CLIMAAX
climate ready regions

Deliverable Phase 1 – Climate risk assessment

STRENGTHENING TRNAVA'S CLIMATE RESILIENCE THROUGH ADVANCED RISK ASSESSMENT AND ADAPTATION STRATEGIES

(TRACAP)

Slovakia, Trnava city

Version 2.0 | May 2025

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

Funded by
the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101093864. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Document Information

Deliverable Title	Phase 1 – Climate risk assessment
Brief Description	
Project name	**STRENGTHENING TRNAVA'S CLIMATE RESILIENCE THROUGH ADVANCED RISK ASSESSMENT AND ADAPTATION STRATEGIES**
Country	Slovakia
Region/Municipality	Trnava region
Leading Institution	City of Trnava
Author(s)	• Ladislav Glinda (City of Trnava) • Roman Výleta (Slovak technical university)
Deliverable submission date	2/9/2025
Final version delivery date	2/9/2025
Nature of the Deliverable	R – Report
Dissemination Level	PU - Public

Version	Date	Change editors	Changes
1.0	2/9/2025	City of Trnava	Deliverable submitted
2.0	…	CLIMAAX's FSTP team	Review completed
5.0	…		Final version to be submitted

2.9.20

Table of contents

List of figures

List of tables

Abbreviations and acronyms

Abbreviation / acronym	Description
API	Application Programming Interface
AWC	Available Water Capacity
CCA	Copernicus Climate Atlas
CDS	Copernicus Climate Data Store
CRA	Climate Risk Assessment
EEA	European Environmental Agency
ET0	Soil standard evapotranspiration
ETa	Actual crop evapotranspiration
ETc	Crop standard evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model
IROP	Integrated Regional Operational Programme
KVHK	Katedra vodného hospodárstva krajiny (Department of Land and Water Resources Management)
LST	Land Surface Temperature
MTT	Mestská televízia Trnava (Trnava local television)
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RP	Return Period
SHMU	Slovak Hydrometeorological Institute
STU	Slovak University of Technology
SVP	Slovenský vodohospodársky podnik (Slovak Water Management Enterprise)
ZZS SR	*Záchranná zdravotná služba slovenskej republiky (Emergency Medical Operations Centre of Slovakia)*

Executive summary

This deliverable presents the results of Phase 1 of the Climate Risk Assessment (CRA) for the City of Trnava within the CLIMAAX project. The assessment addresses climate-related risks, especially urban heatwaves and droughts, which increasingly affect Trnava's infrastructure, population, and ecosystems. The goal was to establish a transparent baseline using harmonized methods and datasets from the CLIMAAX Toolbox while preparing the ground for future integration of local knowledge.

The CRA was developed jointly by the City of Trnava and experts from the Slovak University of Technology (STU). Heatwave and drought workflows from the CLIMAAX Toolbox were implemented using pan-European datasets (e.g. Euro-CORDEX (Jacob et al., 2013), Land Surface Temperature (LST) RSLab , WorldPop, precipitation and evapotranspiration data). This enabled consistent risk comparison at city and regional scales and the identification of vulnerable areas and potential economic impacts.

Key findings include:

- A projected increase in heatwave days of over 180% under RCP 4.5 and 240% under RCP 8.5 for 2036–2065, with hotspots in residential and industrial zones. Scenarios were based on the EuroHEAT workflow (CDS, 2019; WHO, 2009).
- A calculated yield losses of 30–42% for maize and 30–42% for wheat in 2036–2065 due to precipitation deficits. This equates to annual revenue losses of €160,000–320,000 for maize and €50,000–120,000 for wheat per growing season per 12×12 km grid cell (depending on GCM–RCM choice). The selected crops are the most frequent in the Trnava region (Agricultural Cooperative Trnava).
- Preliminary heat risk maps combining LST and vulnerable population data reveal localized zones where targeted adaptation (e.g., greening, cooling shelters) should be prioritized.
- The initial drought analysis identified not only agricultural vulnerabilities, but also potential stress on urban greenery, which will be a key focus in the next phases.
- Early stakeholder engagement validated the relevance of the results, but highlighted the need for clearer interpretation, localized outputs, and integration with planning practices.

Phase 1 demonstrates the applicability of CRA methods in a Central European urban setting and provides a foundation for Phases 2 and 3, where local data, stakeholder co-development, and integration into planning will be emphasized. Results also underline the transferability of the CLIMAAX Toolbox to other medium-sized European cities, supporting knowledge sharing and scaling up adaptation practices.

To summarize Trnava is highly exposed to future climate risks, especially heat and drought. The CRA has delivered actionable insights and identified priority areas for adaptation, including urgent heat mitigation in residential and industrial zones, improved water management for agriculture and urban greenery, and stronger integration of evidence into city planning. The outcomes serve both as a baseline for updating Trnava's adaptation strategy and as a pilot for replicable risk assessments in other Slovak and European cities, ensuring direct local benefits while strengthening the overall impact of the CLIMAAX project.

Introduction

1.1 Background

The city of Trnava, located in western Slovakia, is a historic urban center situated in the Danubian Lowland, one of the warmest and driest regions in the country (Trnava adaptation strategy, 2015). With a population of approximately 62 508 inhabitants (Trnava description), Trnava is an important regional hub for industry, services, education, and culture. It lies within commuting distance of Bratislava and is part of a rapidly urbanizing corridor that is increasingly exposed to environmental and climatic pressures.

Trnava's geographic and climatic conditions make it particularly vulnerable to climate-related hazards, especially heatwaves and droughts. The urban fabric is characterized by densely built-up residential zones, large industrial areas, and relatively limited green infrastructure in some neighborhoods. These characteristics, combined with observed climate trends, have led to a growing concern about urban overheating, the decline of vegetation health, and reduced agricultural productivity in the surrounding peri-urban areas.

Although the city adopted a local adaptation strategy in 2015, this document is now outdated and lacks detailed spatial risk assessments, integration of updated climate scenarios, and effective stakeholder engagement mechanisms required for effective long-term adaptation planning. Furthermore, the city does not have a dedicated climate adaptation department or specialized technical staff, and coordination across municipal departments remains limited.

Recognizing these challenges, Trnava joined the CLIMAAX project to enhance its capacity for climate risk governance. The CLIMAAX initiative offers a harmonized methodology, analytical tools, and financial support for conducting detailed CRAs that align with both EU and national adaptation objectives. Through this project, Trnava aims to update its adaptation strategy based on transparent, science-based assessments and to engage local stakeholders in the co-development of sustainable, targeted climate resilience actions. In doing so, the city seeks not only to strengthen its local adaptive capacity, but also to serve as a model for other medium-sized European cities facing similar challenges.

1.2 Main objectives of the project

The main objective of the CLIMAAX project in Trnava is to modernize the city's climate adaptation strategy by implementing a structured, evidence-based CRA using the CLIMAAX Handbook and Toolbox. This process seeks to fill critical knowledge gaps in the city's risk governance framework and to provide spatially explicit, stakeholder-relevant information that supports informed and timely adaptation planning. Ultimately, it aims to strengthen the city's adaptive capacity and ensure that climate resilience becomes an integral part of Trnava's long-term development vision.

Trnava faces two primary climate-related hazards—urban heatwaves and agricultural and ecological droughts—both of which are projected to intensify in the coming decades due to climate change. The city's current strategy lacks the technical capacity and local data integration needed to properly address these risks. The CLIMAAX methodology enables a harmonized approach to hazard, exposure, and vulnerability analysis, while also ensuring the flexibility to incorporate local knowledge and expert validation.

Specific objectives of the project include:

- Applying the CLIMAAX Toolbox workflows for heatwave and drought risk to generate reproducible and transparent CRA outputs for Trnava.

- Identifying high-risk areas in the city using satellite-based hazard mapping (e.g., LST) and population vulnerability data.
- Quantifying economic impacts from climate-related drought on regional agriculture, particularly maize and wheat (Agricultural Cooperative Trnava), using precipitation deficit and evapotranspiration models.
- Involving key stakeholders (municipality, NGOs, academia, farmers, health services) to ensure the results are relevant, interpretable, and embedded in local planning frameworks.
- Laying the groundwork for an updated adaptation strategy, including guidelines for identifying priority adaptation zones and selecting suitable measures (e.g., urban greening, water retention, cooling shelters).

