towards risk prioritization and governance-oriented assessment.

The refined outputs — including hazard maps, risk indicators, hotspot identification, and prioritization results — are intended to inform spatial planning, infrastructure investment, disaster risk reduction, civil protection, and sectoral policy development. The analysis is therefore designed not only to identify the main risks, but also to clarify how serious, urgent, and manageable they are under current and future climate conditions.

The CLIMAAX Handbook and Toolbox ensure a transparent, consistent, and replicable assessment process while allowing adaptation to the territorial context of Ruse Municipality. Local data, contextual information, and stakeholder knowledge are used to refine, validate, and interpret the workflow outputs. Where possible, locally relevant thresholds, indicators, and contextual factors are incorporated to better reflect actual exposure and vulnerability conditions.

Overall, the objective of Phase 2 is not simply to confirm which climate risks affect Ruse Municipality, but to answer more operational questions: where the most significant risks are located, how they may evolve under climate change, which systems and groups are most affected, and where adaptation efforts should be prioritized.

1.3 Project team

The project is implemented by a multidisciplinary team from Ruse Municipality, ensuring institutional ownership and alignment with local governance structures. The core team includes a Project Manager responsible for overall coordination and reporting, a Financial Expert overseeing financial management and compliance, and two Environmental Experts responsible for technical implementation, data collection, and coordination of the Climate Risk Assessment activities.

The municipal team is supported by an external climate expert with academic and applied expertise in climatology — Zoya Mateeva, Prof. Dr. of Climatology, Department of Climate at the Climate, Atmosphere and Water Research Institute (CAWRI), Bulgarian Academy of Sciences (BAS) — and by the external contractor “D and D Consulting” Ltd.

1.4 Outline of the document’s structure

This document is structured in accordance with the CLIMAAX deliverable template and follows the analytical sequence defined in the CLIMAAX Common Methodology Framework.

Following the introductory section, the report presents the Phase 2 Climate Risk Assessment for Ruse Municipality. The assessment is organized around the key methodological steps: scoping, risk exploration, scenario selection, and regionalized risk analysis. It focuses on the three priority hazards identified for the municipality: river floods, heavy rainfall, and wildfires.

For each hazard, the document presents the applied methodology, datasets and assumptions, hazard and risk outputs, local validation, and decision-relevant conclusions. The main analytical results are included directly in the body of the report to ensure that the deliverable is self-contained and that the link between data, analysis, and prioritization is transparent.

The document then synthesizes the key risk assessment findings through the evaluation of severity, urgency, and resilience capacity, which form the basis for risk prioritization. These findings are explicitly linked to their implications for municipal decision-making and adaptation planning.

The final sections present the main conclusions of Phase 2, including methodological reflections, key limitations and uncertainties, and the added value of the refined assessment. The report concludes with an outline of the planned activities for Phase 3, focused on identifying, assessing, and prioritizing adaptation options tailored to the risk profile of Ruse Municipality.

2 Climate risk assessment – phase 2

2.1 Scoping

The scoping phase established the objectives, territorial focus, analytical boundaries, and stakeholder framework for the Phase 2 Climate Risk Assessment of Ruse Municipality, in line with the CLIMAAX Handbook. Its purpose was to define a locally relevant evidence base for refining and prioritizing the most significant climate risks affecting the municipality and to ensure that the assessment supports practical decision-making and the development of adaptation options.

For Ruse Municipality, scoping was shaped by its specific territorial and functional characteristics: its location on the southern bank of the Danube River, the presence of flood-prone areas along both the Danube and the Rusenski Lom system, its role as a major urban, industrial, and transport centre, and the concentration of population, infrastructure, and economic activity in the city of Ruse and surrounding peri-urban zones. Agricultural land, semi-natural areas, and forest-settlement interfaces further broaden the range of relevant climate hazards and exposure patterns.

This context shaped the selection of the three priority hazards examined in Phase 2 — **river floods, heavy rainfall, and wildfires** — as well as the spatial scale and analytical depth of the assessment. Scoping also considered data availability, the feasibility of applying CLIMAAX workflows, and the need to produce results useful for municipal planning, infrastructure management, civil protection, and future adaptation planning.

Key stakeholders and expert groups were identified early in the process, including representatives of municipal administration, technical departments, civil protection services, environmental and planning experts, and institutions responsible for data provision and risk management. Their involvement supported access to local knowledge, improved interpretation of analytical results, and strengthened institutional ownership of the CRA process.

2.1.1. Objectives

The objective of the Phase 2 Climate Risk Assessment is to refine and operationalize the results of Phase 1 by carrying out a more quantitative, regionalized, and scenario-based analysis of the priority climate risks affecting Ruse Municipality. In line with the CLIMAAX Framework, Phase 2 moves from broad qualitative screening towards structured risk characterization, comparison, and prioritization based on the combined analysis of hazard, exposure, and vulnerability.

For Ruse Municipality, this means focusing on the three priority hazards identified in Phase 1 — **river floods, heavy rainfall, and wildfires** — and translating them into risk information that is spatially explicit, locally interpretable, and usable for municipal planning and decision-making. The CRA is designed to support the municipality in:

- prioritizing climate risks according to severity, urgency, and resilience capacity;
- identifying spatial risk hotspots affecting critical infrastructure, economic activities, public services, and vulnerable population groups;
- supporting more targeted adaptation responses and future investment decisions.

The expected outcome of Phase 2 is a set of robust and policy-relevant risk outputs that provide a clearer basis for the identification, assessment, and prioritization of adaptation options in Phase 3. These outputs are intended to inform municipal and regional planning processes, including spatial planning, infrastructure planning, disaster risk reduction, environmental management, civil protection, and other sectoral strategies relevant to resilience building.

Compared to Phase 1, the CRA objectives remain consistent but become more focused and operational. While Phase 1 concentrated on scoping, hazard identification, and preliminary prioritization, Phase 2 deepens the analysis by refining selected workflows, incorporating local evidence, and producing stronger analytical support for risk governance and adaptation planning.

Limitations, boundaries, and challenges

The Phase 2 CRA is subject to several constraints. The main limitation remains the availability of sufficiently detailed local data, particularly long-term high-resolution historical datasets, hazard-specific impact records, and sector-specific vulnerability indicators. National and European datasets provide an essential analytical basis, but their spatial and thematic resolution does not always fully capture local-scale variability within Ruse Municipality.

Stakeholder participation in Phase 2 was also more targeted than in Phase 1, focusing mainly on institutional stakeholders, technical experts, and data providers. This reflects the analytical and workflow-based nature of the phase, but it also means that some forms of community-level qualitative knowledge are less strongly represented.

Additional challenges arise from uncertainties in future climate projections, scenario assumptions, and the limited availability of locally calibrated impact models. These challenges are addressed through scenario-based analysis, harmonized CLIMAAX workflows, complementary local data sources, and explicit discussion of limitations and uncertainties. The objective is not to eliminate uncertainty, but to reduce it where possible and provide sufficiently transparent results for informed municipal decision-making.

2.1.2. Context

Until recently, climate hazards and impacts in Ruse Municipality have been addressed mainly through sectoral and reactive approaches, such as Danube flood protection, emergency response planning, and civil protection measures. These approaches have largely been based on historical events and short-term hazard management, with limited integration of future climate projections and insufficient coordination across sectors. Repeated disruption caused by intense rainfall and flooding has highlighted gaps in anticipation, preparedness, and systemic risk management.

The need for a more integrated and forward-looking approach is reinforced by Ruse's multi-hazard exposure. The municipality is affected by interacting risks, particularly river flooding from the Danube and Rusenski Lom, heavy rainfall leading to pluvial flooding, and wildfire risk in peri-urban and semi-natural areas. These hazards affect interconnected systems, including urban infrastructure, transport networks, public services, economic activities, and vulnerable population groups, creating cascading impacts that cannot be managed effectively through isolated sectoral measures.

Ruse also plays a strategic role as a major urban, industrial, and transport hub along the Danube River, with strong cross-border connections to Romania. Climate-related disruptions may therefore affect not only the municipality, but also cross-border mobility, trade, logistics, and regional economic stability.

The governance context is shaped by national legislation, sectoral policies, EU requirements, and local strategic documents related to climate adaptation, disaster risk reduction, water management, spatial planning, and environmental protection. Although these frameworks define responsibilities for prevention and response, they provide limited operational guidance for integrated, forward-looking, and spatially explicit risk assessment at municipal level. Climate risk assessment is not yet institutionalized as a continuous coordinated process, but remains distributed across departments with overlapping mandates, limited resources, and fragmented data availability.

The CLIMAAX project addresses these gaps by introducing a harmonized, scenario-based, and spatially explicit methodology aligned with EU climate resilience objectives. For Ruse Municipality, this enables more integrated risk analysis, improved use of available data, and stronger linkage between risk assessment and planning processes.

Key sectors relevant to climate risk in Ruse include urban development and spatial planning, transport and critical infrastructure, water management and drainage systems, public health and social services, agriculture, and peri-urban land use. These sectors are particularly exposed to flooding and heavy rainfall, with potential cascading effects across municipal systems.

Climate risk management in Ruse is also influenced by external drivers, including basin-wide Danube flood dynamics, transboundary processes, national infrastructure priorities, land-use change, and EU funding mechanisms. Climate change acts as an overarching driver, increasing uncertainty regarding future hazard intensity, frequency, and compound effects.

Within this context, the CRA provides a foundation for targeted adaptation planning. It supports the identification of structural and nature-based measures, risk-informed spatial planning, institutional coordination, early warning systems, and social measures focused on vulnerable groups and risk communication.

2.1.3. Participation and risk ownership

Stakeholder involvement in Phase 2 focused on institutional and technical actors directly engaged in climate risk identification, assessment, and management within Ruse Municipality. Compared to Phase 1, participation was more targeted and specialized, reflecting the analytical and workflow-based nature of the assessment.

Stakeholders contributed mainly through:

- provision of locally available data and information;
- validation of key assumptions and thresholds;
- interpretation of hazard and risk assessment results in relation to local conditions and past events.

This focused engagement helped align analytical outputs with local context and institutional practice, while strengthening ownership of the assessment results.

An overview of the institutional structure relevant to climate risk management in Ruse Municipality is presented in Figure 2.1.

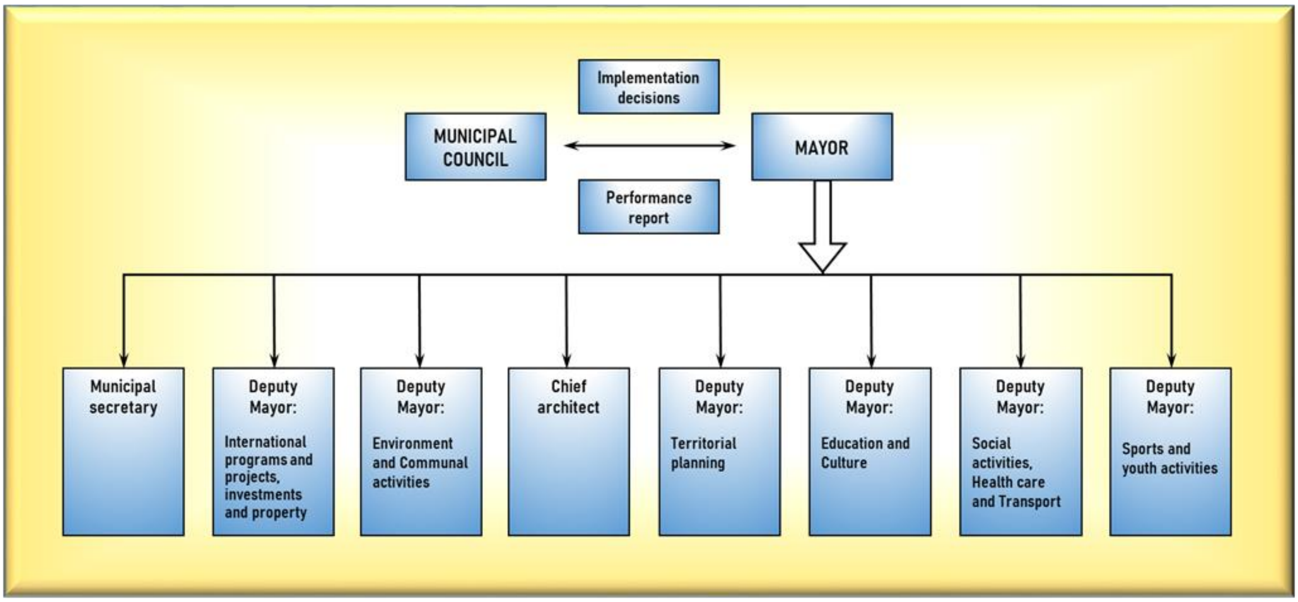


Figure 2.1. Organigram – Ruse Municipality

The Municipal Council provides political oversight and approves strategic documents, budgets, and planning instruments, including those related to climate adaptation and risk management. The Mayor, as executive authority, is responsible for implementing municipal policies and integrating CRA results into planning, investment decisions, and sectoral policies.

Deputy Mayors hold sectoral portfolios directly relevant to climate risk, including investments and property, territorial planning, environment and communal activities, social services, transport, education, and public communication. These functions are important for translating risk assessment results into infrastructure planning, spatial regulation, green infrastructure, emergency preparedness, and awareness-raising.

The municipal administration, including the Secretary, directorates, departments, and specialized units, ensures internal coordination, legal compliance, financial control, and technical support. These structures are also essential for data collection, management, and processing.

Risk ownership in Ruse Municipality is distributed across multiple governance levels. The municipality has primary responsibility for local risk identification, planning, and preventive measures, while national authorities are responsible for hazard monitoring, regulatory frameworks, and emergency response coordination. This distribution creates a fragmented governance context and reinforces the need for shared understanding and coordinated use of climate risk information.

The existing system is relatively effective for acute disaster response, but climate change introduces a long-term and evolving risk dynamic. In periods without extreme events, responsibilities for systematic monitoring, prevention, and adaptation remain less clearly defined.

From a social perspective, the assessment considers vulnerable groups such as residents of flood-prone areas, socially disadvantaged populations, and users of critical infrastructure and public services. Explicit thresholds for acceptable or tolerable risk are limited, but civil protection standards, planning regulations, and sectoral norms provide indirect reference points.

Overall, stakeholder involvement in Phase 2 improved the relevance, interpretation, and usability of the CRA, while highlighting the need for stronger institutional coordination and more systematic integration of climate risk into local governance.

2.1.4. Application of principles

The Phase 2 CRA applies the core principles of the CLIMAAX Framework to ensure that the assessment is socially relevant, methodologically robust, transparent, and forward-looking.

Social justice, equity, and inclusivity

The assessment explicitly considers the unequal distribution of climate risk across population groups, territories, and functional zones. Particular attention is paid to elderly residents, low-income households, outdoor workers, and people living in flood-prone or poorly serviced urban and peri-urban areas, including areas influenced by the Rusenski Lom river system.

This is especially relevant for Ruse, where flood and heavy rainfall impacts tend to concentrate in areas with ageing infrastructure, limited drainage capacity, and lower socio-economic resilience. The analysis therefore considers not only physical hazard patterns, but also the social and territorial conditions that shape vulnerability and adaptive capacity.

Stakeholder engagement supported this principle by incorporating input from municipal services, civil protection authorities, social services, technical experts, and other local actors. Their contributions helped identify vulnerable areas, validate assumptions, and ensure that the assessment reflects local conditions rather than only generalized model outputs.

Quality, rigour, and transparency

Quality and transparency were ensured through the use of harmonized CLIMAAX workflows and documented analytical methods. Hazard and risk analyses used recognized climate, hydrological, spatial, and socio-economic datasets, including EURO-CORDEX projections, Copernicus services, official hydrological and flood-risk sources, and national and local statistical and observational data.

Assumptions, data limitations, and uncertainties are documented explicitly. Workflow implementation through reproducible Jupyter notebooks supports traceability and consistency. The use of multiple complementary sources, including local observations and contextual data, strengthens validation and reduces dependence on a single dataset or model source.

Precautionary approach and forward-looking analysis

The precautionary principle was applied by systematically incorporating future climate scenarios and focusing on risks with potentially severe, cumulative, or cascading impacts, even where uncertainty remains. The analysis uses medium-term future scenarios, primarily under high-emission conditions, to test the exposure of Ruse Municipality to plausible upper-range climate stress.

Particular attention is given to threshold exceedance and compound effects, especially the interaction between heavy rainfall and river flooding, and the projected intensification of fire weather conditions. This supports a preventive and anticipatory understanding of climate risk rather than one based only on past events.

Adaptive management perspective

The CRA is treated as an iterative process that can be updated as new data, improved methods, and additional local evidence become available. This is important for Ruse Municipality, where uncertainties remain regarding future climate dynamics, local impact thresholds, and interactions between multiple hazards.

The assessment therefore supports the identification of no-regret and low-regret measures, including improved monitoring, early warning, preventive planning, and capacity-building actions that remain beneficial under a wide range of future conditions.

Overall, the application of these principles strengthens both the analytical quality and the practical relevance of the CRA and supports more coherent, equitable, and risk-informed adaptation planning in Ruse Municipality.

2.1.5. Stakeholder engagement

To complement the quantitative modelling, a structured stakeholder consultation was conducted among representatives of:

- municipal administration,
- environmental and planning departments,
- civil protection services,
- infrastructure operators,
- local experts.

A total of **51 responses** were collected.

The questionnaire was designed to assess:

- the perceived severity of each priority hazard,
- the perceived urgency of action,
- institutional preparedness,
- the adequacy of the datasets used in the assessment,
- and the prioritization of risks for adaptation planning.

Validation of risk prioritization.

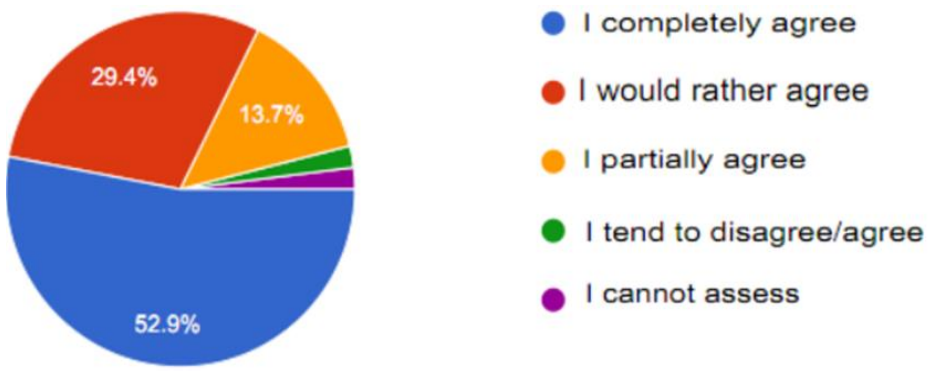


Figure 2.2. Questionnaire. Validation of the priority climate risks according to Deliverable 2

Figure 2.2 presents stakeholder responses regarding the prioritization of climate risks in Deliverable 2. More than half of the respondents (**52.9%**) agreed with the prioritization presented in the assessment, while only a very small share expressed total disagreement. This indicates a **general alignment** between the model-based assessment and stakeholder perception, although it also suggests that further clarification and communication of the analytical results remain important.

Perceived severity, urgency, and overall priority

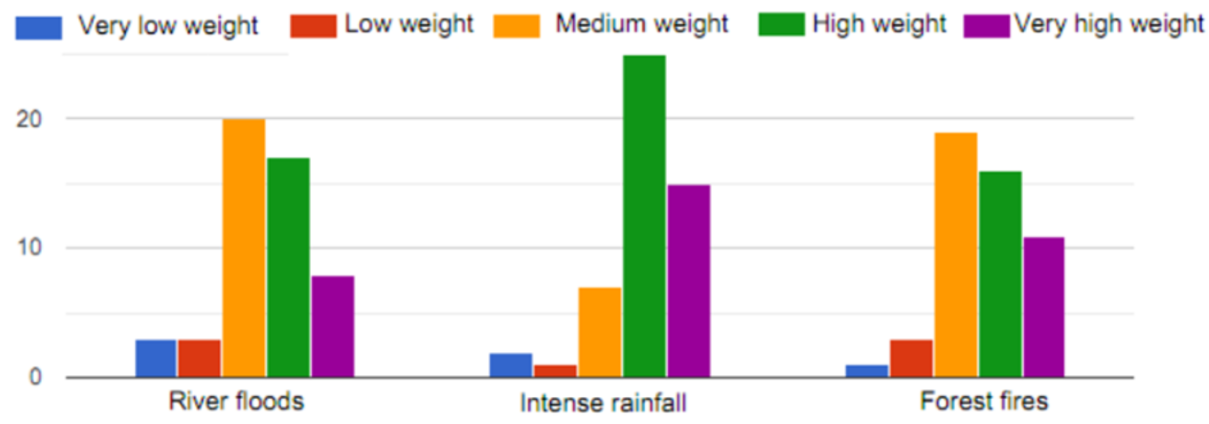


Figure 2.3. Questionnaire. Risk severity

According to the respondents the risk of Extreme rainfall is perceived with the highest severity, followed by Wildfire and River Floods.

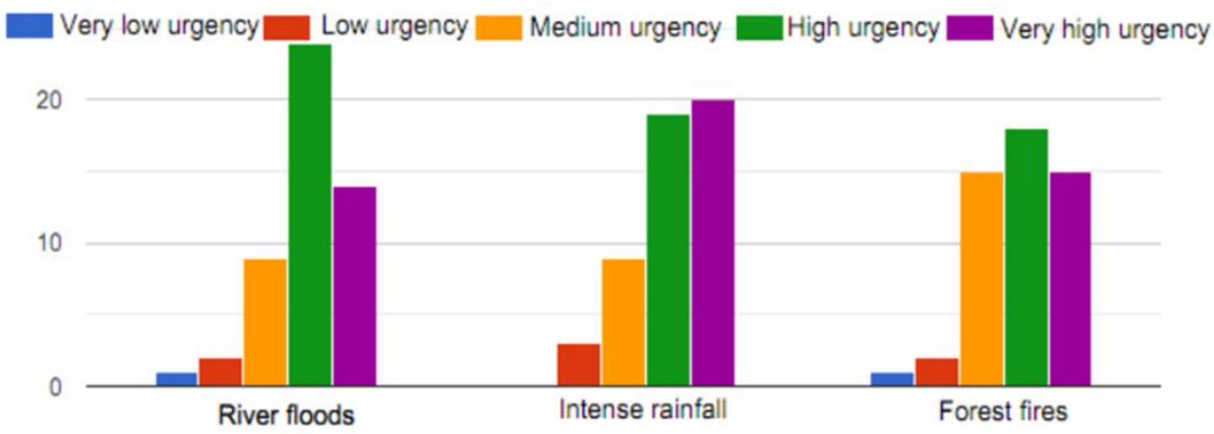


Figure 2.4. Questionnaire. Risk urgency

The respondents assess the risk of Extreme precipitation with the highest urgency, followed by Wildfire and River floods.

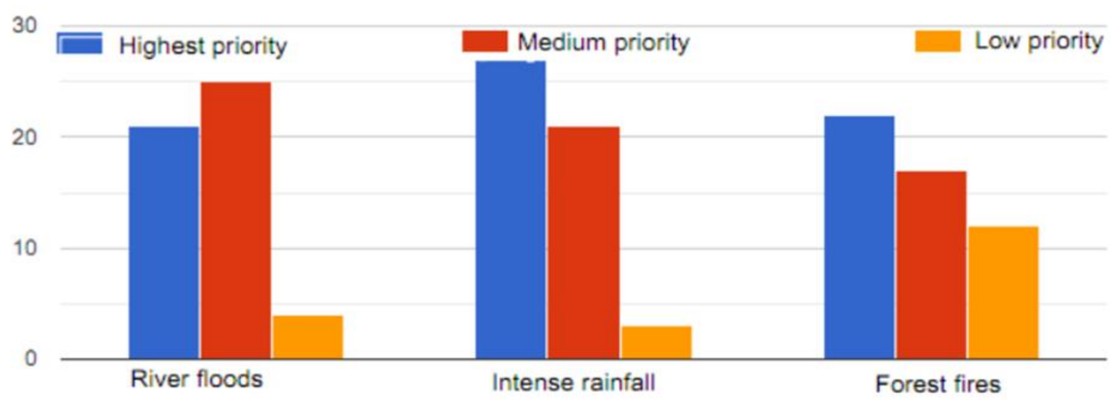


Figure 2.5. Questionnaire. Own prioritization of climate risks

The respondents assess Extreme precipitation as the highest risk overall, followed by River floods and Wildfire.

As shown in **Figures 2.3, 2.4, and 2.5**, a consistent pattern emerges across the three dimensions of stakeholder perception. **Extreme precipitation / heavy rainfall** is perceived as the most critical climate hazard in terms of severity, urgency, and overall priority for action. It is followed by **river flooding** and **wildfire**, although the relative order between the latter two is less pronounced across the responses.

This pattern suggests that stakeholders perceive heavy rainfall as a municipality-wide and highly disruptive hazard, particularly because of its links with urban flooding, drainage overload, and transport disruption. This perception is consistent with the analytical findings presented in Section 2.3.3, which indicate a shortening of return periods and increasing rainfall intensity under future climate conditions.

Data adequacy and missing local information

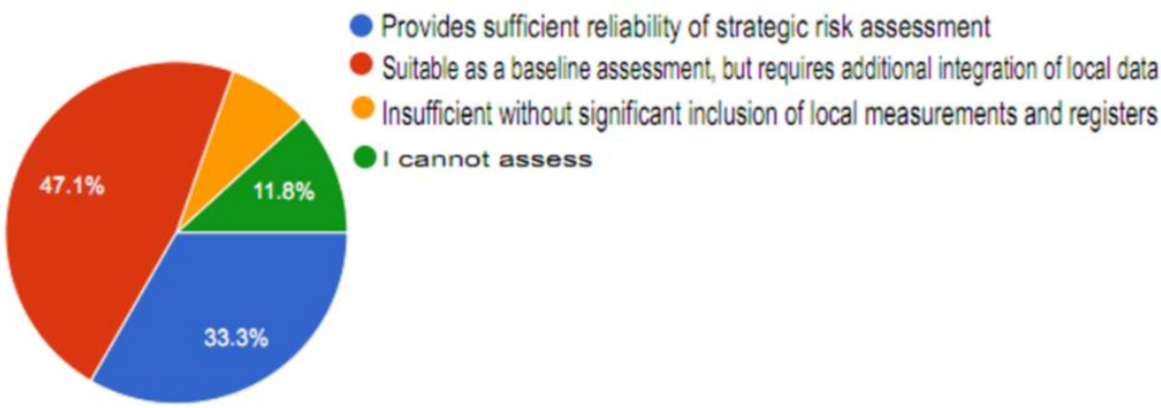


Figure 2.6. Questionnaire. Local data adequacy

As shown in Figure 2.6, most respondents (47.1%) consider that the European harmonized datasets used in the assessment are useful, but should be refined through the incorporation of locally collected data.

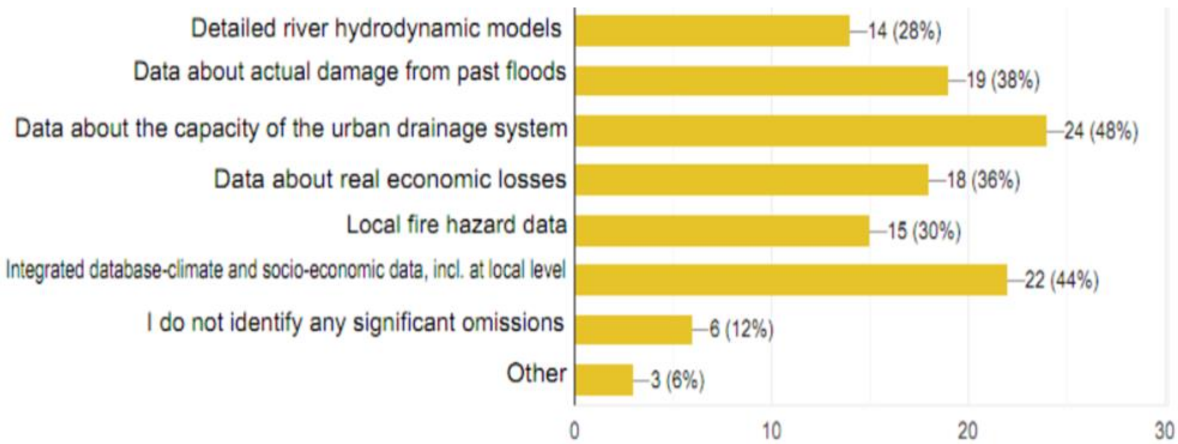


Figure 2.7. Questionnaire. Lack of local data

The main data gaps identified by respondents, presented in **Figure 2.7**, relate to:

- the capacity and condition of urban drainage systems,
- the absence of an integrated local climate database,
- and the lack of systematically recorded infrastructure damage caused by floods.

These perceived gaps correspond directly to limitations identified in the technical analysis, particularly in relation to river floods and heavy rainfall. The stakeholder responses therefore support the need for stronger local data integration and confirm the relevance of the methodological limitations discussed in the hazard-specific analysis in Section 2.3.

Importance of stakeholder involvement and local data sources

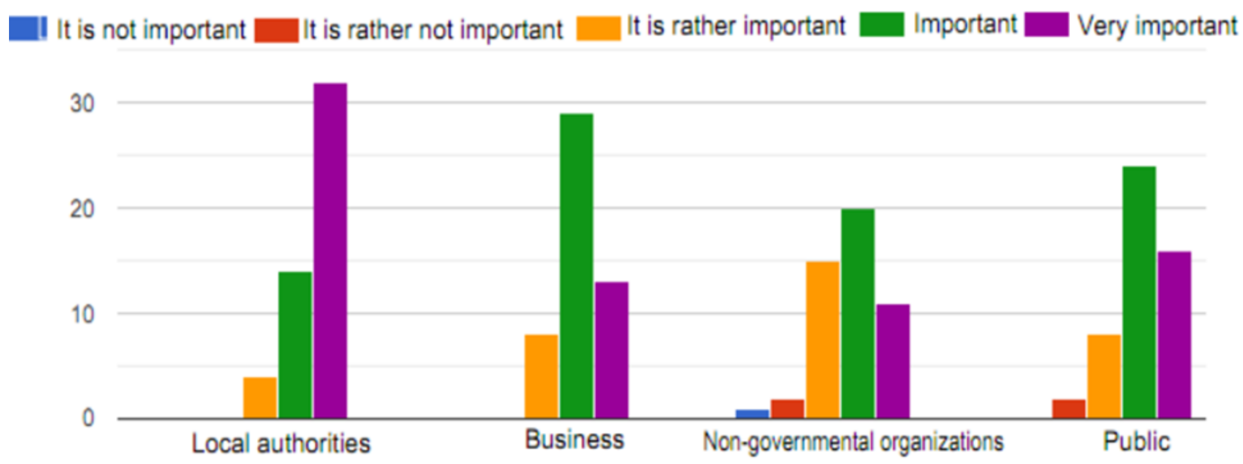


Figure 2.8. Questionnaire. Importance of involvement of stakeholders

Figure 2.8 shows that respondents consider the involvement of local authorities and the public in the assessment of climate hazards and risks to be highly important. This confirms the relevance of participatory approaches for improving both the legitimacy and the practical usability of the assessment.

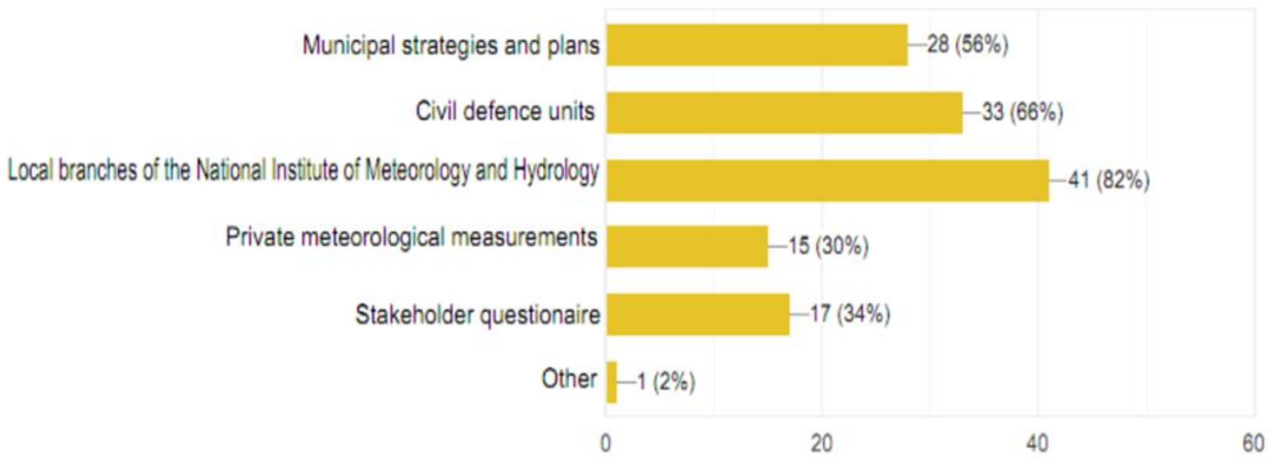


Figure 2.9. Questionnaire. Sources of local climate data

According to **Figure 2.9**, the most important sources of local climate-related data were identified as:

- the local branches of the **National Statistical Institute**,
- the **Civil Protection Service**,
- and the **Municipality** itself.

This finding is important for the further development of climate risk governance in Ruse, as it points to the institutional actors that should be prioritized in future data-sharing and monitoring efforts.

Main conclusions from the stakeholder consultation

The consultation highlights several important conclusions for the Phase 2 assessment.

First, there is a clear convergence between the model-based results and stakeholder perception regarding the importance of the three selected priority hazards. In particular, heavy rainfall is widely recognized as a highly urgent and increasingly disruptive risk, while river flooding continues to be perceived as a major threat because of its implications for infrastructure, economic activity, and exposed population. Wildfire is generally perceived as a lower-priority hazard than flood-related risks, but recent events and increasing climate pressure have raised concern, especially in peri-urban areas.

Second, the consultation confirms that stakeholders do not reject the use of harmonized European datasets; rather, they expect these datasets to be complemented and refined with locally relevant evidence. This supports the overall methodological direction of the assessment.

Third, some differences remain between stakeholder perception and model-based projections. In particular, the future increase in heavy rainfall risk may still be underestimated from an operational perspective, while the longer-term systemic significance of wildfire risk may remain under-recognized due to its historically lower profile in the municipality.

Overall, the stakeholder consultation strengthens the practical relevance of the Climate Risk Assessment by validating the choice of priority hazards, identifying key local data gaps, and highlighting where communication, institutional coordination, and future adaptation planning should be further improved.

The results of the consultation were therefore used as a validation layer for the risk prioritization presented in Section 2.4, particularly in relation to urgency, data adequacy, and the practical relevance of proposed adaptation priorities.

2.2. Risk Exploration

Building on the scoping and initial risk identification undertaken in Phase 1, the Risk Exploration step further refines the climate risks relevant to Ruse Municipality. While Phase 1 provided a broad screening of possible climate hazards, Phase 2 focuses on selecting those risks that require detailed regionalized analysis and can directly inform municipal planning and adaptation decisions.

In line with the CLIMAAX Climate Risk Assessment framework, this step serves as a bridge between contextual scoping and quantitative risk analysis. It aims to:

- confirm the relevance of the hazards identified in Phase 1 using updated climate evidence, local territorial characteristics, and available data;
- select and prioritize the risks requiring detailed assessment;
- define the climate scenarios and analytical assumptions used in the regionalized analysis.

For Ruse Municipality, risk exploration reflects the municipality's specific territorial profile: its location along the Danube River, the flood dynamics of both the Danube and the Rusenski Lom system, its role as a major urban, industrial, and transport centre, and the concentration of population, infrastructure, and economic assets in urban and peri-urban zones. Particular attention is given to areas where climate-related hazards may produce cascading impacts across infrastructure, public services, transport, economic activity, and vulnerable population groups.

The Risk Exploration step therefore provides the analytical rationale for selecting the three priority hazards assessed in detail in Section 2.3: **river floods, heavy rainfall, and wildfires**.

2.2.1. Screen risks (selection of main hazards)

The screening and selection of the main climate hazards for Phase 2 builds directly on the hazard identification and preliminary prioritization carried out in Phase 1. In Phase 1, a broader range of climate-related hazards was considered, including river flooding, extreme precipitation, heat-related phenomena, drought, and wildfires.

In Phase 2, the focus shifts from broad identification to a more targeted assessment of hazards that are both significant for Ruse Municipality and suitable for detailed regionalized analysis using CLIMAAX workflows and complementary local evidence.

The selection was guided by four criteria:

- relevance and severity under current and projected climate conditions;
- potential impacts on population, critical infrastructure, economic activity, and ecosystems;
- availability of data suitable for regionalized hazard and risk analysis;
- consistency with stakeholder-relevant risks identified during the project.

Based on these criteria, three hazards were selected for detailed assessment: **river floods, heavy rainfall, and wildfires**.

River floods

River flooding remains one of the most significant climate-related risks for Ruse Municipality. It is associated not only with the Danube River, but also with the Rusenski Lom system, whose tributaries can generate rapid and localized flooding during intense rainfall.

Phase 1 demonstrated the municipality's structural exposure to river flooding due to the location of residential areas, industrial zones, transport infrastructure, port-related functions, and public services in flood-prone areas. Phase 2 therefore retains river flooding as a priority hazard and advances the analysis towards spatially explicit assessment of flood hazard, exposure, and impacts.