Expected benefits of applying the CLIMAAX Handbook:

- Establishment of a standardized yet flexible CRA framework aligned with EU and national adaptation strategies.
- Increased technical capacity within the city administration through exposure to structured workflows and expert support.
- Stronger evidence base for public investment decisions and integration of climate risk into spatial planning, infrastructure design, and land use policies.
- Improved stakeholder coordination across departments and sectors, fostering shared ownership of climate risk management.
- Preparation of Trnava for accessing future EU funding for adaptation, green infrastructure, and nature-based solutions by demonstrating a clear risk assessment process.

By the end of the project, Trnava will have a clearer understanding of its current and future climate risks and will be equipped with the tools, data, and stakeholder engagement processes needed to implement and sustain effective climate resilience measures. This will not only update the city's adaptation strategy but also provide a replicable model for evidence-based climate risk governance across the region.

1.3 Project team

The CLIMAAX project in Trnava is jointly implemented by the City of Trnava and the Slovak University of Technology in Bratislava (STU). The cooperation between the municipal administration and the academic partner ensures that the Climate Risk Assessment (CRA) is both technically sound and aligned with local planning needs. The project team combines municipal coordination capacities with scientific and technical expertise in climate risk analysis.

City of Trnava

The City Office of Trnava serves as the lead institution for the project, coordinating administrative, strategic, and planning efforts. The municipal team includes:

- Ing. Ladislav Glinda – Head of the Department of Investment Construction. He oversees the integration of climate risk considerations into municipal construction and infrastructure projects.
- Ing. Monika Pavelková – Department of Strategic Planning and Project Management. She is responsible for aligning CRA outputs with local development strategies and managing interdepartmental coordination.

Slovak University of Technology (STU)

The Department of Land and Water Resources Management at the Faculty of Civil Engineering (KVHK), STU Bratislava, was subcontracted by the City of Trnava to provide scientific and technical support for the project. STU was responsible for:

- Implementing and customizing the CLIMAAX Toolbox workflows (heatwave and drought risk) (CLIMAAX GitHub, 2025), (Phase1-2).
- Processing high-resolution geospatial and climate datasets (Phase1-2).
- Conducting spatial risk analyses and data interpretation tailored to Trnava's local context, (Phase 1-2).
- Supporting stakeholder engagement through the preparation of maps, summaries, and workshop materials (Phase 1-2).
- Ensuring methodological consistency with the CLIMAAX Handbook (CLIMAAX Handbook, 2025) and Toolbox and providing all outputs in formats accessible to local planners and decision-makers (Phase 1-2).

This close collaboration between the City of Trnava and STU created a foundation for building local capacity, improving technical understanding of climate risks, and preparing for the next phases of adaptation strategy development (Phase 3).

1.4 Outline of the document's structure

This deliverable is structured according to the CLIMAAX Handbook and the official M6 reporting template. It documents the outcomes of Phase 1 of the Climate Risk Assessment (CRA) conducted for the city of Trnava, focusing on the two most pressing hazards: heatwaves and droughts.

- **Section 1 – Introduction** provides background information on the city, outlines the main objectives of the project, introduces the project team, and explains how the document is organized.
- **Section 2 – Climate Risk Assessment – Phase 1** forms the core of the report and follows the CLIMAAX methodological steps:
  - *Scoping:* definition of project goals, regional context, stakeholder involvement, and known limitations.
  - *Risk Exploration:* identification and justification of key climate hazards based on local and European data.
  - *Risk Analysis:* technical application of the CLIMAAX Toolbox workflows for heatwave and drought, including data sources, processing methods, and key outputs.
  - *Preliminary Findings:* assessment of the severity, urgency, and local capacity for each hazard.
  - *Monitoring and Evaluation:* summary of lessons learned and stakeholder feedback.
  - *Work Plan:* outline of the next steps for Phases 2 and 3.
- **Section 3 – Conclusions** provides a synthesis of the main achievements, challenges, and insights gained in this phase.
- **Section 4 – Progress Evaluation** evaluates the progress against project milestones and key performance indicators and explains how Phase 1 supports the next stages.
- **Sections 5 and 6** include supporting documentation and references used throughout the assessment.

This structure ensures a clear, transparent, and replicable approach to climate risk assessment, aligned with EU adaptation frameworks and suitable for use in Trnava's future planning and investment processes.

2 Climate risk assessment – phase 1

2.1 Scoping

2.1.1 Objectives

The primary objective of this Climate Risk Assessment (CRA) is to support the modernization of Trnava's climate adaptation strategy through the application of the CLIMAAX methodology. This first phase focuses on building a solid evidence base using harmonized European datasets provided by CLIMAAX and applying toolbox workflows for heatwave and drought risk assessments. The results offer a broader-scale perspective on climate-related hazards, providing strategic insights for policymakers and forming a valuable foundation for future integration of high-resolution local data in subsequent phases.

Specific objectives planned for this project include:

1. Enhancing the climate adaptation strategy of Trnava by incorporating high-resolution geospatial and climate data with local vulnerability assessments.
2. Updating the current adaptation plan by applying the CLIMAAX framework to ensure it reflects the most recent scientific knowledge and risk assessment methodology.
3. Strengthening the city's emergency preparedness by improving cooperation between municipal departments and external stakeholders, including academic institutions, NGOs, and private-sector actors.
4. Informing local policy development by identifying priority zones for targeted climate adaptation measures.
5. Ensuring that the CRA results are directly usable for decision-making in urban planning, infrastructure investment, and land-use management.

This CRA is intended to guide long-term urban planning, adaptation investment, and policy development by offering transparent and reproducible risk assessment outputs. It also ensures that Trnava's actions remain aligned with national and EU climate resilience targets.

Limitations and boundaries:

This first phase is based predominantly on pan-European datasets available through the CLIMAAX Toolbox (e.g., Euro-CORDEX projections, exposure grids, satellite-derived temperature). While these datasets provide valuable regional insights and allow for relative change assessments under different climate scenarios, the current analysis does not yet fully integrate high-resolution local datasets (e.g., local climate stations, cadastral-scale socio-economic data). These refinements are planned for subsequent phases of the project.

2.1.2 Context

Until now, climate risks in Trnava have been addressed mainly through the 2015 Adaptation Strategy (Trnava adaptation strategy, 2015), which outlined general goals but lacked spatial analysis, climate scenarios, or vulnerability mapping. Assessments were qualitative and did not use satellite data, vulnerability indices, or harmonized workflows. The absence of an up-to-date, evidence-based climate risk assessment left the 2018 strategy outdated and misaligned with national and EU requirements. At the same time, Trnava's spatial and economic expansion has increased exposure to heatwaves and droughts. The CLIMAAX-supported CRA helps close this gap by providing spatially explicit, scenario-based assessments to guide planning, zoning, and investment decisions.

Slovakia's Climate Change Adaptation Strategy (EPRS; Revision and update of the national adaptation strategy to climate change, 2024) and Low Carbon Development Strategy (Ministry of Environment of SR, 2020; OECD, 2023) stress the need for local climate risk assessments.

Regionally, the IROP 2021–2027 prioritizes sustainable urban development and nature-based solutions (OECD, 2023). Trnava's participation in CLIMAAX contributes directly to these priorities and aligns with the EU Strategy on Adaptation to Climate Change.

Adaptation responsibility is shared across City Office departments (Environment, Urban Planning, Crisis Management), but without a dedicated team, coordination remains weak. The city has collaborated with SHMU and STU, and CLIMAAX offers a framework to strengthen governance and institutionalize climate risk management.

Key sectors at risk include urban planning (overheating in dense areas), public health (heatwave impacts on elderly and disadvantaged groups), agriculture and water (rainfall variability, shortages), and infrastructure and energy (stress from prolonged heat and drought), (Trnava adaptation strategy, 2015).

External pressures further shape Trnava's climate risks: rapid urbanization in the Bratislava–Trnava corridor, national adaptation strategies (EPRS, IROP), partnerships with SHMU and STU, and European-level initiatives such as the Covenant of Mayors (Covenant of mayors for climate and energy, 2016).

Several no-regret measures are under way, including tree planting, shading, small-scale water retention (Strom do domu project, 2021), improved insulation and passive cooling, rainwater harvesting, public awareness campaigns, and interdepartmental coordination mechanisms.

2.1.3 Participation and risk ownership

In the initial stage of CLIMAAX, Trnava focused on identifying and engaging stakeholders central to climate risk governance. A preliminary mapping highlighted core actors for heatwave and drought management. Consultations with City Office departments (environment, urban planning, crisis management) ensured alignment with local planning needs, while NGOs and academic partners (e.g., STU Bratislava) provided input on data, health, and social aspects. These actors will support validation of results and co-development of adaptation priorities in the next phase, through workshops and consultations.

Key stakeholders:

- **Municipal authorities:** Trnava City Office – Environment (coordination), Urban Planning (zoning/design), Crisis Management (early warning).
- **NGOs and civil organizations:** Environmental groups, senior citizen networks, socially excluded communities, and local farmers (data gathering, feedback).
- **Urban planning professionals:** Local architects/planners (green infrastructure, design input).
- **Academic partners:** Slovak University of Technology (STU) (toolbox setup, analysis, adaptation strategy support).

Currently, climate risk ownership in Trnava is informally spread across City Office departments, with no formal coordination. CLIMAAX offers a chance to clarify roles, strengthen collaboration, and institutionalize risk management, with long-term responsibility expected to remain at the municipal level, supported by national institutions and academia.

Trnava has no formal definition of "acceptable risk." Public discussions and the 2015 strategy recognize heatwaves as a major public health threat, while droughts affect water supply, green space, and peri-urban agriculture. The CRA aims to establish local risk thresholds and trigger points for action.

CRA communication channels:

- Internal briefings for municipal staff.
- Workshops with NGOs, planners, and public health professionals.

- Public-facing maps, factsheets, and visuals shared online.
- Localized risk maps for affected communities through participatory sessions.

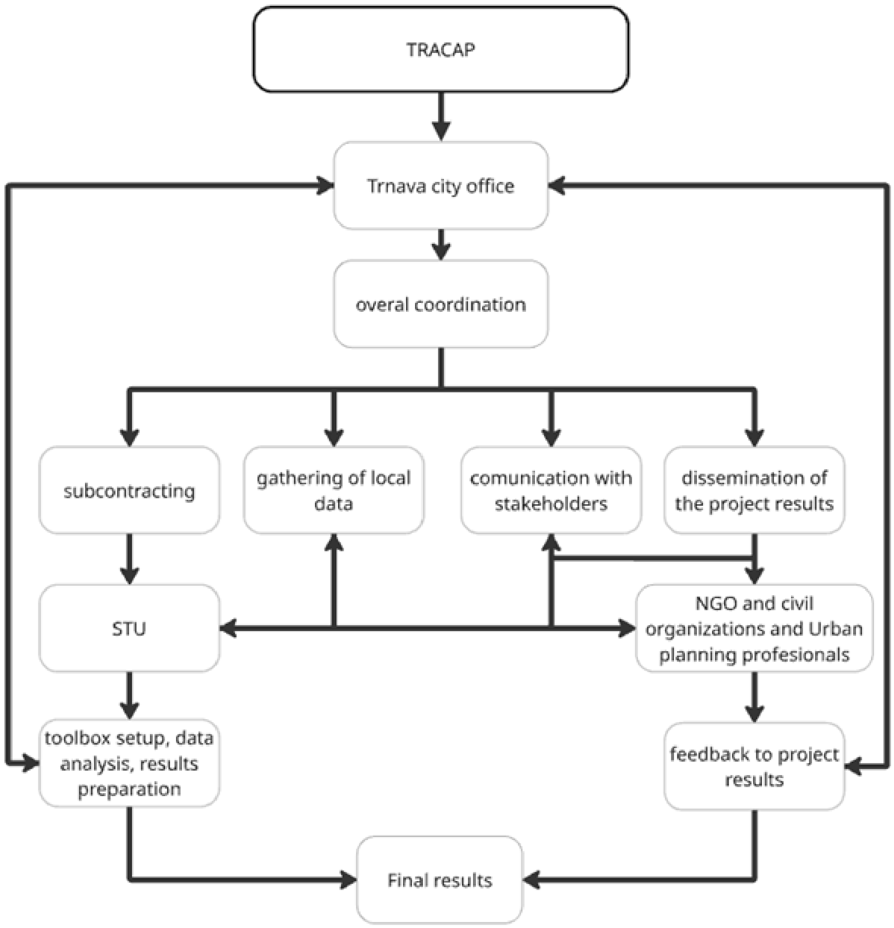

Figure 2-1 TRACAP project organigram with brief description of the project coordination

A stakeholder organigram will be refined in Phase 2 to formalize roles and interconnections.

2.2 Risk Exploration

Climate risk exploration for the City of Trnava began with a screening of the most pressing environmental risks, based on locally observed impacts, institutional knowledge, and previously published materials—particularly the Adaptation Strategy of Trnava (2015) and complementary regional documentation. This screening forms the qualitative foundation of the CRA, identifying key climate hazards and sensitive areas before CLIMAAX-specific data and tools are applied.

2.2.1 Screen risks (selection of main hazards)

Based on stakeholder consultations and earlier strategies, Trnava identified two priority hazards: heatwaves/urban heat islands (UHI) and droughts, both already highlighted in the 2015 adaptation strategy (Trnava adaptation strategy, 2015).

According to the Copernicus Climate Atlas (CCA), daily maximum temperatures are projected to rise, with more frequent tropical nights (>20 °C). For drought, summer precipitation shows a decreasing trend, linked to lower shallow soil moisture and more consecutive dry days. All comparisons are based on the median model ensemble at +2 °C warming. Other risks, such as heavy rainfall and wind, show no significant changes (CCA). SHMU projections confirm the strongest impacts from rising temperatures and heatwaves, alongside more frequent droughts and extremalization of the hydrological cycle, with rainfall events expected to intensify by 7–14% by 2030 (Pecho et al., 2023).

1. **Heatwaves and Urban Overheating:**
Trnava records increasing hot days (>30 °C), with UHIs strongest in the city center, housing estates, and industrial areas. Vulnerable groups include elderly residents, children in kindergartens and schools without shading, chronically ill, and those in poorly insulated housing.

- **Data sources (pre-CLIMAAX):** SHMU station Jaslovské Bohunice (2013), local planning documents, SHMU UHI studies (Holec et al., 2020).
- **Limitations:** Based only on 2013 observations, no detailed LST modeling, no climate scenarios, and vulnerability assessments relied on qualitative judgment.

2. Droughts and Soil Moisture Deficit:
Located in the dry Danubian Lowland, Trnava often faces summer droughts due to high evapotranspiration and low rainfall (Intersucho; Pecho et al., 2023). Affected areas include urban greenery, peri-urban agriculture, and shallow groundwater-dependent zones.

- **Data sources (pre-CLIMAAX):** SHMÚ precipitation data, national soil moisture reports, anecdotal municipal records.
- **Limitations:** No detailed drought modeling, limited soil moisture or evapotranspiration data, no scenario analysis, and weak integration of land use, hydrology, and agriculture. Cascading impacts on green infrastructure and ecosystem services were not assessed.

These two hazards were prioritized for detailed assessment due to their rising intensity, urban impacts, and high relevance to health, infrastructure, and environmental well-being.

2.2.2 Workflow selection

2.2.2.1 Workflow #1

The heatwave/UHI workflow is crucial for Trnava, given its location in the warm Danubian Lowland, extensive asphalt/concrete surfaces, and rising summer temperatures. It supports identification of overheating zones, vulnerable groups, and adaptive capacity.

- **Impacts:** Human health, cooling energy demand, thermal comfort, and overheating of infrastructure.
- **Exposed areas:** Dense housing estates (historic centre), commercial zones (e.g., City Park Trnava OC), 25 kindergartens, 9 primary schools, 3 universities (~13,000 students), elderly homes, faculty hospital with 641 beds, and industrial parks/logistics hubs.
- **Vulnerable groups:** Elderly and chronically ill (esp. in older flats), children in unshaded schools, low-income households without AC, and outdoor workers.

Current knowledge (pre-CLIMAAX): Heat-prone zones identified qualitatively, but no high-resolution LST/UHI maps or social vulnerability overlays. Limited integration with planning tools and no analysis of cascading effects (e.g., heat plus drought on vegetation).
This workflow addresses these gaps.