A key local characteristic is the coexistence of two flood regimes:

- large-scale, slow-onset flooding associated with the Danube River;
- faster, rainfall-responsive flooding associated with the Rusenski Lom catchment.

This dual flood regime justifies a more differentiated flood risk assessment for Ruse Municipality.

Heavy rainfall

Heavy rainfall was selected as a priority hazard because of its direct relevance for urban systems in Ruse. Short-duration intense rainfall can lead to pluvial flooding, drainage system overload, road blockage, and disruption of public services.

Unlike river flooding, heavy rainfall is not limited to river corridors. It affects the wider urban territory, especially areas with:

- high shares of impervious surfaces;
- low-lying topography;
- ageing or insufficient drainage infrastructure;
- high concentration of residential, service, and economic functions.

Phase 2 therefore treats heavy rainfall as a distinct hazard, while also recognizing its role as an amplifier of river flood risk, particularly in relation to the Rusenski Lom system.

Wildfires

Wildfires have historically been perceived as a lower-priority hazard in northern Bulgaria, but Phase 1 identified them as an emerging climate risk. Rising temperatures, prolonged dry periods, vegetation stress, land abandonment, and human activity are expected to increase wildfire susceptibility, particularly in peri-urban, agricultural, and semi-natural areas around Ruse.

The inclusion of wildfires in Phase 2 reflects the need to assess not only historically dominant hazards, but also those expected to intensify under future climate conditions. Wildfire risk is particularly relevant for ecosystems, agricultural land, air quality, peri-urban settlements, and emergency response capacity.

Ruse-specific spatial manifestation of selected hazards

The selected hazards are expressed across two main spatial gradients:

- the **Danube river corridor**, where flood hazard is concentrated but potentially severe;
- the **urban–peri-urban interface**, where heavy rainfall, localized flooding, wildfire, and infrastructure exposure interact.

Heavy rainfall affects densely built-up urban areas with limited drainage capacity, causing surface flooding, traffic disruption, and localized infrastructure damage. River flooding affects the Danube floodplain, including residential, industrial, transport, and port-related zones. The Rusenski Lom system introduces an additional inland flood driver, closely linked to short-duration intense rainfall and rapid catchment response.

Wildfire risk is concentrated in peri-urban, agricultural, and semi-natural areas, where seasonal dryness, vegetation, land management practices, and human activity overlap. Although wildfire impacts in the urban core have historically been limited, risk is increasing in interface zones near settlements, transport routes, and unmanaged land.

Climate trends supporting prioritization

Observed and projected climate trends support the selection of the three hazards. Regional climate evidence indicates increasing variability and intensity of precipitation in Northern Bulgaria, including the Ruse region, reinforcing the relevance of heavy rainfall and pluvial flooding.

For river flooding, future risk is influenced by changes in precipitation patterns, seasonal runoff, and upstream hydrological dynamics within the Danube basin. Although uncertainty remains regarding future flood peaks, the high exposure of Ruse's urban, industrial, and transport systems justifies continued prioritization of river flooding.

For wildfires, rising temperatures and more frequent hot and dry periods are expected to increase fire weather danger, especially during the summer season. This supports the treatment of wildfire as an emerging but increasingly relevant climate risk for the municipality.

Data availability and analytical feasibility

The selection of river floods, heavy rainfall, and wildfires was also shaped by data availability and analytical feasibility. For all three hazards, relevant climate, hazard, exposure, and vulnerability data are available through CLIMAAX workflows and complementary local sources.

At the same time, important data gaps remain, particularly regarding high-resolution local damage records, urban drainage capacity, infrastructure condition, and sector-specific vulnerability indicators. These limitations reinforce the need for a transparent Phase 2 assessment that combines harmonized European datasets with the best available local evidence.

Together, the three selected hazards form a focused but sufficiently comprehensive risk portfolio for Ruse Municipality, enabling a robust and policy-relevant regionalized risk analysis.

2.2.2 Choose Scenario

Scenario logic

The scenario framework for Phase 2 builds on the approach established in Phase 1, but narrows it into a more focused configuration suitable for regionalized risk analysis. While Phase 1 considered a broader range of possible future developments, Phase 2 concentrates on the climate and socio-economic pathways most relevant to the three selected hazards: **river floods, heavy rainfall, and wildfires**.

The purpose of scenario selection is to support forward-looking assessment of how hazard intensity, exposure, vulnerability, and resilience capacity may evolve over time.

Climate scenarios and time horizons

The assessment distinguishes between three time horizons:

- **Short term: 0–5 years**, representing current and near-term risk based on observed climate variability and recent trends;
- **Medium term: 20–30 years**, approximately to 2050, representing the core analytical horizon for Phase 2;
- **Long term: 50–100 years**, towards 2100, used mainly as strategic context.

The medium-term horizon is the most relevant for municipal planning, infrastructure investment, and adaptation policy. It corresponds to the timeframe in which current planning and investment decisions will shape future exposure and resilience.

Consistent with the CLIMAAX methodology and Phase 1 assumptions, **RCP4.5 and RCP8.5** are retained as the main climate pathways where supported by the selected workflows and datasets. RCP8.5 is used particularly as a stress-test scenario to assess risk under high climate forcing. These scenarios support the analysis of:

- increasing intensity of heavy rainfall;
- changes in river flood-generating conditions;
- rising fire weather danger and longer fire seasons.

The long-term horizon remains important for understanding the broader direction of climate change, but Phase 2 gives priority to short- and medium-term risks because these are more directly relevant for municipal decision-making.

Socio-economic scenarios

Socio-economic assumptions focus on drivers that influence exposure, vulnerability, and response capacity in Ruse Municipality. These include:

- demographic ageing;
- concentration of population and economic activity in the city of Ruse;
- continued exposure of critical infrastructure and urban services;
- pressure on peri-urban and infrastructure-intensive zones.

In line with Phase 1, **SSP2** and **SSP3** are used as the most relevant socio-economic pathways. SSP2 represents a continuation of current development trends, with moderate economic development and incremental adaptation. SSP3 serves as a stress-test scenario, reflecting weaker governance capacity, lower investment in adaptation, and reduced institutional ability to cope with increasing climate pressure.

These pathways are particularly relevant for Ruse because risk is shaped not only by hazard intensity, but also by infrastructure condition, governance capacity, demographic structure, and the ability to finance adaptation.

Integrated scenario logic

Phase 2 combines climate and socio-economic dimensions in a unified risk assessment logic. Climate scenarios define how hazard intensity and frequency may evolve, while socio-economic scenarios influence exposure, vulnerability, and resilience capacity.

This approach is consistent with the CLIMAAX understanding of risk as the interaction between physical climate processes and social, territorial, and institutional conditions. By focusing on a limited and coherent set of scenarios, the assessment remains transparent, comparable, and directly relevant for municipal planning.

Table 2.1. Overview of the scenario framework used in Deliverable Phase 2

Dimension	Short-term (0–5 years)	Medium-term (20–30 years)	Long-term (50–100 years)
Climate conditions	Observed climate variability and recent trends	RCP4.5 and RCP8.5 projections	Contextual reference (primarily RCP8.5)
Socio-economic pathways	Current demographic and land-use trends	SSP2 (baseline) and SSP3 (stress-test)	Exploratory, high uncertainty
Main analytical purpose	Baseline and near-term risk	Core regionalized risk analysis	Strategic context and interpretation
Relevant hazards	River floods, heavy rainfall, wildfires	River floods, heavy rainfall, wildfires	River floods, heavy rainfall, wildfires

The table summarizes the selected climate and socio-economic scenarios across temporal horizons and clarifies their role in the assessment. It supports transparency and comparability while keeping the scenario framework focused on the hazards and planning needs most relevant to Ruse Municipality.

2.3. Regionalized Risk Analysis

This section presents the Regionalized Risk Analysis for Ruse Municipality, building on the screening-level assessment developed in Phase 1 and advancing it towards a more locally grounded, quantitative, and decision-relevant evaluation of priority climate risks.

The analysis focuses on the three priority hazards identified for the municipality: **river floods, heavy rainfall, and wildfires**. For each hazard, both hazard and risk dimensions are assessed by combining the CLIMAAX methodological framework with the territorial, hydrological, climatic, land-use, infrastructural, and demographic characteristics of Ruse Municipality.

Compared to Phase 1, the Regionalized Risk Analysis introduces greater spatial, thematic, and analytical refinement. Harmonized European datasets and CLIMAAX workflows are complemented with local and regional evidence, including flood hazard and risk maps, hydrological information, local wildfire records, observational precipitation data, stakeholder input, and relevant scientific studies. These sources are used to validate, contextualize, and interpret the workflow outputs rather than treating them as generic model results.

The local relevance of the assessment is strengthened by explicitly considering:

- the dual flood dynamics of the **Danube River** and the **Rusenski Lom** system;
- the role of heavy rainfall in generating pluvial flooding, urban drainage overload, and cascading urban impacts;
- the growing importance of wildfire conditions in peri-urban, agricultural, and semi-natural areas under increasing heat and dryness.

The analysis also applies probabilistic and scenario-based approaches to characterize not only where hazards occur, but how their frequency, intensity, and impacts may evolve under future climate conditions. This enables the assessment to move from hazard identification towards quantified and interpretable risk information relevant for municipal planning.

Overall, Section 2.3 provides the core analytical basis for the subsequent evaluation of **severity, urgency, resilience capacity, and risk priority**. It therefore serves as the main evidence base for adaptation planning and future investment decisions in Ruse Municipality.

2.3.1. Hazard #1 - River floods: fine-tuning to the local context of Ruse Municipality

The river flood risk assessment for Ruse Municipality builds on the methodological foundation established in Phase 1 and advances it towards a more spatially explicit, probabilistic, and impact-oriented analysis. The CLIMAAX River Flood workflow was regionalized to reflect the two distinct flood regimes shaping risk in the municipality:

(i) the **Danube River**, characterized by large-scale, slow-onset fluvial flooding influenced by upstream hydrological conditions across the international Danube basin; and (ii) the **Rusenski Lom River system**, characterized by faster catchment response and localized flooding triggered by intense precipitation.

Compared to Phase 1, where the assessment focused mainly on hazard screening and qualitative identification of potentially affected areas, Phase 2 introduces a more complete hazard–exposure–vulnerability–impact chain. The main methodological improvements are:

- calculation of probabilistic risk indicators: Expected Annual Damage (EAD), Expected Annual Population Exposed (EAPE), and Expected Annual Population Displaced (EAPD);
- application of sector-specific depth–damage functions to estimate economic losses;
- spatial overlay of flood hazard with buildings, population, and critical infrastructure;
- validation of CLIMAAX/JRC-Copernicus flood layers against official flood hazard and risk maps and local hydrological evidence.

The assessment combines harmonized European datasets with locally relevant information. European flood extent and depth maps provide the baseline probabilistic hazard layers, while local and regional sources are used to validate, contextualize, and interpret the results within the actual hydrological and administrative setting of Ruse Municipality. These sources include official flood hazard and risk maps from the Flood Risk Management Plan (FRMP) of the Danube River Basin Directorate (DRBD), hydrological observations from the Executive Agency for Exploration and Maintenance of the Danube River, historical flood records, and available municipal spatial information on infrastructure and land use.

This approach does not replace the CLIMAAX workflow outputs, but strengthens their local interpretation. It allows the assessment to move from descriptive flood hazard mapping towards decision-relevant flood risk estimation, linking flood depth and probability to economic loss, population exposure, displacement, and critical infrastructure vulnerability.

Table 2.2. Data overview – River floods workflow (Phase 2, Ruse Municipality)

Component	Core European datasets / CLIMAAX workflow	Local and regional data used for validation and contextualization	Risk / impact outputs	Role in the analysis
Hazard	River flood extent and water depth maps for RP10, RP50, RP100 and RP500; JRC /	FRMP flood hazard and risk maps of the Danube River Basin Directorate; hydrological	Flood depth distribution per return period; spatial delineation of	Baseline hazard modelling, local validation, and interpretation of Danube and

	Copernicus EMS, 3 arc-second resolution	observations from the Executive Agency for Exploration and Maintenance of the Danube River; historical flood records	flood-prone zones	Rusenski Lom flood dynamics
Exposure	Building footprints and land-use categories derived from OpenStreetMap; JRC population grids	Municipal infrastructure registers where available; FRMP critical infrastructure layers; local spatial planning information	Identification of exposed buildings, population, and critical infrastructure	Spatial refinement of exposed assets and receptors
Vulnerability	Sector-specific depth–damage functions; reconstruction and content values adjusted using national CPI	Contextual interpretation using regional land-use and construction patterns	Damage estimation by building type and sector	Translation of flood depth into economic consequences
Impact / risk metrics	Probability-weighted aggregation across return periods	Cross-check against FRMP risk zones and historical flood impact patterns	Total damage per return period; EAD; EAPE; EAPD; exposed critical infrastructure	Decision-relevant quantification of flood risk

Table 2.2 summarizes the data framework used for the river flood assessment. The hazard component is based on harmonized European flood extent and depth datasets for multiple return periods, enabling probabilistic risk estimation. These outputs are cross-checked against official FRMP maps and historical flood records to ensure that the modelled flood extents and depth patterns are consistent with the observed and institutionally recognized flood regimes of the Danube and Rusenski Lom systems.

Exposure is represented through building footprints, land-use classification, population grids, and available local infrastructure information. This enables spatial identification of assets and residents located in flood-prone areas. Vulnerability is operationalized through sector-specific depth–damage functions adjusted to the national economic context, allowing flood intensity to be translated into monetary damage estimates.

The resulting indicators - EAD, EAPE, EAPD, total damage per return period, and critical infrastructure exposure - provide a quantitative basis for municipal adaptation planning, investment prioritization, and emergency preparedness.

The assessment also acknowledges important limitations. The 3 arc-second raster resolution may smooth fine-scale urban topography, and the JRC/Copernicus layers do not explicitly model all local flood protection infrastructure. For this reason, interpretation is supported by FRMP documentation, hydrological observations, and historical local evidence to reduce the risk of over- or underestimating exposure.

1. **Hazard assessment – River floods**

The river flood hazard assessment for Ruse Municipality explicitly accounts for the dual-river system shaping local flood dynamics:

(i) the Danube River, characterized by large-scale, relatively slow-onset fluvial flooding influenced by upstream hydrological conditions across the international Danube basin; and

(ii) the Rusenski Lom River system, characterized by a smaller catchment, faster hydrological response, and localized flooding triggered by intense rainfall.

This distinction is a key methodological refinement compared to generalized hazard representations. It ensures that both boundary-driven flooding from the Danube and internally generated, precipitation-driven flooding from the Rusenski Lom catchment are considered within the same analytical framework.

Validation of flood hazard patterns with official basin-level data

To validate spatial consistency, the JRC/Copernicus flood extent and depth layers used in the CLIMAAX workflow were compared with the officially adopted Flood Risk Management Plan (FRMP) maps of the Danube River Basin Directorate. The FRMP maps, including RP20, RP100, and RP1000 flood scenarios, confirm the main spatial patterns identified by the CLIMAAX workflow:

- high-probability flood zones are concentrated along the Danube corridor;
- inland flood-prone areas are clearly associated with the Rusenski Lom valley;
- flood exposure increases significantly under medium- and low-probability scenarios, particularly where floodplains overlap with urban, industrial, and transport infrastructure.

This cross-validation represents an important improvement compared to Phase 1, where the comparison with officially adopted basin-level hazard maps was not systematically documented.

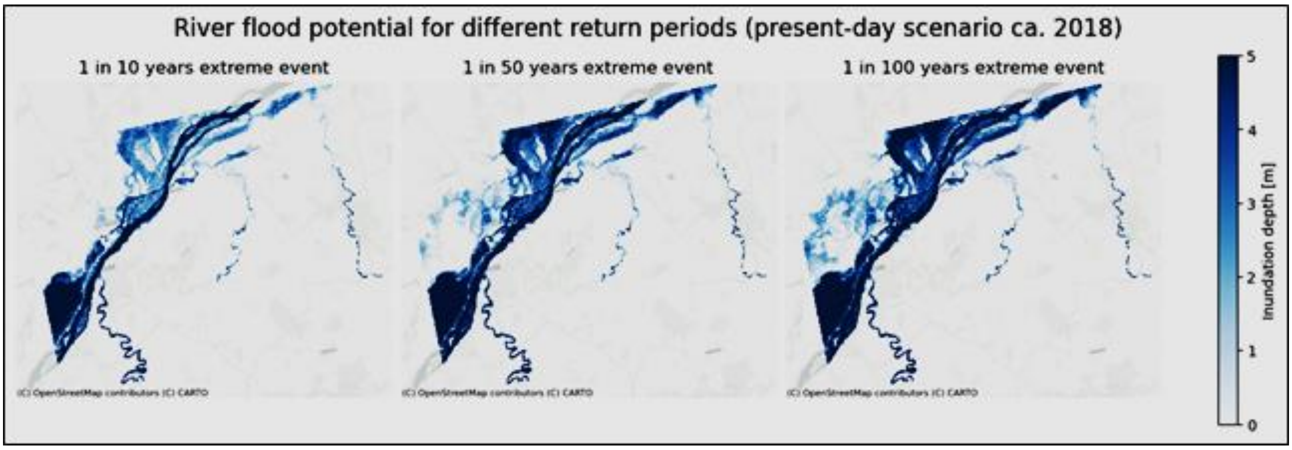


Figure 2.10. Flood hazard extent and depth – baseline scenario (multiple return periods) (Source: CLIMAAX River Flood Hazard workflow).

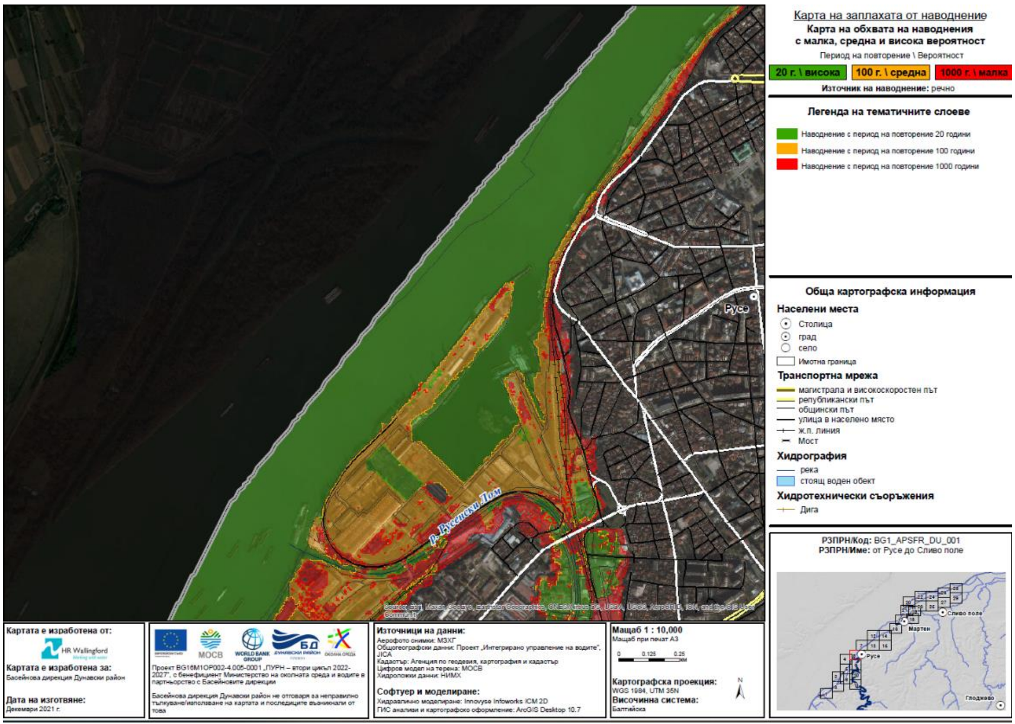


Figure 2.11. Flood hazard extent - low, medium and high probability (Source: Danube River Basin Directorate).

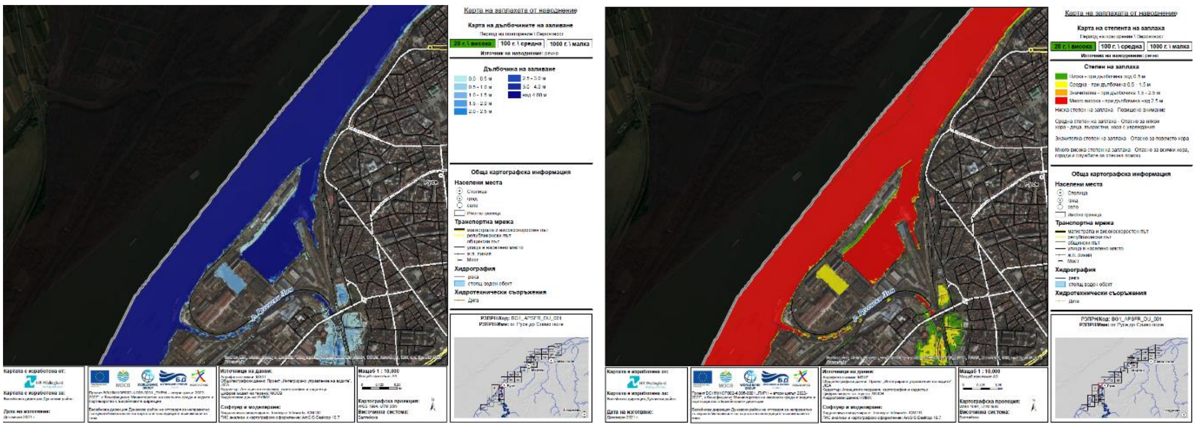


Figure 2.12. Flood depth and hazard, rcp20 (Source: Danube River Basin Directorate).

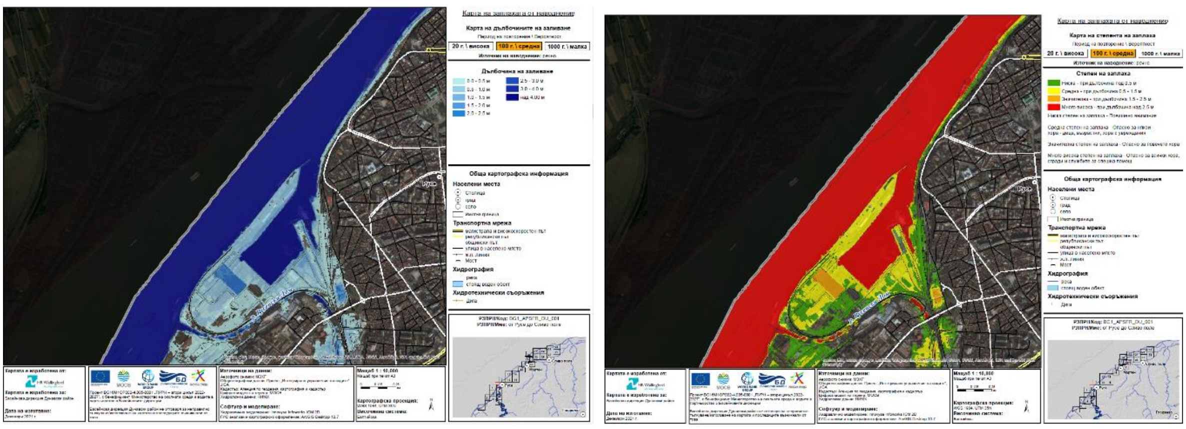


Figure 2.13. Flood depth and hazard, rcp100 (Source: Danube River Basin Directorate).

Figure 2.11 presents flood extent and water depth for selected return periods based on JRC flood hazard datasets. The spatial pattern shows a continuous and laterally extensive floodplain along the Danube River, while the Rusenski Lom system produces more fragmented but spatially penetrating flood extents affecting inland settlements, peri-urban areas, and infrastructure corridors.

The comparison with FRMP maps confirms a strong spatial correspondence, particularly for the RP100 scenario. Local differences between the datasets are mainly explained by differences in modelling resolution, hydraulic assumptions, and the representation of flood protection infrastructure in the FRMP layers. This triangulation strengthens confidence in the hazard delineation used for subsequent exposure and damage modelling.

Climate-informed hazard interpretation

In line with the CLIMAAX framework, the flood hazard assessment incorporates climate-change considerations through scenario-based interpretation of return period behaviour under projected hydro-climatic changes. The flood extent and depth layers are derived from JRC/Copernicus datasets, while their interpretation is linked to expected changes in:

- precipitation intensity;
- runoff variability;
- seasonal flow regimes;
- snowmelt timing in upstream Danube catchments.

This approach does not represent a locally recalibrated hydrodynamic simulation under RCP forcing. Instead, climate change is treated as a modifying factor influencing the likelihood, persistence, and recurrence of flood-generating conditions. This distinction is important: the hazard maps provide standardized probabilistic baselines, while climate scenarios support forward-looking interpretation of how flood risk may evolve.

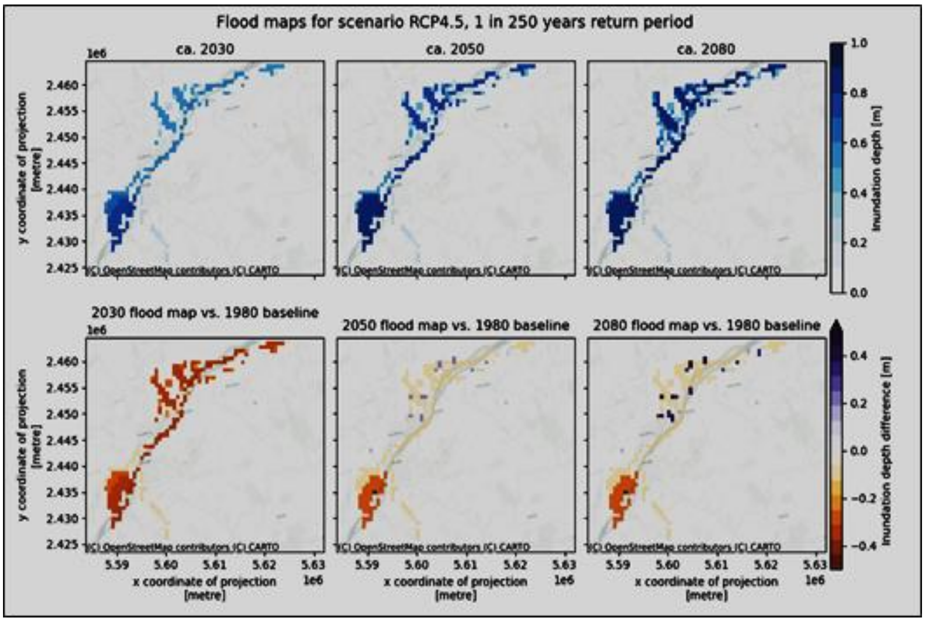


Figure 2.14. River flood hazard under climate scenarios (a)RCP4.5 and (b) RCP8.5 for Ruse Municipality (Source: CLIMAAX River Flood Hazard workflow)

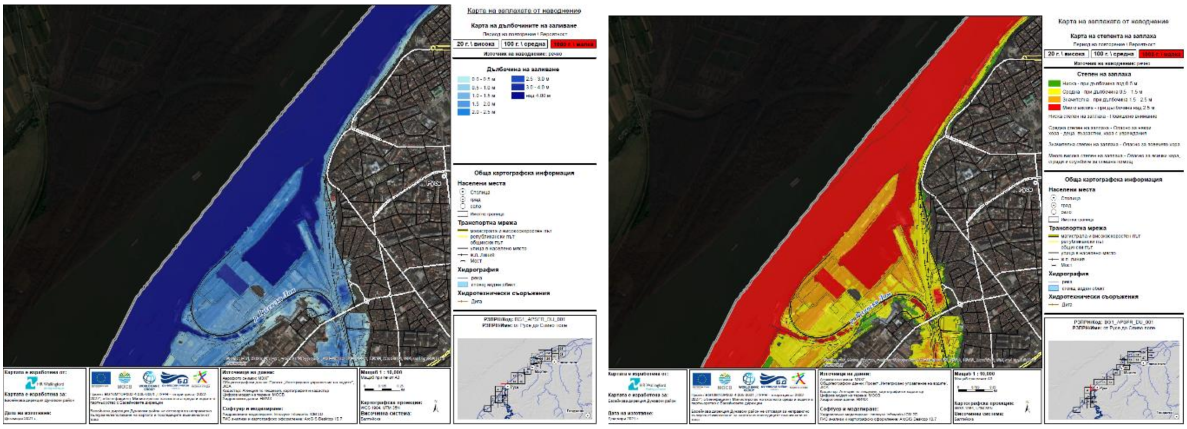


Figure 2.15. Flood depth and hazard, rcp1000 (Source: Danube River Basin Directorate).

The climate-informed comparison indicates that the main flood-prone corridors remain structurally consistent across scenarios, especially along the Danube. However, the Rusenski Lom system appears more sensitive to precipitation variability and catchment response. Under higher climate stress, the key concern is not necessarily a uniform increase in maximum flood depth, but rather:

- more frequent activation of flood-prone areas;
- greater persistence of moderate-depth flooding;
- increased recurrence of inundation in low-lying and tributary-influenced zones.

This is important for municipal risk management, because repeated moderate flooding can generate cumulative structural damage, infrastructure fatigue, and social disruption even in the absence of extreme peak-depth events.

Hazard intensity metrics and return period structure

Flood hazard intensity is operationalized through water depth, consistent with the depth–damage approach used in the CLIMAAX flood workflow. Depth-based hazard layers allow direct coupling with:

- sector-specific depth–damage functions;
- population exposure thresholds;
- displacement modelling;
- critical infrastructure exposure analysis.

Return periods provide the probabilistic structure for hazard characterization. The CLIMAAX workflow uses RP10, RP50, RP100, and RP500, while the FRMP maps use RP20, RP100, and RP1000. These return periods are treated as standardized benchmarks for comparing flood severity and supporting probability-weighted risk metrics such as Expected Annual Damage.

Under climate change, return periods should be interpreted cautiously. A flood event historically associated with a 100-year return period may occur more frequently in future decades if precipitation intensity, runoff dynamics, or upstream hydrological conditions change.

Table 2.3. Flood hazard characteristics by return period – Ruse Municipality

Return period	*Max flood depth (m)*	*Avg flood depth (m)*	*Inundated area (km²)*	*Dominant affected zones*
RP20 (high probability)	~2–3	~1.0–1.5	Limited	Danube riparian strip, lower Rusenski Lom reaches
RP100 (medium probability)	~3–4	~1.5–2.0	Moderate	Expanded Danube floodplain; Rusenski Lom valley; urban-adjacent areas
RP1000 (low probability, extreme)	≥4–5	≥2.0–2.5	Extensive to very extensive	Combined Danube and Rusenski Lom flood domains; peri-urban, industrial, and infrastructure zones

Note: Return period terminology is harmonized with the Danube River Basin FRMP classification. Values are approximate and intended for comparative interpretation of hazard escalation.

Table 2.3 summarizes the principal flood hazard characteristics across return periods. The results show a non-linear relationship between return period and affected area. While maximum flood depths increase progressively, the spatial expansion of inundation zones accelerates disproportionately between medium- and low-probability events.

This effect is particularly important in the Rusenski Lom catchment, where valley geometry and local topographic confinement can translate moderate increases in flood magnitude into substantial lateral floodplain activation. Along the Danube corridor, hazard escalation is expressed mainly through floodplain widening and increased depth persistence rather than abrupt topographic spillover.

This pattern has direct implications for:

- emergency planning thresholds;
- evacuation corridor planning;
- protection of transport and utility infrastructure;
- prioritization of flood-sensitive urban and peri-urban zones.

Data processing and localization

To ensure municipal-level analytical relevance, all hazard rasters were:

- clipped to the administrative boundary of Ruse Municipality;
- harmonized in terms of coordinate reference system;
- resampled or aligned to ensure spatial consistency;
- overlaid with exposure and vulnerability layers used in the CLIMAAX workflow.

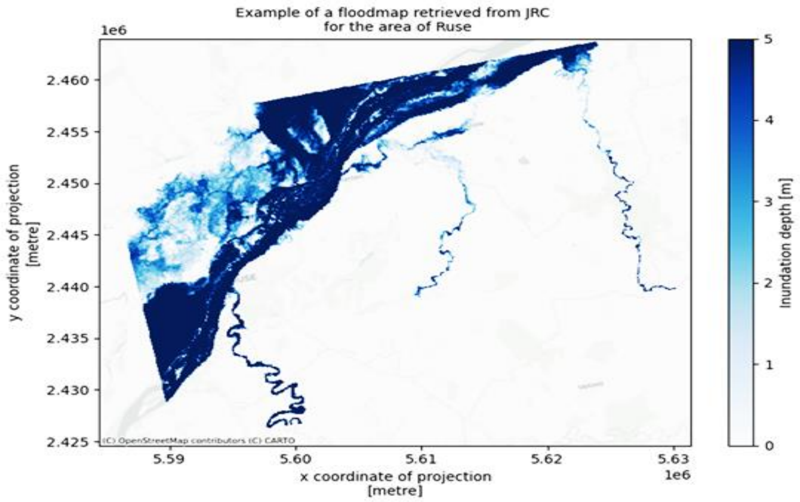


Figure 2.16. River flood hazard potential – localized raster output

The localized hazard outputs demonstrate how European-scale flood datasets can be operationalized at municipal scale. They confirm:

- concentration of high-hazard zones along the Danube floodplain;
- persistent inland flood vulnerability along the Rusenski Lom valley;
- spatial overlap between flood-prone zones and peri-urban infrastructure corridors.

These localized hazard layers constitute the direct input for exposure overlay, damage estimation, and population impact modelling in the following risk assessment stage.

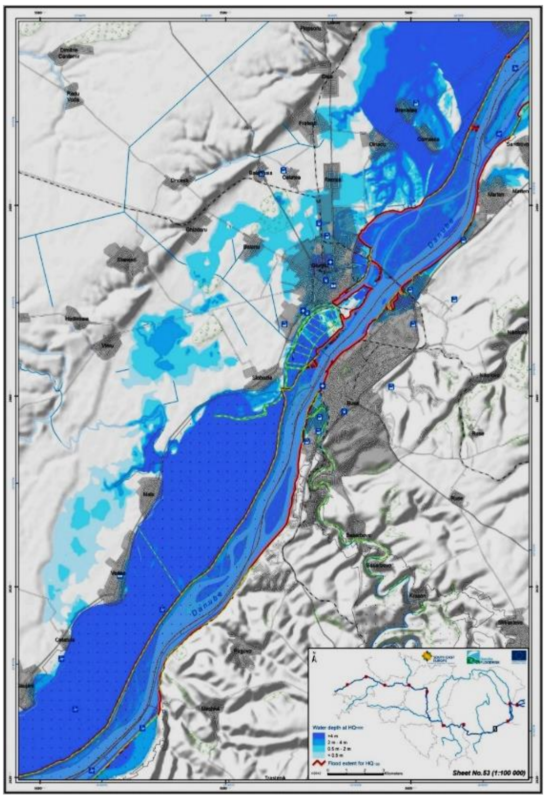


Figure 2.17. Danube flood risk map – water depth near Ruse (Source: Danube River Basin Directorate)

The FRMP water-depth map near Ruse provides an additional validation layer for the hazard assessment. It confirms the spatial concentration of flood-prone zones along the Danube corridor and supports the consistency of the CLIMAAX-based hazard outputs with nationally endorsed hydraulic modelling products.

Minor spatial discrepancies between datasets are expected and are mainly attributable to:

- differences in modelling resolution;
- representation of flood protection infrastructure;
- assumptions regarding hydraulic boundary conditions.

This comparison strengthens the methodological robustness of the hazard assessment and improves confidence in the use of CLIMAAX outputs for municipal-scale risk interpretation.

Methodological strengths and limitations

The river flood hazard assessment is aligned with EU Floods Directive principles and CLIMAAX methodological recommendations. Its main strengths are:

- integration of harmonized European flood datasets with official basin-level FRMP maps;
- explicit differentiation between Danube and Rusenski Lom flood regimes;
- use of multiple return periods for probabilistic interpretation;
- direct preparation of hazard layers for exposure and impact modelling.

At the same time, several limitations remain:

1. Existing flood protection infrastructure is not fully represented in the JRC/Copernicus raster layers, which may lead to conservative overestimation of flood extent in some defended areas.
2. The 3 arc-second resolution may smooth fine-scale urban topographic features relevant for local flood pathways.
3. Climate-informed interpretation does not constitute dynamic hydraulic recalculation under RCP forcing, but rather scenario-based interpretation of probabilistic flood behaviour.

These limitations are addressed by cross-checking CLIMAAX outputs against FRMP maps, local hydrological information, and historical flood evidence.

Overall conclusion on river flood hazard

The river flood hazard assessment provides a robust and locally validated basis for flood risk modelling in Ruse Municipality. Compared to Phase 1, the assessment introduces:

- explicit differentiation between Danube and Rusenski Lom flood dynamics;
- systematic validation with official FRMP maps;
- climate-informed interpretation of flood probability and persistence;
- localized hazard layers suitable for direct overlay with exposure and vulnerability data.

The results confirm that flood hazard in Ruse is not limited to the Danube corridor. The Rusenski Lom system represents a significant inland flood driver, particularly under intense rainfall conditions. This finding is essential for adaptation planning, because it supports differentiated flood management approaches for the Danube floodplain, inland river corridors, peri-urban zones, and critical infrastructure areas.

2. Risk assessment – River floods

The river flood risk assessment for Ruse Municipality builds on the analytical structure established in Phase 1, but significantly extends it by applying an integrated **hazard–exposure–vulnerability modelling chain**. Whereas Phase 1 focused mainly on identifying flood-prone zones and vulnerable receptors, Phase 2 quantifies direct economic damage, population exposure, potential displacement, and critical infrastructure exposure across multiple probabilistic flood scenarios.