2.2.2.2 Workflow #2

The drought workflow is critical for Trnava, where frequent dry spells, uneven rainfall, and vegetation stress affect both urban greenery and agriculture. It enables analysis of precipitation deficits, soil moisture trends, and exposure of sensitive areas.

- **Impacts:** Decline of urban green spaces, reduced agricultural yields, higher irrigation demand, and potential depletion of local water sources.
- **Exposed areas:** Urban parks, alleys, and grasslands without irrigation; roadside vegetation and new tree plantings; private gardens and small-scale urban farming; and peripheral fields in Modranka and Zavar dependent on shallow groundwater.

- **Vulnerable groups:** Farmers and gardeners facing yield loss and irrigation costs; municipal maintenance teams with limited budgets; children and seniors reliant on shaded green areas; residents in districts with low greenery coverage; and communities dependent on shallow wells and aquifers.

Current knowledge (pre-CLIMAAX): Drought noted qualitatively in past strategies, but without indices such as vegetation health or soil moisture maps. No quantitative link between land use and vulnerability, little data on groundwater recharge or irrigation capacity, and weak integration with urban planning tools.

This workflow will provide the missing spatial and temporal insights.

2.2.3 Choose Scenario

For the Climate Risk Assessment in Trnava, medium-term climate scenarios (2036–2065) were selected as the most appropriate planning horizon. This timeframe aligns with the lifecycle of current and upcoming urban development projects, infrastructure investments, and adaptation strategies, making it highly relevant for municipal decision-making. Moreover, this period was chosen because all adaptation measures currently being developed or planned in the coming years should be designed with this horizon in mind, ensuring their long-term effectiveness and relevance.

1. Heatwave Scenario Use Case:

The CLIMAAX toolbox allows access to climate change scenario based on EURO-CORDEX (Jacob et. al., 2013) downscaled projections, particularly under the RCP 4.5 (stabilization pathway) and RCP 8.5 (high-emission pathway). Results provided in the heatwave hazard workflow was calculated as a mean values from 8 different GCM and RCM (CDS, 2019). The values of the heat days occurrence was estimated with the heatwave events thresholds for maximum and minimum daily temperature provided by EuroHEAT project (WHO, 2009). The results were prepared for both RCP 4.5 and RCP 8.5. For heatwave risk assessment, the most useful metric is the projected change in the number of heat days. This indicator allows direct comparison with historical climate data and helps evaluate the frequency and intensity of future heatwave events, increased exposure of vulnerable populations over time.

This information supports decisions related to:

- Heat-resilient building design,
- Greening and shading strategies,
- Cooling center planning and public health preparedness.

However, a current limitation is the lack of direct modeling of the combined effect of heat and drought on urban vegetation (e.g., tree stress or mortality), which reduces the ability to fully assess cascading impacts on green infrastructure and cooling services.

2. Drought Scenario Use Case:

For the drought workflow, the selected medium-term 2036 – 2065 with RCP 4.5 scenarios enable modeling of:

- Precipitation deficits and anomalies,
- Soil moisture declines and vegetation stress in agricultural areas surrounding Trnava.

These outputs are valuable for:

- Assessing the resilience of peri-urban agricultural zones,
- Guiding land-use planning and crop selection strategies.

Again, a key limitation remains the limited representation of drought impact on urban vegetation, especially under scenarios of prolonged heat stress and irrigation shortages. While agricultural impacts can be modeled with available indicators, more detailed simulation of urban ecosystem responses is still needed.

The selected medium-term climate scenarios offer a practical balance between scientific forecasting and policy relevance. They allow Trnava to integrate climate risk projections into upcoming adaptation strategies and spatial plans. However, additional modeling capacity may be needed in future phases to address compound risks (e.g., drought-induced urban tree mortality) and support nature-based adaptation planning.

2.3 Risk Analysis

2.3.1 Workflow #1 Heatwaves

The hazard and vulnerability data were selected according to the recommended approaches of the CLIMAAX heatwave workflow. For the analysis of Trnava city, the heatwave hazard assessment EuroHEAT and heatwave risk assessment workflows were chosen. The selection of the hazard workflow was based on the criterion of using an ensemble of GCM and RCM models, which reduces potential uncertainties compared to the use of a single GCM–RCM combination. Data from the Trnava adaptation strategy (mentioned in Table 2-1) will be incorporated in the next phases to enable comparison with the CLIMAAX results, while vulnerability and exposure data will serve as inputs to the heatwave risk assessment workflow.

Table 2--1 Data overview workflow #1 Heatwaves

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
Heatwaves in Europe derived from climate projection, bias-adjusted EuroCordex from 1971-2100 (source)	WorldPop data about vulnerable population, over 65 and under 5 years of age (100x100m) (source)	Overheated areas (10x10m) RSLab (Parastatidis et al., 2017)	Map of the possible heat risk level to vulnerable population (heatwave risk assessment workflow)
Climate adapt heat days occurrence, UTCI days over 32°C (source)	Map of the cooling air circulation in the City of Trnava (300x300m) (Trnava adaptation strategy)	Map of the green areas covered by the Thress crown (300x300m) (Trnava adaptation strategy)	Map of the possible heat risk level to urban greenery (needed)
Climate adapt occurrence of the tropical nights with minimum temperature over 20 °C (source)	Map of the density of people over 75 years of age (300x300m) (Trnava adaptation strategy)	Map of the unshaded impervious surfaces (300x300m) (Trnava adaptation strategy)	
Copernicus interactive climate atlas the mean of daily maximum temperatures and, the frequency of tropical nights (defined as nights with minimum temperatures above 20 °C), (source CCA)	Map of the density of children under the 4 years of age (300x300m) (Trnava adaptation strategy)	Map of the limited accessibility to green areas larger than 2 hectares with more than 60% vegetation cover. (300x300m) (Trnava adaptation strategy)	
	Map of the top-floor apartments in non-insulated buildings (300x300m) (Trnava adaptation strategy)	List of schools and kindergartens without additional thermal insulations (Trnava adaptation strategy)	
	Map of the heat insulation of the buildings for living (300x300m) (Trnava adaptation strategy)		

2.3.1.1 Hazard assessment

For the heatwave hazard assessment, the workflow based on EuroHEAT (WHO, 2009) data was selected. It began with downloading the heat-related EuroHEAT dataset from the Copernicus Climate Data Store (CDS Heatwaves, 2019) using the API. Heat spell data from 1986 to 2085 were retrieved for both RCP 4.5 and RCP 8.5 scenarios. For the area of Slovakia, national definition data from EuroHEAT were not available. The workflow then proceeded with data exploration and the selection of a representative point for data extraction—specifically, a location in the city center of

Trnava. The results provided information on the occurrence of heat days at the selected pixel. The analysis indicates that the frequency of heat days is expected to increase significantly in the coming decades. To improve interpretation, the code was upgraded to display the output as a relative change for the period 2036–2065 under RCP 8.5, compared to the reference period 1986–2015. The results, shown in Figure 2-2, reveal a relative increase in the occurrence of heat days by up to 240% (all other supporting maps were uploaded to Zenodo). These findings highlight Trnava as one of the regions with the highest projected negative impact from climate change in Slovakia.