The assessment follows the CLIMAAX River Flood risk workflow, fine-tuned to the municipal context through:

- harmonization of hazard layers to the administrative boundary of Ruse Municipality;
- building-level spatial analysis;
- application of sector-specific depth–damage functions;
- adjustment of reconstruction and content values using national CPI;
- overlay with population and critical infrastructure layers;
- validation against Danube River Basin FRMP maps and local historical flood evidence.

This represents a substantial analytical advancement compared to Phase 1, as flood hazard is translated into quantified and spatially explicit risk metrics relevant for planning, investment, and emergency preparedness.

Integrated hazard, exposure and vulnerability framework

Flood hazard inputs consist of flood extent and water depth rasters for multiple return periods (RP10, RP50, RP100, RP500), derived from JRC/Copernicus datasets and interpreted in conjunction with official FRMP hazard and risk zones. These layers were clipped to the municipal boundary, spatially harmonized, and aligned with exposure datasets.

Exposure is represented through three main spatial layers:

- building footprints and land-use categories derived from OpenStreetMap;
- gridded population distribution data from JRC;
- critical infrastructure locations, including healthcare, emergency services, transport nodes, fuel stations, public facilities, and other strategic assets.

Vulnerability is operationalized through sector-specific depth–damage functions based on the JRC methodology, CPI-adjusted reconstruction and content values, and depth thresholds used to identify population exposure and displacement.

This structure allows flood risk to be quantified transparently and reproducibly, while maintaining a clear distinction between hazard intensity, exposed assets, and vulnerability.

Economic flood risk: damage to buildings

Economic flood risk was calculated at building level by intersecting flood depth rasters with individual building footprints. For each building polygon:

- flood depth was extracted,

- building footprint area was calculated,
- land-use type was identified,
- sector-specific depth–damage functions were applied.

Damage estimation followed a depth–damage relationship consistent with JRC methodology:

$$Damage = f(depth) \times BuildingValue$$

where building value reflects reconstruction cost and content replacement adjusted for national CPI.
Damage was computed separately for each return period and then aggregated spatially to produce:

- total damage per return period,
- and probabilistic Expected Annual Damage (EAD) through probability-weighted aggregation across return periods.

This building-level modelling represents a significant refinement over Deliverable 1, where damage estimation was more aggregated and less spatially explicit.

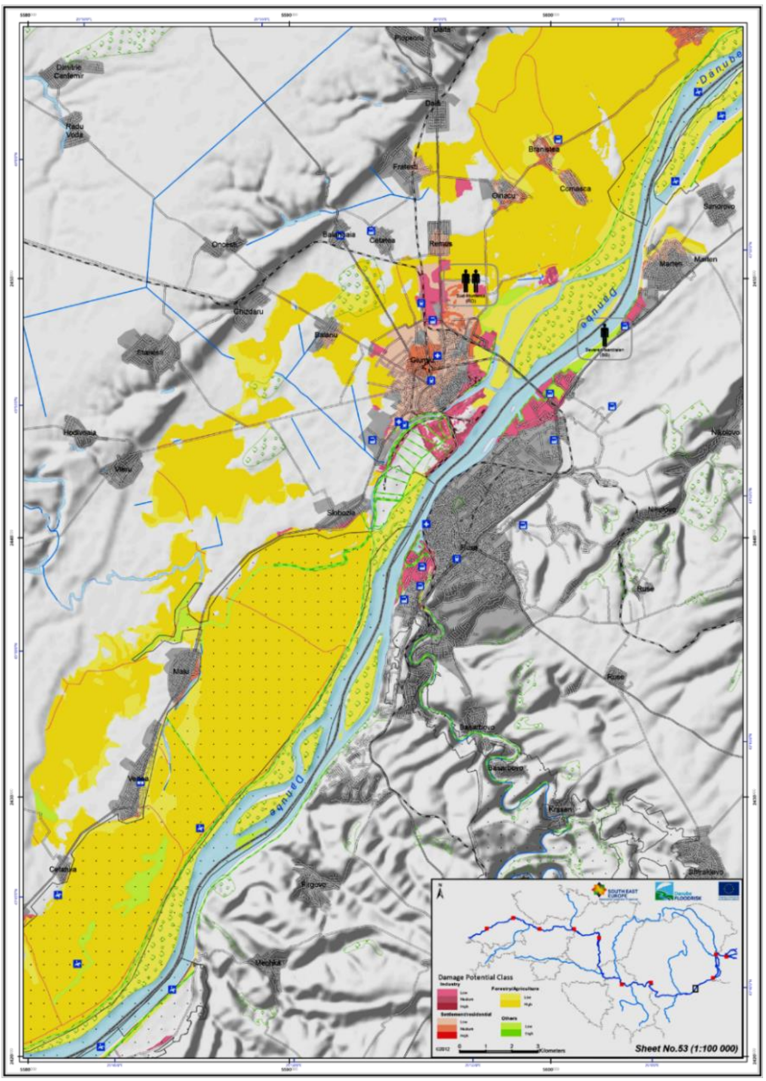


Figure 2.18. Danube flood risk map near Ruse: Damage potential

Figure 2.18 presents the spatial distribution of estimated building damage along the Danube corridor. The concentration of high-damage zones corresponds to areas combining:

- elevated flood depths,
- high building density,
- and economically valuable land-use types.

The spatial overlap between FRMP-identified flood zones and high-damage clusters further confirms the internal consistency of hazard and risk modelling.

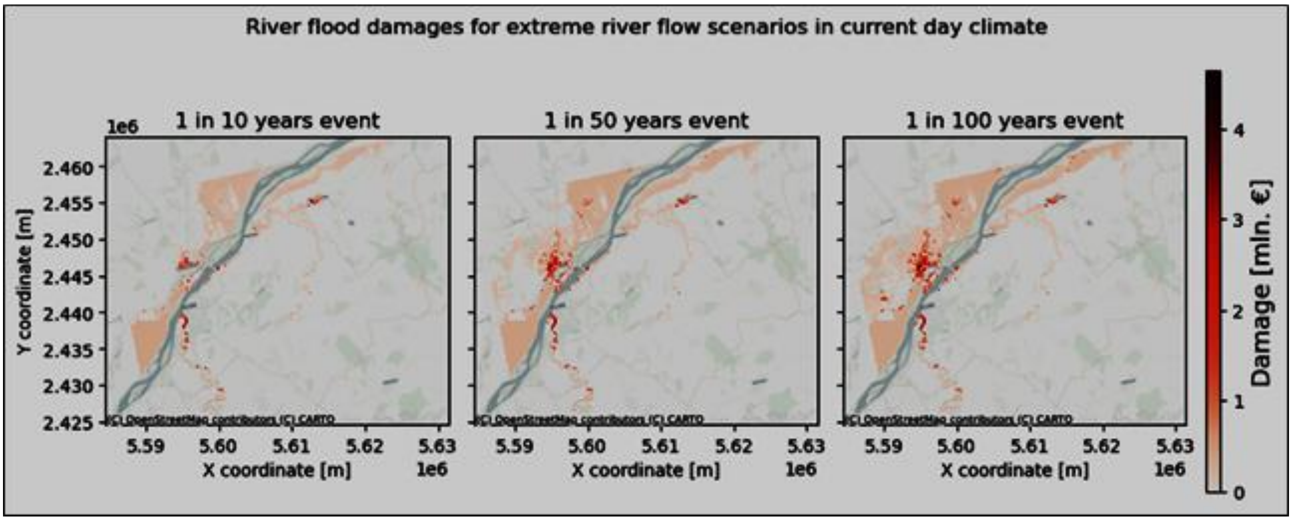


Figure 2.19. River flood damages for extreme river flow scenarios in current-day climate (1-in-10, 1-in-50 and 1-in-100-year events) (Source: Ruse-Flood Risk workflow)

Figure 2.19 illustrates the spatial escalation of building damage across increasing return periods.

The maps show that damage intensity increases through two interacting mechanisms:

1. **Hydraulic amplification** – greater flood depths result in higher percentage damage per structure.
2. **Exposure amplification** – expanding inundation areas intersect with higher-density built-up zones.

Particularly high damage concentrations are observed along the Rusenski Lom corridor, where mixed residential and commercial structures coincide with recurrent inundation zones. In contrast, some Danube floodplain segments exhibit high depths but relatively limited economic damage due to lower development density.

This differentiation demonstrates that exposure distribution plays a decisive role in shaping overall flood risk patterns.

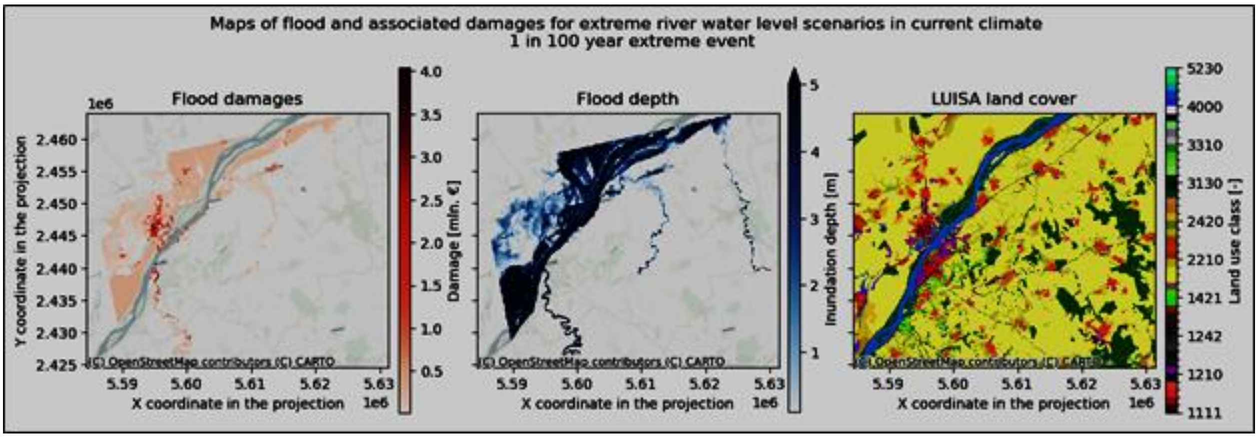


Figure 2.20. Maps of flood and associated damages for extreme river water level scenarios in current climate – 1 in 100 year extreme event (Source: Ruse-Flood Risk workflow)

Figure 2.20 provides a spatially integrated interpretation of flood risk for the RP100 scenario. By overlaying flood depth, land cover, and estimated economic damage, the figure illustrates how hazard intensity translates into differentiated impact depending on asset concentration.

The map highlights:

- high-damage clusters in dense urban and industrial zones,
- moderate-damage areas in peri-urban mixed-use corridors,
- and hydraulically vulnerable but economically low-impact zones in sparsely developed floodplains.

This visualization supports a causal understanding of risk generation and provides a spatial rationale for prioritizing adaptation measures in zones where hazard and exposure converge.

Scenario-based hydraulic simulations (ReSak modelling)

In addition to the probabilistic CLIMAAX-based risk modelling, supplementary hydraulic simulations were consulted to explore extreme wave height scenarios along the Danube River and the Rusenski Lom system.

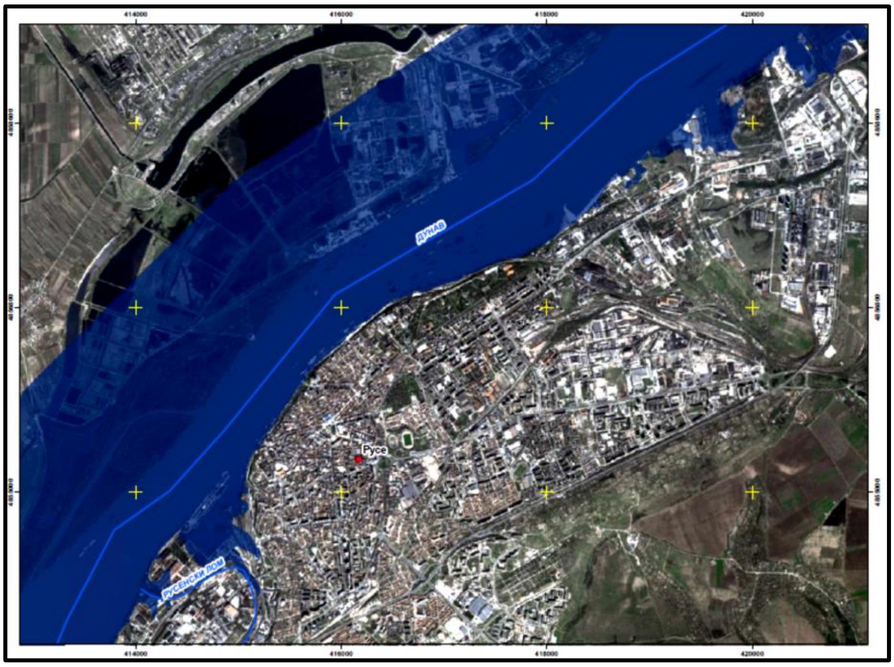


Figure 2.21. Sample map of flooded areas when simulating a wave height of 5m in transport corridor 7 and the Danube River – Ruse (Source: ReSak)

Figure 2.22. Sample map of flooded areas when simulating a wave height of 10 m in transport corridor 7 and the Danube River – Ruse (Source: ReSak)

These simulations illustrate potential inundation patterns under high water-level scenarios exceeding typical probabilistic return periods. While not directly integrated into the probabilistic EAD calculations, they provide scenario-based stress-testing insight into transport corridor vulnerability and port-adjacent infrastructure exposure.

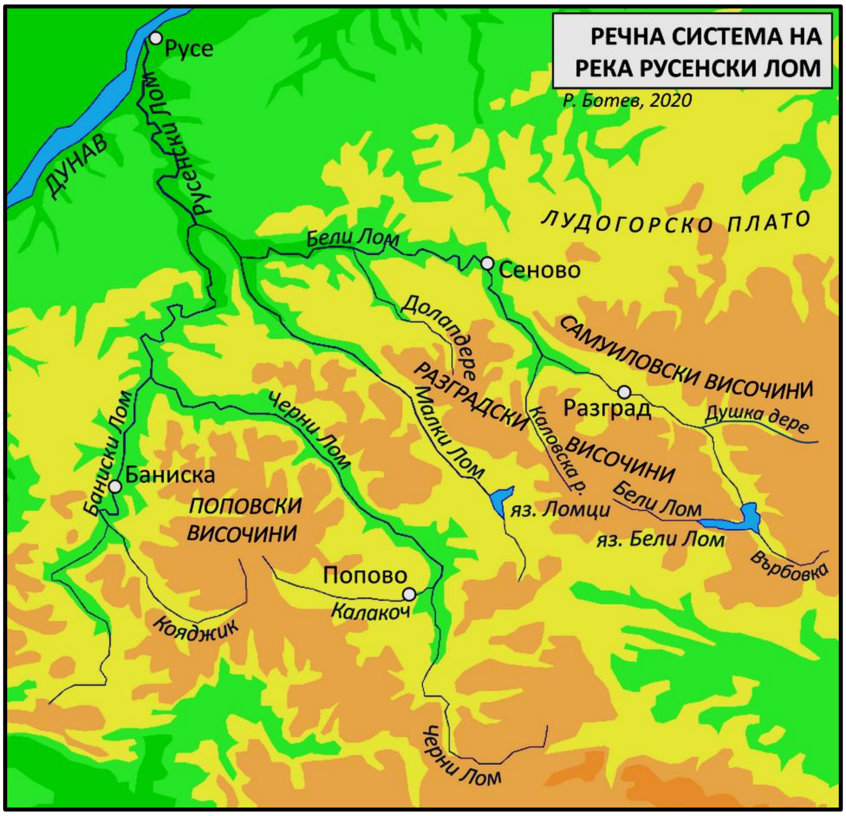


Figure 2.23. Rusenski Lom river system

Figure 2.24. Rusenski Lom river near Basarbovo village not far from Ruse

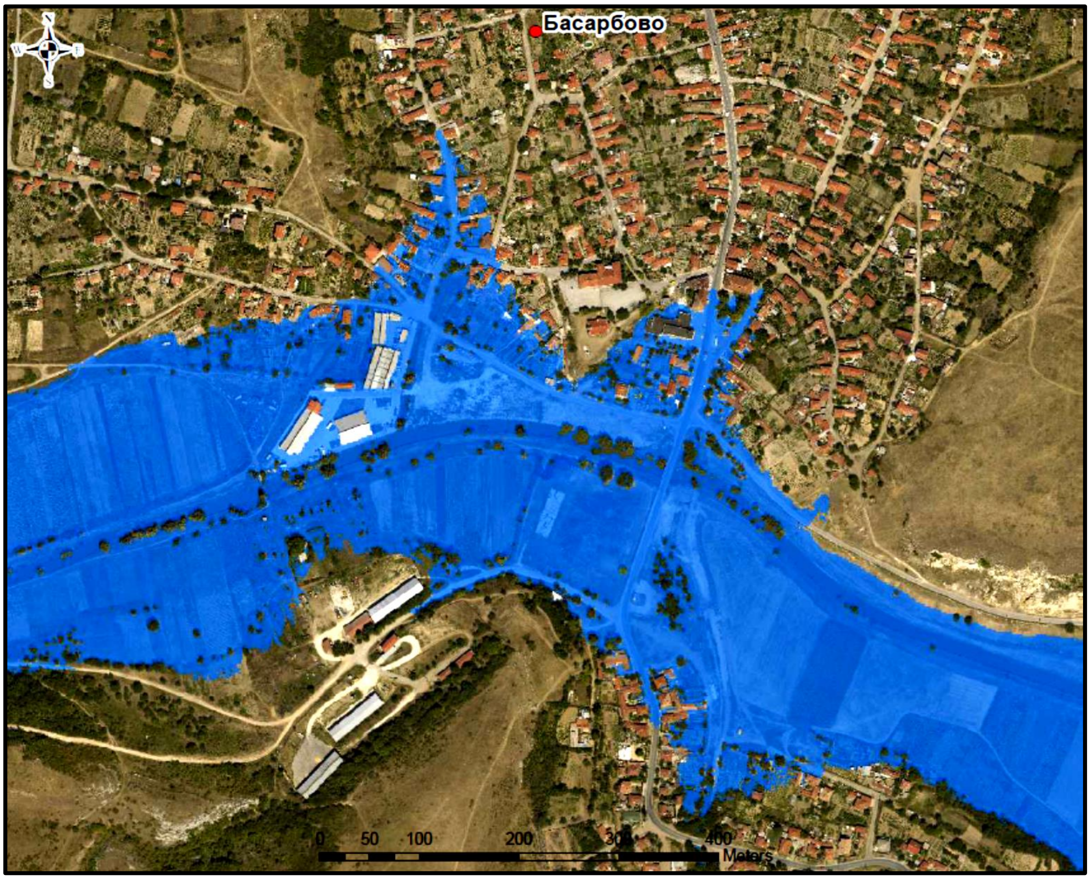


Figure 2.25. Sample map of flooded areas when simulating a wave height of 4m on the Rusenski Lom River in the area of Basarbovo village

The Rusenski Lom simulations highlight the tributary's rapid floodplain activation potential under elevated water levels. Compared to the Danube corridor, where inundation tends to expand laterally across broad floodplains, the Rusenski Lom exhibits localized depth intensification within confined valleys, amplifying structural risk in nearby settlements.

These supplementary simulations complement the CLIMAAX workflow by illustrating plausible high-impact configurations beyond standardized return periods.

Quantified economic risk results

Table 2.4. Total building damage by flood return period for Ruse Municipality, current climate (Source: CLIMAAX River Flood Risk workflow)

Return period	Total building damage (€)	Incremental increase compared to previous RP
RP10	37,459,958	–
RP50	57,490,664	+53%
RP100	65,987,647	+15%
RP500	78,423,142	+19%

The results reveal a non-linear damage progression. The strongest increase occurs between RP10 and RP50, where damages rise by 53%. This indicates that moderate flood escalation already intersects with high-value exposed assets and that significant economic impacts are generated not only by rare extreme events, but also by more frequent flood scenarios.

The increase between RP50 and RP100 is smaller, suggesting partial saturation of some high-value exposed zones. Damage rises again towards RP500 as flooding expands into additional peri-urban, industrial, and infrastructure areas.

For Ruse Municipality, flood risk is therefore driven by the interaction of:

- increasing flood depth and spatial extent;
- concentration of buildings and economic assets in flood-prone zones;
- dual flood dynamics associated with both the Danube and the Rusenski Lom.

Expected Annual Damage

Expected Annual Damage was calculated through probability-weighted aggregation of damages across return periods:

$$EAD = \Sigma [P(RP_i) \times Damage(RP_i)]$$

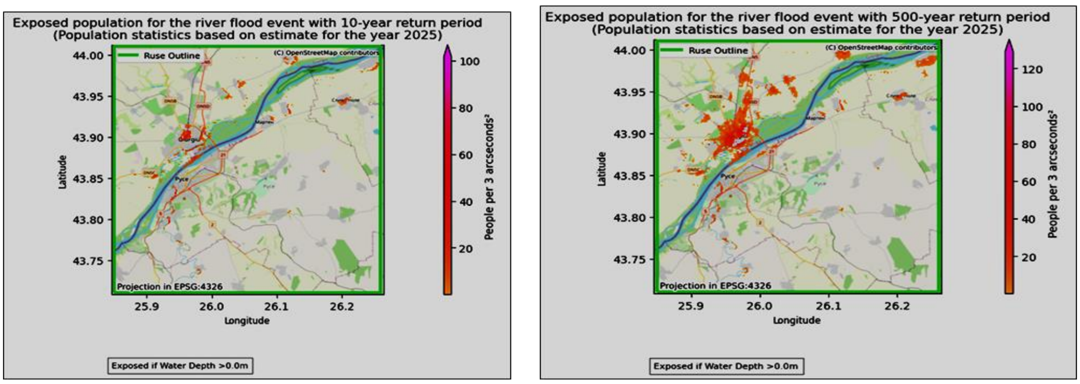
where the probability of occurrence corresponds to the inverse of the return period.

For Ruse Municipality, the mean **Expected Annual Damage (EAD)** is estimated at approximately **€4.99 million per year** under current-climate assumptions. This value represents the long-term annualized economic burden of river flooding and provides a useful benchmark for evaluating flood protection, drainage improvement, spatial planning, and other adaptation investments.

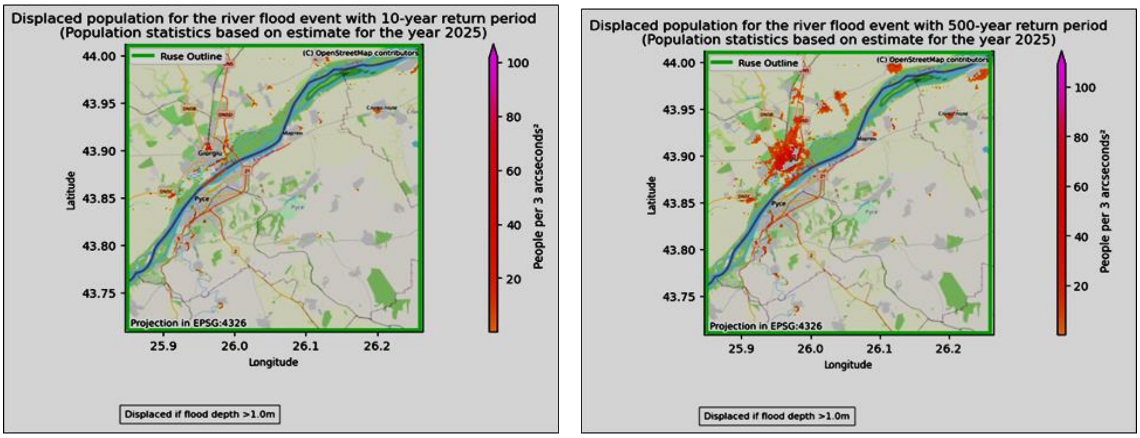
Population exposure and displacement

Population-related flood risk was assessed by overlaying flood depth rasters with gridded population data. Two complementary indicators were calculated:

- **Expected Annual Population Exposed (EAPE)** — population located within inundated areas;
- **Expected Annual Population Displaced (EAPD)** — population exposed to flood depths exceeding a safety-relevant displacement threshold.



Figures 2.26. Population exposure vs. 2 different flood return periods: a) – 10-year return period; b) – 500-year return period (Source: Ruse-Buildings Population Risk workflow)



Figures 2.27. Population displacement vs.2 flood return periods: a) – 10-year return period; b) – 500-year return period (Source: Ruse-Buildings Population Risk workflow)

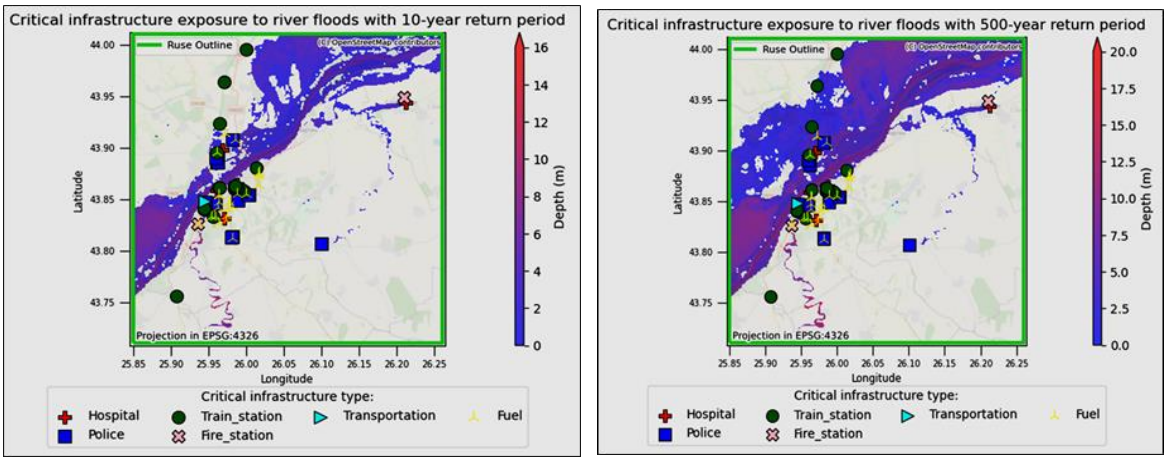
The results show a clear increase in affected population with higher return periods. As flood extent and depth expand, residential areas and peri-urban settlements become increasingly exposed.

The **Expected Annual Population Exposed (EAPE)** is estimated at approximately **4,186 people**, indicating recurrent social exposure to river flooding. The **Expected Annual Population Displaced (EAPD)** is estimated at approximately **3,018 people**, showing that a substantial share of the exposed population may require temporary relocation during severe flood events.

Compared to Phase 1, where demographic vulnerability was described mainly through general indicators, Phase 2 introduces direct, depth-based quantification of social impacts. This improves the operational relevance of the assessment for evacuation planning, shelter capacity, emergency logistics, and social protection measures.

Critical infrastructure exposure and indirect impacts

Critical infrastructure exposure was assessed by overlaying flood hazard layers with infrastructure assets and by comparing the CLIMAAX-generated exposure outputs with DRBD flood risk maps for RP20, RP100, and RP1000 scenarios.



Figures 2.28. Critical infrastructure exposed to river flooding for 2 flood return periods: a) – 10-year return period; b) – 500-year return period. (Source: Ruse-Buildings Population Risk workflow)

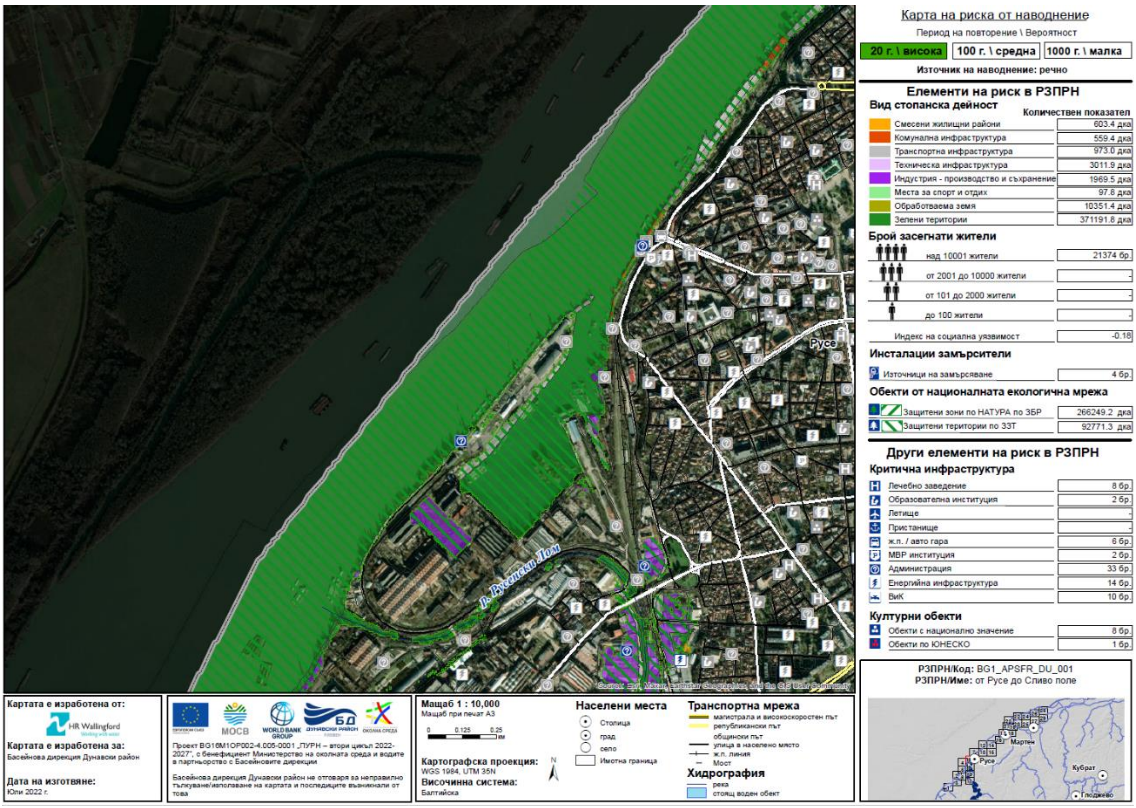


Figure 2.29. Risk Map (RP20) (Source: Danube River Basin Directorate)

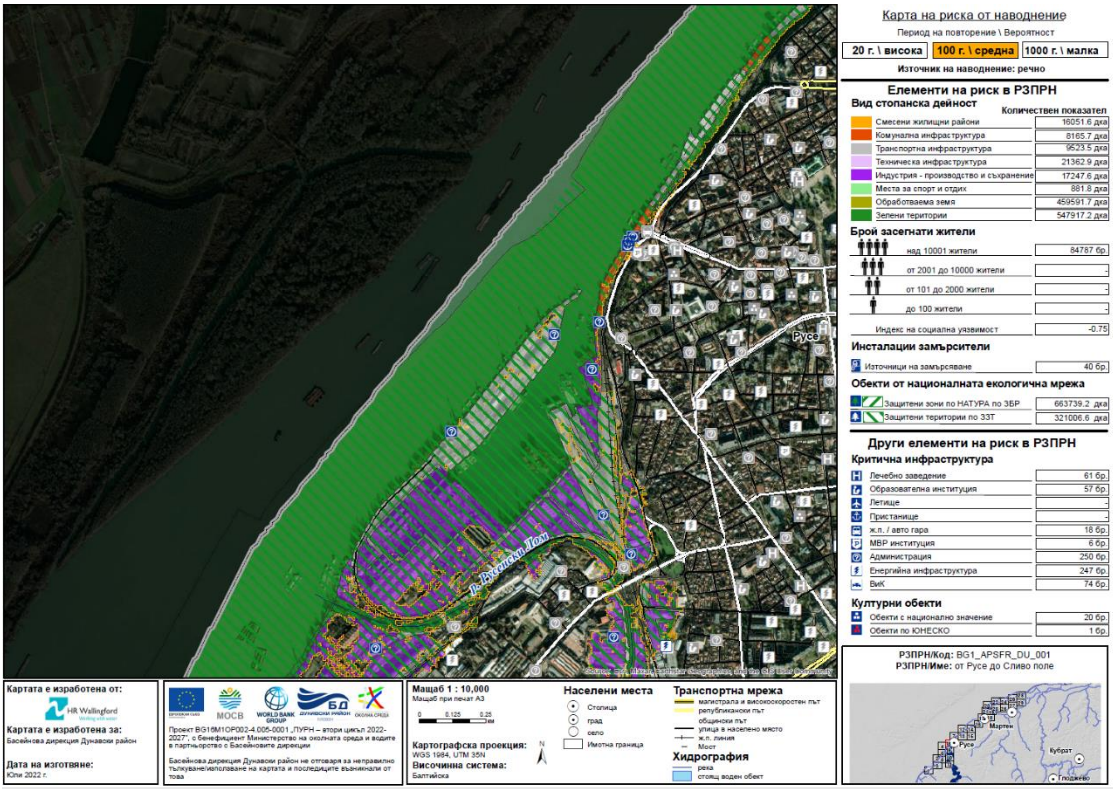


Figure 2.30. Risk Map (RP100) (Source: Danube River Basin Directorate)

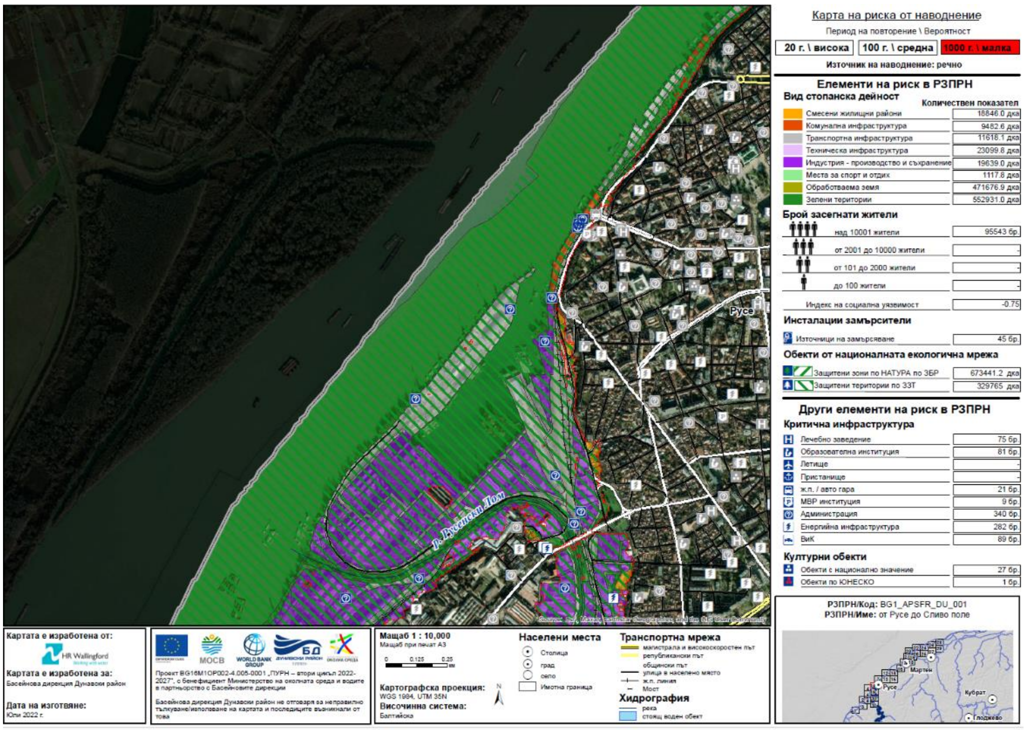


Figure 2.31. Risk Map (RP1000) (Source: Danube River Basin Directorate)

The comparison shows a progressive and structurally non-linear increase in infrastructure exposure across return periods.

Under high-probability scenarios, exposed infrastructure is mainly concentrated along the Danube riparian strip and selected lower sections of the Rusenski Lom valley. Under medium-probability scenarios, exposure expands significantly, affecting transport corridors, public facilities, energy and fuel infrastructure, and selected administrative and service assets. Under extreme scenarios, exposure becomes multi-sectoral and spatially extensive, increasing the risk of cascading impacts.

The Rusenski Lom corridor shows particularly sharp escalation between high- and medium-probability scenarios. This reflects the proximity of built-up areas to the river channel and the confined valley morphology. It also reinforces the role of the Rusenski Lom as a key internal flood risk driver within the municipality.

Although direct monetary losses to critical infrastructure were not quantified in this phase, the spatial co-occurrence of infrastructure assets and flood-prone areas indicates substantial indirect risk. Potential impacts include interruption of mobility, delayed emergency response, reduced access to public services, disruption of energy and fuel supply, and longer recovery times.

Supplementary scenario-based hydraulic simulations

Supplementary hydraulic simulations were retained as stress-test evidence for high water-level configurations along the Danube River and the Rusenski Lom system. These simulations are not integrated into the probabilistic EAD calculation, but they provide useful contextual evidence on potential high-impact flood configurations.

The supplementary simulations confirm two important patterns. Along the Danube, inundation expands laterally across broader floodplain areas and affects transport and port-adjacent infrastructure. Along the Rusenski Lom, floodplain activation is more localized but can intensify rapidly in confined valley sections and near settlements such as Basarbovo.

These results complement the CLIMAAX workflow by illustrating plausible high-impact configurations beyond standardized return period scenarios and by supporting the need for differentiated flood management approaches for the Danube corridor and the Rusenski Lom valley.