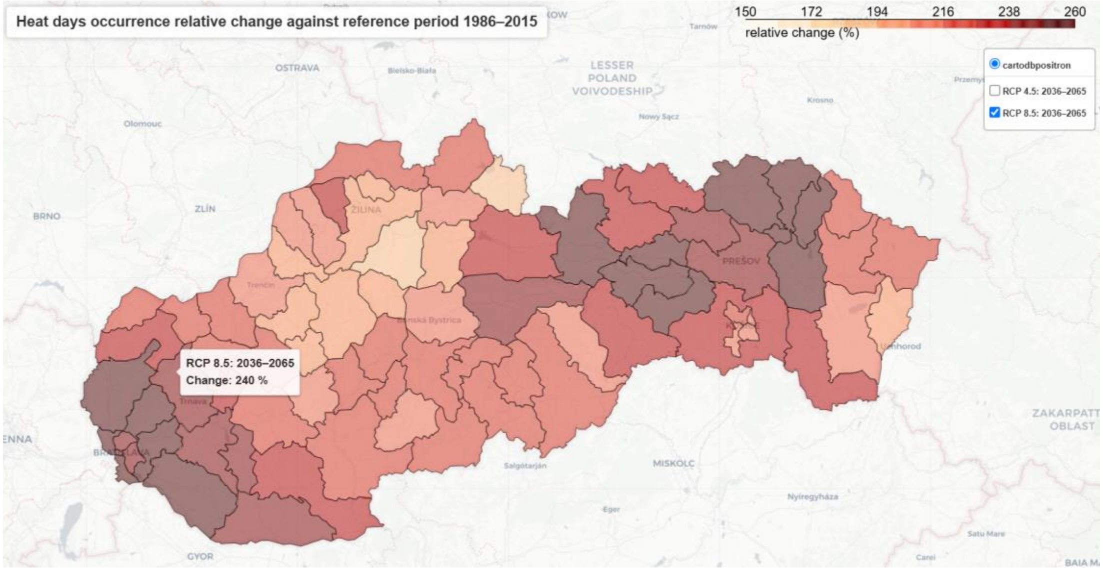

Figure 2-2 Heat days occurrence relative change for years 2036-2065 rcp.8.5 against reference period 1986-2015. (Figure source: CLIMAAX Heatwave workflow)

2.3.1.2 Risk assessment

For the risk assessment, the heatwave risk workflow based on Land Surface Temperature (LST) and vulnerable population data was selected. First, LST raster images from RSLab (Parastatidis et al. 2017) were downloaded for the years 2013–2024, covering the summer months June to August (a total of 53 images).

Subsequently, prepared code was applied to estimate the maximum LST values for the selected period in order to highlight the most overheated areas. However, the initial results showed that the most overheated zones also depended on whether nearby agricultural land had been harvested or not. Interestingly, this indicated that agricultural land could reflect more heat than densely built-up areas in the Trnava city center, depending on the phase of the summer season.

To better capture consistent heat island patterns within the city, the median LST values were used, rather than maximum values. The median-based analysis highlighted parts of the city center that were regularly overheated in recent years. The original heatwave risk workflow also provided the possibility to save all maps as .tif files. For better visualization, the QGIS software was used to display the most overheated parts in the city of Trnava with the use of median values (Figure 2-3). For the final stage, vulnerable population data from WorldPop were downloaded. These data provided information about the number of vulnerable people living within each 100 × 100 m pixel for the selected area. The age ranges for vulnerable population groups recommended by the CLIMAAX workflow were individuals older than 65 years and younger than 5 years. For further processing using the risk matrix, the data were classified into 10 equal intervals based on the density of the vulnerable population. The LST data were classified according to temperature values, while the vulnerable population was classified according to population density.

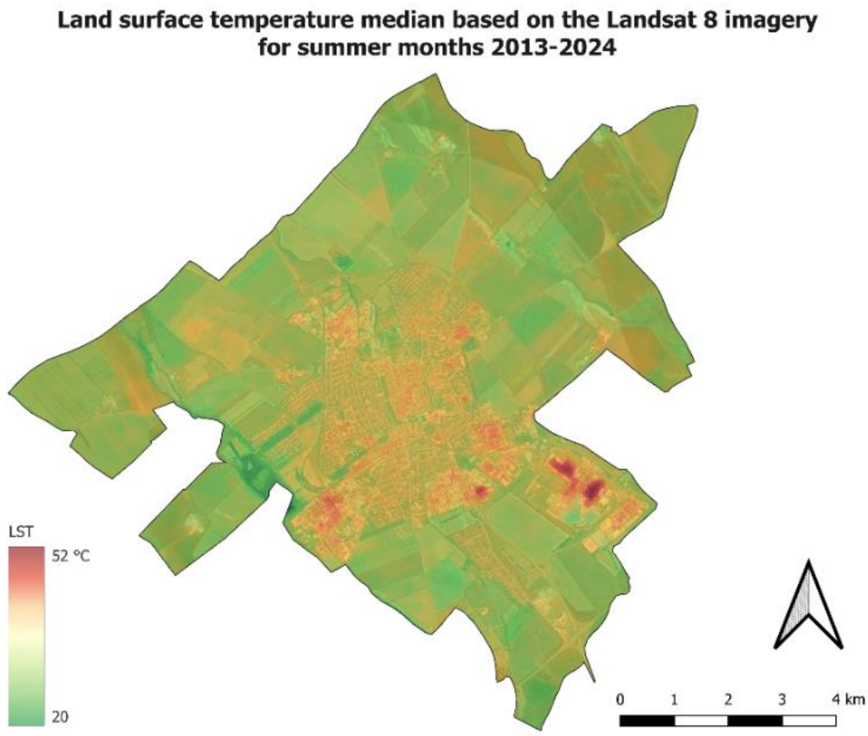

Figure 2-3 Land surface temperature map based on the median values for summer months 2013-2024. Visualization prepared from the .tif maps exported from the Climaax heatwave risk workflow. (Figure source: based on the results from CLIMAAX Heatwave workflow)

The results of the heatwave risk workflow provide a map of potential heat risk levels for the vulnerable population. This map highlights areas with the highest risk. For more precise identification of the most critical zones, the data were exported to QGIS for detailed spatial analysis. For the evaluation of the final heat risk map for the vulnerable population, the maps of overheating and the distribution of the vulnerable population were each classified into 10 equal intervals. These layers were then summed. The maximum possible heat risk level for the vulnerable population is 20 (if both the overheating and vulnerability scores are 10). In the next stages, efforts will focus on areas with a heat risk level above 13 which represents areas with high and very high risk Figure 2-4.

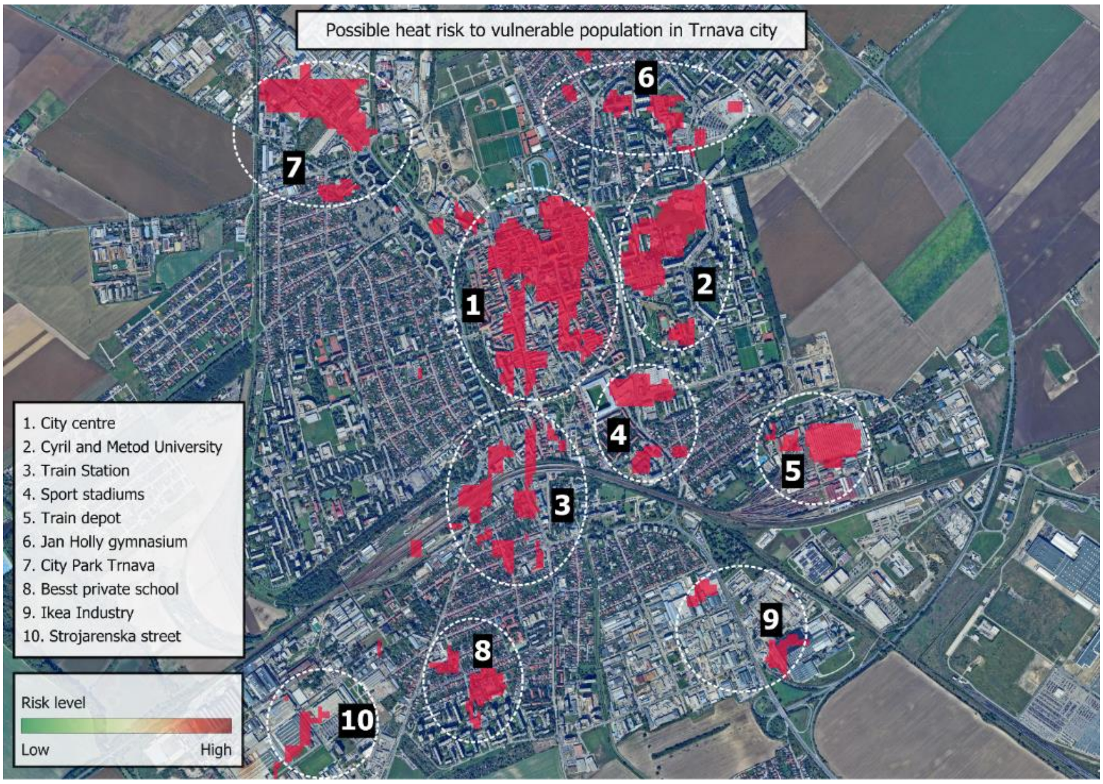

Figure 2-4 Selection of the area with the highest heat risk level in the city of Trnava (Figure source: based on the results from CLIMAAX Heatwave workflow)

Each of these areas has been named after the most representative building or street to support better localization. These locations will be discussed with local stakeholders and urban planners to validate whether they are truly problematic. If confirmed, they will be selected for detailed examination and the implementation of adaptation measures.

2.3.2 Workflow #2 Drought

The data in Table 2-2 were recommended by the CLIMAAX agriculture drought workflow. For the hazard assessment, three combinations of GCM and RCM models were selected to minimize potential uncertainties compared to using only a single combination. All other data were downloaded within the workflow.

Table 2--2 Data overview workflow #2 Drought

Hazard data	***Vulnerability data***	***Exposure data***	***Risk output***
Agriculture drought - Soil standard evapotranspiration (ET0), actual crop evapotranspiration (ETa), crop standard evapotranspiration (ETc), (Zotarelli et al., 2009)	**Agriculture drought** - Crop specific information (Doorenbos et al. 1979; Steduto et al., 2012)	**Agriculture drought** - USGS GDTEM 2010 digital elevation model (Danielson et al., 2011),	**Agriculture drought** - Maize and Wheat loss based on the precipitation deficit.
Agriculture drought – reference evapotranspiration demand (i.e., how much water does a standard plant requires to live) combining thermal radiation and wind data (Mancosu et al., 2016)	**Agriculture drought** - cropland full-irrigation availability (Allen et al., 1998)	**Agriculture drought** - Crop production [ton] data for 2010 is retrieved from the (Crop Production Statistics Data, 2019)	**Agriculture drought** - Maize and Wheat loss based on the deficit of precipitation with revenue loss from precipitation deficit.
Agriculture drought - EURO-CORDEX climate projections for **precipitation flux, maximum temperature, minimum temperature, relative humidity, wind speed** and **solar downward radiation** at 12 km spatial resolution and **daily** temporal resolution for 3 GCM and RCM combinations (CDS Cordex, 2019)		**Agriculture drought** - crops aggregated value. Data is sourced from the FAO Global Agro-Ecological Zones (GAEZ) data	
Agriculture drought - Available water Capacity (Hengl et al., 2019)			
Agriculture drought - The thermal climate zones (Van Velthuizen et al., 2007)			

2.3.2.1 Hazard assessment

For the estimation of drought hazard, the agricultural drought workflow was selected. The workflow begins with the selection of the study area, which in this case includes the NUTS2 regions of Slovakia. The next step involves selecting the climate model and projection time period. A total of three GCM–RCM combinations were selected under the RCP 4.5 scenario to minimize uncertainties (see Table 2-3). The chosen time period for this workflow is the mid-term horizon: 2036–2065.
Since there were no significant differences among the three selected GCM–RCM combinations, the combination of GCM = MPI-M-MPI-ESM-LR and RCM = SMHI-RCA4 was chosen for visualization purposes. All other graphical results are available on Zenodo (to comply with the page limit of this document). As the climate zone, the sub-continental temperate zone was selected. Maize and wheat, the most common crops in the Trnava region, were selected for this workflow (Agricultural Cooperative Trnava). Based on the crop table provided in the drought workflow, the sowing and harvest days were set as follows:

- For wheat: day 336 (sowing) and day 151 (harvest).
- For maize: day 136 (sowing) and day 286 (harvest).

The computational steps then proceed with the download of auxiliary data such as Available Water Capacity (AWC), Elevation, and Thermal Climate Zones, which help to further characterize the selected region. Before running the hazard calculation, pre-prepared crop-specific information was loaded (e.g., length of the growing period, sowing and harvest dates, rooting depth, etc.).
For the hazard calculation, maize and wheat were focused, which are commonly cultivated in the southwestern part of Slovakia. The calculation of reference evapotranspiration (ET_0) was based on the selected climatic and crop parameters. Finally, the workflow continues with the estimation of yield reduction percentage, which is based on the combination of ET_0, precipitation data, and crop-

specific characteristics. The code for the visualization was upgraded to show the exact location of the selected area.

The main results of the agricultural drought workflow are the projected yield loss due to precipitation deficit balance between 30–42% for maize and 30–42% for wheat. The range of percentage is dependent on the selected GCM and RCM combination. The results for GCM = mpi_m_mpi_esm_lr and RCM = smhi_rca4 combination are displayed below in Figure 2-5. The results for all three selected model combinations are listed in Table 2-3. This percentage of projected yield loss poses a significant threat to agriculture in the region.

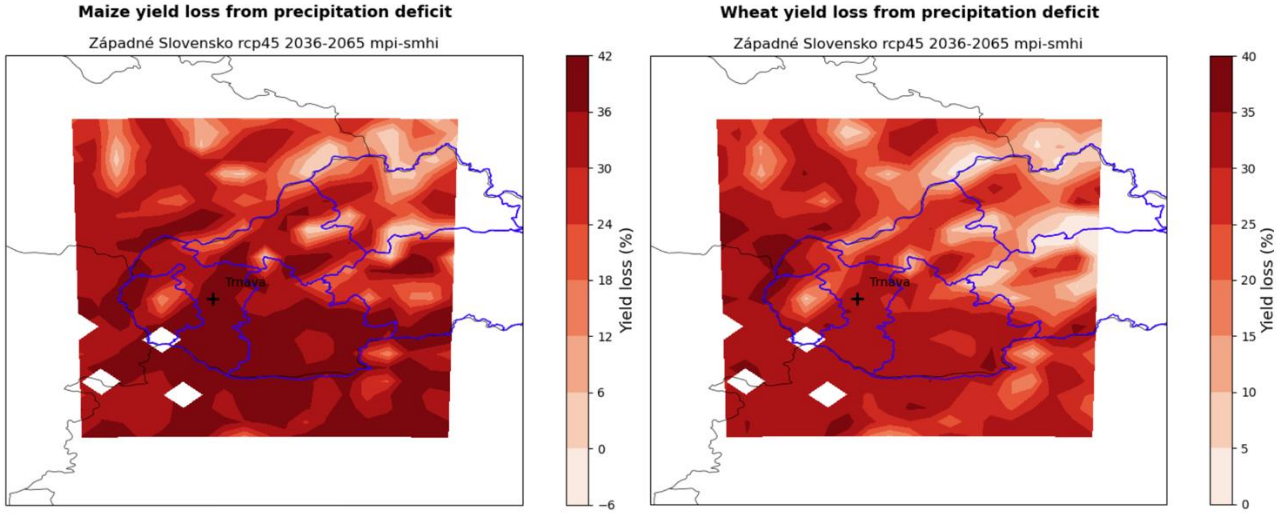

Figure 2-5 The projected Maiz and Wheat yield loss from precipitation deficit for Trnava city (black cross) RCP 4.5, 2036-2065 for GCM = mpi_m_mpi_esm_lr and RCM = smhi_rca4 combination (Figure source: CLIMAAX Agriculture drought workflow)

2.3.2.2 Risk assessment

The main goal of the selected risk assessment workflow was to estimate revenue loss, expressed as the *lost opportunity cost* of not applying irrigation. This workflow builds upon the results of the hazard assessment and incorporates exposure data including crop production volumes, crop-specific economic values, and irrigation availability. The workflow calculates the economic value per pixel for the studied crops (based on the CLIMAAX agricultural drought workflow) through the following steps:

- Calculate the revenue per ton of total crop production (USD/ton total).
- Multiply the total revenue per ton by the fraction of the studied crops to derive the value per ton for the studied crops (USD/ton studied).
- Multiply the studied crop revenue per ton by their production to estimate the revenue in each grid cell originating from the studied crops (USD/grid cell).
- Multiply the revenue per grid cell by the yield loss (from the hazard workflow) to obtain the revenue reduction due to absence of irrigation (USD/grid cell).
- Convert all final values from USD to EUR using the average exchange rate from 2010 (IFPRI, 2010).

The final output (Table 2-3) represents the potential revenue loss in the absence of irrigation, with estimated losses ranging from €160,000 to €320,000 per 1 growing season for maize, and €50,000 to €120,000 for wheat. The example of the graphical results for selected model are presented in Figures 2-6 and 2-7.