Integration of local historical flood records and empirical evidence

To complement the model-based flood risk assessment developed within the CLIMAAX framework, a set of local historical flood records for Ruse Municipality was compiled from regional water management authorities. Although the dataset is limited in size and does not provide systematic quantitative measurements of damages or water levels, it represents a valuable empirical source because it captures the real-world manifestation of flood processes at municipal scale.

The integration of such local data is important because harmonized European-scale datasets may not fully capture fine-scale hydrological dynamics, urban drainage limitations, or localized runoff processes. Historical records therefore provide a necessary grounding of the CLIMAAX outputs in observed events and impacts.

A first key observation is the strong association between flood occurrence and intense precipitation. Most recorded floods are linked to prolonged or heavy rainfall, intensive precipitation, or short-duration extreme weather phenomena such as micro-cyclones. This indicates that pluvial flooding and surface runoff processes play a significant role in the local flood regime, especially in urbanized areas and smaller catchments.

Secondly, the dataset confirms the dual flood regime identified by the CLIMAAX analysis. Flood events are associated both with the Danube River system and with the Rusenski Lom catchment and its tributaries. Danube-related events are typically linked to high water levels and broader floodplain impacts, while Rusenski Lom events are more localized, rapid-onset, and driven by precipitation and catchment response.

The spatial distribution of flood impacts also confirms the relevance of local hotspots. Records indicate a concentration of events in the city of Ruse, particularly in low-lying urban areas and zones near the confluence of the Rusenski Lom and the Danube. Additional recurrent impacts are observed in settlements such as Basarbovo and in several peri-urban and rural areas.

The temporal distribution reveals clustering of flood events in the mid-2000s, particularly in 2005, followed by additional events in 2006 and 2007. More recent records from 2022 and 2025 indicate that flood risk remains active under current climatic conditions.

Hydrological context: discharge dynamics of the Rusenski Lom River

To further support the interpretation of flood events at local scale, hydrological data on river discharge from the Rusenski Lom River at the Bozhichen gauging station were analyzed. This dataset provides a quantitative complement to the historical records and supports the linkage between observed flood impacts and underlying hydrological processes.

The discharge time series illustrates the variability and temporal dynamics of river flow, including periods of elevated discharge that may correspond to increased flood risk. Peak discharge events reflect rapid catchment response to precipitation, which is consistent with the rainfall-driven flood mechanisms identified in the local event records.

The analysis confirms that the Rusenski Lom system is characterized by relatively fast hydrological response and localized flow amplification. This can lead to sudden discharge increases over short periods and reinforces the interpretation of the river as a key driver of rapid-onset inland flood events within the municipality.

Although a direct one-to-one correspondence between individual discharge peaks and recorded flood events cannot be established within the scope of this dataset, the temporal patterns of discharge variability provide strong supporting evidence for the role of precipitation-driven processes and catchment-scale dynamics in shaping local flood risk.

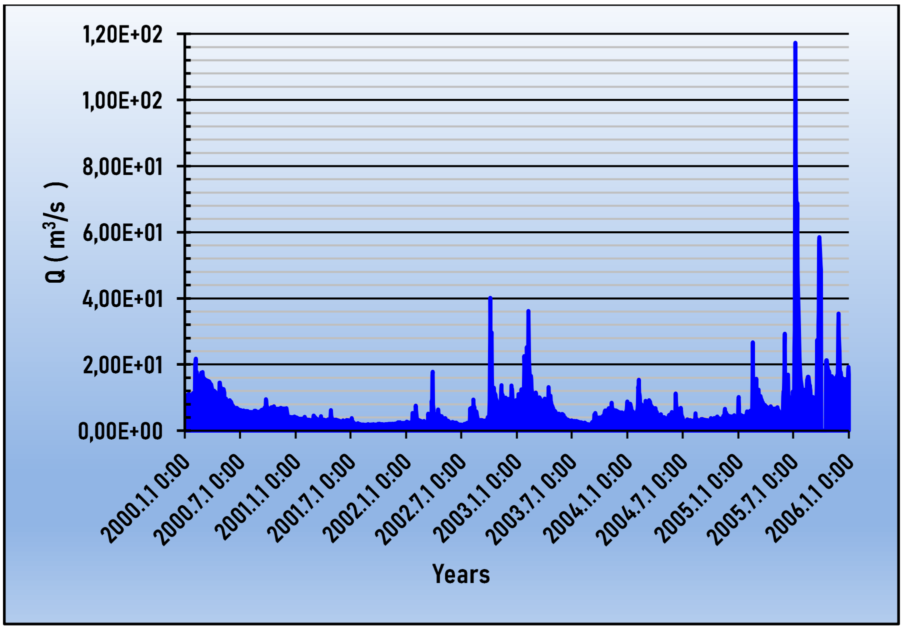


Figure 2.32. Daily discharge of the Rusenski Lom River at the Bozhichen gauging station.

The time series illustrates the temporal variability of river flow, including periods of elevated discharge associated with increased flood potential and rapid catchment response to precipitation.

Recent municipal efforts have also introduced new monitoring and early warning capabilities through the implementation of the ACWA system under the NBSINFRA project (HORIZON-CL3-2022-INFRA-01). Although the system has been operational for a relatively short period and does not yet provide long-term datasets, it represents an important step toward improved real-time monitoring and early warning for flood events. In the longer term, the accumulation of high-resolution hydrological and meteorological data from such systems is expected to improve calibration, validation, and operational interpretation of model-based flood risk assessments.

Observed flood impacts

The historical records provide qualitative insight into the types of damage associated with flood events. These include damage to road infrastructure and bridges, drainage system failures, inundation of residential and industrial areas, interruption of economic activity, and flooding of agricultural land.

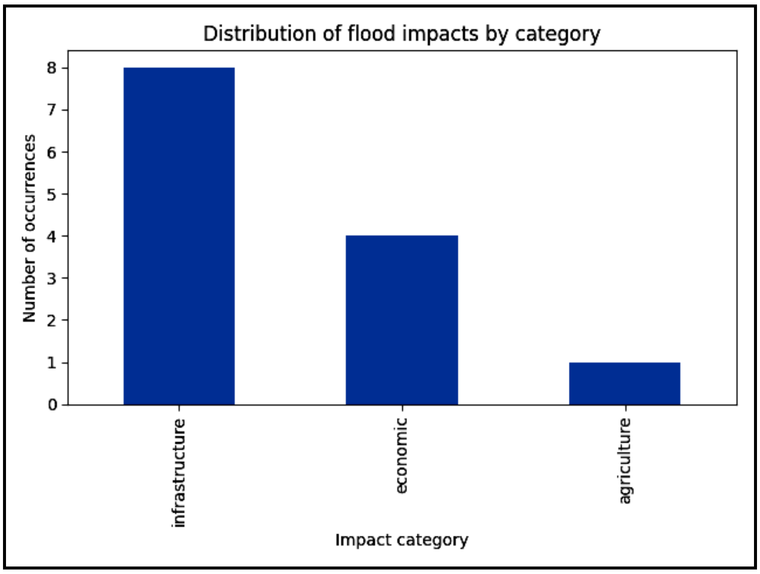


Figure 2.33. Distribution of observed flood impacts by category

The figure highlights the dominance of infrastructure-related damages, followed by economic disruptions and agricultural impacts.

The impact distribution confirms that flood risk in Ruse is not only a hydrological issue, but also an infrastructure and service-continuity issue. This supports the interpretation of critical infrastructure exposure as a major source of indirect and cascading risk.

Synthesis of key empirical findings

The analysis of local historical flood records identifies several empirical patterns that complement and strengthen the model-based assessment:

- **Episodic clustering of flood events**: flood occurrence is concentrated within specific periods, notably the mid-2000s, indicating non-linear temporal dynamics.
- **Spatial concentration of impacts**: events are concentrated in the city of Ruse and nearby settlements, confirming recurrent local hotspots.
- **Importance of pluvial flooding**: most events are triggered by precipitation rather than solely by river overflow, highlighting the relevance of rainfall-driven flooding.
- **Multi-source flood regime**: the dataset confirms the coexistence of large-scale Danube flooding and localized Rusenski Lom/catchment-driven flooding.
- **Significance of moderate but frequent events**: non-extreme events can still generate substantial impacts, supporting the model finding that RP10–RP50 scenarios are relevant for planning.
- **Infrastructure-driven impact patterns**: observed damages are primarily infrastructure-related, followed by economic and agricultural effects.
- **Hydrological consistency**: discharge data from the Rusenski Lom support the interpretation of rapid, precipitation-driven flood dynamics.

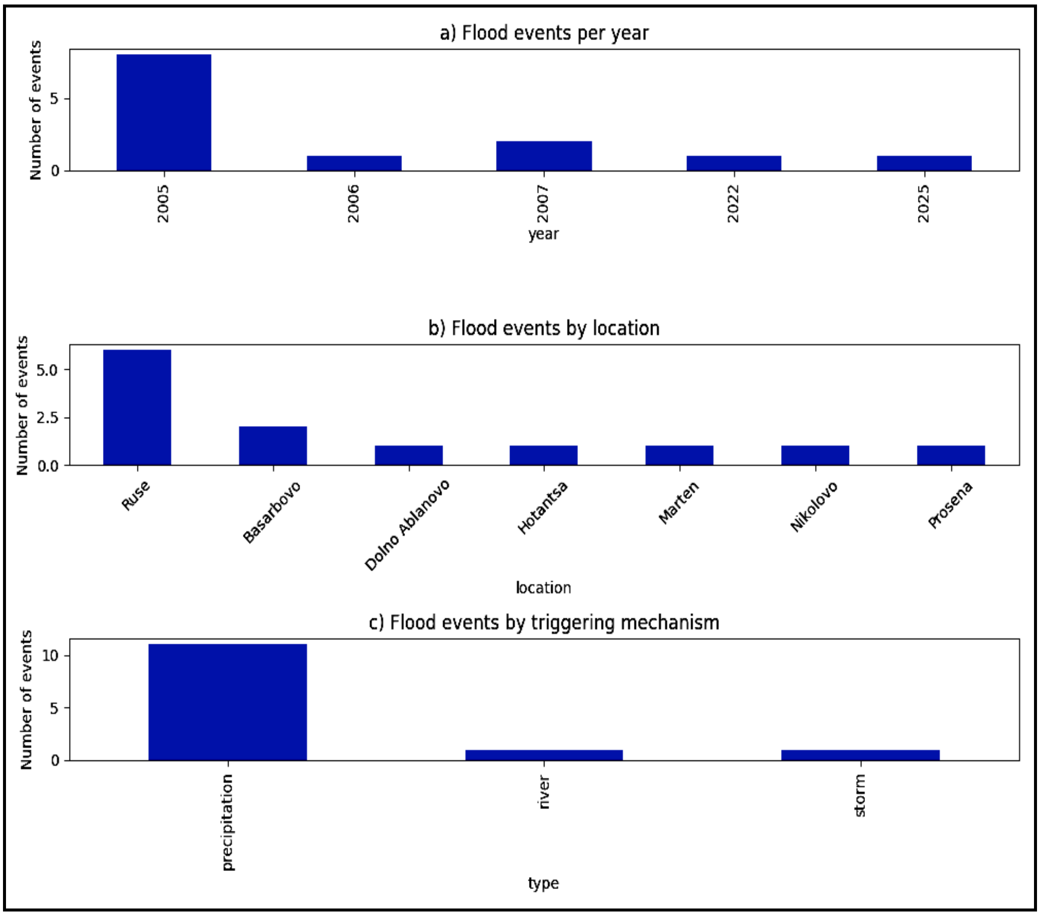


Figure 2.34. Empirical patterns of historical flood events in Ruse Municipality – (a) temporal distribution of events; (b) spatial distribution by settlement; (c) distribution by triggering mechanism.

Table 2.5. Summary statistics of recorded historical flood events in Ruse Municipality

Metric	Value
Total events	13
Years covered	2005-2025
Most active year	2005
Top location	Ruse
Dominant trigger	precipitation

Overall, the integration of local historical flood records significantly enhances the robustness and interpretability of the flood risk assessment. By grounding model outputs in observed events and impacts, the analysis bridges the gap between large-scale modelling and local-scale reality. This supports more context-sensitive adaptation planning, particularly in relation to urban drainage management, infrastructure resilience, hotspot-targeted interventions, and the further development of local monitoring and early warning systems such as ACWA.

Integrated synthesis of flood risk outputs

Table 2.6. Overview of flood risk outputs and impact metrics – River floods, Phase 2

Risk component	Indicator / Metric	Methodological basis	Spatial / temporal resolution	Relevance for local decision-making
Economic damage to buildings	Total building damage per return period (€)	Depth–damage functions (Huizinga et al., 2017) applied to OSM building footprints intersected with flood depth rasters	Building-level aggregation within 3 arc-second flood grids; RP-based	Quantifies direct asset losses under increasing flood severity; supports prioritization of protective investments and structural mitigation
Expected Annual Damage (EAD)	Mean Expected Annual Damage (million €)	Probability-weighted integration of damage–return period curve	Municipal scale; annualized	Provides a consolidated probabilistic indicator of long-term economic risk; supports cost–benefit analysis and investment planning
Critical infrastructure exposure	Number and spatial distribution of exposed infrastructure assets	Overlay of flood depth maps with OSM-based infrastructure layers (healthcare, emergency services, transport, fuel, energy)	Point-based infrastructure locations; RP-based	Supports contingency planning, emergency preparedness, and prioritization of infrastructure resilience upgrades
Population exposure	Expected Annual Population Exposed (EAPE)	Overlay of flood depth rasters with JRC population grids; probability-weighted aggregation	3 arc-second population grids; annualized	Identifies chronic and recurrent social exposure; informs risk communication and vulnerability mapping
Population displacement	Expected Annual Population Displaced (EAPD)	Depth-threshold-based subset of exposed population; integrated across return periods	Population grid; annualized	Supports evacuation planning, shelter capacity assessment, and emergency logistics
Spatial risk differentiation	High / medium / low risk zones	Integrated interpretation of hazard intensity, exposure density, and vulnerability functions	Municipal scale; scenario-based	Enables land-use zoning, spatial planning restrictions, and targeted adaptation measures
Indirect risk signals	Potential service and mobility disruption	Spatial co-occurrence of infrastructure, population clusters, and high-risk flood zones	Scenario-based; qualitative overlay	Highlights cascading risk potential and supports multi-sectoral resilience planning

The integrated results show that river flood risk in Ruse Municipality is shaped by the interaction of hazard intensity, exposure concentration, and dual hydrological dynamics. Moderate but recurrent floods already generate significant impacts, while extreme events substantially expand the area of exposed assets and infrastructure.

The assessment also shows that flood risk is not limited to one corridor. The Danube generates large-scale fluvial risk, while the Rusenski Lom introduces rapid, rainfall-driven inland flooding. This distinction is essential for adaptation planning, as both systems require differentiated management approaches.

Methodological strengths and limitations

The Phase 2 flood risk assessment demonstrates clear methodological advancement compared to Phase 1 through:

- building-level damage modelling;
- probability-weighted annualized metrics;
- direct integration of hazard, exposure, and vulnerability data;
- spatial identification of population, infrastructure, and economic exposure;
- validation with official FRMP maps and local historical records.

Several limitations remain. The 3 arc-second hazard and population datasets may smooth fine-scale urban topography. Existing flood protection infrastructure is not fully represented in the JRC/Copernicus hazard layers, which may lead to conservative exposure estimates in defended areas. Depth–damage functions are based on standardized European relationships and may not capture all local construction characteristics. Climate-informed interpretation does not include dynamic hydraulic recalculation under RCP forcing.

Despite these limitations, the assessment provides a transparent, reproducible, and policy-relevant evidence base for flood risk management in Ruse Municipality.

Decision-relevant conclusions

The regionalized river flood risk assessment leads to the following conclusions for municipal decision-making:

- Flood risk is spatially concentrated but multi-source, requiring differentiated management of the Danube floodplain and the Rusenski Lom corridor.
- The Rusenski Lom represents a critical inland flood driver, particularly for non-Danube-facing settlements and peri-urban infrastructure.
- Recurrent moderate flood events already generate substantial economic and social impacts, indicating that adaptation should address frequent events as well as extreme scenarios.
- Critical infrastructure exposure represents a major source of indirect and cascading risk, especially for transport, emergency response, energy supply, and public services.
- The quantified indicators — EAD, EAPE, EAPD, total damage per return period, and infrastructure exposure — provide a direct basis for prioritizing flood protection, drainage improvements, spatial planning controls, early warning, and emergency preparedness measures.

Overall, Phase 2 moves the flood assessment from descriptive hazard screening to probabilistic, impact-based risk quantification. This provides a robust foundation for classifying river flooding as a **very high-priority climate risk** for Ruse Municipality.

2.3.2. Hazard #2 - Wild Fires: fine-tuning to the local context of Ruse Municipality

Wildfire risk assessment for Ruse Municipality is an important component of the Phase 2 regionalized climate risk analysis. Although wildfires have historically been regarded as a secondary hazard compared to flood-related risks, their relevance is increasing under climate change due to intensifying summer heat, prolonged dry periods, rising evapotranspiration, soil moisture deficit, and increasing climatic variability in the region.

Phase 1 identified wildfire as an emerging climate-sensitive hazard through qualitative screening and scenario discussion. Phase 2 advances this assessment by combining:

- Fire Weather Index (FWI)-based modelling within the CLIMAAX framework;
- Bulgarian national wildfire risk methodology;
- meteorological fire-danger interpretation based on soil moisture deficit;
- empirical wildfire records for Ruse Municipality for the period 2019–2025;
- spatial interpretation of wildfire exposure in forest–settlement interface zones.

This represents a methodological progression from general hazard framing towards empirically supported, spatially explicit, and climate-sensitive wildfire risk characterization.

Climatic context and structural drivers

Recent climatic evidence for the Ruse region indicates a shift towards conditions that are more favourable to wildfire development. The relevant structural drivers include:

- increasing mean temperatures, particularly during the vegetation and summer season;
- higher interannual precipitation variability;
- concentration of rainfall into more intense events;
- longer dry intervals between precipitation episodes;
- increased summer soil moisture deficit and vegetation desiccation.

This combination supports a transition from a relatively stable precipitation regime towards a more variable regime with drought-prone summers. For wildfire risk, this is important because fire danger depends not only on high temperatures, but on the interaction of heat, low fuel moisture, wind, vegetation condition, and human ignition sources.

In this context, wildfire risk in Ruse Municipality should be understood as a **climate-amplified hazard**: ignition is predominantly anthropogenic, but the probability of spread, intensity, and suppression difficulty increases under hot, dry, and windy conditions.

Integration of national, regional, and local methodological frameworks

Wildfire risk is structured around the classical risk relationship:

Risk = Hazard × Exposure × Vulnerability

At national level, Bulgarian wildfire risk methodology formalizes wildfire risk through an integral indicator combining fire frequency and burned area: **R_fire risk = R_density × R_actual combustibility** , where:

- **R_density** represents the annual number of fires per 1,000 ha of forest area;
- **R_actual combustibility** represents the average burned area per 1,000 ha.

The resulting wildfire risk values are classified as:

- **Low:** R ≤ 0.1
- **Medium:** 0.1 < R ≤ 0.3
- **High:** R > 0.3

A corrective upgrade mechanism is applied where more than 50% of forests fall within Class I fire hazard.

According to national mapping, Ruse District falls within a low-to-moderate wildfire risk class. However, this classification represents a retrospective structural average at regional level and does not capture intra-municipal heterogeneity, wildland–urban interface exposure, anthropogenic ignition patterns, or episodic extreme events.

For this reason, Phase 2 supplements national structural classification with:

- CLIMAAX FWI-based climate hazard modelling;
- Soil Moisture Deficit Fire Danger Index interpretation;
- local empirical wildfire records;
- spatial analysis of exposure in forest–settlement interface areas.

The Soil Moisture Deficit Fire Danger Index, used in national meteorological fire-danger monitoring, is particularly relevant because it captures the cumulative drying of soil and vegetation. This provides a dynamic short- to medium-term indicator of fire susceptibility under heat and drought conditions.

Empirical validation: local wildfire records, 2019–2025

An official dataset from the Regional Directorate “Fire Safety and Civil Protection” – Ruse for the period 2019–2025 was integrated into the Phase 2 wildfire assessment.

For the analysed period, the records indicate:

- **19 wildfire events**;
- **total burned area: 1,309 decares**;
- **mean annual frequency: approximately 2.7 events per year**;
- strong seasonal concentration;
- predominantly anthropogenic ignition.

Three key empirical patterns are relevant for local wildfire risk interpretation.

First, wildfire impacts are characterized by **extreme-event concentration**. Most events are relatively small, but rare large fires dominate cumulative burned area. In 2020, 10 fires were recorded, with a total burned area of approximately **706 decares**. The largest single event affected **585 decares** of broadleaf forest. This heavy-tailed distribution indicates that wildfire risk in Ruse is governed not only by event frequency, but by episodic high-impact events.

Second, wildfire occurrence is strongly seasonal. **17 of the 19 recorded events**, or approximately **89%**, occurred in **July and August**. This seasonal clustering corresponds to maximum summer temperatures, prolonged dry periods, and wind-enhanced fire spread. The meteorological conditions recorded in most events — hot, dry, sunny weather, frequently with strong wind — are consistent with the logic of FWI-based modelling.

Third, all recorded wildfire events were classified as **anthropogenic in origin**. Recurring locations include Sredna Kula district, Nikolovo village, Basarbovo village, peripheral urban–forest interface zones, and areas near railway lines and roads. This confirms the structural importance of the **wildland–urban interface (WUI)** in shaping local wildfire exposure.

Phase 2 methodological advancement

Compared to Phase 1, the wildfire assessment in Phase 2 introduces several important methodological improvements:

- empirical fire frequency analysis;
- empirical burned-area magnitude assessment;
- seasonality quantification;
- anthropogenic ignition interpretation;
- identification of recurring spatial hotspots;
- integration of national wildfire risk methodology;
- linkage between climatic instability, local fire records, and WUI exposure;
- use of CLIMAAX FWI-based modelling to assess future fire-weather conditions.

This moves the assessment from descriptive hazard framing towards a locally validated and climate-sensitive wildfire risk interpretation.

Table 2.7. Data overview – Wild Fires workflow (Phase 2)

Component	Data / indicator	Source	Role in analysis	Risk / impact output
Climate-driven hazard	Fire Weather Index components and composite FWI	Copernicus C3S; CLIMAAX workflow	Characterizes fire-conducive weather conditions	Spatial and temporal wildfire hazard patterns
Climate variables	Temperature, precipitation deficit, wind speed, relative humidity	Copernicus / EURO-CORDEX / CLIMAAX workflow	Supports baseline and future fire-danger assessment	Fire-weather evolution under climate scenarios
National risk context	Integral wildfire risk indicator combining fire density and actual combustibility	Bulgarian national wildfire methodology; Lyubenov, 2016	Provides national and regional benchmark	Structural wildfire risk classification
Meteorological fire danger	Soil Moisture Deficit Fire Danger Index	NIMH	Captures vegetation dryness and drought-driven susceptibility	Short- to medium-term fire-danger interpretation
Fuel and land cover	Forest, shrubland, grassland, agricultural land, burnable vegetation	CORINE Land Cover; EFFIS	Represents fuel availability and landscape susceptibility	Identification of burnable and fire-prone zones
Exposure	Population grids, built-up areas, transport corridors, energy and public infrastructure	JRC; OSM; municipal data where available	Identifies exposed assets and receptors	Overlap of wildfire-prone zones with people and infrastructure

Interface vulnerability	Settlement proximity, vegetation type, historical fire recurrence	Local fire records; land-cover data	Represents WUI-related vulnerability	Identification of interface hotspots
Local empirical validation	Fire records, burned area, ignition type, location, meteorological conditions	Regional Directorate "Fire Safety and Civil Protection" – Ruse, 2019–2025	Validates modelled fire danger, seasonality, and interface relevance	Empirically supported wildfire risk interpretation

Integrated position within the multi-hazard framework

Wildfire risk in Ruse Municipality is:

- structurally low-to-moderate at district level;
- empirically variable at municipal level;
- strongly concentrated in summer;
- predominantly anthropogenic in ignition;
- spatially linked to wildland–urban interface zones;
- amplified by heat, drought, wind, and vegetation drying.

Although wildfire remains lower in priority than flood-related risks, it should not be treated as a static secondary hazard. It is a dynamic climate-amplified risk that interacts with drought, heatwave stress, agricultural vulnerability, land abandonment, ecosystem degradation, and emergency response capacity.

The role of wildfire in the Phase 2 multi-hazard framework is therefore to identify where preventive action is needed before the risk escalates further. This includes improved fire-weather monitoring, public awareness during the summer season, reduction of anthropogenic ignition sources, better management of interface zones, and coordination with fire safety and forestry authorities.

1. Hazard assessment – Wild Fires

The wildfire hazard assessment for Ruse Municipality builds on the methodological foundations established in Phase 1 and advances towards a quantitative, scenario-based analysis aligned with the CLIMAAX wildfire workflow.

While Phase 1 addressed wildfire hazard mainly through descriptive indicators and qualitative interpretation, Phase 2 operationalizes wildfire hazard using the **Fire Weather Index (FWI)** and climate sensitivity modelling. This enables a probabilistic assessment of extreme fire-weather occurrence and provides a transparent link between climate drivers and wildfire potential.

Wildfire hazard is understood as a climate-driven process governed by the interaction of:

- air temperature;
- precipitation deficit;
- wind speed;
- relative humidity.

These variables are integrated within the Fire Weather Index framework, which is widely used at European level as a proxy for fire-weather danger. In the context of Ruse Municipality, FWI-based modelling is particularly relevant because local wildfire records show that most events occur under hot, dry, sunny, and windy summer conditions.

National hazard cartography and fire intensity context

To contextualize the CLIMAAX-derived fire-weather hazard within Bulgarian wildfire governance practice, national cartographic products were consulted. These products provide a regional validation layer and help distinguish structural wildfire risk from locally amplified risk in interface areas.

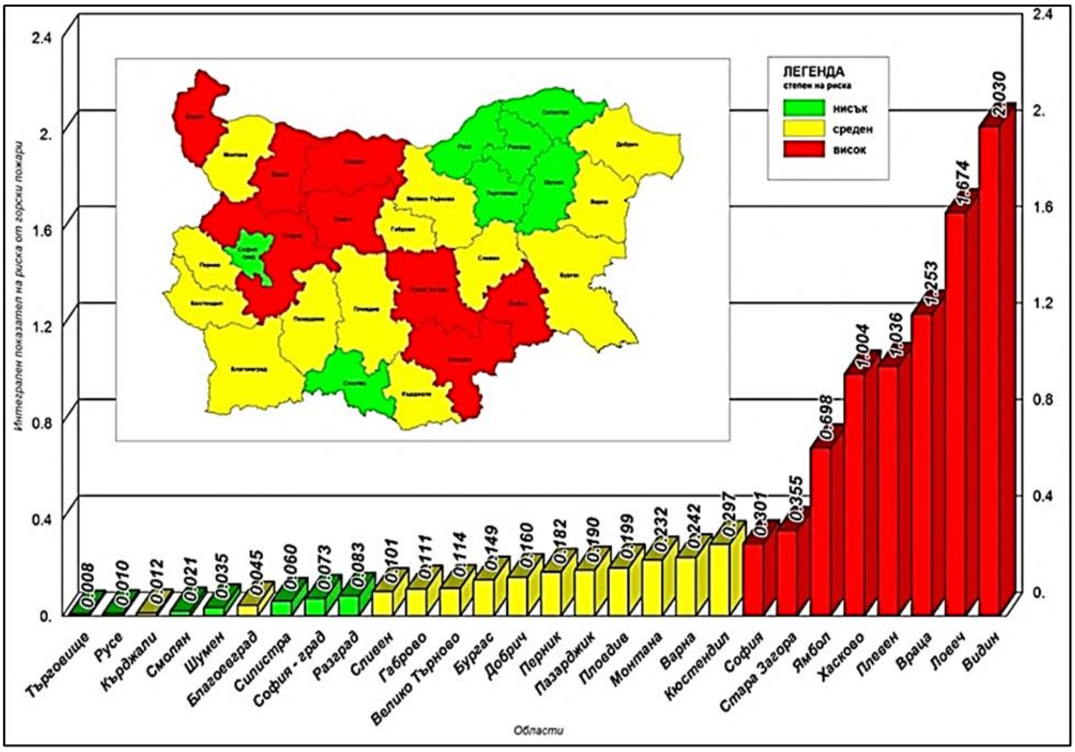


Figure 2.35. Wildfire Risk Level (Rfire risk) at NUTS3 (regional) Level (Source: Lyubenov, 2016)

Figure 2.28 positions Ruse District within the low-to-moderate wildfire risk class. However, this indicator reflects an aggregated regional average and is not designed to capture intra-municipal variability, wildland–urban interface exposure, or extreme-event tail risk.

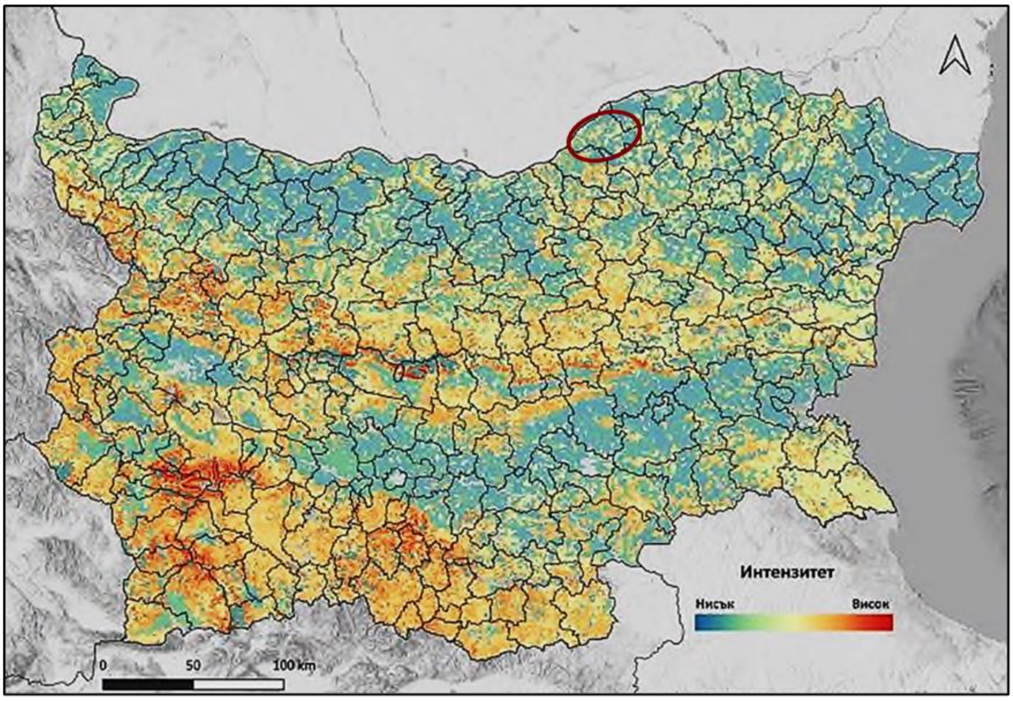


Figure 2.36. Map of Potential Fire Intensity in Bulgaria (regional level) (Source: Council of Ministers, 2022)

The national potential fire intensity map indicates low-to-moderate potential intensity for the Ruse region compared with mountainous and coniferous terrains. This supports the interpretation that the main escalation pathway for Ruse is not structurally extreme baseline fire intensity, but rather the climate-driven amplification of fire-weather conditions combined with anthropogenic ignition near interface zones.

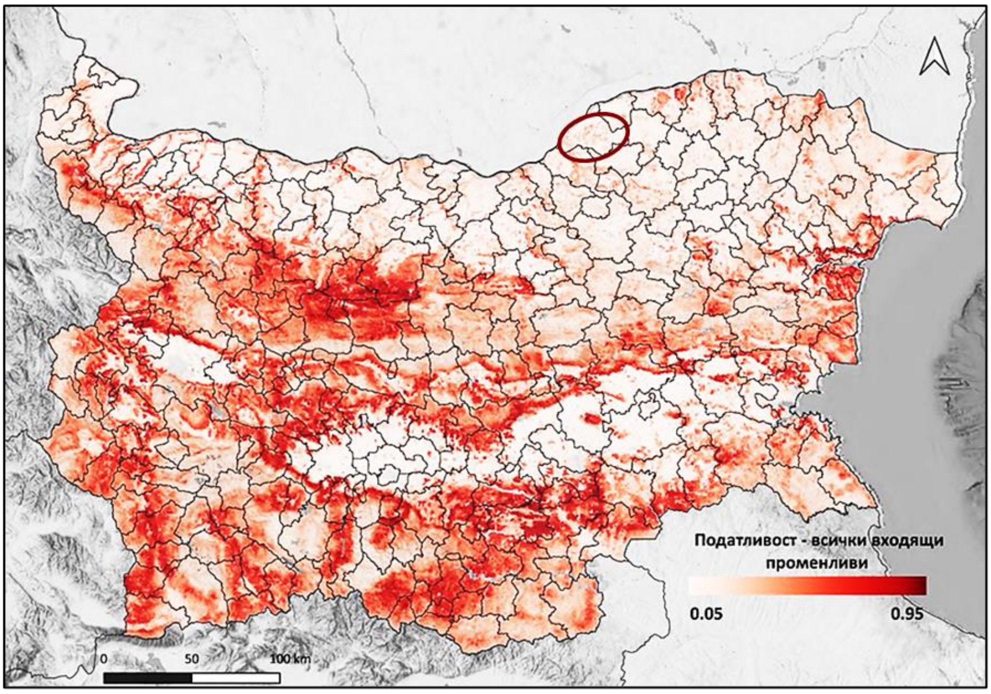


Figure 2.37. Map of Aggregated Wildfire Risk across the Territory of Bulgaria (regional level) (Source: Council of Ministers, 2022)

The aggregated wildfire risk map confirms the moderate regional profile, but also reinforces that district-level aggregation cannot resolve local hotspots driven by land cover, settlement proximity, transport infrastructure, and human activity. For this reason, the national maps are used as contextual validation, while the Phase 2 analysis further examines local fire records, fire-weather indicators, and exposure patterns.

Historical wildfire hazard baseline

The hazard assessment begins with the characterization of historical wildfire hazard conditions for the period **1981–2010**, using perturbed Fire Weather Index simulations following the methodology of El Garroussi et al. (2024). FWI data were extracted for the BG32 region and spatially aggregated in accordance with CLIMAAX regionalization guidance.

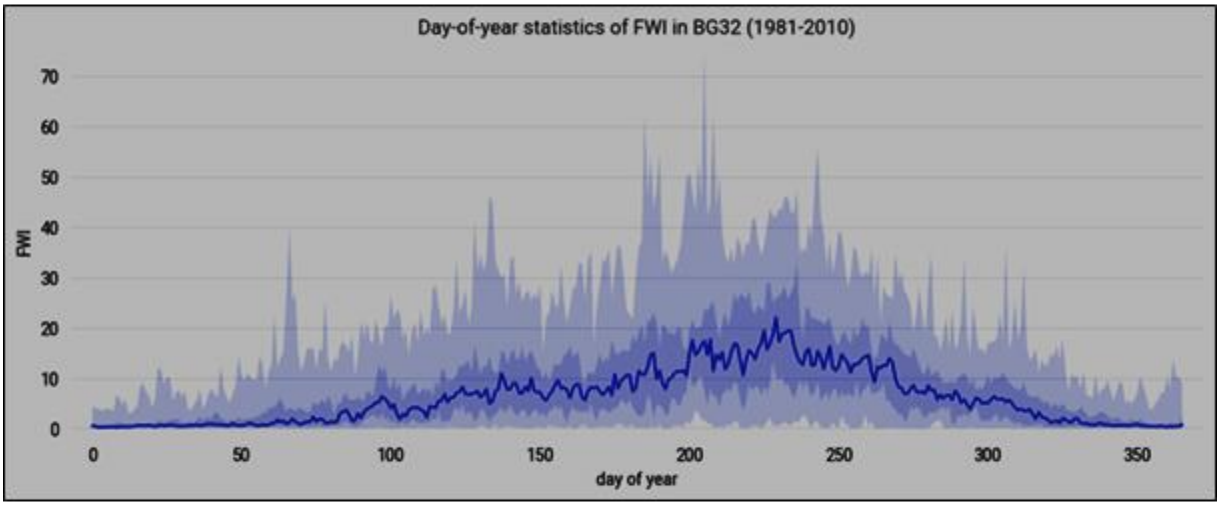


Figure 2.38. Day of year statistics of FWI in BG32 (1981–2010) (Source: Ruse – Fire Hazard workflow)

The seasonal FWI profile shows a pronounced summer concentration of wildfire hazard, with median and maximum values peaking during **July and August**. This temporal structure aligns directly with local empirical wildfire occurrence in Ruse Municipality, where **17 of 19 recorded fires** during 2019–2025 occurred in July–August. This consistency strengthens the validity of FWI as a representative hazard proxy for the local context.

Return period analysis of extreme fire weather

To quantify the recurrence of extreme fire-weather conditions, annual maximum FWI values were fitted to a probability distribution.

Return period is defined as: **T = 1 / P,** where **T** represents the recurrence interval and **P** represents the annual exceedance probability.