Table 2-3 The results of the drought workflow for selected GCM and RCM combinations

GCM + RCM combination	Projected yield losses [%] (maize/wheat)	Projected revenue losses 1000€ per grid cell 12x12km (maiz/wheat)
mpi_m_mpi_esm_lr + smhi_rca4	36-42 / 30-35	160-240 / 80 -120
cnrm_cerfacs_cm5 + knmi_racmo22e	30-35 / 36-40	160-240 / 80 - 120
cnrm_cerfacs_cm5 + cnrm_aladin63	36-42 / 30-42	240 -320 / 50 - 100

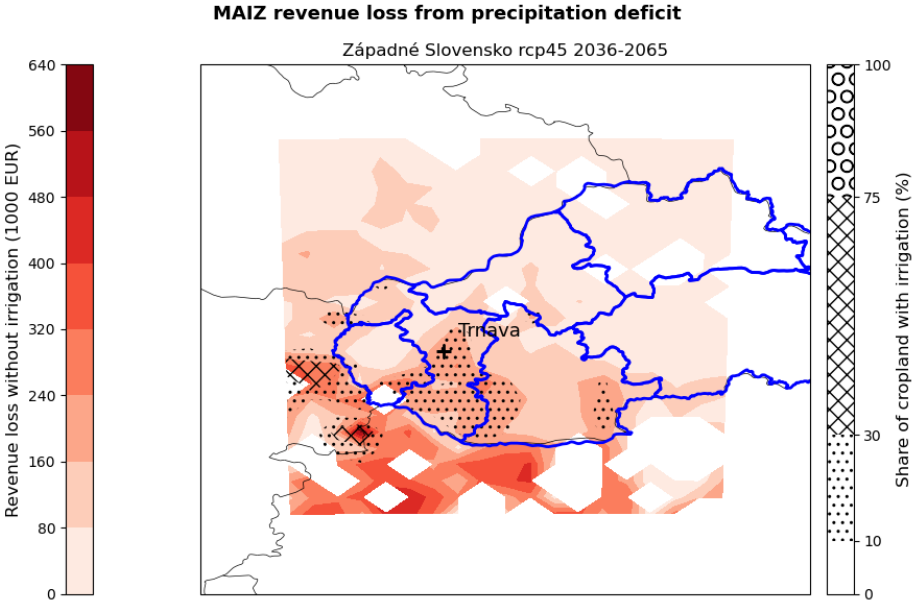

Figure 2-6 The maiz revenue loss from precipitation deficit without irrigation (1000Eur) per grid cell 12x12 km, for Trnava city (black cross) for the RCP 4.5, 2036-2065 for GCM = mpi_m_mpi_esm_lr and RCM = smhi_rca4 combination (Figure source: CLIMAAX Agriculture drought workflow)

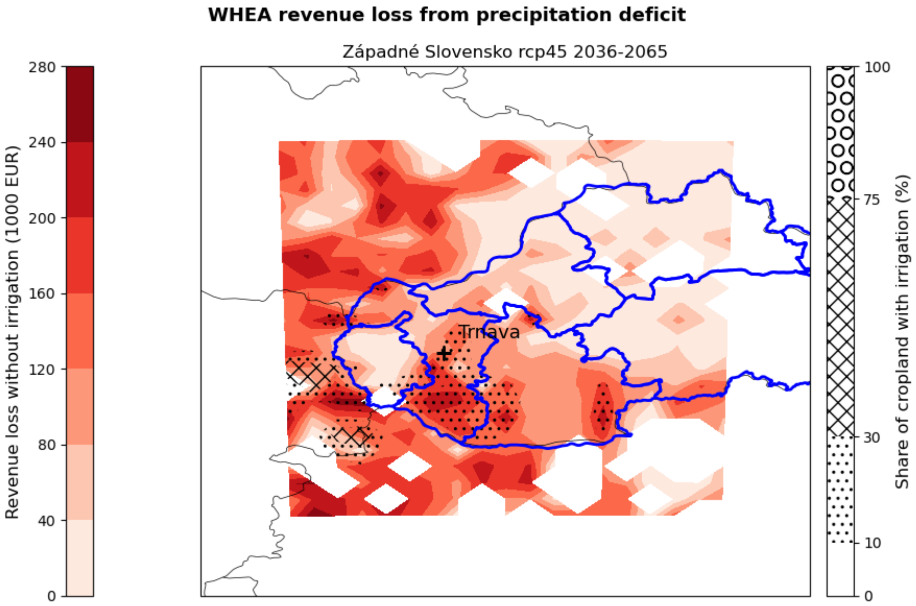

Figure 2-7 The wheat revenue loss from precipitation deficit without irrigation (1000Eur) per grid cell 12x12 km, for Trnava city (black cross) for the RCP 4.5, 2036-2065 for GCM = mpi_m_mpi_esm_lr and RCM = smhi_rca4 combination (Figure source: CLIMAAX Agriculture drought workflow)

2.4 Preliminary Key Risk Assessment Findings

2.4.1 Severity

The severity of climate risks in Trnava is high for both heatwaves and droughts, with the potential to affect large spatial areas, critical infrastructure, and vulnerable population groups. Based on annual reports from the Emergency Medical Operations Centre for the Trnava Self-Governing Region for the years 2018–2022, more than 500 heat-related collapses were recorded per summer season. In terms of drought risk, the Trnava Self-Governing Region is one of the most threatened by agricultural drought. According to the Intersucho portal (Trnka et al. 2015), which estimates drought impacts on crop yields, this area is consistently among the most affected in Slovakia. These risks are expected to intensify due to projected climate trends and, without intervention, may result in irreversible consequences for public health, ecosystem services, and the local economy.

Table 2--4 Collapsed due to severe heat in Trnava self-governing region (source: ZZS SR)

Number of citizens collapsed due to severe heat in Trnava self-governing region	
Year	**Number of citizens**
2018	590
2019	537
2020	550
2021	456
2022	645
2023 (till July,10)	345

1. **Heatwaves and Urban Overheating**

   Heatwaves are already causing severe stress in Trnava, particularly in densely built-up areas with limited vegetation and poor building insulation. Climate projections under RCP 8.5 indicate that the frequency of heat days could increase by more than 240% by 2036–2065, compared to the baseline period of 1986–2015. This makes Trnava one of the most severely affected regions in Slovakia.

Impacts include:

- Human health risks, especially for the elderly, children, and people with chronic illnesses.
- Energy system stress, due to increased cooling demand.
- Infrastructure deterioration, especially for public transport and road surfaces.
- Urban livability declines, especially in unshaded or poorly ventilated areas.

Certain residential zones, such as displayed on Figure 2-7, and the historical city center, have been repeatedly identified as urban heat hotspots, with consistently high Land Surface Temperature (LST) values over the past decade. Without significant mitigation, these areas will continue to face compounding health, social, and economic challenges.

2. **Droughts and Soil Moisture Deficit**

Drought is a severe and persistent hazard for both urban green infrastructure and peri-urban agriculture. Trnava's location in the dry Danubian Lowland makes it especially vulnerable to prolonged dry periods and precipitation deficits. Based on future climate scenarios (2036–2065), modelled yield losses for maize range from 30–42%, and for wheat from 30–42% (see Table 2-3), assuming no irrigation. These translate into annual revenue losses of €160,000–€320,000 for maize and €50,000–€120,000 for wheat per growing season, demonstrating a significant economic burden for local farmers and the food system.

Additional impacts include:

- Loss of urban biodiversity due to vegetation dieback in parks and roadside greenery.
- Degraded visual and recreational quality of public green spaces.
- Increased irrigation costs and pressure on water supply infrastructure.

- Reduced resilience of peri-urban landscapes to compound events (e.g., heatwaves + drought).

Although the drought hazard evolves more slowly than heatwaves, its cumulative effects can be equally severe, threatening the long-term functionality of ecosystems and food production systems.

Overall Assessment:

Trnava faces high-severity risks from both hazards, with:

- Immediate and potentially irreversible health consequences from heatwaves.
- Progressive and economically disruptive impacts from recurring droughts.
- Cascading effects likely, including strain on emergency services, energy systems, and food security.

Given the systemic and wide-reaching nature of these risks, urgent adaptation planning and implementation are required to reduce future damages and build long-term resilience.