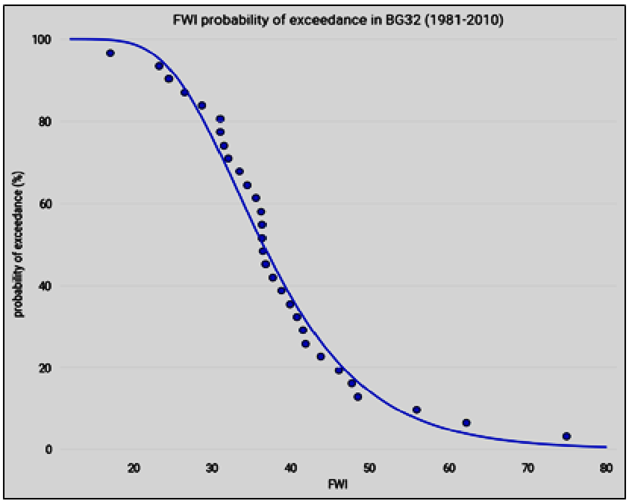


Figure 2.39. FWI probability of exceedance in BG32 (1981–2010) (Source: Ruse – Fire Hazard workflow)

The fitted distribution indicates that high FWI values recur with relatively short return periods. This means that severe fire-weather conditions are not isolated anomalies, but form a recurrent component of the regional climate.

This finding is consistent with local observations of episodic large wildfire events, including the **585-decare event in 2020** and the **292-decare event in 2022**. These events demonstrate that even in a region classified as low-to-moderate at district level, local wildfire risk can produce significant impacts under favourable fire-weather conditions.

Climate sensitivity and response surface analysis

To assess hazard sensitivity to projected climate change, a response surface methodology was applied using perturbed historical FWI simulations. The analysis quantifies:

- probability of exceeding a critical threshold, **FWI ≥ 60**;
- changes in fire-season length;
- non-linear interaction effects between temperature and precipitation changes.

The threshold **FWI ≥ 60** was selected as a high-danger indicator corresponding to conditions conducive to rapid fire spread and difficult suppression.

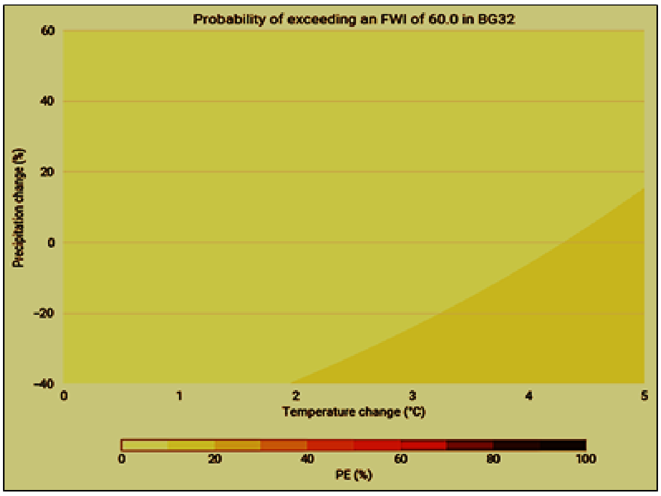


Figure 2.40. Probability of exceeding an FWI of 60.0 in BG32 (Source: Ruse – Fire Hazard Response workflow)

The response surface demonstrates that:

- increasing temperature produces a strong upward shift in exceedance probability;
- decreasing precipitation amplifies fire danger;
- combined warming and drying generate non-linear hazard escalation.

The interaction between temperature increase and precipitation reduction produces stronger hazard amplification than either driver alone. This confirms wildfire hazard as a compound climate-sensitive system, strongly influenced by both heat and moisture deficit.

Climate-informed wildfire hazard projections

Future wildfire hazard was assessed by evaluating response surface models under EURO-CORDEX climate projections, with emphasis on **RCP8.5** as a high-stress climate pathway.

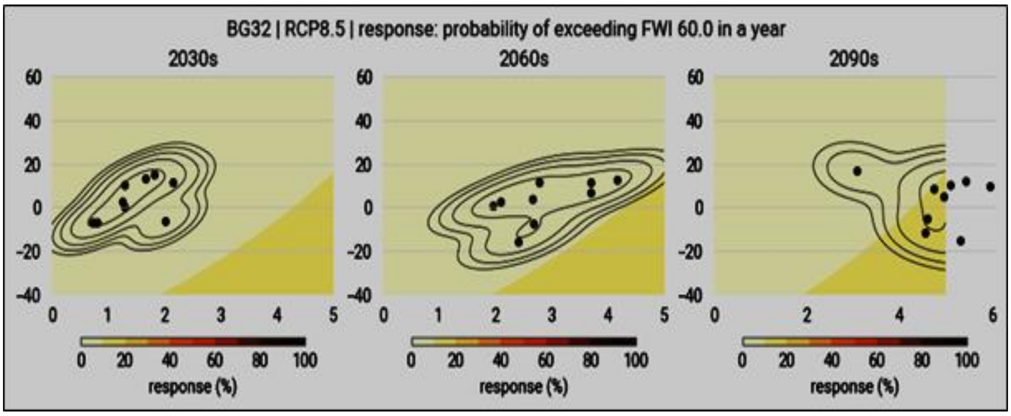


Figure 2.41. BG32/RCP8.5 response: probability of exceeding FWI 60.0 in a year (Source: Ruse – Fire Hazard Projections workflow)

The projections indicate:

- a clear upward trajectory in the probability of extreme fire-weather conditions;
- increasing interannual variability;
- strengthening of the late-century hazard signal.

Although ensemble spread widens towards the end of the century, the direction of change remains consistent. This supports the interpretation that wildfire hazard is likely to intensify under future climate conditions.

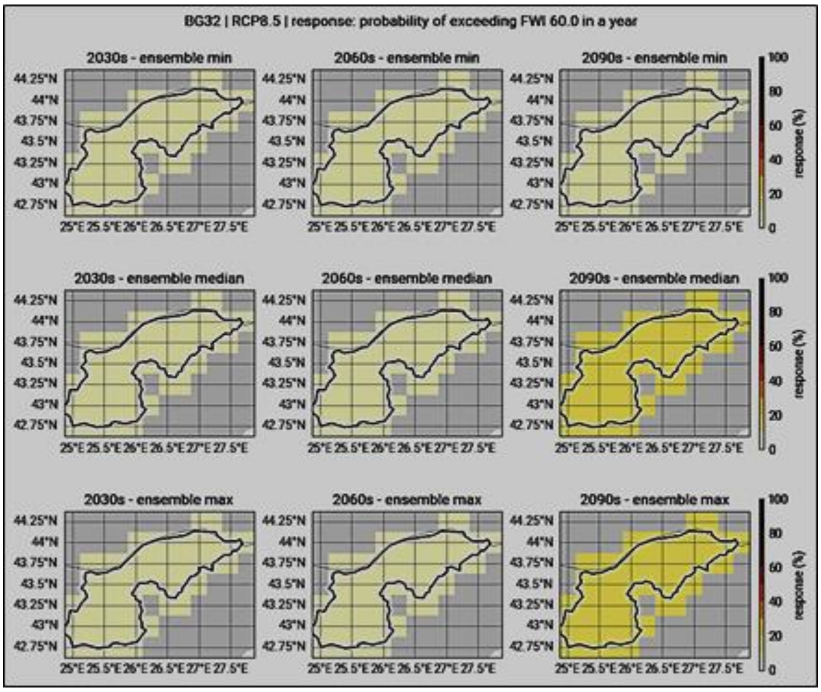


Figure 2.42. BG32/RCP8.5 response: spatial distribution of probability of exceeding FWI ≥ 60 in a year (Source: Ruse –Fire Hazard Projections workflow)

The spatial evaluation reveals intra-regional variability within BG32, confirming that wildfire hazard is not spatially uniform. Areas characterized by higher summer temperature anomalies, reduced precipitation, greater fuel continuity, and stronger interface exposure show elevated projected fire danger.

This spatial heterogeneity justifies municipal-scale hazard interpretation rather than reliance only on district-level averages.

Seasonal FWI patterns and fire-season length

Complementing the probabilistic modelling, a dedicated FWI hazard workflow was applied using Copernicus Climate Data Store projections.

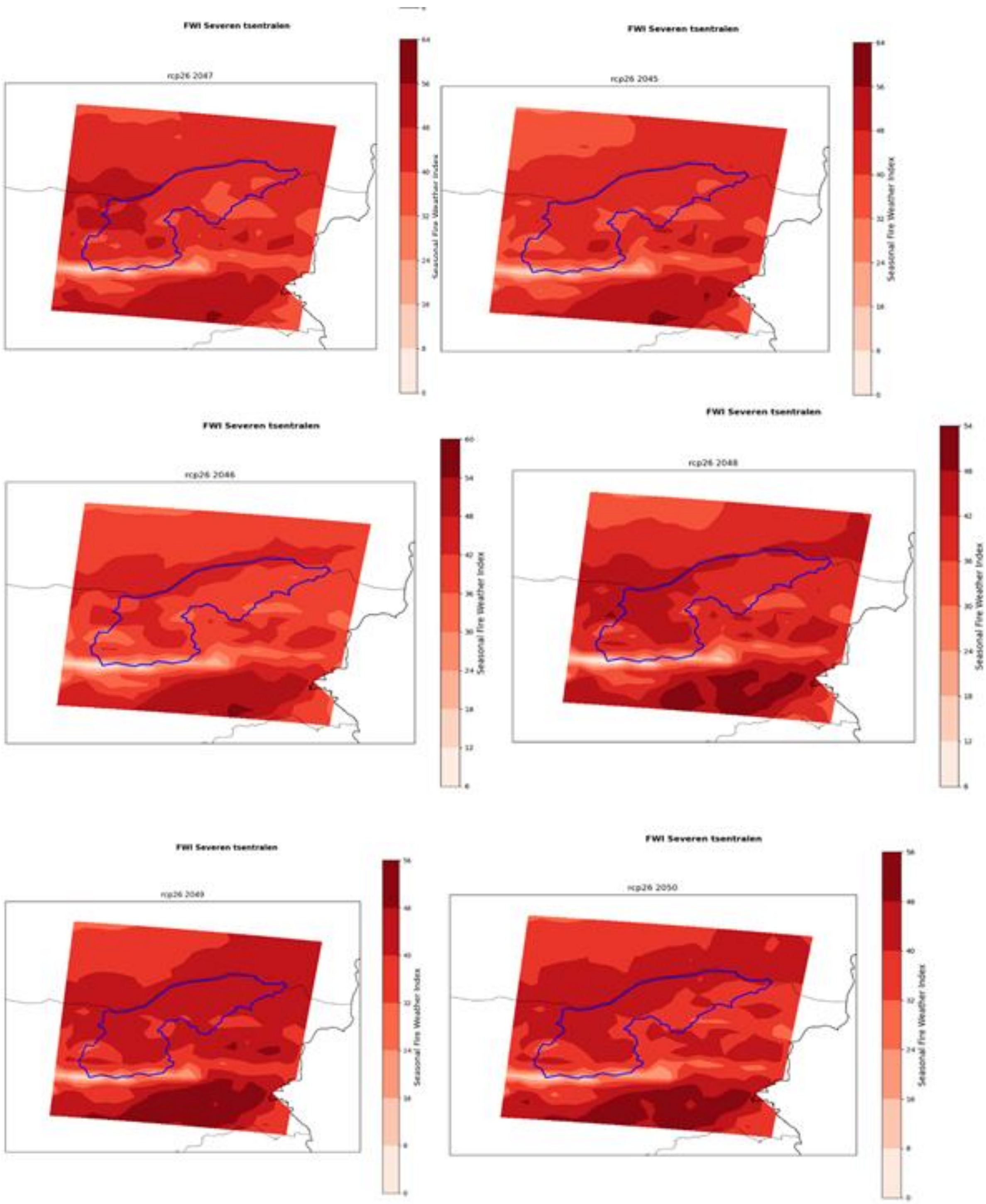


Figure 2.43. FWI Seasonal Intensity – Central Northern Bulgaria, RCP2.6 (2045–2050) (Source: Ruse –Hazard Fire FW workflow)

Even under a lower-emission scenario, the maps indicate an expansion of areas experiencing high to very high fire-danger classes during summer. This confirms that wildfire hazard intensification is not limited to high-emission scenarios only.

Fire-weather days were defined as days with **FWI > 30**, representing sustained conditions favourable for ignition and spread.

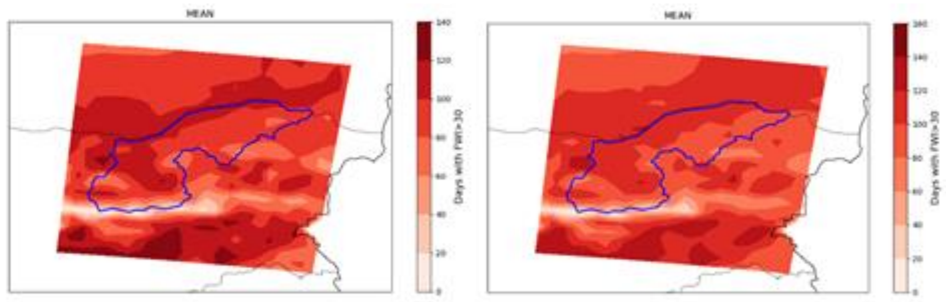


Figure 2.44. Fire weather season length – historical (left) vs future 2050 (right), (RCP8.5) (Source: Ruse – Hazard Fire FWI workflow)

The comparison shows:

- extension of the fire-weather season;
- earlier seasonal onset;
- later seasonal termination.

A longer fire-weather season increases cumulative exposure time, even if peak fire intensity does not increase uniformly. For Ruse Municipality, this implies a longer period during which anthropogenic ignition sources can trigger wildfire events.

Empirical validation of the hazard signal

The projected wildfire hazard intensification aligns with observed local wildfire dynamics for 2019–2025. The local records show:

- strong July–August concentration of wildfire occurrence, with approximately **89% of events** occurring in these two months;
- dominance of hot, dry, windy meteorological conditions;
- heavy-tailed burned-area distribution, where rare large events dominate total burned area;
- anthropogenic ignition concentrated in forest–settlement interface zones and near transport corridors.

The alignment between:

- FWI seasonal peaks;
- climate response modelling;
- projected increase in fire-weather conditions;
- and empirical local fire occurrence

confirms the analytical robustness of the hazard framework. It also demonstrates that FWI-based modelling is relevant for interpreting wildfire hazard in the local context of Ruse Municipality.

Methodological strengths and limitations

The wildfire hazard assessment has several methodological strengths:

- integration of historical FWI analysis, climate sensitivity modelling, and future projections;
- probabilistic exceedance analysis;
- scenario-based climate interpretation;
- empirical validation using local wildfire records;

- spatially differentiated hazard interpretation;
- consistency with national wildfire risk mapping and meteorological fire-danger concepts.

Several limitations remain:

- FWI aggregation at regional level may mask micro-topographic and local land-cover effects;
- fuel load variability is approximated through land-cover and vegetation proxies;
- climate projection uncertainty increases towards the end of the century;
- ignition probability remains strongly influenced by anthropogenic behaviour, which is not fully modelled;
- local fire records are valuable but limited in temporal coverage and do not provide a long-term statistical baseline.

Despite these limitations, the wildfire hazard assessment represents a clear methodological advancement compared to Phase 1. It provides a transparent, climate-informed, and empirically grounded basis for the subsequent wildfire risk assessment, where fire-weather hazard is combined with exposure and vulnerability components.

2. Risk assessment - Wildfires

Conceptual framework for wildfire risk assessment

The wildfire risk assessment for Ruse Municipality is developed in alignment with the integrated CLIMAAX risk framework and is conceptually consistent with the European Forest Fire Information System (EFFIS). Wildfire risk is understood as the interaction of three interdependent components:

- **Hazard** – probability and intensity of fire-conducive climatic conditions;
- **Exposure** – presence of population, infrastructure, ecosystems, and economic assets in fire-prone areas;
- **Vulnerability** – susceptibility of exposed elements to damage or disruption.

Formally, this can be expressed as: **Risk = Hazard × Exposure × Vulnerability**

Compared to Phase 1, where wildfire was assessed mainly through hazard screening and qualitative interpretation, Phase 2 explicitly separates and then recombines these components through two complementary analytical strands:

- quantitative probabilistic population exposure modelling;
- spatially explicit integrated risk mapping using Fire Weather Index, fuel availability, and vulnerability indicators.

This dual approach provides both an aggregated regional perspective and a spatially differentiated interpretation relevant for municipal planning.

Population exposure to wildfire hazard

Methodological approach

The population exposure assessment combines projected wildfire hazard with population distribution. The hazard component is represented by the annual probability of exceeding the critical Fire Weather Index threshold: **FWI ≥ 60**

This threshold represents conditions conducive to rapid fire spread and difficult suppression. Population exposure is calculated by overlaying:

- probabilistic wildfire hazard projections under RCP8.5;
- gridded population projections under SSP1, based on Wang et al. (2022).

SSP1 is used as a reference scenario because it reflects moderate demographic change and sustainability-oriented development, making it suitable for long-term planning. For each grid cell, exposure is calculated as the number of inhabitants located in areas where wildfire hazard probability exceeds selected thresholds.

This probabilistic exposure metric represents a clear methodological progression beyond Phase 1, where wildfire exposure was described qualitatively.

Regional population dynamics

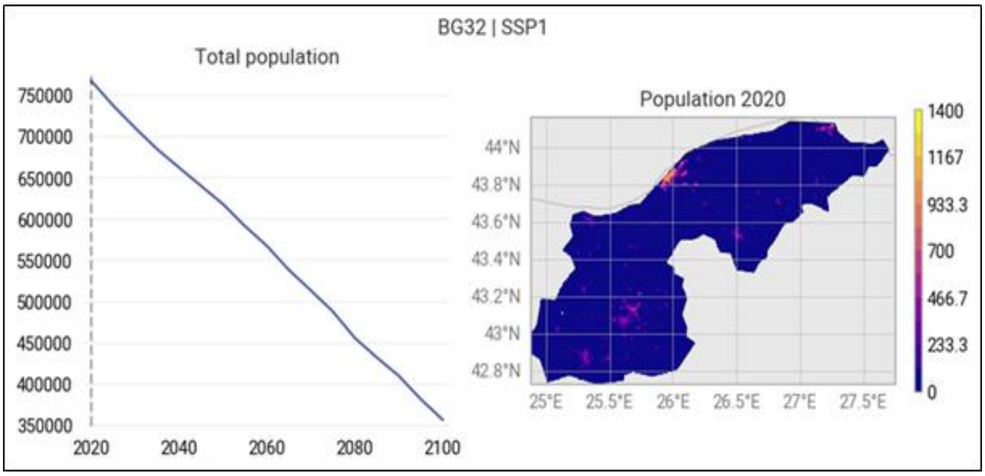


Figure 2.45. Projected population distribution and total population evolution in BG32 under SSP1 (Source: Ruse - Fire Risk Assessment Population workflow)

Figure 2.44 confirms strong population concentration in urban and peri-urban areas, particularly around the city of Ruse, while large rural areas remain sparsely populated. Overall demographic change is relatively limited compared to projected climate-driven hazard amplification.

This means that future wildfire risk growth is driven primarily by **increasing fire-weather hazard**, rather than by major demographic expansion. However, settlements located at the urban–rural and forest–settlement interface, such as Sredna Kula, Nikolovo, and Basarbovo, represent structurally elevated exposure zones because they combine population presence, combustible vegetation, and anthropogenic ignition sources.

Affected population by hazard intensity

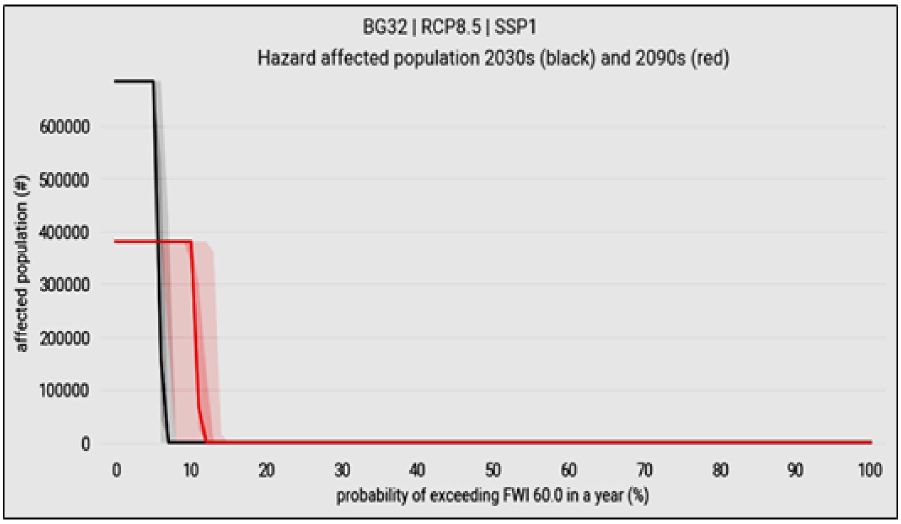


Figure 2.46. Population affected by wildfire hazard levels in the 2030s and 2090s (BG32, RCP8.5, SSP1) (Source: Ruse - Fire Risk Assessment Population workflow)

Figure 2.39 illustrates the relationship between wildfire hazard intensity and affected population. As expected, higher hazard thresholds affect smaller areas and therefore smaller populations. However, comparison between the 2030s and 2090s shows a systematic upward shift in population exposure across almost all hazard levels.

This indicates that more inhabitants are projected to be exposed to elevated wildfire hazard conditions over time. The widening uncertainty bands in the late-century projections reflect climate model spread, but the direction of change remains consistent. The result confirms that wildfire exposure growth is primarily climate-driven.

Temporal evolution of population at risk

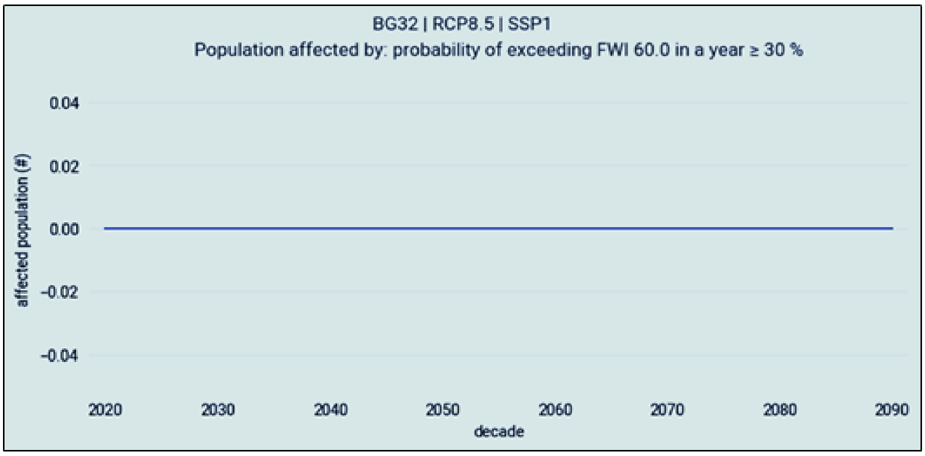


Figure 2.47. Temporal evolution of population exposed to PE(FWI ≥ 60) ≥ 30% (Source: Ruse - Fire Risk Assessment Population Workflow)

The time series demonstrates a steady increase in the population exposed to a high probability of extreme fire-weather conditions. Even under relatively moderate demographic assumptions, the probability of exposure increases over time due to structural climate hazard amplification.

This finding is consistent with local empirical evidence showing that significant wildfire events occur under hot, dry, and windy conditions. The policy implication is that wildfire risk escalation in Ruse Municipality should be addressed primarily through hazard mitigation, land management, WUI prevention, and preparedness, rather than through demographic assumptions alone.

Spatially explicit wildfire risk assessment

Definition of wildfire danger

Following the EFFIS logic, wildfire danger is defined as the combined effect of:

- climatic suitability for fire development, represented by the Fire Weather Index;
- fuel availability, represented by burnable vegetation and land-cover characteristics.

Both components were normalized using a min–max transformation and combined to produce a composite fire danger index.

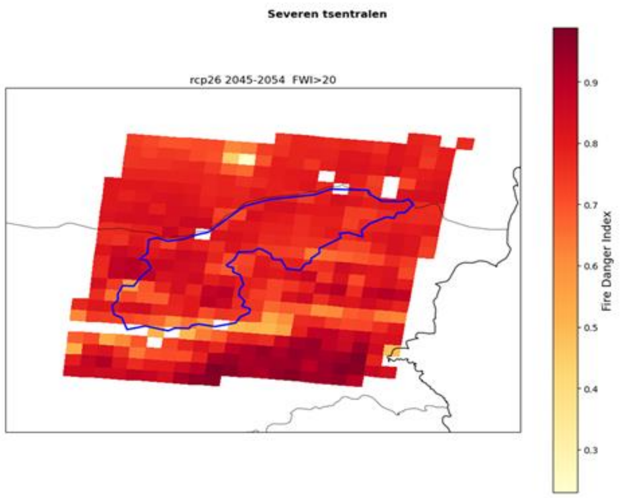


Figure 2.48. Composite wildfire danger index (Source: Ruse – Risk Fire FWI workflow)

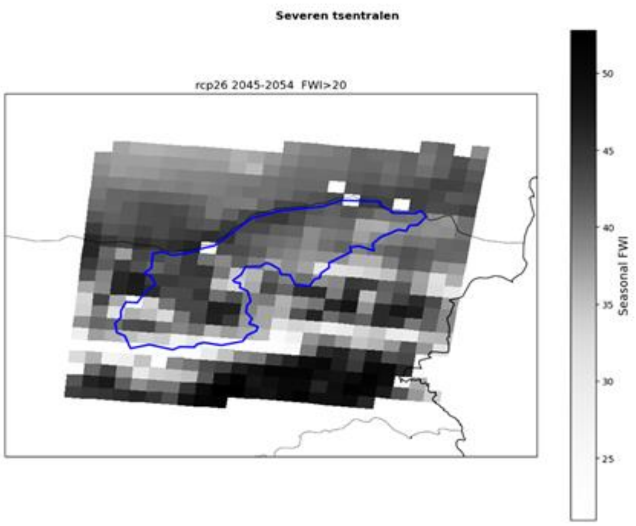


Figure 2.49. Seasonal Fire Weather Index (Source: Ruse – Risk Fire FWI workflow)

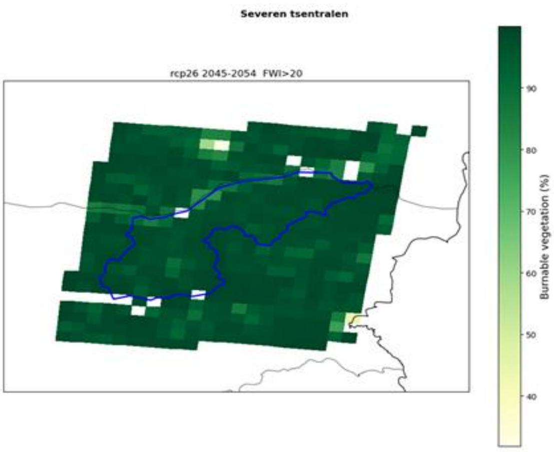


Figure 2.50. Burnable vegetation distribution (Source: Ruse – Risk Fire FWI workflow)

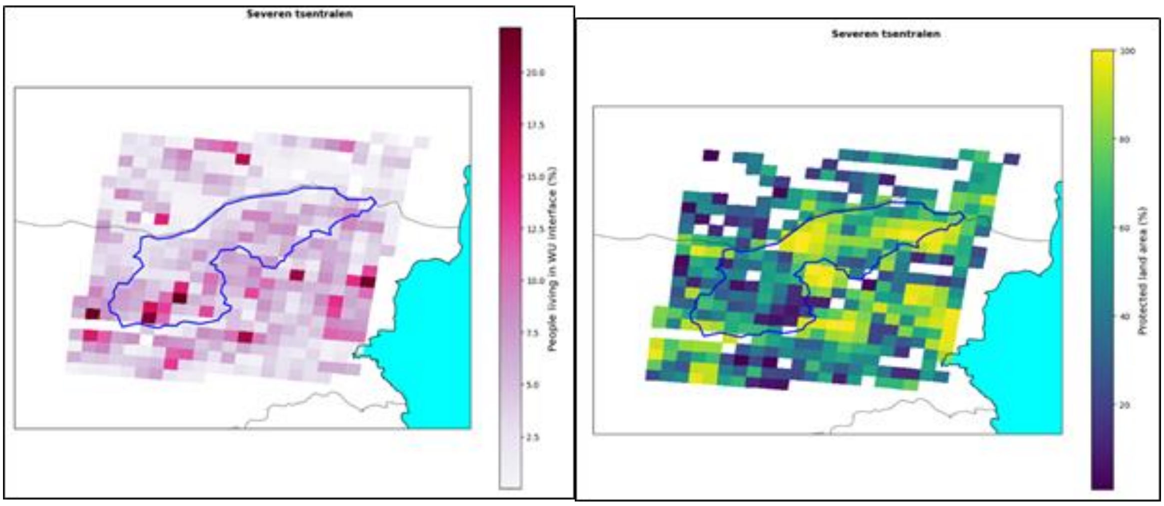
The resulting maps identify zones where high fire-weather conditions coincide with substantial fuel continuity. These areas represent the baseline wildfire danger hotspots. In the context of Ruse Municipality, such zones are particularly important where they overlap with peri-urban settlements, transport corridors, and unmanaged vegetated areas.

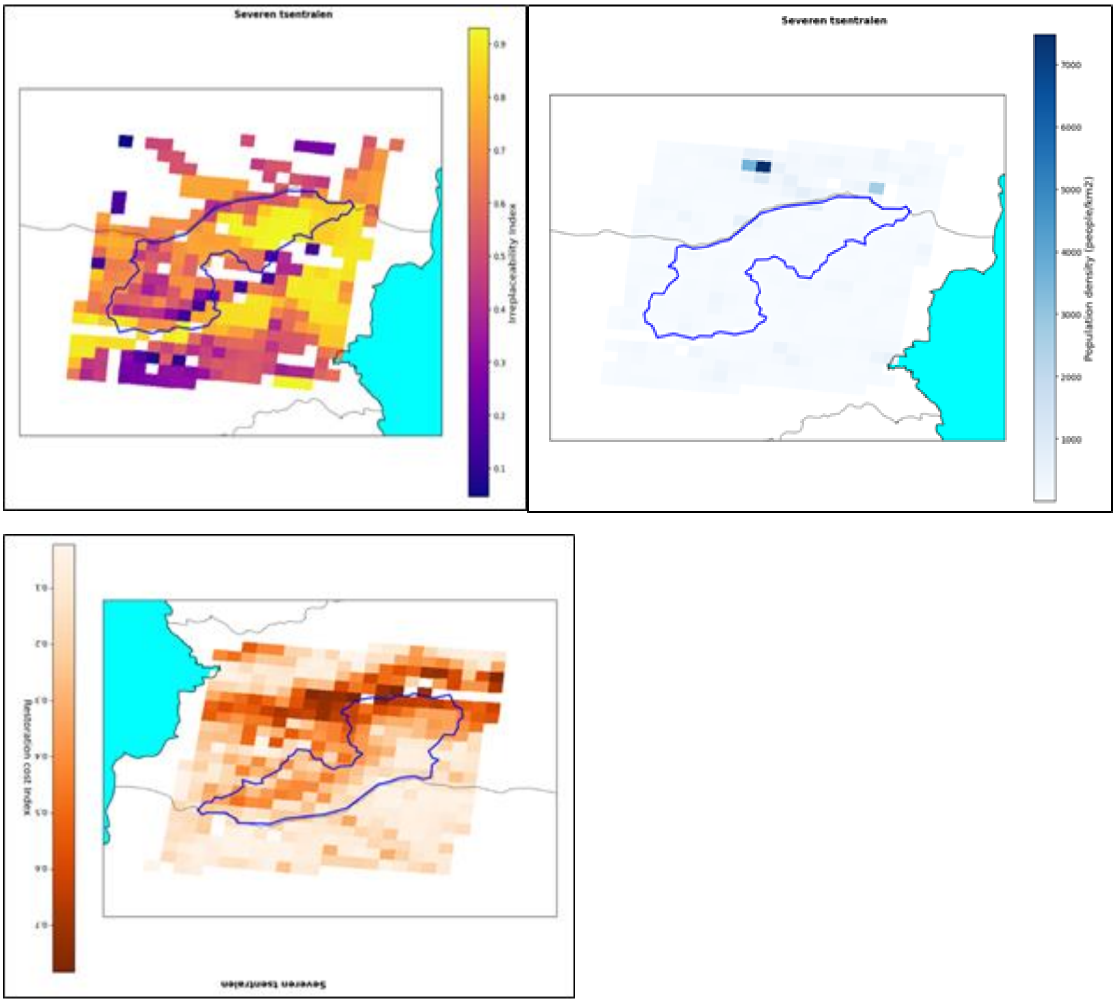
Vulnerability assessment

Wildfire vulnerability was assessed through a set of indicators reflecting human, ecological, and economic sensitivity. These include:

- population density;
- presence of wildland–urban interface zones;
- protected areas;
- ecosystem irreplaceability;
- restoration cost proxies.

This multidimensional approach moves beyond simple population counting and captures the fact that wildfire impacts may affect not only people and buildings, but also ecosystems, biodiversity, landscape functions, and recovery costs.





Figures 2.51. Spatial distribution of wildfire vulnerability indicators (Source: Ruse – Risk Fire FWI workflow)

The vulnerability maps show that the highest vulnerability areas do not fully overlap with the highest climatic hazard zones. This spatial decoupling is important: it demonstrates why a hazard-only assessment would be insufficient. Wildfire risk becomes highest where fire-conducive weather, burnable vegetation, exposed assets, and vulnerable receptors coincide.

Local empirical validation of wildfire dynamics, 2019–2025

To ensure that the model-based hazard and risk indicators are grounded in municipal reality, the assessment integrates empirical wildfire records from the Regional Directorate "Fire Safety and Civil Protection" – Ruse for the period 2019–2025.

During this period, **19 wildfire events** were recorded in the municipality, with a mean frequency of approximately **2.7 events per year** and a total burned area of **1,309 decares**.

Seasonal concentration and climate sensitivity

Wildfire occurrence shows strong seasonal clustering: more than 80% of recorded fires occurred in July–August, consistent with peak summer heat, persistent water deficit, and prolonged dry periods. The local dataset also indicates that the dominant meteorological conditions during wildfire events were hot, dry, windy, and sunny. This directly supports the use of FWI-based indicators in the CLIMAAX workflow.

Tail risk and episodic extremes

Although the number of fires is moderate, the burned-area distribution is strongly asymmetric. Most fires remain limited in size, but rare large events dominate cumulative impacts. Two high-impact outliers are especially important:

- **585 decares burned in 2020**;
- **292 decares burned in 2022**.

These values deviate substantially from typical event sizes and demonstrate that average annual frequency alone is insufficient for characterizing wildfire risk. Ruse Municipality exhibits a low-frequency, high-impact pattern, where rare extreme events dominate overall damage.

Anthropogenic ignition and interface concentration

All recorded events in the dataset are classified as anthropogenic in origin. Recurring locations include peri-urban districts and settlements such as Sredna Kula, Nikolovo, and Basarbovo, as well as areas near railway lines and roads.

This confirms that local wildfire risk is shaped by the interaction between climate-amplified fire weather and human ignition pressure in wildland–urban interface zones.

Table 2.8. Recorded wildfires in Ruse Municipality (2019–2025) – Local Fire Safety Directorate dataset

Date	Fire Type	Location	Landscape / Condition	Burned Area (decares)	Damage	Meteorological Conditions
23.06.2025	Surface fire	Ruse, Sredna Kula district, near railway line	Dry	7	7 decares mixed forest	Hot, dry, calm, sunny
27.07.2025	Surface fire	Nikolovo village, behind Dunarit residential blocks	Dry	15	15 decares coniferous forest	Hot, dry, strong wind, sunny
14.07.2024	Crown fire	Ruse, Sredna Kula district, "Trite Galaba" area	Dry	85	85 decares coniferous forest	Hot, dry, strong wind, sunny
07.08.2024	Surface fire	Ruse–Sofia main road (km 8–9)	Dry	3	3 decares broadleaf forest	Hot, dry, strong wind, sunny
26.02.2023	Non-forest land fire	Ruse, Sredna Kula district	Moist	1	1 decare non-forest land	Cool, humid, windy, sunny
18.07.2023	Surface fire	Ruse, Dolapite district, unguarded railway crossing	Dry	90	50 decares broadleaf; 40 decares coniferous	Hot, dry, strong wind, sunny
24.07.2022	Surface fire	Nikolovo village, outside regulation zone	Dry	292	182 decares broadleaf forest	Hot, dry, strong wind, sunny
03.08.2022	Surface fire	Ruse, Obraztsov Chiflik district, near railway overpass	Dry	60	60 decares broadleaf forest	Hot, dry, strong wind, sunny

13.07.2020	Surface fire	Basarbovo village, compartment 21	Dry	1	1 decare coniferous forest	Hot, dry, strong wind, sunny
14.07.2020	Surface fire	Basarbovo village	Dry	1	1 decare coniferous forest	Hot, dry, strong wind, sunny
15.07.2020	Surface fire	Basarbovo village	Dry	1	1 decare coniferous forest	Hot, dry, strong wind, sunny
17.07.2020	Surface fire	Nikolovo village	Dry	60	60 decares broadleaf forest	Hot, dry, strong wind, sunny
25.07.2020	Surface fire	Ruse, Sredna Kula district, outside regulation zone, compartment 12A	Dry	16	16 decares coniferous forest	Hot, dry, strong wind, sunny
07.08.2020	Surface fire	Ruse, "Buyna Yana" area	Dry	10	10 decares coniferous forest	Hot, dry, strong wind, sunny
08.08.2020	Surface fire	Bazan village, near the airfield	Dry	585	585 decares broadleaf forest	Hot, dry, strong wind, sunny
12.08.2020	Surface fire	Prosena village, "Yotovo Dere" area	Dry	20	20 decares broadleaf forest	Hot, dry, strong wind, sunny
14.08.2020	Surface fire	Ruse, "Buyna Yana" area	Dry	2	2 decares mixed forest	Hot, dry, strong wind, sunny
22.08.2020	Surface fire	Prosena village, "Yotovo Dere" area	Dry	10	10 decares broadleaf forest	Hot, dry, strong wind, sunny
24.08.2019	Surface fire	Ruse, Sredna Kula district, between Rusenski Lom River and railway line	Dry	50	38 decares coniferous forest; 12 decares non-forest land	Hot, dry, strong wind, sunny

Table 2.8 provides event-level evidence on location recurrence, seasonal clustering, burned-area magnitude, anthropogenic ignition, and meteorological conditions. These records validate the seasonal hazard signal identified by the CLIMAAX FWI outputs and support the focus on interface areas where fire danger can translate into locally significant risk.

Integrated risk assessment through Pareto analysis

To integrate wildfire danger and vulnerability without imposing subjective weighting, a Pareto-based multi-criteria approach was applied. In this approach, pixels located on the Pareto front represent locations where multiple risk dimensions are simultaneously unfavourable.

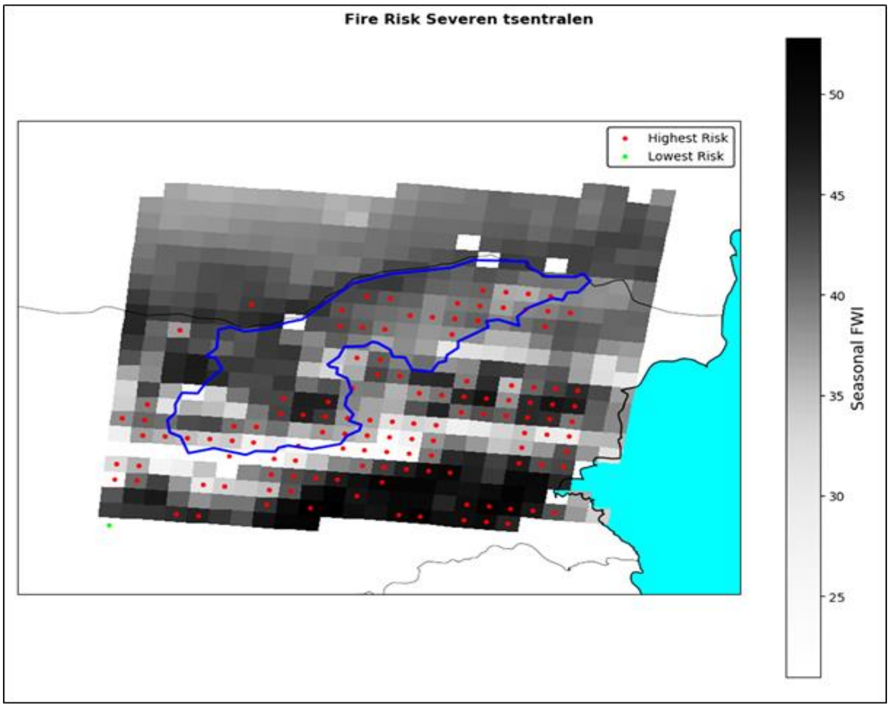


Figure 2.52. Spatial distribution of wildfire risk based on Pareto analysis (Source: Ruse – Risk Fire FWI workflow)

The integrated risk map shows that the highest wildfire risk does not always coincide with the highest FWI values. Moderate hazard combined with high vulnerability and exposure can generate risk levels comparable to, or higher than, areas with extreme hazard but limited exposure.

This confirms that wildfire risk in Ruse Municipality is governed by interface dynamics, not by climatic intensity alone. Areas where settlements, transport infrastructure, burnable vegetation, and anthropogenic ignition sources overlap should therefore be treated as priority zones for prevention and preparedness.

Empirical consistency check

The integrated risk map aligns with locally observed recurring wildfire locations, including:

- Sredna Kula;
- Nikolovo;
- Basarbovo;
- Dolapite;
- peripheral railway and road corridors.

This consistency strengthens confidence in the modelling outputs. It confirms that the risk model identifies spatial patterns that correspond with observed fire occurrence and not only with theoretical fire-weather hazard.

Interpretation of wildfire risk drivers

The analysis shows that wildfire risk in Ruse Municipality is shaped by three main drivers.

First, **climatic amplification** increases the probability of fire-conducive conditions through higher temperatures, precipitation deficit, wind effects, and longer fire-weather seasons.

Second, **anthropogenic ignition** remains the dominant trigger of wildfire events. This means that prevention, awareness, enforcement, and management of human activity near vegetated areas are central to risk reduction.

Third, **spatial overlap between vegetation and settlements** creates localized hotspots, particularly in peri-urban and wildland–urban interface zones. In these areas, even moderate fire-weather hazard can generate substantial risk when exposure and vulnerability are high.

A critical finding is that wildfire risk is not uniformly distributed. It is concentrated in interface zones where climate-amplified hazard, burnable vegetation, human activity, and exposed assets intersect. This explains why local risk can temporarily exceed the level suggested by regional wildfire classifications.

Implications for adaptation and risk governance

The wildfire risk assessment indicates:

- structural intensification of fire-weather hazard;
- increasing population exposure under future climate conditions;
- spatial concentration of risk in WUI zones;
- strong dependence on anthropogenic ignition;
- episodic high-impact events despite moderate average frequency.

Strategic priorities for adaptation and risk governance include:

- mapping and active management of forest–settlement interface zones;
- seasonal prevention campaigns before and during July–August;
- fuel management in peri-urban forests and unmanaged vegetated areas;
- early warning based on FWI thresholds and soil moisture deficit indicators;
- coordination between municipal planning, fire safety services, forestry authorities, and transport infrastructure operators;
- integration of wildfire risk into spatial planning and land-use management.

Compared to Phase 1, Phase 2 provides:

- probabilistic hazard modelling;
- population exposure quantification;
- spatial vulnerability integration;
- multi-criteria risk synthesis;
- empirical validation with local fire records.

This represents a clear methodological advancement and supports targeted, climate-informed wildfire adaptation planning.

Decision-relevant conclusions

The regionalized wildfire risk assessment leads to the following conclusions for municipal risk management:

- Wildfire risk in Ruse Municipality is structurally low-to-moderate at regional level, but dynamically increasing under climate change.

- Peri-urban and wildland–urban interface zones are the main local hotspots and should be prioritized for prevention, monitoring, and awareness measures.
- Anthropogenic ignition is the dominant trigger, confirming the importance of behavioural prevention, public communication, and enforcement.
- Rare but high-impact events dominate cumulative burned area, requiring preparedness for extreme scenarios despite relatively low average annual frequency.
- Climate change is expected to extend the fire-weather season and increase the probability of extreme fire-weather conditions, placing additional pressure on response capacity.
- Integrated wildfire risk is highest where fire-weather hazard, fuel availability, population exposure, ecological sensitivity, and human ignition sources overlap.

Overall, Phase 2 moves the wildfire assessment from qualitative hazard screening to an empirically validated, climate-sensitive, and spatially explicit risk assessment. Although wildfire remains lower in priority than flood-related hazards, it represents a dynamically amplifying risk that requires proactive management in the next adaptation phase.

2.3.3. Hazard #3 — Extreme precipitation (fine-tuning to the local context of Ruse Municipality)

Heavy rainfall constitutes a structurally relevant climate hazard for Ruse Municipality due to its capacity to trigger pluvial flooding, overload urban drainage systems, disrupt transport and public services, and amplify fluvial flood impacts along the Danube River and the Rusenski Lom system.

Unlike river flooding, which follows identifiable floodplain corridors, extreme precipitation can affect the entire municipal territory simultaneously. Urban and peri-urban zones with high impervious surface coverage are particularly sensitive because intense rainfall rapidly generates surface runoff, reduces infiltration, and places pressure on drainage and sewerage systems.

For Ruse Municipality, heavy rainfall is therefore assessed both as a standalone hazard and as a compound risk amplifier. It directly contributes to pluvial flooding and urban disruption, while also intensifying flood risk in smaller catchments, particularly the Rusenski Lom system, where response time is shorter and rainfall-driven runoff can develop rapidly.

Recent climatological evidence for Northern Bulgaria indicates increasing variability in precipitation patterns, characterized by concentration of rainfall into short-duration intense events, longer dry intervals between precipitation episodes, and increasing temperature-driven evaporation. This transition towards greater climatic variability reinforces the systemic relevance of extreme precipitation for urban risk assessment in Ruse.

Climate signal and local evidence base

Within the broader Danubian Plain climatic regime, the Ruse region is characterized by moderate long-term annual precipitation, but with increasing irregularity in the distribution of rainfall over time. Long-term local observations from the Ruse meteorological station and associated regional stations provide an important empirical basis for validating the model-based assessment.

The local evidence indicates three important features:

- precipitation is increasingly unevenly distributed across months and years;
- annual totals may be strongly influenced by a limited number of high-intensity events;

- disruptive rainfall already occurs under present-day climate conditions.

This empirical foundation strengthens the interpretation of the CLIMAAX workflow outputs. It also supports the use of locally relevant thresholds, because the operational relevance of rainfall depends not only on the amount of precipitation, but also on local drainage capacity, urban morphology, soil sealing, and the timing and concentration of rainfall events.

Justification of the 50 mm / 24h critical rainfall threshold

A key methodological refinement introduced in Phase 2 is the adoption of a **50 mm / 24h threshold** as the impact-relevant indicator for disruptive rainfall events in Ruse Municipality.

Although generic screening approaches often use lower thresholds, such as 20–30 mm / 24h, these values are more appropriate for identifying intense rainfall in general, not necessarily rainfall that produces systemic disruption. National climatological studies for Bulgaria indicate that rainfall totals of 20–30 mm within 24 hours occur relatively frequently, particularly during the warm half of the year, and often do not generate substantial damage or major disruption.

By contrast, rainfall events exceeding **40–50 mm / 24h** are more clearly associated with hydrological and urban impacts, including localized flooding, drainage and sewerage overload, damage to road infrastructure, damage to buildings, and interruption of services. This is particularly relevant in the flat and gently sloping territories of Northern Bulgaria, including the Ruse region.

From a risk assessment perspective, using a lower threshold would inflate the frequency of hazardous events and reduce the ability of the analysis to distinguish between intense but manageable rainfall and genuinely disruptive rainfall. The 50 mm / 24h threshold therefore provides a more meaningful boundary between ordinary heavy rainfall and events with elevated potential for material damage, infrastructure stress, and social consequences.

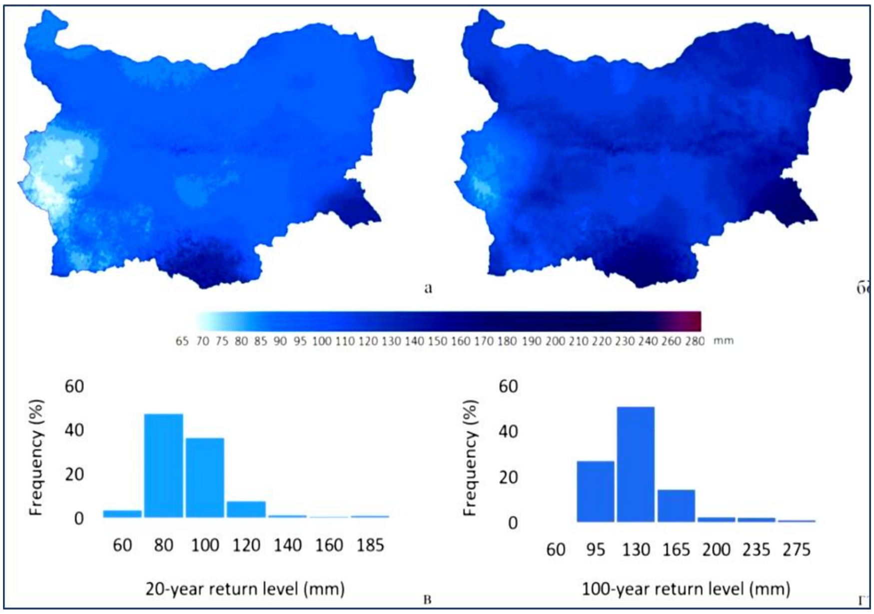


Figure 2.53. Distribution of characteristic values of maximum 24-hour precipitation with a recurrence period of once every 20 years and once every 100 years (Source: Malcheva, K., Marinova, T., & Bocheva, L.)

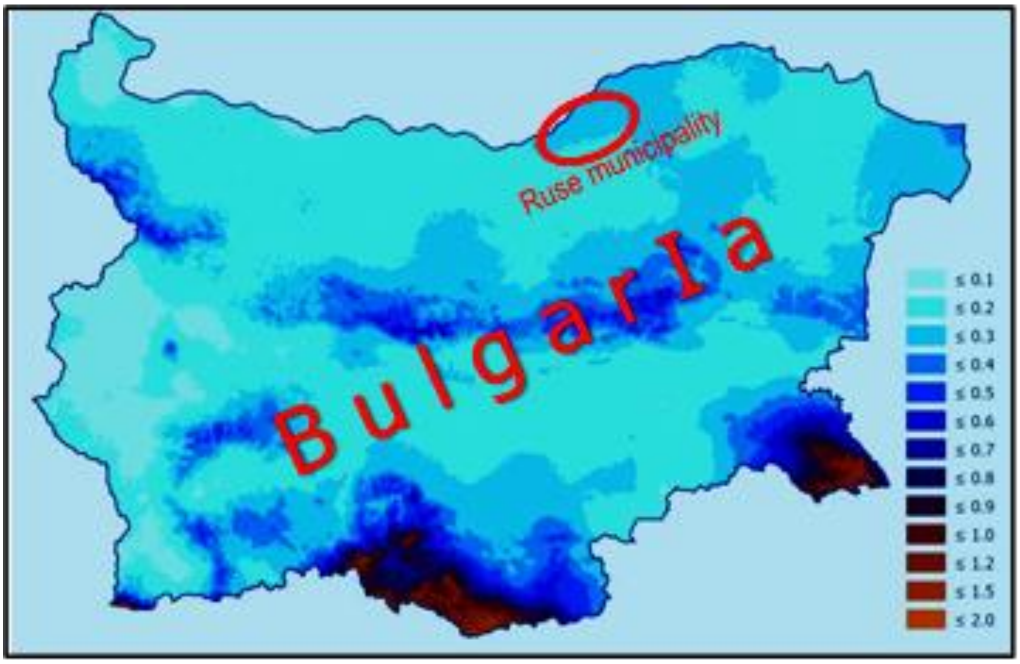


Figure 2.54. Mean annual number of days with extreme precipitation in Bulgaria for the period 1931-2019 (Source: Bocheva, L. and K. Malcheva)

These national cartographic products support the selection of the 50 mm / 24h threshold as a locally relevant disruptive rainfall indicator. In this deliverable, the threshold is therefore used not as a generic climatological marker, but as an impact-relevant boundary for assessing pluvial flooding and urban disruption potential in Ruse Municipality.

This refinement represents a clear methodological advancement compared to Phase 1, where heavy rainfall was identified qualitatively but not yet linked to a locally justified disruption threshold.

Table 2.9. Data overview – Extreme Precipitation (Phase 2)

Hazard data	Vulnerability data	Exposure data	Impact metrics / Risk output
CLIMAAX Extreme Precipitation Indicator (maximum 24h rainfall)	Urban sensitivity to pluvial flooding (soil sealing, drainage limitations, runoff concentration)	Built-up areas, population density, transport corridors, critical infrastructure (spatial overlay)	Return period of 50 mm / 24h threshold
EURO-CORDEX regional projections (≈12.5 km, bias-adjusted)	Qualitative sensitivity of urban systems	High impervious surface zones	Change in return period (years)
Annual maxima (1976–2005 baseline)	No quantitative vulnerability modelling applied	Population concentration zones	Change in rainfall magnitude at fixed frequency (mm)
Mid-century projections (2041–2070, RCP8.5)	—	—	Relative (%) and multiplicative change factor
Extreme value modelling (GEV) and IDF relationships	—	—	Qualitative disruption likelihood

The workflow combines model-based climate projections with local observational evidence. The CLIMAAX outputs quantify future changes in extreme precipitation, while the local data validate whether the selected threshold and interpretation are meaningful for the Ruse context.

1. Hazard Assessment

Hazard assessment methodology

The heavy rainfall hazard assessment is based on dynamically downscaled regional climate projections from EURO-CORDEX, using daily precipitation outputs at approximately 12 km spatial resolution.

The selected model chain is:

- **GCM:** ICHEC-EC-EARTH
- **RCM:** KNMI-RACMO22E

This model chain was used to ensure methodological consistency with the CLIMAAX workflow and to provide a coherent representation of regional atmospheric circulation relevant to Southeastern Europe.

Two standard 30-year climatological periods were analysed:

- **Baseline period:** 1976–2005
- **Future period:** 2041–2070

The future period corresponds to **RCP8.5**, used as a stress-test scenario to assess upper-bound adaptation needs under high climate forcing.

The hazard assessment focuses on **maximum 24-hour accumulated precipitation**, which is the most operationally relevant duration for municipal-scale impact analysis. This duration is strongly associated with:

- rapid urban surface runoff generation;
- exceedance of drainage system capacity;
- pluvial flooding in low-lying urban zones;
- transport disruption;
- interaction with fluvial flood dynamics along the Danube and Rusenski Lom.

Compared to Phase 1, Phase 2 introduces explicit extreme value modelling and return period derivation, replacing earlier qualitative hazard characterization.

Extreme value modelling approach

For each relevant grid cell intersecting Ruse Municipality, annual maxima of 24-hour precipitation were extracted for both the baseline and future periods. Extreme value analysis was then applied using a **Generalized Extreme Value (GEV)** distribution, enabling derivation of intensity–frequency relationships.

The GEV framework allows estimation of:

- return periods associated with the 50 mm / 24h threshold;
- rainfall magnitude for selected return periods;
- frequency shifts under climate change;
- intensity amplification at fixed recurrence intervals.

Return periods analysed include commonly used design and impact-relevant frequencies, including 2, 5, 10, 25 and 50 years. This makes the results relevant for municipal planning, drainage assessment, and infrastructure adaptation.

Spatial domain and processing

The analysis covers the administrative territory of Ruse Municipality and its immediate surroundings in order to capture boundary effects. Hazard indicators were computed on the native EURO-CORDEX grid and then extracted for grid cells intersecting the municipality.

For cartographic presentation and GIS compatibility, the outputs were regridded to WGS84. This step was applied only for visualization and spatial harmonization and does not alter the underlying model signal.

Local observational validation and extended analysis

To strengthen the local relevance of the model-based assessment, locally observed precipitation data were integrated into the analysis. The observational dataset includes ground-based precipitation measurements and enables identification of both frequent moderate-to-heavy rainfall events and rarer high-impact events.

Two thresholds were considered:

- **20 mm / 24h** as a standard intensity threshold for moderate-to-heavy rainfall;
- **50 mm / 24h** as a locally validated disruption threshold.

The local data show that events exceeding 20 mm / 24h occur regularly, confirming the continuous pressure exerted by moderate-to-heavy rainfall on urban drainage systems and infrastructure. At the same time, multiple events exceeding 50 mm / 24h are observed. The highest recorded daily precipitation exceeds 70 mm, demonstrating that rainfall events significantly above the disruption threshold already occur under present-day climate conditions.

This is important for two reasons. First, it confirms that the 50 mm / 24h threshold is not an abstract theoretical value, but a realistic local disruption boundary. Second, it shows that observed high-impact events may locally exceed modelled medium-return-period values, while remaining consistent with the projected direction of climate change.

Seasonal distribution and rainfall-generating mechanisms

The local observational record shows a clear seasonal pattern. The highest daily precipitation totals are predominantly recorded during late spring and early summer, especially May–July. This reflects the influence of frontal and convective precipitation processes typical for the Danubian Plain.

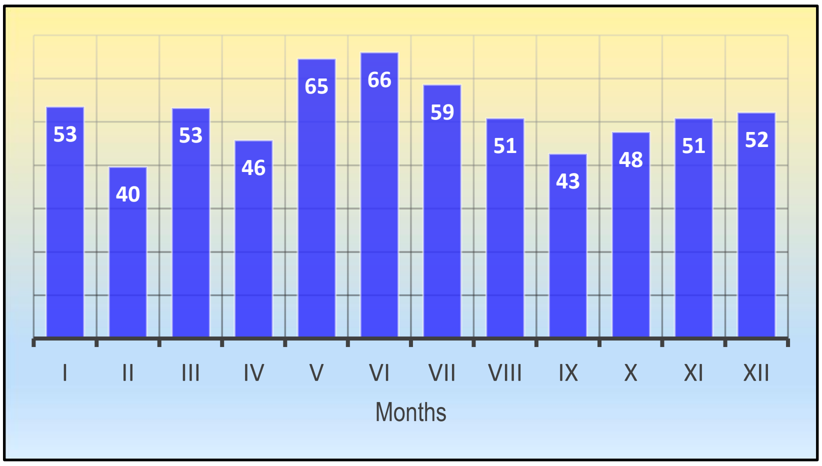


Figure 2.55. Intra-annual course of monthly precipitation totals for Ruse meteorological station, long-term observational record

The monthly distribution shows a clear precipitation maximum during late spring and early summer, especially May–June. Lower values during winter months reflect more stable atmospheric conditions and generally lower precipitation intensity.

These warm-season rainfall events are often characterized by high intensity, short duration, and strong spatial variability. They are therefore particularly relevant for rapid surface runoff and pluvial flooding.

Significant rainfall events also occur during late autumn and winter, typically associated with larger synoptic-scale systems. These events tend to be longer in duration and may contribute to cumulative soil saturation, increasing susceptibility to flooding.

This indicates a dual seasonal rainfall regime:

- short-duration frontal and convective extremes in spring and summer;
- longer-duration frontal precipitation in autumn and winter.

Both mechanisms contribute to flood risk, but through different pathways: rapid runoff and pluvial flooding in the first case, and cumulative wetness and flood susceptibility in the second.

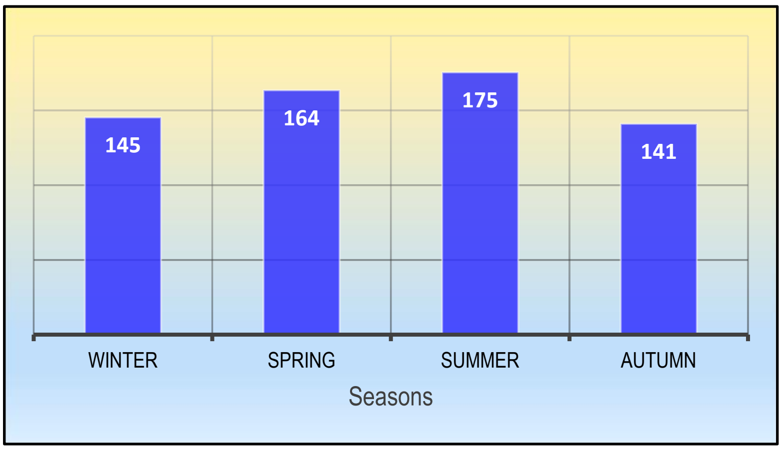


Figure 2.56. Seasonal precipitation totals for Ruse meteorological station

The seasonal totals confirm the dominance of spring–summer precipitation, while autumn and winter remain relevant for longer-duration rainfall and soil saturation processes.

Interannual variability and deviation patterns

The observational record also shows substantial variability in annual precipitation totals. This variability reflects increasingly irregular rainfall patterns, including both wet and dry years and strong deviations from monthly norms.

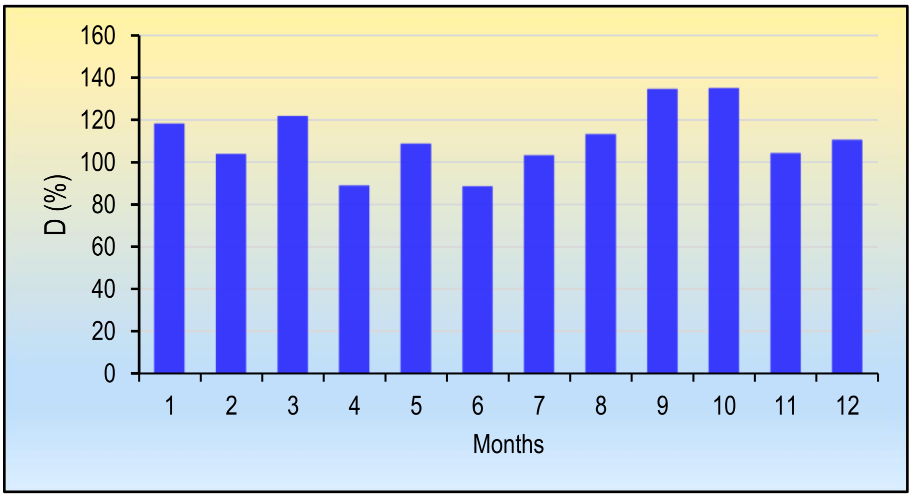


Figure 2.57. Relative deviation of monthly precipitation totals from the long-term climatological norm, 1893–2023, Ruse

The deviation pattern shows substantial intra-annual variability, with both positive and negative anomalies across months. Higher deviations suggest increasing irregularity and stronger concentration of rainfall in selected periods.

Years with high annual precipitation are often influenced by a limited number of intense rainfall events rather than by evenly distributed precipitation throughout the year. Conversely, years with lower annual totals may still include isolated extreme events, but their contribution to annual precipitation remains more limited.

This behaviour indicates:

- increasing intra-annual variability;
- concentration of rainfall into fewer but more intense events;
- reduced predictability of precipitation distribution.

These characteristics are consistent with the regional climate signal identified by the model-based analysis.

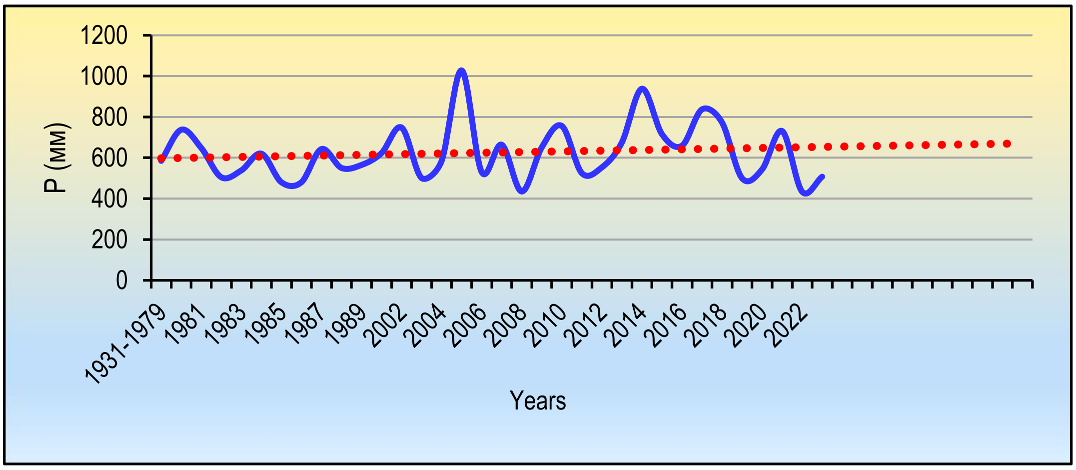


Figure 2.58. Annual precipitation totals and long-term variability, 1980–2023, Ruse meteorological station

The annual time series shows pronounced interannual variability, with alternating wet and dry years and occasional extreme values. The indicative trend suggests a slight increase in annual precipitation, but more importantly, growing variability rather than a uniform rise.

Observed characteristics of extreme rainfall

The local observational data confirm:

- frequent occurrence of events exceeding 20 mm / 24h;
- repeated exceedance of the 50 mm / 24h disruption threshold;
- maximum observed daily precipitation exceeding 70 mm.

These findings demonstrate that moderate-to-heavy rainfall events are a regular feature of the local climate, while high-impact events are already present under current conditions.

Although the available observational dataset does not support a fully robust statistical trend analysis for extremes, it provides strong empirical evidence of both frequent operational stress events and rarer disruptive events. This validates the use of a two-level interpretation: 20 mm / 24h as a frequent pressure indicator, and 50 mm / 24h as the disruption threshold used for risk interpretation.

Heavy rainfall hazard results

Baseline extreme precipitation characteristics, 1976–2005

Under baseline climate conditions, extreme 24-hour precipitation over Ruse Municipality exhibits moderate spatial variability consistent with the Danubian Plain climatic regime.

For the 50 mm / 24h threshold, baseline return periods range approximately between **10 and 25 years**, depending on grid-cell location. This indicates that historically such events were relatively infrequent, but sufficiently intense to generate localized flooding, especially in sealed or poorly drained urban areas.

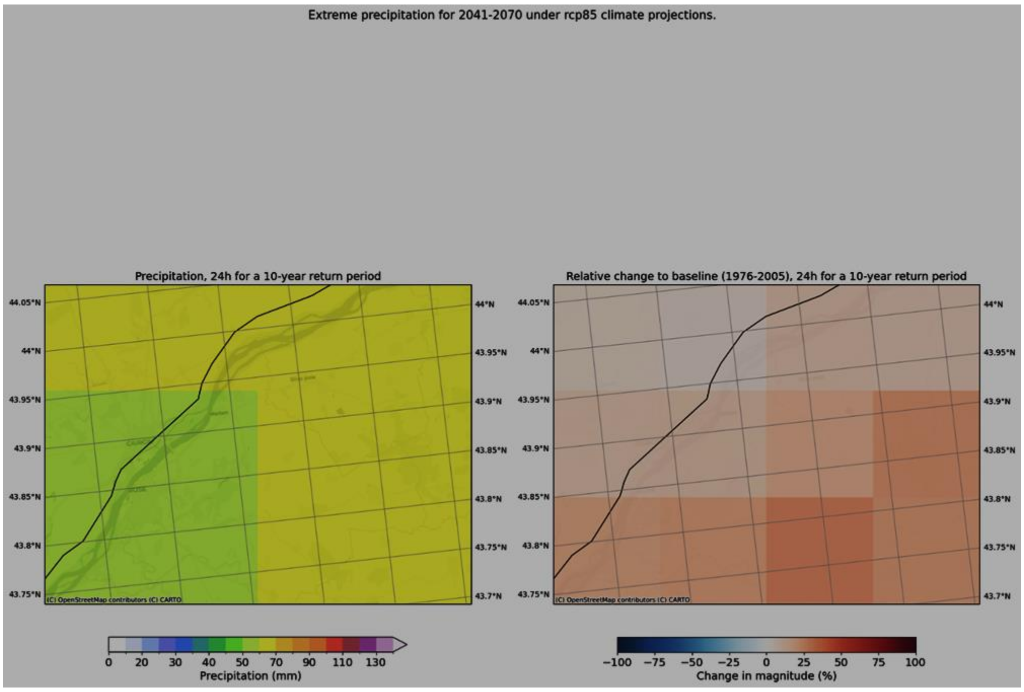


Figure 2.59 - Spatial distribution of expected 24-hour precipitation (mm) for selected return periods (baseline period 1976–2005).

The baseline spatial pattern shows:

- slightly higher intensities in southern and peri-urban parts of the municipality;
- relatively homogeneous hazard across the municipal territory;
- absence of strong localized micro-climatic gradients at model resolution.

The baseline intensity–frequency relationship provides the reference against which future hazard amplification is assessed.

Projected changes in extreme precipitation, 2041–2070

Climate projections indicate a systematic intensification of extreme 24-hour precipitation across Ruse Municipality by mid-century under RCP8.5.

This intensification appears in two complementary dimensions:

1. **Intensity amplification** — higher rainfall amounts for fixed return periods;
2. **Frequency amplification** — shorter return periods for fixed rainfall thresholds.

At a fixed 5-year return period, projected 24-hour rainfall intensities increase by approximately **5% to more than 20%**, depending on grid-cell location.

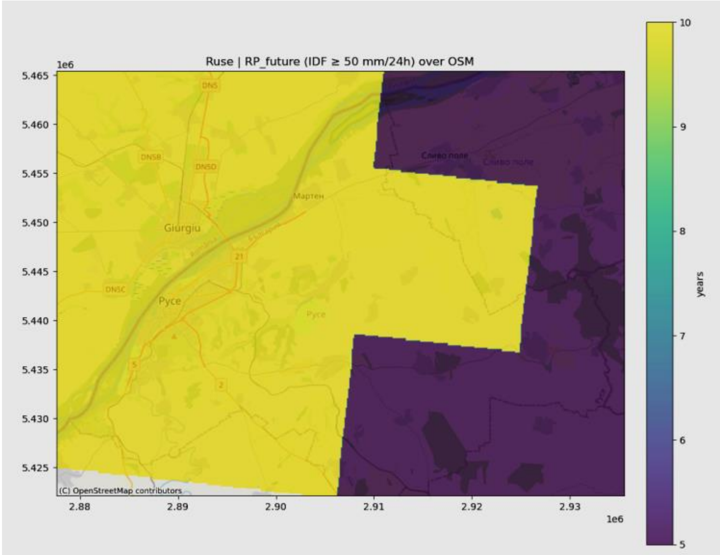


Figure 2.60 - Expected 24-hour precipitation (mm) for a 5-year return period under future climate conditions (2041–2070, RCP8.5).

The projected pattern shows spatially consistent intensification, with no compensating decrease zones. This means that heavy rainfall intensification affects both urban and peri-urban areas.

Relative change in hazard intensity

The relative difference between future and baseline intensities reveals a uniformly positive change across the municipality.

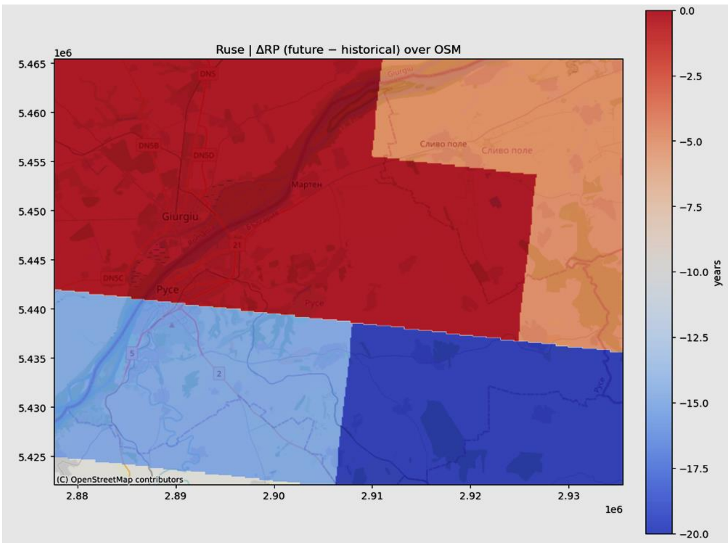


Figure 2.61 - Relative change (%) in expected 24-hour precipitation between 1976–2005 and 2041–2070 for selected return periods.

The map demonstrates:

- no systematic reduction areas;
- municipal-wide intensification;
- consistent magnitude increases across return periods.

This spatial coherence reduces the likelihood that the projected intensification is only a model artefact and supports its interpretation as a structural hazard shift.

2. Risk Assessment — Extreme Precipitation

Risk framing and assumptions

The heavy rainfall risk assessment translates projected hazard changes into risk-relevant indicators by linking climate-driven changes in extreme precipitation to a locally calibrated disruption threshold.

Unlike the river flood workflow, where exposure and vulnerability are modelled explicitly, the heavy rainfall assessment operates as a **hazard-based risk proxy**. It focuses on how often disruptive rainfall thresholds are exceeded and how rainfall intensity changes at recurrent return periods.

The following assumptions are applied:

- **Critical rainfall magnitude:** 50 mm / 24h
- **Reference return period for intensity analysis:** 5 years

The 50 mm / 24h threshold represents the boundary at which rainfall transitions from intense but generally manageable to disruptive under Bulgarian urban conditions. The 5-year return period is used as a practical reference because it is relevant for recurrent infrastructure stress and urban drainage performance.

This framing enables comparison between baseline and future climate conditions in terms of both probability shift and intensity amplification.

Risk indicators

Five core indicators were derived from the extreme value modelling outputs:

1. baseline return period of the 50 mm / 24h threshold;
2. future return period of the same threshold;
3. absolute change in return period;
4. change in rainfall magnitude at a fixed return period;
5. multiplicative change factor at fixed frequency.

Return period is defined as: $T = 1 / P$, where **T** is the return period in years and **P** is the annual exceedance probability.

A reduction in return period therefore implies a higher annual probability of disruptive rainfall.

Changes in frequency: return period shifts

For the 50 mm / 24h threshold, baseline return periods range between approximately **10 and 25 years**. Under future climate conditions, they shorten to approximately **5–10 years** under RCP8.5.

This means that rainfall events previously considered relatively rare may occur up to twice as frequently by mid-century.

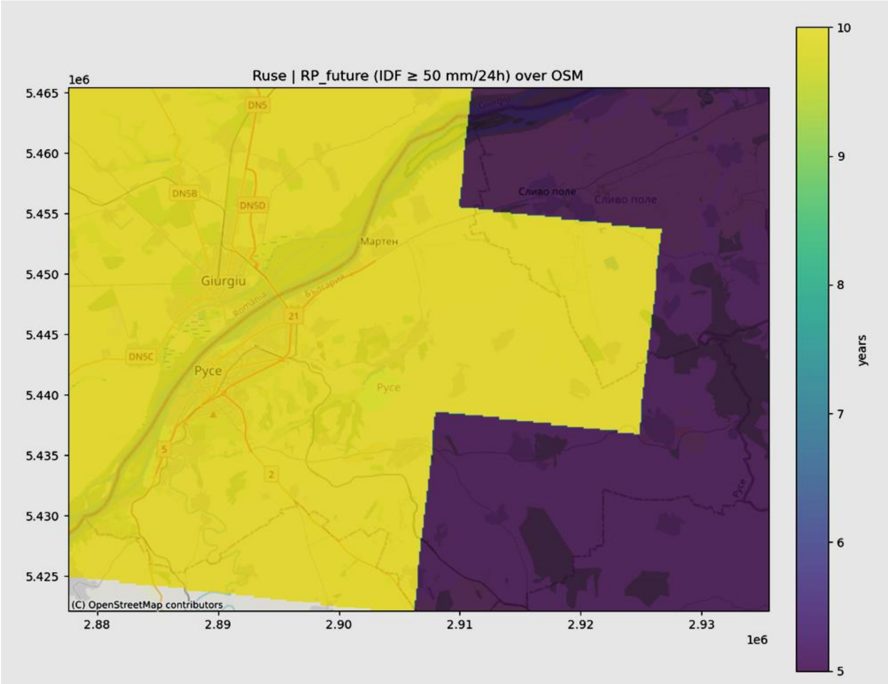


Figure 2.62 - Future return period (years) of a 50 mm/24h rainfall event under RCP8.5 (2041–2070).

The spatial distribution demonstrates a systematic frequency shortening across the entire municipality.

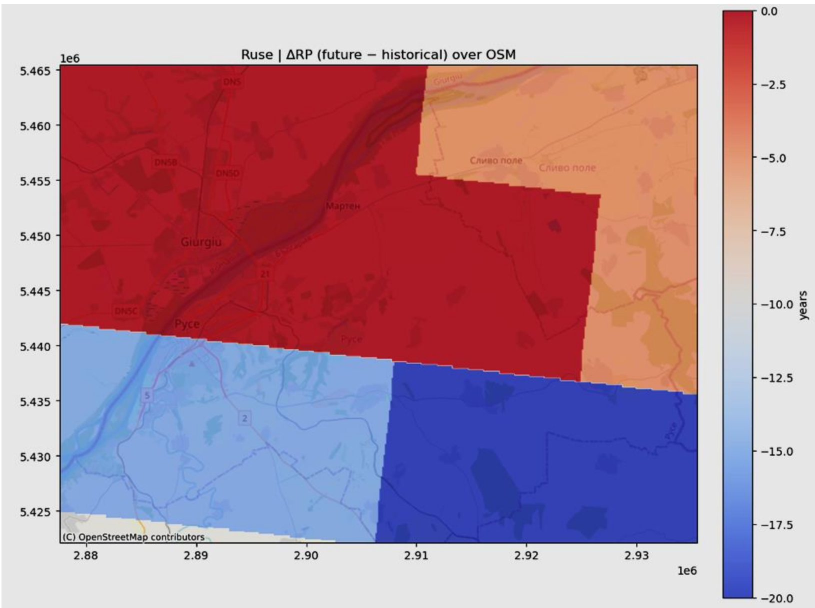


Figure 2.63 - Change in return period (years) for a 50 mm/24h rainfall event between baseline and future periods.

The change map confirms:

- no compensating increase in return periods;
- spatially coherent frequency amplification;
- strongest shifts in zones already characterized by moderate baseline recurrence.

This pattern indicates structural intensification rather than isolated local anomalies.

Changes in magnitude: intensity shifts

At a fixed 5-year return period, projected 24-hour rainfall intensities increase by approximately **2–9 mm** across the municipality. In relative terms, this corresponds to an increase of approximately **5% to 22%** compared to baseline.

At a representative grid cell near the city of Ruse:

- baseline 5-year rainfall: approximately **40.8 mm / 24h**;
- future 5-year rainfall: approximately **47.6 mm / 24h**;
- multiplicative change factor: approximately **1.17**.

This confirms a substantial upward shift in rainfall magnitude at recurrent, impact-relevant frequencies.

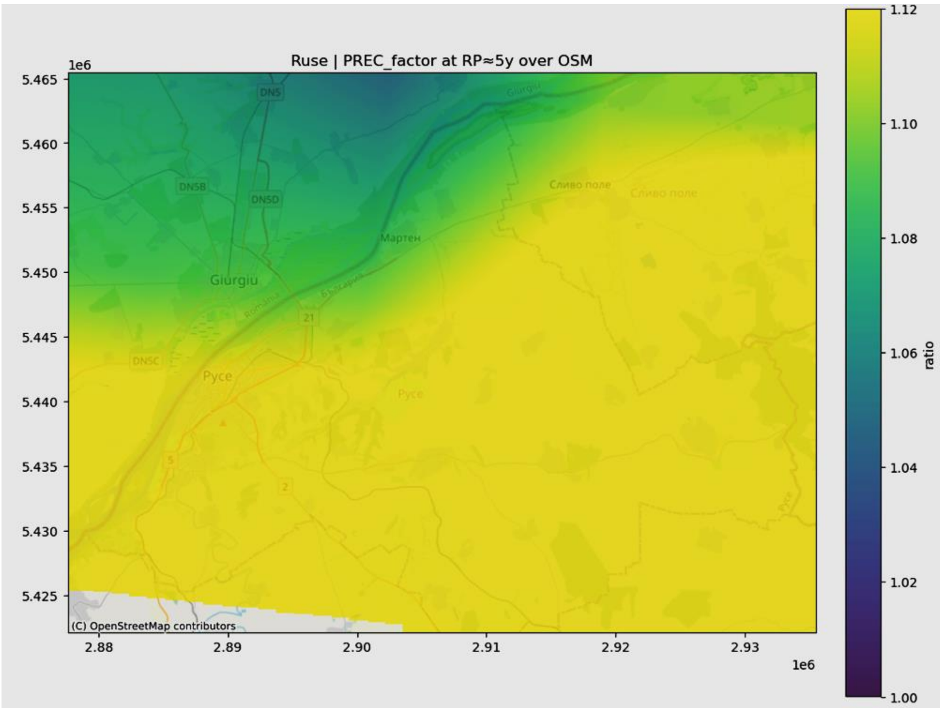


Figure 2.64. Absolute change in 24-hour rainfall magnitude (mm) at a 5-year return period.

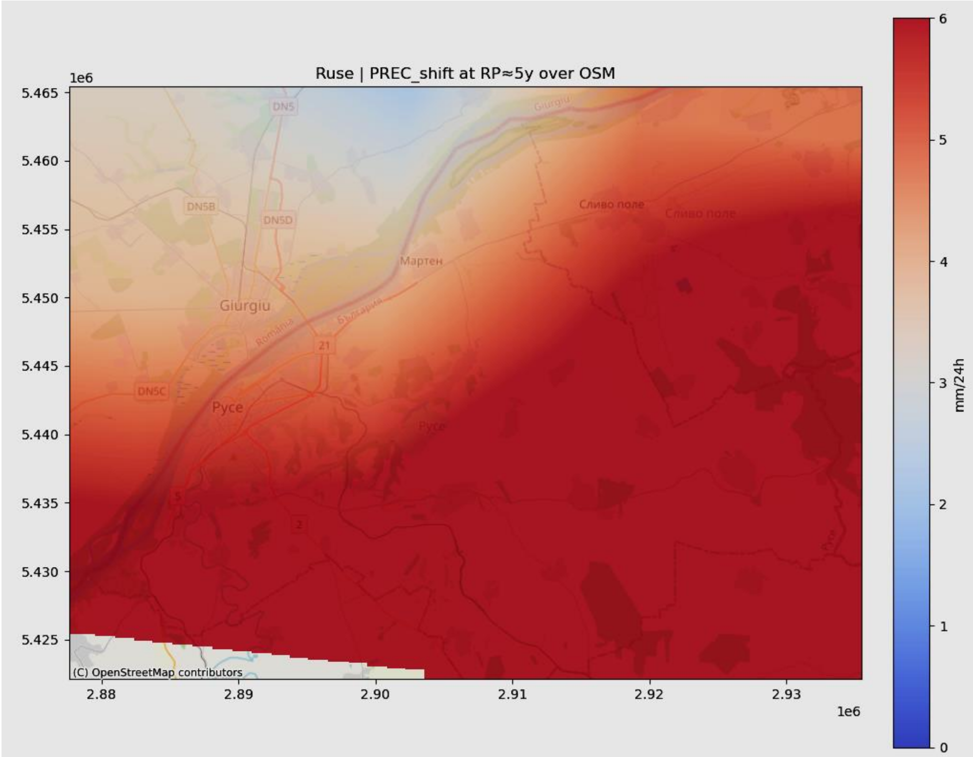


Figure 2.65. Multiplicative change factor of 24-hour rainfall at a 5-year return period.

The multiplicative change factor consistently exceeds 1.0 across the municipality, reinforcing the spatial coherence of rainfall intensification.

Climate-informed interpretation of local observations

When the modelled changes are interpreted together with local observations, the risk signal becomes stronger. Observed daily precipitation already exceeds 70 mm in the local record, while the modelled results indicate increasing intensity and frequency of extreme rainfall by mid-century.

This means that:

- in the near term, more frequent exceedance of operational thresholds such as 20 mm / 24h can be expected;
- by mid-century, high-impact rainfall events exceeding 50 mm / 24h are likely to become more frequent;
- in the longer term, further amplification may increase the likelihood of events exceeding the upper range of currently observed extremes.

These projections should not be interpreted as exact forecasts of individual events. They indicate a robust directional change: rainfall extremes are becoming more intense, more frequent, and more disruptive for urban systems.

Compound hazard escalation

The combined increase in frequency and intensity constitutes a compound escalation of heavy rainfall risk.

Risk amplification occurs through two reinforcing mechanisms:

1. **More frequent exceedance of the 50 mm / 24h disruption threshold**;
2. **Greater rainfall volumes per event at recurrent return periods**.

This dual shift implies:

- increased peak runoff generation;
- higher probability of drainage system exceedance;
- increased surface water accumulation in sealed urban areas;
- more frequent disruption to transport and mobility;
- greater pressure on emergency response and municipal maintenance systems;
- increased potential for pluvial–fluvial interaction, especially in the Rusenski Lom system.

Even in the absence of fully explicit urban drainage modelling, the hazard signal itself indicates rising urban disruption potential.

Heavy rainfall therefore emerges as a systemic urban risk, particularly for:

- dense urban zones;
- low-lying areas;
- locations with limited drainage capacity;
- transport corridors prone to short-term inundation;
- zones where pluvial runoff interacts with river flood dynamics.

Limitations and uncertainty considerations

The results are subject to known limitations of regional climate modelling and extreme precipitation analysis:

- EURO-CORDEX resolution does not fully represent sub-kilometre convective storms;
- results are sensitive to the selected model chain;
- statistical uncertainty remains in GEV parameter estimation;
- no explicit hydraulic or urban drainage model is included;
- exposure and vulnerability are interpreted qualitatively rather than through direct damage modelling.

However, several elements strengthen the robustness of the assessment:

- spatial coherence of projected intensification;
- consistency between intensity and frequency indicators;
- alignment with national climatological studies;
- validation through local observational precipitation data;
- stakeholder confirmation that drainage capacity and flood-related damage records are key data gaps;
- reproducibility of the CLIMAAX Jupyter workflow.

The results should therefore be interpreted as directionally robust evidence suitable for strategic adaptation planning, rather than deterministic short-term forecasts.

Summary of key findings

Table 2.10. Summary of heavy rainfall hazard and risk indicators for the municipality of Ruse

Indicator	Baseline climate, 1976–2005	Future climate, 2041–2070, RCP8.5	Change / risk interpretation
Critical rainfall threshold	50 mm / 24h	50 mm / 24h	Locally calibrated disruptive rainfall boundary
Return period of 50 mm / 24h	~10–25 years	~5–10 years	Disruptive events become up to twice as frequent
Change in return period	–	–	−20 to 0 years across municipality; systematic shortening
Reference return period for intensity analysis	5 years	5 years	Fixed recurrence used for magnitude comparison
24h rainfall at 5-year RP, municipal range	~38–43 mm	~40–52 mm	Intensification across the territory
Absolute intensity change, 5-year RP	–	–	+2 to +9 mm / 24h
Relative intensity change, 5-year RP	–	–	+5% to +22%
Multiplicative change factor	1.00	1.05–1.22	Systematic amplification of extreme rainfall
Diagnostic grid cell near Ruse city	~40.8 mm	~47.6 mm	+6.8 mm; change factor ~1.17
Local observed extremes	Daily extremes already exceed 50 mm; maximum observed daily totals exceed 70 mm	Future intensification expected	Observed data confirm that disruptive rainfall already occurs
Overall hazard signal	Moderate extreme rainfall regime	Stronger and more frequent extremes	Robust and spatially coherent climate signal
Overall risk implication	Occasional pluvial flooding and drainage stress	More frequent exceedance of drainage thresholds	Escalating systemic urban disruption risk

The synthesis confirms a structurally consistent intensification of heavy rainfall hazard across Ruse Municipality.

Two reinforcing dynamics are observed:

1. **Frequency shift** — events exceeding the 50 mm / 24h disruptive threshold occur more often;
2. **Intensity shift** — rainfall volumes increase at recurrent return periods.

The combined frequency–intensity amplification indicates that heavy rainfall is transitioning from an episodic stressor to a structurally relevant urban hazard.

Decision-relevant conclusions

The regionalized analysis leads to the following conclusions for municipal decision-making:

- Heavy rainfall is a municipality-wide hazard, not confined to floodplain corridors.
- Disruptive rainfall events are projected to become substantially more frequent by mid-century.
- Rainfall intensity is increasing, leading to higher runoff volumes and greater pressure on drainage systems.
- Local observations confirm that high-impact rainfall already occurs under current conditions, including daily totals exceeding 70 mm.
- The 50 mm / 24h threshold is justified as an impact-relevant disruption boundary for Ruse Municipality.
- Urban drainage capacity is a critical limiting factor and should be treated as a key determinant of risk.
- Heavy rainfall acts as a compound risk amplifier, increasing both pluvial flooding and river flood impacts, particularly in the Rusenski Lom system.
- The main affected systems are urban drainage, roads and transport corridors, public services, critical infrastructure, and emergency response capacity.

Overall, Phase 2 moves the heavy rainfall assessment from qualitative hazard recognition to quantified, locally validated, and scenario-based risk interpretation. The analysis confirms that heavy rainfall should be classified as a **high-priority climate risk** for Ruse Municipality and should be addressed through drainage system upgrades, nature-based runoff management, risk-informed urban design, transport resilience planning, and improved early warning and response procedures.

2.3.4. Additional assessments based on local models and data

Phase 2 substantially extends the climate risk assessment developed in Phase 1 by combining CLIMAAX workflows with locally relevant datasets, official maps, observational records, stakeholder input, and hazard-specific contextual evidence. While Phase 1 provided a structured baseline diagnosis based mainly on hazard screening, exposure patterns, and preliminary prioritization, Phase 2 advances the analysis towards more localized, quantitative, and decision-relevant risk interpretation.

The added value of Phase 2 lies not only in the application of standardized CLIMAAX workflows, but also in the systematic interpretation of workflow outputs through the actual territorial, hydrological, infrastructural, and socio-economic conditions of Ruse Municipality. This is particularly important because climate risk in Ruse is shaped by the interaction between the Danube corridor, the Rusenski Lom catchment, densely urbanized areas, peri-urban settlements, critical infrastructure, transport corridors, and semi-natural interface zones.

The additional use of local models and data served three main purposes:

- to validate whether standardized European-scale outputs correspond to locally observed or officially recognized risk patterns;
- to refine the interpretation of hazard and risk results using local thresholds, observations, and empirical evidence;
- to translate hazard outputs into information that is directly usable for municipal planning, investment prioritization, civil protection, and adaptation design.

This approach directly addresses the need for a Phase 2 assessment to move beyond spatial clipping of generic datasets and towards substantive local contextualization and interpretation.

Added value for hazard assessment

Phase 2 maintains methodological continuity with Phase 1, while significantly improving the diagnostic value of the hazard assessment. Table 2.X summarizes how each priority hazard was treated in Phase 1 and how Phase 2 upgraded the analysis through workflow refinement and integration of local evidence.

Table 2.11. Phase 1 vs. Phase 2: added value from local models and data for hazard assessment

Hazard	Phase 1 baseline	Phase 2 local upgrade	Added value for municipal planning
River floods	Regional hazard screening; identification of flood-prone areas; qualitative exposure zones	CLIMAAX river flood workflow applied across return periods; differentiation between Danube and Rusenski Lom flood regimes; comparison with official FRMP flood hazard and risk maps; use of local historical flood records and hydrological evidence	Enables spatially differentiated flood interpretation, supports hotspot identification, and strengthens the basis for flood protection, land-use planning, and emergency preparedness
Heavy rainfall	General identification of extreme precipitation as a relevant hazard; limited quantitative analysis	EURO-CORDEX-based extreme value analysis; GEV and IDF derivation; locally justified 50 mm / 24h disruption threshold; integration of local observational precipitation data; interpretation of return period shortening and intensity amplification	Supports stormwater planning, drainage adaptation, transport resilience, and prioritization of areas exposed to pluvial flooding and urban disruption
Wildfires	Contextual discussion of wildfire susceptibility and climate sensitivity	CLIMAAX FWI-based hazard modelling; national wildfire risk methodology; local wildfire records for 2019–2025; seasonal concentration analysis; interpretation of WUI exposure and anthropogenic ignition	Supports peri-urban prevention, fuel management, fire-weather monitoring, and coordination between municipal planning, fire safety, and forestry actors

The progression from Phase 1 to Phase 2 is particularly evident in three respects. First, hazard analysis is no longer limited to general identification, but is linked to local territorial patterns and hazard-specific dynamics. Second, future climate conditions are addressed explicitly through scenario-based interpretation. Third, hazard outputs are connected to practical planning needs and not presented only as technical modelling results.

For river floods, the main improvement is the explicit differentiation between the Danube and Rusenski Lom systems, supported by official FRMP maps and local flood records. For heavy rainfall, the key improvement is the transition from qualitative recognition to quantified analysis of return period shifts, supported by a locally justified 50 mm / 24h threshold and local precipitation observations. For wildfires, the assessment shifts from general susceptibility discussion to a climate-sensitive interpretation of fire weather, burnable vegetation, anthropogenic ignition, and wildland–urban interface exposure.

Overall, the Phase 2 hazard assessment is therefore more diagnostic, traceable, and territorially relevant than in Phase 1.

Added value for risk assessment

The added value is even more important at the level of risk assessment. Phase 1 framed risk mainly in conceptual terms, using the relationship between hazard, exposure, and vulnerability. Phase 2 operationalizes this framework through CLIMAAX workflows, local validation, and decision-relevant indicators.

Table 2.12. Phase 1 vs. Phase 2: added value from local models and data for risk assessment

Risk	Phase 1 baseline	Phase 2 local upgrade	Added value for decision-making
River flood risk	Qualitative identification of exposed and vulnerable areas	Expected Annual Damage (EAD), Expected Annual Population Exposed (EAPE), Expected Annual Population Displaced (EAPD), damage estimates by return period, critical infrastructure exposure, comparison with official flood risk maps	Provides quantitative evidence for prioritizing flood protection, infrastructure resilience, emergency planning, spatial planning controls, and investment decisions
Heavy rainfall risk	Qualitative interpretation of urban sensitivity to extreme precipitation	Hazard-based risk proxy using the 50 mm / 24h disruption threshold; return period shortening from approximately 10–25 years to 5–10 years; projected intensity increase of +5% to +22%; validation with local observations showing present-day exceedance of 50 mm and daily totals above 70 mm	Provides direct evidence for stormwater management, drainage upgrades, nature-based runoff retention, transport resilience, and early warning
Wildfire risk	General recognition of WUI exposure and climate sensitivity	Population exposure modelling under FWI thresholds; composite fire danger mapping; vulnerability indicators; Pareto-based integrated risk mapping; empirical validation with 2019–2025 local wildfire records	Supports targeted prevention in interface zones, public awareness, seasonal preparedness, fuel management, and integration of wildfire risk into peri-urban land-use planning

Phase 2 therefore introduces a clearer distinction between hazard information and actual risk implications. For river floods, the analysis quantifies direct economic and social impacts. For heavy rainfall, it establishes a direct link between precipitation intensification and urban system disruption, even though direct damage modelling is not included. For wildfires, it integrates fire-weather hazard, burnable vegetation, exposure, vulnerability, and local empirical fire occurrence.

These outputs allow Ruse Municipality to move from general awareness of climate risk towards a more operational understanding of where risk is concentrated, what drives it, and where adaptation intervention is most justified.

Cross-hazard contribution of local data

The local datasets and contextual evidence used in Phase 2 played different but complementary roles across the three priority hazards.

For river floods, official FRMP maps and local historical flood records were used to validate the spatial pattern of modelled flood hazard and to confirm the importance of both the Danube and Rusenski Lom systems. This helped avoid treating flood risk as a single-corridor Danube problem and highlighted the significance of rainfall-driven inland flooding.

For heavy rainfall, local observational precipitation data supported the selection of the 50 mm / 24h disruption threshold and confirmed that high-impact rainfall already occurs under current climate conditions. The local observations also showed strong seasonal and interannual variability, helping to interpret the projected future increase in rainfall intensity and frequency.

For wildfires, local records for 2019–2025 validated the seasonal fire-weather signal, confirmed the dominance of anthropogenic ignition, and identified recurring interface locations such as Sredna Kula, Nikolovo, Basarbovo, Dolapite, and areas near roads and railways. This strengthened the interpretation of wildfire risk as climate-amplified but locally triggered and spatially concentrated.

Across all hazards, stakeholder input confirmed the need for stronger integration of local data, especially regarding drainage capacity, infrastructure condition, damage records, and operational preparedness. This feedback was used not only as a validation layer, but also as a guide for interpreting capacity gaps and identifying adaptation priorities.

From assessment to adaptation: bridge to action

A key function of Phase 2 is to create a clear bridge between climate diagnostics and adaptation planning. By quantifying risks, identifying hotspots, and distinguishing severity, urgency, and resilience capacity, the assessment provides the evidence base for the next phase of the CLIMAAX process.

This progression can be summarized as:

Hazard projections → Local validation → Risk indicators → Spatial hotspots → Risk prioritization → Adaptation pathways → Measures and investment logic

In operational terms, the refinements achieved in Phase 2 support action in several municipal domains:

- **civil protection**, through improved understanding of flood, rainfall, and wildfire preparedness needs;
- **urban planning**, through better integration of floodplains, drainage constraints, WUI zones, and risk hotspots into spatial decisions;
- **infrastructure adaptation**, through clearer identification of exposed assets, drainage bottlenecks, transport vulnerabilities, and service continuity risks;
- **ecosystem and land-use management**, especially in peri-urban, agricultural, and semi-natural areas affected by wildfire and runoff processes;
- **risk communication**, through clearer explanation of thresholds, return periods, future scenarios, and local impacts.

In this sense, the additional assessments based on local models and data are not a separate analytical layer detached from the core CLIMAAX workflow. They strengthen the interpretability, credibility, and practical usability of the workflow outputs.

Uncertainty and traceability

Uncertainty remains associated with climate projections, particularly regarding the magnitude and spatial variability of extreme events at municipal scale. These uncertainties arise from model resolution, scenario assumptions, limited local impact records, and the absence of fully calibrated local impact models for all hazards.

The assessment addresses these uncertainties through:

- use of harmonized CLIMAAX workflows and reproducible Jupyter notebooks;
- comparison of model outputs with official local and regional datasets;
- integration of empirical records for floods, rainfall, and wildfires;
- use of locally justified thresholds where generic indicators would be less informative;
- explicit documentation of assumptions and limitations.

The results should therefore be interpreted as robust directional estimates of risk evolution, not as deterministic forecasts. They are sufficiently reliable to support strategic adaptation planning, prioritization, and identification of measures in Phase 3.

All datasets, models, local evidence, and supporting studies used in the analysis are documented in Section 6, ensuring transparency and traceability of the assessment.

2.4. Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

The Key Risk Assessment step in Phase 2 was implemented as a targeted, expert-based engagement process, aligned with the CLIMAAX Key Risk Assessment protocol. Its purpose was to support the interpretation, comparison, and prioritization of the model-derived and locally validated risk outputs presented in Section 2.3.

Engagement was carried out through structured consultations and technical discussions involving institutional stakeholders and domain experts directly responsible for risk management, planning, infrastructure, civil protection, environmental management, and service delivery in Ruse Municipality. Participants included representatives from relevant municipal departments, including environment, spatial planning, infrastructure, civil protection, and social services, as well as technical experts involved in data provision, analysis, and interpretation.

Given the analytical nature of Phase 2, participation was intentionally focused on actors capable of interpreting quantitative outputs and linking them to operational decision-making. Priority groups were represented indirectly through the involvement of municipal units responsible for social services, civil protection, and urban planning, which integrate considerations related to vulnerable populations and exposed territories identified in earlier stages of the Climate Risk Assessment.

The detailed analyses presented in Section 2.3 provide the quantitative and spatial evidence underpinning the prioritization results. The Key Risk Assessment synthesizes these outputs into decision-relevant indicators, ensuring that prioritization reflects both model-based results and local validation, while maintaining traceability to the datasets, workflows, thresholds, and assumptions used in the assessment.

Table 2.13. Summary of key quantitative risk indicators

Hazard	Key indicator	Current / baseline result	Future / projected change	Interpretation
River floods	Expected Annual Damage (EAD)	Approx. €4.99 million/year	Expected to increase under climate-amplified flood conditions	Persistent annual economic burden and very high-risk priority
Heavy rainfall	Return period of 50 mm/24h event	Approx. 10–25 years	Approx. 5–10 years by mid-century	Disruptive rainfall becomes substantially more frequent
Wildfires	Probability of FWI ≥ 60 and fire-weather season length	Lower but already seasonally concentrated	Increasing probability and longer fire-weather season	Dynamically increasing risk, especially in WUI zones

The CLIMAAX evaluation dashboard served as the central tool for structured review and comparison of risk assessment outputs. Risks associated with the three priority hazards were assessed across the core CLIMAAX evaluation dimensions:

- **Severity** – magnitude of potential impacts on assets, population, infrastructure, ecosystems, and services;
- **Urgency** – likelihood, timing, and expected acceleration of risk under current and future climate conditions;
- **Capacity to respond** – institutional, technical, financial, and operational ability to prevent, absorb, respond to, and recover from impacts.

The dashboard supported a comparative evaluation across hazards and helped participants assess trade-offs and relative priorities in a transparent way. It also made uncertainties explicit, ensuring that assumptions and limitations were discussed rather than remaining implicit in the modelling outputs.

Stakeholder feedback played a direct role in refining the interpretation of the quantitative results. Participants generally confirmed the relevance of the three priority risks — river floods, heavy rainfall, and wildfires — and validated the spatial patterns of hotspots identified through the workflows and local evidence.

Several contextual insights emerged from the engagement process:

- Capacity constraints were consistently emphasized, particularly in relation to ageing infrastructure, limited municipal budgets, fragmented institutional responsibilities, and the need for stronger coordination between departments.
- Heavy rainfall was perceived as particularly urgent because of its frequent occurrence and system-wide effects on urban drainage, transport, mobility, and services.
- River flooding was confirmed as a very high-priority risk because of its potential economic damage, population exposure, displacement effects, and critical infrastructure implications.

- Wildfire risk, while lower than flood-related risks in the overall prioritization, was recognized as increasingly relevant in peri-urban and wildland–urban interface areas, especially under prolonged drought, heat, and anthropogenic ignition pressure.
- Participants stressed the need to align risk prioritization with municipal planning and investment cycles, distinguishing between risks requiring immediate operational measures and those requiring longer-term structural adaptation.

Where differences in perception emerged, particularly regarding urgency and relative ranking of hazards, these were documented and used to clarify assumptions, revisit model outputs, and ensure consistency between analytical results and stakeholder understanding.

The engagement process therefore functioned not only as a validation exercise, but also as a co-interpretation step linking model-based evidence with local operational knowledge. As a result, the final prioritization of risks is based on a triangulated approach integrating:

- quantitative modelling outputs from CLIMAAX workflows;
- spatial analysis of hazard, exposure, and vulnerability;
- local empirical evidence and official datasets;
- stakeholder perception and institutional knowledge, including the questionnaire results presented in Section 2.1.5.

This combined approach ensures that the Key Risk Assessment is analytically robust, locally grounded, and decision-relevant. It also strengthens risk ownership within the municipal administration by involving responsible institutions in the evaluation process and increasing the likelihood that results will be integrated into planning, investment, emergency preparedness, and adaptation measures in Phase 3.

2.4.2 Gather output from Risk Analysis step

The Key Risk Assessment for Ruse Municipality builds on the quantitative and qualitative outputs generated during the Regionalized Risk Analysis step. These outputs provide the evidence base for evaluating the three priority risks across the CLIMAAX dashboard dimensions of severity, urgency, and capacity to respond.

The evidence used for the Key Risk Assessment combines workflow-based outputs with local contextual interpretation. It includes:

- hazard intensity and probability maps for river floods, heavy rainfall, and wildfires under current and future climate conditions;
- exposure layers, including population distribution, residential areas, critical infrastructure, transport networks, economic assets, and peri-urban interface zones;
- vulnerability indicators reflecting social vulnerability, infrastructure sensitivity, ecological sensitivity, territorial characteristics, and institutional constraints;
- composite risk maps and indices integrating hazard, exposure, and vulnerability to identify hotspots and compare relative risk levels;
- scenario-based outputs showing how hazard and risk characteristics are expected to evolve under future climate conditions;
- local validation evidence, including official flood hazard and risk maps, local precipitation observations, local wildfire records, hydrological information, and stakeholder feedback.

In practical terms, the outputs used for the Key Risk Assessment include the following.

For **river floods**, the assessment used return-period-based hazard patterns, flood extent and depth, total building damage by return period, Expected Annual Damage (EAD), Expected Annual Population Exposed (EAPE), Expected Annual Population Displaced (EAPD), critical infrastructure exposure, and validation against official basin-level flood maps and local historical flood evidence.

For **heavy rainfall**, the assessment used changes in rainfall intensity and frequency, return period shifts for the locally justified 50 mm/24h disruption threshold, projected changes in 24-hour rainfall magnitude, multiplicative change factors, local observational precipitation data, and interpretation of impacts on pluvial flooding, urban drainage capacity, transport disruption, and surface runoff.

For **wildfires**, the assessment used Fire Weather Index-based hazard indicators, probability of exceedance of FWI ≥ 60, projected fire-weather season length, population exposure projections, burnable vegetation distribution, WUI-related vulnerability patterns, Pareto-based integrated risk mapping, and local fire records from 2019–2025.

These analytical results were not considered in isolation. They were interpreted together with supplementary local evidence and stakeholder knowledge in order to improve their relevance for Ruse Municipality. This included official local and basin-level flood maps, local precipitation and hydrological observations, empirical wildfire records, municipal territorial characteristics, infrastructure-related information, and feedback on institutional preparedness and data gaps.

The transition from Regionalized Risk Analysis to Key Risk Assessment follows a traceable sequence:

hazard characterization → exposure and vulnerability analysis → local validation → composite risk interpretation → severity / urgency / capacity scoring → final risk prioritization

This sequence ensures that prioritization is not based on generic hazard scores alone, but on a structured interpretation of modelled results, local evidence, stakeholder input, and municipal decision-making needs.

2.4.3 Assess Severity

Severity was assessed for the current and future climate risks in Ruse Municipality using the four CLIMAAX categories: **limited, moderate, substantial, and critical**. The assessment considered the magnitude of potential impacts, frequency of occurrence, spatial extent, potential irreversibility, and the capacity of each hazard to generate cascading effects across municipal systems.

In Ruse Municipality, severity is shaped not only by hazard intensity, but also by the concentration of exposed population, infrastructure, economic assets, and critical services. This is particularly relevant for the Danube corridor, the Rusenski Lom catchment, densely built urban areas, transport infrastructure, and peri-urban interface zones.

Current severity

Under current conditions, **river flooding** is assessed as having **substantial severity**. This reflects the municipality's structural exposure along both the Danube River and the Rusenski Lom system, where residential areas, transport infrastructure, public services, and economic assets are located within or near flood-prone zones. The Phase 2 analysis shows that river flooding already represents a significant economic and social risk, with estimated Expected Annual Damage of approximately €4.99 million, recurrent population exposure, potential displacement, and exposure of critical infrastructure.

Heavy rainfall is assessed as having **moderate severity** under current conditions. Such events already generate pluvial flooding, drainage overload, short-term transport disruption, and pressure on municipal services. However, their impacts are generally more localized and shorter in duration than major river flood events. The local observational data confirm that disruptive rainfall events exceeding 50 mm/24h already occur, but under current conditions their impacts remain mainly operational rather than system-wide.

Wildfires are assessed as having **limited severity** under current conditions. Local records show that wildfire events occur in Ruse Municipality and may affect peri-urban zones, forested areas, agricultural land, and air quality. However, compared with flood-related hazards, current wildfire impacts are less frequent, less spatially extensive, and more localized. The classification as limited does not imply absence of risk, but reflects its lower current severity relative to the other two priority hazards.

Future severity

Under future climate conditions, the severity of all three priority risks is projected to increase.

River flooding is assessed as reaching **critical severity**. This reflects the combined influence of increased precipitation intensity, possible changes in hydrological regimes, and the high concentration of exposed assets in flood-prone zones. Future flood events may generate large-scale economic damage, prolonged disruption of transport and public services, displacement of residents, and cascading impacts on emergency response, utilities, and local economic activity.

Heavy rainfall is projected to increase to **substantial severity**. The Phase 2 assessment indicates that the return period of disruptive 50 mm/24h rainfall events may shorten from approximately 10–25 years under baseline conditions to approximately 5–10 years by mid-century. Rainfall intensity also increases at recurrent return periods. This means that heavy rainfall is expected to become more frequent, more disruptive, and more relevant for urban drainage, transport, surface runoff, and pluvial–fluvial interaction, particularly in the Rusenski Lom system.

Wildfires are projected to increase to **moderate severity**. The Fire Weather Index analysis indicates increasing probability of extreme fire-weather conditions and a lengthening fire season. Although wildfire risk remains lower than flood-related risks in the overall prioritization, future conditions are expected to increase wildfire impacts in peri-urban and wildland–urban interface zones, especially where hot, dry, and windy conditions coincide with anthropogenic ignition sources.

Irreversibility and cascading effects

Severity is also influenced by the potential for long-lasting or cascading impacts. In Ruse Municipality, such impacts may include repeated damage to infrastructure, reduced reliability of transport and public services, disruption of economic activity, environmental degradation, loss of soil and ecosystem quality, and risks to human safety and livelihoods during extreme events.

Flood-related hazards have the strongest cascading potential. River flooding can disrupt transport, utilities, emergency response, public services, and economic activities simultaneously. Heavy rainfall can act both as an independent urban hazard and as a trigger or amplifier of river flooding, especially in smaller catchments and low-lying urban zones. Wildfires have lower current cascading potential, but may increasingly affect air quality, ecosystems, peri-urban settlements, and emergency response capacity under future climate conditions.

Role of stakeholder input

Stakeholder input supported the severity assessment by providing practical evidence on infrastructure vulnerabilities, operational disruptions, exposed areas, and the disproportionate impacts of extreme events on vulnerable groups. Municipal departments, civil protection services, and technical experts generally confirmed the high severity of flood-related risks and the increasing importance of heavy rainfall as a system-wide stressor.

Wildfire risk was perceived as comparatively lower under current conditions, but stakeholders acknowledged its growing relevance under hotter and drier future conditions, particularly in peri-urban areas and forest–settlement interface zones.

Severity classification

Based on the combined assessment of hazard characteristics, exposure, vulnerability, model outputs, local evidence, and stakeholder input, the severity of the three priority risks is classified as follows:

Table 2.14. Risk severity

Risk	Current severity	Future severity	Interpretation
River flooding	Substantial	Critical	Already causes significant economic and social risk; future conditions may generate large-scale disruption and cascading impacts
Heavy rainfall	Moderate	Substantial	Currently operationally disruptive; projected to become more frequent and more intense, increasing urban system stress
Wildfires	Limited	Moderate	Currently localized and less frequent; projected to intensify due to longer fire-weather season and increasing climate stress

Interpretation for decision-making

The severity assessment confirms that flood-related hazards form the dominant risk cluster for Ruse Municipality. River flooding already has substantial severity and is projected to become critical under future climate conditions. Heavy rainfall, although currently moderate, is becoming a more important system-wide stressor because of projected frequency and intensity increases and its role as a flood amplifier.

Wildfire risk remains comparatively lower in severity, but its upward trajectory justifies preventive attention, especially in peri-urban and wildland–urban interface zones. This classification supports a differentiated adaptation logic: immediate and structural action for flood-related risks, and proactive monitoring and prevention for wildfire risk before it escalates further.

2.4.4 Assess Urgency

Urgency was assessed using the CLIMAAX categories: **no action needed, watching brief, more action needed, and immediate action needed**. The assessment considered the timing of impacts, rate of risk escalation, hazard onset, persistence of impacts, response time, and stakeholder input.

For Ruse Municipality, urgency is particularly influenced by the difference between sudden-onset hazards, such as floods and heavy rainfall, and progressively developing hazards, such as wildfire conditions driven by heat, drought, and fuel accumulation. The assessment therefore considers both current operational pressure and projected future escalation.

River flooding

Urgency classification: Immediate action needed

River flooding is assessed as requiring **immediate action** under both current and future conditions. This reflects the combination of substantial current severity, critical future severity, high exposure of population and infrastructure, and the potential for long recovery periods after major events.

The urgency is especially high along the Danube and Rusenski Lom corridors, where flood-prone areas intersect with residential zones, transport infrastructure, economic assets, and critical services. Flood events may develop with limited local response time, particularly in the Rusenski Lom catchment, and can result in prolonged disruption to mobility, public services, emergency response, and economic activity.

This classification is supported by the Phase 2 flood risk results, including Expected Annual Damage of approximately €4.99 million, recurrent population exposure, potential displacement, and exposure of critical infrastructure. Stakeholders also confirmed that flood risk already requires continuous operational management and should remain a leading priority for municipal planning and adaptation.

River flooding therefore requires immediate and continuous action through flood protection, early warning, emergency preparedness, maintenance of critical infrastructure, spatial planning controls, and targeted measures in flood-prone zones.

Heavy rainfall

Urgency classification: More action needed

Heavy rainfall is classified as requiring **more action needed**, with a clearly increasing trend. Although it does not yet reach the same municipality-wide urgency classification as river flooding, it is becoming a rapidly escalating risk, particularly in urban areas with constrained drainage capacity.

This classification reflects moderate current severity, projected substantial future severity, sudden-onset dynamics, and increasing frequency of disruptive rainfall. The Phase 2 analysis shows that the return period of the locally justified **50 mm/24h** disruption threshold may shorten from approximately **10–25 years** under baseline conditions to approximately **5–10 years** by mid-century. This means that disruptive rainfall events are expected to occur substantially more often.

Heavy rainfall has very limited response time once an event begins. Its impacts are often localized, but they can be recurrent and operationally significant, affecting drainage systems, roads, transport corridors, public services, and emergency response. It also acts as a risk amplifier for river flooding, particularly in relation to the Rusenski Lom system and pluvial–fluvial interaction zones.

The urgency classification therefore supports accelerated adaptation, especially for stormwater management, urban drainage upgrades, nature-based runoff retention, transport resilience, maintenance regimes, and improved early warning and response procedures.

Wildfires

Urgency classification: More action needed

Wildfire risk is also assessed as requiring **more action needed**. Current severity remains limited, but future severity is projected to increase to moderate as fire-weather conditions intensify and the fire season lengthens.

Wildfire risk develops through slower-onset processes, including rising temperatures, prolonged dry periods, soil moisture deficit, vegetation desiccation, and fuel accumulation. This provides a wider window for preventive action than flood-related hazards. However, once ignition occurs, spread can be rapid, especially under hot, dry, and windy conditions in peri-urban and wildland–urban interface zones.

The local fire records confirm strong July–August concentration, anthropogenic ignition, and recurrence in interface locations such as Sredna Kula, Nikolovo, Basarbovo, Dolapite, and areas near transport corridors. This means that wildfire urgency is primarily linked to prevention and preparedness rather than immediate structural protection.

The required actions include seasonal prevention campaigns, reduction of anthropogenic ignition sources, fuel and vegetation management, monitoring of fire-weather conditions, improved coordination with fire safety and forestry authorities, and integration of wildfire risk into peri-urban land-use planning.

Cross-hazard dynamics and stakeholder input

All three hazards show persistent and reinforcing risk characteristics. River flooding is structurally persistent due to hydrological and topographical conditions. Heavy rainfall is increasing due to more intense and irregular precipitation patterns. Wildfire risk is shaped by the interaction between climate stress, vegetation condition, and human ignition.

Stakeholder input played an important role in confirming urgency levels. Municipal services and civil protection authorities emphasized the immediate operational pressure associated with flood-related risks and the increasing burden of recurrent heavy rainfall on urban systems. Wildfire risk was perceived as less urgent in current operational terms, but stakeholders recognized the need for systematic prevention in peri-urban areas and recurring ignition zones.

Stakeholders also noted that vulnerable populations in flood-prone areas experience urgency more acutely than aggregate indicators may suggest, reinforcing the prioritization of river flooding and heavy rainfall in adaptation planning.

Table 2.15. Risk urgency

Risk	Urgency classification	Interpretation
River flooding	Immediate action needed	Current risk already requires continuous management; future severity becomes critical and cascading impacts are likely
Heavy rainfall	More action needed	Disruptive events are becoming more frequent and increasingly stressful for drainage, transport, and urban services
Wildfires	More action needed	Risk is dynamically increasing and requires preventive management, especially in WUI zones

Interpretation for decision-making

The urgency assessment supports a tiered adaptation approach for Ruse Municipality. River flooding requires immediate and continuous intervention through structural, planning, and emergency management measures. Heavy rainfall requires accelerated adaptation because it is becoming a high-frequency urban stressor and flood amplifier. Wildfire risk requires proactive prevention before climate change further increases fire-weather danger and interface exposure.

This differentiation ensures that adaptation planning can address immediate operational risks while also preparing for risks whose urgency is increasing under future climate conditions.

2.4.5 Understand Resilience Capacity

The resilience capacity of Ruse Municipality to respond to the three priority climate risks — **river flooding, heavy rainfall, and wildfires** — was assessed using the CLIMAAX categories: **low, medium, substantial, and high**.

The assessment integrates findings from Phase 1, outputs from the Regionalized Risk Analysis, stakeholder input, and contextual socio-economic information, including the Institute for Market Economics regional profile for 2025. Resilience capacity was evaluated across five dimensions: **financial, human, physical, natural, and social capacity**, with attention to the effectiveness, coverage, sustainability, and future adequacy of existing response systems.

The overall resilience capacity by hazard is assessed as follows:

Table 2.16. Resilience capacity

Risk	Resilience capacity	Interpretation
River flooding	Medium	Existing flood protection, warning, and response systems are in place, but infrastructure exposure, maintenance needs, and future climate pressure limit adaptive capacity
Heavy rainfall	Medium	Routine maintenance and emergency response capacity exist, but urban drainage systems remain a major bottleneck under increasing rainfall intensity
Wildfires	Low	Response capacity exists mainly through regional and national structures, while local prevention, interface management, and preparedness remain underdeveloped

This differentiation reflects the fact that flood-related risks benefit from more established institutional and infrastructure systems, while wildfire resilience remains less developed and more dependent on external response structures.

Financial capacity

Financial capacity is assessed as **moderate**, contributing to a medium overall resilience level for flood-related risks. Ruse Municipality benefits from relatively stable local revenues, but available resources are largely committed to mandatory services, maintenance, and ongoing infrastructure needs. This limits flexibility for proactive, long-term climate adaptation investments.

Flood protection, drainage maintenance, and emergency response activities are funded, but often through project-based mechanisms and external national or EU sources. This creates limitations for systematic drainage modernization, large-scale infrastructure adaptation, and long-term preventive investment.

For wildfires, financial capacity is weaker, particularly for preventive landscape management, fuel reduction, interface-zone management, and local preparedness measures.

Human capacity

Human capacity is assessed as **medium**. The municipality has experienced staff in civil protection, infrastructure management, environmental management, and spatial planning. Operational knowledge for flood response and emergency coordination is well established.

However, gaps remain in climate modelling, scenario interpretation, integration of climate projections into planning, and understanding of compound and cascading risks. For wildfire risk, coordination exists with regional fire safety and forestry services, but local preventive planning capacity is still limited.

Overall, the lack of fully institutionalized climate-risk expertise constrains the transition from reactive emergency response to forward-looking adaptation planning.

Physical capacity

Physical capacity differs by hazard.

For **river flooding**, physical capacity is assessed as **medium**. Flood protection infrastructure along the Danube, national warning systems, and emergency response mechanisms are in place. However, critical infrastructure remains exposed in flood-prone zones, and maintenance needs limit long-term effectiveness.

For **heavy rainfall**, physical capacity is also assessed as **medium**, but with important weaknesses. Urban drainage systems are the main bottleneck. Parts of the drainage infrastructure are ageing and not designed for the projected increase in rainfall intensity and frequency. During extreme rainfall events, system overload can lead to pluvial flooding, road disruption, and pressure on emergency services.

For **wildfires**, physical capacity is assessed as **low to medium**. Fire monitoring and suppression systems exist at regional and national level, but local preventive infrastructure, landscape management, and systematic WUI risk reduction are limited.

Natural capacity

Natural capacity is assessed as **medium**. Ruse Municipality benefits from riverine ecosystems, green areas, peri-urban landscapes, and open spaces that provide some buffering capacity through infiltration, shading, retention, and ecological regulation.

However, urbanization, soil sealing, infrastructure expansion, and land-use change reduce natural retention and cooling functions. Existing natural systems are not sufficient to compensate for increasing rainfall intensity, flood pressure, heat, drought, and wildfire susceptibility.

There is significant potential for nature-based solutions, including green infrastructure, flood retention areas, urban greening, cooling corridors, and peri-urban vegetation management, but these are not yet systematically implemented as part of a comprehensive adaptation strategy.

Social capacity

Social capacity is assessed as **medium**. The municipality has functioning social services and emergency support mechanisms, which are important for protecting vulnerable groups during floods, rainfall-related disruptions, and other extreme events.

However, elderly residents, low-income households, residents of flood-prone areas, and people dependent on public services have lower adaptive capacity. Public awareness remains largely reactive and event-driven, rather than preventive. Community-level preparedness, risk communication, and household-level adaptation are still insufficiently developed.

For wildfire risk, public awareness is particularly limited because the hazard has historically been perceived as secondary in the region. This reinforces the need for targeted summer prevention campaigns and communication in peri-urban and interface zones.

Existing and emerging measures

Existing resilience measures include:

- flood protection infrastructure along the Danube;
- emergency response and civil protection systems;
- national early warning and meteorological services;
- routine maintenance of drainage networks;
- regional fire monitoring and suppression capacity.

Planned or emerging measures include:

- infrastructure rehabilitation projects supported through national or EU funding;
- gradual integration of risk considerations into spatial planning;
- exploration of nature-based solutions and green infrastructure;
- improved monitoring and early warning initiatives, including locally relevant systems where available.

While these measures reduce current risk, they remain fragmented, project-driven, and not yet sufficient to address future climate conditions systematically.

Resilience capacity interpretation

The resilience capacity assessment identifies a structural mismatch between increasing climate risks and only moderate or low capacity to respond.

For **river flooding**, medium capacity reflects the existence of established flood protection and emergency systems, but also recognizes the limitations created by exposed infrastructure, financial constraints, and increasing future flood severity.

For **heavy rainfall**, medium capacity reflects operational response mechanisms and routine drainage maintenance, but also highlights the insufficient capacity of urban drainage systems to cope with increasing rainfall intensity and frequency.

For **wildfires**, low resilience capacity reflects the weaker development of local preventive systems, limited WUI management, lower public awareness, and dependence on regional or national suppression capacity.

Implications for decision-making

The resilience capacity assessment shows that current systems are generally sufficient for short-term response, but not yet adequate for long-term adaptation under climate change.

This implies that:

- river flooding requires both immediate action and capacity strengthening, particularly for flood protection, infrastructure resilience, emergency planning, and spatial planning controls;
- heavy rainfall requires systemic adaptation of urban drainage, stormwater management, road infrastructure, and nature-based runoff retention;
- wildfire risk requires development of preventive capacity, including interface-zone management, fuel reduction, public awareness, and stronger coordination between municipal, fire safety, forestry, and infrastructure actors.

Overall, resilience capacity in Ruse Municipality should be strengthened not only through new infrastructure, but also through better data systems, interdepartmental coordination, local monitoring, public communication, and integration of climate risk into routine municipal planning.

2.4.6 Decide on Risk Priority

Risk prioritization in Phase 2 was conducted using the CLIMAAX evaluation dashboard, integrating the results of the assessments of **severity**, **urgency**, and **resilience capacity**. The process followed the CLIMAAX Key Risk Assessment Protocol and was supported by structured discussions with municipal stakeholders and technical experts.

Priority levels were determined based on the combined effect of:

- current and future severity, particularly under projected climate conditions;
- urgency, reflecting the timing, likelihood, and rate of risk escalation;
- resilience capacity, indicating the municipality’s ability to prevent, absorb, respond to, and recover from impacts.

This integrated approach ensures that prioritization reflects not only the potential magnitude of each risk, but also the extent to which Ruse Municipality is prepared to manage it under current and future climate conditions.

Table 2.17. CLIMAAX Dashboard on risk prioritisation

Risk Workflow	Severity		Urgency	Capacity	Risk Priority
	C	F		Resilience/ CRM	
River flooding					Very High
Heavy rainfall					High
Fire					Moderate

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

Risk prioritization outcome

The prioritization results show a clear hierarchy of climate risks for Ruse Municipality.

River flooding is identified as the highest priority risk. It combines substantial current severity, critical future severity, immediate urgency, and only medium resilience capacity. The Phase 2 analysis shows that river flooding can generate significant economic damage, population exposure, displacement, and critical infrastructure disruption. Its potential for cascading impacts across transport, emergency response, utilities, public services, and economic activity places it at the top of the municipal climate risk agenda.

Heavy rainfall is assigned a high priority. Although its current severity is classified as moderate, it is projected to increase to substantial severity under future climate conditions. The return period of disruptive 50 mm/24h rainfall events is projected to shorten from approximately 10–25 years to approximately 5–10 years by mid-century, while rainfall intensity also increases. Heavy rainfall is therefore both a direct urban hazard and a risk amplifier for flooding, particularly through drainage overload, pluvial flooding, transport disruption, and interaction with the Rusenski Lom system.

Wildfire is classified as a moderate-priority risk. Its current severity remains limited, but future severity increases to moderate, and urgency is assessed as "more action needed." Local wildfire records confirm strong summer seasonality, anthropogenic ignition, and recurrence in peri-urban and wildland–urban interface zones. Although wildfire risk remains lower than flood-related risks, it is dynamically increasing under climate change and requires proactive prevention before impacts intensify further.

This prioritization demonstrates that flood-related hazards — river flooding and heavy rainfall — form the dominant risk cluster for Ruse Municipality. At the same time, wildfire should not be treated as negligible, because climate change is expected to increase fire-weather danger and extend the period of exposure.

Table 2.18. Final CLIMAAX logic check

Risk workflow	Hazard description	Affected areas / sectors	Current severity	Future severity	Urgency	Resilience capacity	Capacity justification	Risk priority
River flooding	Flooding caused by high water levels of the Danube River and the Rusenski Lom system, influenced by upstream precipitation, snowmelt, local rainfall, and catchment response	Low-lying urban areas, riverfront zones, industrial areas, transport infrastructure, utilities, residential areas, public services	Substantial	Critical	Immediate action needed	Medium	Flood defenses, warning systems, and emergency response mechanisms exist, but ageing infrastructure, exposed assets, maintenance needs, financial constraints, and limited integration of climate projections reduce long-term adaptive capacity	Very High
Heavy rainfall	Short-duration, high-intensity rainfall exceeding or stressing urban drainage capacity and generating pluvial flooding	Urban road network, residential areas, public buildings, health and social services, drainage systems, transport corridors, low-lying urban zones	Moderate	Substantial	More action needed	Medium	Emergency response and routine drainage maintenance exist, but drainage systems are insufficient for projected increases in extreme rainfall; nature-based solutions and systematic stormwater adaptation are not yet fully implemented	High
Wildfire	Vegetation and forest fires driven by high temperatures, drought, wind, fuel availability, and human ignition sources	Forested areas, peri-urban zones, agricultural land, wildland–urban interface areas, biodivers	Limited	Moderate	More action needed	Low	Fire monitoring and response capacity exists mainly through regional and national systems, but local prevention, landscape management, WUI risk	Moderate

		ity, air quality, transport corridors					reduction, public awareness, and climate-adaptive planning remain limited	

Final synthesis for decision-making

The CLIMAAX-based prioritization confirms that **river flooding requires immediate and continuous intervention**, combining structural protection, spatial planning controls, maintenance, early warning, and emergency preparedness.

Heavy rainfall requires accelerated adaptation, particularly in urban drainage, stormwater management, transport resilience, surface runoff control, and nature-based retention measures. Its role as a flood amplifier makes it especially important for integrated planning.

Wildfire risk requires proactive and preventive management, with a focus on peri-urban and wildland–urban interface zones, fuel management, reduction of anthropogenic ignition sources, seasonal awareness campaigns, and coordination with fire safety and forestry authorities.

The prioritization provides a clear evidence base for Phase 3, where adaptation options will be identified and evaluated. It supports the alignment of resources and actions with the most critical and actionable risks, strengthening climate risk governance and adaptation planning in Ruse Municipality.

2.5. Monitoring and Evaluation

Phase 2 of the Climate Risk Assessment significantly improved the understanding of how the three priority risks in Ruse Municipality — **river flooding, heavy rainfall, and wildfires** — develop, interact, and translate into impacts on infrastructure, population, public services, ecosystems, and economic activity.

A key finding is that flood-related risks are systemic and interdependent. Heavy rainfall and river flooding reinforce each other through pluvial–fluvial interactions, particularly in low-lying urban areas, drainage-constrained zones, and the Rusenski Lom catchment. These interactions can generate cascading impacts on urban drainage systems, transport networks, critical infrastructure, emergency response, and public services. This systemic character supports the classification of river flooding as **Very High priority** and heavy rainfall as **High priority** in Section 2.4.

The structured application of the CLIMAAX Key Risk Assessment Protocol improved transparency in risk prioritization and supported a more consistent interpretation of risk across municipal departments and technical experts.

Key implementation challenges

Several constraints affected the assessment process:

- limited availability of high-resolution local data, particularly for urban drainage capacity, infrastructure condition, and recorded damage;
- fragmented data ownership across institutions, limiting systematic data integration;

- difficulties in translating technical outputs, such as return periods, probabilistic indicators, and Fire Weather Index metrics, into actionable information for non-technical decision-makers;
- time and resource limitations, which restricted the depth of stakeholder engagement and local validation.

These challenges were addressed through triangulation of CLIMAAX workflow outputs with local empirical evidence, including official flood maps, local precipitation information, wildfire records for 2019–2025, stakeholder consultation results, and explicit documentation of assumptions and uncertainties.

Role of stakeholders in monitoring and evaluation

Stakeholders play a central role in ensuring that climate risk assessment results are usable, operational, and relevant for decision-making. Municipal departments, civil protection services, infrastructure operators, and technical experts contributed to:

- validating hazard relevance and spatial risk patterns;
- interpreting impacts on critical systems and vulnerable areas;
- identifying practical constraints in response and adaptation capacity;
- highlighting data gaps and monitoring needs.

Stakeholder feedback confirmed the high relevance of flood-related risks and the need for stronger integration of local datasets, particularly on drainage capacity, infrastructure condition, and damage records. This feedback directly informed the prioritization logic in Section 2.4 and the proposed monitoring framework below.

Learning and iterative improvement

The Climate Risk Assessment is treated as an iterative and adaptive process rather than a one-off analysis. Learning is ensured through:

- refinement of workflows between Phase 1 and Phase 2;
- integration of new datasets and local knowledge;
- feedback loops between modelling, stakeholder validation, and decision-making;
- documentation of uncertainties and data limitations.

Phase 2 improved the use of EURO-CORDEX projections, Copernicus datasets, official flood hazard and risk maps, wildfire statistics, local precipitation evidence, and CLIMAAX-derived risk indicators. At the same time, it highlighted critical data gaps requiring future attention, including:

- high-resolution rainfall and runoff data;
- urban drainage capacity and performance information;
- systematic recording of damage and losses;
- spatially explicit vulnerability indicators;
- stronger monitoring of peri-urban wildfire interface zones.

Monitoring approach and institutional integration

Ruse Municipality does not yet operate a fully integrated climate risk monitoring system. However, several existing mechanisms provide a functional baseline, including emergency management and civil protection systems, national meteorological early warning, infrastructure monitoring and maintenance systems, and emerging local monitoring initiatives.

Building on these mechanisms, Phase 2 establishes a pragmatic monitoring framework aligned with the identified priority risks. Monitoring should focus on:

- hazard evolution, including the frequency and intensity of extreme rainfall, flood events, and wildfire-conducive conditions;
- impact indicators, including flood incidents, drainage failures, transport disruption, burned area, and affected infrastructure;
- exposure and vulnerability trends, including population and critical assets located in risk-prone zones;
- institutional capacity indicators, including early warning integration, staff training, data-sharing, and uptake of risk information into planning;
- effectiveness of adaptation measures to be identified and developed in Phase 3.

In line with the CLIMAAX approach, reassessment of key risks is recommended every **5–10 years**, and after major climate-related events. High-priority risks, especially river flooding and heavy rainfall, should be monitored more frequently through operational municipal and national data sources.

Communication and use of results

The results of the Climate Risk Assessment will be communicated through structured technical reports, risk maps, summary tables, stakeholder consultations, and integration into municipal planning and policy documents.

Communication should be tailored to different audiences:

- technical users require detailed analysis, datasets, assumptions, and methodology;
- decision-makers require summarized priorities, implications, and investment relevance;
- public stakeholders require clear and accessible messages about risks, preparedness, and expected future changes.

A key improvement need identified during the stakeholder process is clearer communication of future risk scenarios, uncertainty, and the practical meaning of technical indicators such as return periods, EAD, FWI thresholds, and rainfall disruption thresholds.

Overall impact of Phase 2

Phase 2 strengthened institutional awareness of climate risks, improved shared understanding across departments, enabled evidence-based prioritization, and increased readiness to support adaptation planning, investment decisions, and future funding applications.

Despite data and resource constraints, the assessment achieved a clear shift from descriptive analysis in Phase 1 to decision-oriented risk evaluation in Phase 2. The monitoring framework below translates the priority risks into measurable indicators linking hazard dynamics, impacts, exposure, vulnerability, and institutional capacity.

Table 2.19. Monitoring and Evaluation Framework – Municipality of Ruse

Indicator category	Indicator	Measure / unit	Baseline / observed situation	Monitoring target / approach	Data source / frequency
Heavy rainfall	Extreme rainfall events	mm per event, 24h	115–155 mm in 24–31 h recorded during October 2025 events, exceeding the monthly norm of approx. 57 mm	Track frequency of events above 50 mm/24h and 80 mm/24h	NIMH precipitation records / Annual
Heavy rainfall	Localised pluvial flooding	Number of incidents	Multiple local floods and road inundations during October 2025	Maintain or reduce incident trend relative to recent baseline	Municipal incident reports / Quarterly
Heavy rainfall	Severe rainfall warnings	Number of warning days, e.g. Orange Code	Several Orange Code warnings issued in October 2025	Ensure timely early warning and post-event documentation for all severe rainfall events	NIMH warning archive / Seasonal
River flooding	Urban drainage failures	Number of documented failures	Blocked drains, surcharge, and drainage overload reported during flood episodes	Progressive reduction through maintenance and adaptation planning	Municipal infrastructure records / Quarterly
River flooding	Transport disruption due to flooding	Number of incidents	Roads blocked and vehicles stranded during flood episodes	Reduce disruption below recent baseline	Traffic and emergency logs / Quarterly
Wildfires	Fire incidents	Number of incidents	Approx. 26 local fire incidents reported in September 2025, including smaller events	Maintain or reduce incidents relative to recent baseline	Fire brigade records / Annual
Wildfires	Burned area	ha / decares	Approx. 0.55 ha affected in September 2025 local incidents; larger historical events recorded in 2019–2025 dataset	Track annual burned area and identify recurrent hotspots	Fire service reports / Annual
Wildfires	Regional wildfire exposure	Number / area affected	17 forest fires in North-Eastern Bulgaria affecting approx. 1,290 ha in 2024	Integrate regional wildfire risk trends into local prevention planning	Forestry and regional data / Annual
Vulnerability and exposure	Population in risk-prone zones	Number of residents	More than 100,000 residents in the core urban area, with exposed groups in flood-prone and drainage-sensitive zones	Reduce exposure through planning, protection, and targeted preparedness	Census, population grids, municipal risk maps / 5–10 years
Vulnerability and exposure	Critical infrastructure at risk	Count / type	Roads, bridges, transport corridors, utilities, and service facilities affected or potentially exposed	Regular update of exposed assets and risk screening	Municipal asset inventory / Annual

Institutional capacity	Early warning integration	Yes / No; qualitative status	Warnings issued, but integration into planning and operational protocols remains incomplete	Strengthen cross-departmental use of warning information	Administrative reporting / Annual
Institutional capacity	Climate risk training	Number of sessions	Limited training, mainly involving technical units	At least one climate risk training or coordination session per year	HR and training records / Annual
CRA performance	Stakeholder engagement	Number of events / consultations	Multiple consultations and questionnaire-based stakeholder engagement conducted	At least two engagement activities per CRA cycle	Project records / Per phase
CRA performance	Quality and validation of risk outputs	Yes / No; qualitative feedback	Flood, heavy rainfall, and wildfire risk outputs produced and reviewed	Validation by stakeholders and technical experts	CRA dashboard and project records / Per phase
CRA performance	Uptake into planning	Yes / No; number of documents	Preliminary discussions ongoing	Formal inclusion of climate risk results in at least two planning or policy instruments	Planning documents / 5–10 years
CRA performance	Risk communication clarity	Qualitative feedback	Need for clearer future scenarios and uncertainty communication identified	Improve clarity of maps, indicators, and public-facing messages in the next cycle	Stakeholder surveys / Per phase

The indicators above are designed to support iterative monitoring of priority climate risks and institutional capacity in Ruse Municipality. They build on existing data sources and operational practices and should be updated as new local datasets, monitoring systems, and adaptation measures become available.

2.6. Work plan Phase 3

Objective of Phase 3

The objective of Phase 3 is to translate the prioritized climate risks identified in Phase 2 into a structured set of feasible, targeted, and locally applicable adaptation options for Ruse Municipality.

Building on the Key Risk Assessment in Section 2.4, Phase 3 will focus on the three prioritized risks:

- **Very High priority:** river flooding;
- **High priority:** heavy rainfall / extreme precipitation;
- **Moderate priority:** wildfires.

Phase 3 shifts the work from risk characterization to action-oriented adaptation planning. Proposed measures will be directly linked to quantified hazard and risk indicators, identified spatial hotspots, stakeholder feedback, and institutional capacity constraints.

The overall aim is to support evidence-based municipal decision-making, particularly in spatial planning, infrastructure investment, stormwater and flood risk management, civil protection, land-use management, and disaster risk reduction.

Main activities

Activity 3.1 Prioritization of key climate risks and affected systems

Building on the Phase 2 risk analysis and CLIMAAX dashboard results, the project team will confirm and operationalize the established risk hierarchy:

- river flooding — Very High priority;
- heavy rainfall — High priority;
- wildfires — Moderate priority.

The activity will refine the identification of priority systems and sectors based on spatial risk patterns, model outputs, local validation, and stakeholder input. Particular attention will be given to:

- urban areas and residential zones exposed to pluvial and fluvial flooding;
- transport and logistics infrastructure along the Danube corridor;
- drainage systems, utilities, and critical infrastructure;
- public services, health, and social support systems;
- peri-urban, agricultural, and semi-natural areas exposed to wildfire risk;
- wildland–urban interface zones with recurrent ignition or exposure patterns.

This activity will ensure that adaptation planning is risk-driven, spatially targeted, and focused on systems where impacts are most significant, recurrent, or likely to increase under future climate conditions.

Activity 3.2 Identification of potential adaptation measures

For each priority risk and affected system, a portfolio of adaptation measures will be identified. The process will draw on:

- CLIMAAX Toolbox outputs and guidance;
- EU and national adaptation frameworks;
- relevant examples from comparable Danube, riverine, and peri-urban regions;
- local expert knowledge and stakeholder input.

Each measure will be explicitly linked to:

- the relevant hazard driver, such as river flooding, heavy rainfall, or fire-weather conditions;
- the affected system, such as drainage infrastructure, transport corridors, exposed settlements, or WUI zones;
- the risk component addressed: hazard, exposure, vulnerability, or resilience capacity.

Potential measures may include:

- structural measures, such as flood protection, drainage upgrades, and infrastructure reinforcement;
- nature-based solutions, such as retention areas, green infrastructure, permeable surfaces, cooling and runoff-reduction measures;
- planning and regulatory tools, such as risk-informed zoning, development restrictions in exposed areas, and WUI management;

- institutional and operational measures, such as early warning, emergency preparedness, maintenance protocols, interdepartmental coordination, and public communication.

Activity 3.3 Feasibility and relevance screening

The identified measures will be screened against practical criteria to ensure that the final portfolio is implementable at municipal level. The screening will consider:

- technical feasibility;
- financial viability and potential funding sources;
- institutional capacity and governance requirements;
- alignment with existing municipal plans, strategies, and regulatory frameworks;
- expected effectiveness under future climate conditions;
- co-benefits, including environmental, social, health, and economic benefits;
- possible implementation barriers and maintenance needs.

This step will translate a broad list of adaptation options into a shortlist of realistic, actionable, and locally relevant measures.

Activity 3.4 Linking risk assessment to adaptation planning

A core principle of Phase 3 is to ensure full traceability between Phase 2 results and proposed adaptation measures. Each option will be explicitly linked to:

- specific risk findings, such as EAD hotspots, return period shortening, drainage pressure, population exposure, WUI risk, or FWI threshold exceedance;
- affected spatial areas, systems, or population groups;
- relevant capacity gaps identified in Section 2.4.5;
- stakeholder priorities and data needs identified in Section 2.1.5.

This will ensure that adaptation planning is evidence-based, transparent, and consistent with both the quantitative assessment and local operational knowledge.

Scope limitations

Phase 3 focuses on strategic-level planning, prioritization, and preparation for future implementation. It does not include:

- detailed engineering design of adaptation measures;
- project-level cost–benefit analysis or financial modelling;
- procurement preparation;
- implementation planning at contractor or construction level.

These elements fall outside the scope of the CLIMAAX process and require additional technical studies, detailed design work, dedicated investment planning, and separate financing procedures.

The purpose of Phase 3 is therefore to provide a decision-ready foundation for adaptation, not full project preparation.

Expected outputs of Phase 3

The final outputs of Phase 3 will include:

- a prioritized portfolio of adaptation options for Ruse Municipality;
- a clear link between risks, affected systems, adaptation measures, and expected benefits;
- identification of short-, medium-, and long-term implementation pathways;
- recommendations for integration into municipal planning, investment, and policy processes;
- inputs suitable for future funding applications under EU, national, and other financing instruments.

The outputs will be suitable for integration into:

- municipal development plans;
- spatial planning instruments;
- disaster risk reduction and civil protection planning;
- infrastructure and stormwater management programmes;
- environmental and land-use strategies;
- future project pipelines and funding applications.

Strategic relevance

Phase 3 will ensure that the Climate Risk Assessment process delivers operational value for Ruse Municipality. It will support the transition from risk identification and analysis towards practical climate risk management.

In strategic terms, Phase 3 will help the municipality to:

- align climate adaptation with planning and investment cycles;
- strengthen prioritization of infrastructure and resilience investments;
- improve coordination between municipal departments and external institutions;
- support access to EU and national funding instruments;
- improve long-term climate resilience governance;
- create a stronger basis for implementing targeted, evidence-based adaptation measures.

3. Conclusions Phase 2- Climate risk assessment

Main conclusions

Phase 2 of the CLIMAAX Climate Risk Assessment for Ruse Municipality achieved a clear transition from the broad risk screening undertaken in Phase 1 towards a more quantified, spatially explicit, locally validated, and decision-relevant risk assessment.

The assessment confirms that climate risks in Ruse Municipality are systemic and interdependent. They are shaped by the interaction of:

- climate hazards, including precipitation extremes, river flood dynamics, and fire-weather conditions;
- spatial exposure, especially in urban areas, flood-prone corridors, critical infrastructure zones, and peri-urban interface areas;
- vulnerability factors, including ageing infrastructure, drainage limitations, socio-economic sensitivity, and institutional capacity constraints.

A key conclusion is that flood-related risks dominate the municipal climate risk profile. **River flooding** is classified as a **Very High priority risk**, with severity increasing from substantial under current conditions to critical under future conditions, and with urgency assessed as requiring immediate action. **Heavy rainfall** is classified as a **High priority risk**, supported by clear evidence of increasing frequency and intensity, including the shortening of return periods for 50 mm/24h events from approximately 10–25 years to approximately 5–10 years by mid-century. **Wildfire** is classified as a **Moderate priority risk**, with current severity assessed as limited and future severity increasing to moderate, particularly in peri-urban and wildland–urban interface zones.

The analysis also demonstrates that heavy rainfall acts as a system-wide risk driver. It affects the wider urban territory, places pressure on drainage and transport systems, and can amplify river flood risk through pluvial–fluvial interactions, especially in relation to the Rusenski Lom system.

Overall, Phase 2 confirms that climate risks in Ruse Municipality are expected to increase in frequency, intensity, and systemic impact, particularly affecting urban infrastructure, drainage systems, transport and economic corridors, public services, and vulnerable population groups.

Key findings

The most important analytical outcomes of Phase 2 are:

- **Risk prioritization with quantified evidence:** river flooding is ranked as Very High priority, heavy rainfall as High priority, and wildfire as Moderate priority.
- **Clear climate signal for hazard intensification:** the analysis shows increased extreme rainfall intensity, shortening of return periods for disruptive precipitation events, increasing probability of extreme fire-weather conditions, and lengthening of the fire-weather season.
- **Improved spatial understanding of risk:** flood risk is concentrated along the Danube and Rusenski Lom corridors; heavy rainfall affects municipality-wide urban and peri-urban systems; wildfire risk is concentrated in wildland–urban interface areas and locations with recurring anthropogenic ignition.
- **Identification of key vulnerability drivers:** ageing drainage and infrastructure systems, high surface sealing in urban areas, exposed transport and service infrastructure, vulnerable population groups, and limited integration of climate risk into planning processes.
- **Evidence of multi-hazard and cascading effects:** heavy rainfall amplifies river flooding; infrastructure disruption can propagate across transport, utilities, emergency response, and

public services; wildfire risk is linked to drought, heat stress, fuel availability, and human ignition.

- **Validation through stakeholder input and local evidence:** stakeholder consultation confirmed the relevance of the three selected hazards, highlighted heavy rainfall as a particularly urgent and system-wide risk, and identified key data gaps, especially in drainage capacity, infrastructure condition, and systematic damage records.

Challenges addressed and remaining gaps

Phase 2 addressed several important methodological and practical challenges:

- transition from qualitative screening to quantitative and scenario-based risk analysis;
- integration of CLIMAAX workflows with local and regional evidence, including official flood maps, local precipitation observations, wildfire records, and stakeholder feedback;
- application of a consistent multi-risk framework across river flooding, heavy rainfall, and wildfires;
- establishment of a transparent prioritization process using the CLIMAAX dashboard;
- clearer linkage between hazard, exposure, vulnerability, risk indicators, and decision-making needs.

Several limitations remain:

- limited availability of high-resolution local datasets, especially for urban drainage capacity, infrastructure condition, runoff dynamics, and systematic damage records;
- uncertainty associated with regional climate projections, particularly for extreme events at municipal scale;
- absence of fully locally calibrated impact models for all hazards;
- limited temporal coverage of some local empirical datasets;
- constrained time and resources for broader stakeholder engagement.

These limitations have been explicitly documented in the assessment. They do not invalidate the results, but they indicate priorities for future monitoring, data collection, model refinement, and institutional capacity-building.

Overall assessment

Phase 2 represents a substantial methodological and analytical advancement compared to Phase 1. It provides quantified and spatially explicit risk information, a transparent prioritization of climate risks, and traceable links between hazard dynamics, exposure, vulnerability, local validation, and municipal decision-making.

The assessment establishes a decision-ready evidence base for:

- targeted adaptation planning;
- prioritization of investments;
- integration of climate risks into spatial, infrastructure, environmental, and disaster risk management policies;
- preparation of future funding applications and project pipelines.

The results provide a coherent basis for Phase 3, where the prioritized risks will be translated into feasible, locally appropriate, and evidence-based adaptation measures aligned with the strategic needs of Ruse Municipality.

4. Progress evaluation

Table 4.1 Overview key performance indicators

Key performance indicators	*Progress*
1 climate multirisk assessment report published – by the end of month 16	Completed
workshop with stakeholders – by the end of month 15	Completed
international workshop for sharing of experience and best practices – by mid-2025	Completed

Table 4.2 Overview milestones

Milestones	*Progress*
M5: Completion of Data Collection and Research for Multi-Risk Assessment (Activity 2.1 & 2.2)	Completed
M6: Stakeholder workshop on multi-risk assessment (Activity 2.3) by the end of month 15	Completed - 16.01.2026
M7: Attend the CLIMAAX workshop held in Barcelona – by mid-2025	Completed - 09.06.2025 -12.06.2025
M8: Submission of Multi-Risk Assessment Report (Activity 2.4) by the end of month 16	Completed - 19.01.2026

5. Supporting documentation

CLIMAAX Jupyter Notebooks for the priority risks:

- River Floods
- Heavy Rainfall
- Wildfires

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National and municipal data sources (Bulgaria)

- Executive Agency for Exploration and Maintenance of the Danube River – hydrological data and river management information.
- Integrated Municipal Development Plan (IMDP) of Ruse Municipality (latest available).
- National Institute of Meteorology and Hydrology (NIMH), Bulgaria – precipitation records, warning systems, and climate data.
- National Statistical Institute (NSI), Bulgaria – population and socio-economic data.
- Regional Directorate “Fire Safety and Civil Protection” – Ruse – wildfire records (2019–2025).
- Regional Inspectorate of Environment and Water (RIEW – Ruse) – environmental monitoring data.
- Ruse Municipality – infrastructure inventories, spatial planning documents, emergency records, and local development plans.