2.4.2 Urgency

Both heatwaves and droughts represent increasingly urgent climate risks for Trnava due to their rising frequency, intensity, and the limited adaptive capacity of key urban and peri-urban systems. Based on the projections used in this CRA, these hazards are expected to significantly worsen during the 2036–2065 period. This timeframe aligns well with Trnava's current and upcoming infrastructure lifespans and planning cycles, which are expected to conclude after 2030. Therefore, the selected projection period is highly relevant, as it ensures that all proposed adaptation measures will be targeted toward the conditions anticipated during the critical decades ahead.

1. Heatwaves and Urban Overheating

Heat-related risks are expected to intensify rapidly, with the number of heat days projected to increase by over 240% under the RCP 8.5 scenario by mid-century. This trend represents a short- to medium-term threat, particularly for vulnerable population groups, public infrastructure, and energy demand. The compounding effects of tropical nights, insufficient shading, and aging building stock lacking passive cooling make urgent adaptation action necessary. Given that extreme heat events can trigger acute health impacts, emergency response gaps, and even premature deaths, preventive measures (e.g., greening, insulation, cooling centers) must be planned and implemented within the next 5–10 years to avoid escalating damages.

2. Droughts and Soil Moisture Deficit

Drought-related risks represent a slightly slower-onset but persistent hazard, especially in the context of Trnava's dry climate, shallow soils, and dependence on summer precipitation. The analysis indicates that droughts will become more frequent and severe in the coming decades, with yield reductions of 30–42% projected for key crops like maize and wheat. Although the impacts may unfold gradually, they can have long-term consequences on urban vegetation, agricultural viability, and water resource availability. Urgent measures are needed to enhance drought monitoring, improve irrigation efficiency, and introduce drought-resilient crop strategies.

Overall Assessment:

- The urgency of climate action in Trnava is high for both hazards:
- Heatwaves require immediate attention, particularly to protect human health and mitigate urban overheating.
- Drought interventions must begin in the near term to avoid long-term losses in green infrastructure and food production capacity.
- The CRA highlights the need for early action within the next municipal planning cycle (2025–2030), especially in sectors lacking current mitigation or preparedness measures.

2.4.3 Capacity

The City of Trnava currently manages climate risks by drawing on established knowledge of regional climate trends, empirical experience with observed impacts, and the city's settlement structure. A more systematic approach was introduced through the "Adaptation Strategy of the City of Trnava to the Impacts of Climate Change – Heatwaves" (Trnava adaptation strategy, 2015), which, based on climate analyses and demographic profiles, outlined measures gradually integrated into planning documents, investments, and municipal asset management.

Key ongoing measures:

- **Public awareness and outreach** via MTT – Mestská Televízia Trnava (Trnava local Television), the city website (Trnava.sk), social media (Facebook, Instagram), and municipal publications such as *Novinky z radnice (News from Town Hall)*, building on national campaigns led by state authorities and institutions such as the Slovak Hydrometeorological Institute (SHMU).
- **Adaptation measures** such as shading and cooling public spaces by increasing canopy coverage or installing shelters, renovating fountains and water elements, promoting green roofs and facades, and targeted care for urban greenery and soils.

Other climate-related risks are mainly addressed by national institutions, such as the Slovak Water Management Enterprise (SVP), the Slovak Hydrometeorological Institute (SHMU), and District Offices. Within the city, the Department of Spatial Development and Strategic Concepts coordinates strategic projects and supports infrastructure investments. Trnava also has solid project management and grant implementation capacity, supported by schools and social institutions for outreach to vulnerable groups.

This institutional framework positions Trnava as a capable regional partner and leader in promoting best practices in public awareness and climate adaptation.

Relevant references:

- Municipal structure, including affiliated institutions (Local Government Structure, 2025).
- Municipal budget and financial data (Difference between Trnava city budget revenues and expenditures by year, 2025).

The city integrates the adaptation strategy into all investment and planning activities across sectors, assigning high importance to climate resilience. Examples of recent or planned projects include:

- Greening and shading of the pedestrian bridge at *Starohájska* and the entrance area in front of the municipal polyclinic.
- Construction of the artificial water stream *Agátka* currently nominated for the CEZAAR award for the architecture in Slovakia (CEZAAR, 2025).
- Revitalization of the *Ružový park*, including the renovation of the Trnávka stream section near the city library.
- Inner-block revitalization projects.
- Creation of new water and green areas in the *Štrky*, *Kravský pasienok*, and *Medzihráj* localities.
- Recently completed redevelopment of the area near the *Jednota* department store, including a new water feature (fountain) and new plantings.
- The *"Strom do domu"* project (Strom do domu, 2021), a unique initiative connecting municipal tree planting with citizen participation and stewardship on private land.
- Installation of water mist diffusers in front of public buildings and private establishments.

2.5 Preliminary Monitoring and Evaluation

The first phase provided valuable insights into data availability and methodology. Workflow results created a solid foundation and were positively received by stakeholders, though some outputs still require adjustment to be stakeholder-ready. Technically, no major issues arose, as an external expert team handled toolbox setup and assessment.

Stakeholders—including the City Office, planners, and NGOs—highlighted key benefits:

- Updating Trnava's adaptation strategy with focus on drought and heatwaves.
- Predicting frequency and impacts of hazards for protecting vulnerable groups.
- Assessing effects on water resources, particularly the Trnávka River.
- Promoting SMART adaptation measures (e.g., irrigation, sprinklers, citizen alerts).
- Quantifying future agricultural losses to support adaptation and compensation.

For the next phases, SHMU's bias-adjusted 1x1 km climate scenarios will be purchased. The main improvement lies in developing locally sourced vulnerability and exposure data, such as:

- **Heatwaves:** population distribution, heat shelters, freshwater access, heat perception maps.
- **Droughts:** drought reports (Intersucho), farmer feedback on crops, and impacts on urban greenery.

2.6 Work plan

The second phase will focus on improving the quality of the Climate Risk Assessment (CRA) results through the incorporation of local data and experiences. Equally important, it will enhance the interpretation and communication of these results to stakeholders—the most critical aspect of the process. The work plan will proceed with the following steps:

- Bias-corrected, high-resolution climate scenarios from SHMU (or other available sources) will be acquired. These will include maximum and minimum daily temperatures under the selected RCP 4.5 and RCP 8.5, taking into account local physical–geographical and climatic conditions, for the projected period 2030–2060. In addition, data on relative dry days and precipitation will be included. The scenarios will be compared with Euro-CORDEX data and used for the final evaluation.
- **L**ocal data on vulnerable population groups will be collected in cooperation with the Trnava City Office and the Slovak University of Technology (STU), with the aim of improving the accuracy of the heatwave risk analysis. Information on critical locations (areas) where people are most affected by heat will also be gathered based on local experience.
- The results of the drought workflows will be presented to local farmers and stakeholders to improve their understanding of how drought patterns may evolve in the future. Additionally, they will be informed about the Intersucho project (Intersucho), which offers free weekly drought predictions and warnings.
- In collaboration with STU and the Trnava City Office, a methodology will be developed to identify areas of urban greenery most vulnerable to drought and heatwaves.

The third phase will focus on updating the city's adaptation strategy, ensuring the long-term sustainability of the CRA methodology used in this project, and disseminating the results through city information channels and dedicated workshops.

3 Conclusions Phase 1- Climate risk assessment

The first phase of the CLIMAAX project in Trnava marks a significant step toward developing a robust, evidence-based climate adaptation strategy. Through the application of the CLIMAAX Toolbox workflows for heatwaves and droughts, Trnava has begun to build a spatially explicit climate risk evidence base that will serve as a foundation for informed policy decisions and targeted adaptation actions.

Key Achievements and Findings:

- ***Successful workflow application:*** Two CLIMAAX Toolbox workflows were successfully applied, one for urban overheating and heatwave risk, and the other for agricultural drought. These workflows produced high-resolution risk maps using harmonized European datasets and local observations.
- ***Identification of high-risk areas:*** The heatwave workflow identified zones in Trnava with consistent overheating, particularly in the city center, housing estates, and industrial areas. Combined with WorldPop vulnerability layers, a heat risk index was developed and mapped, highlighting areas where vulnerable populations face the greatest exposure to extreme heat. In these zones, there is a high potential for the occurrence of urban heat islands, which pose a significant health threat to vulnerable groups (people over 65 years of age and children under 5 years) during heatwave events.
- ***Quantification of agricultural drought risks:*** The drought workflow projected significant yield losses due to precipitation deficits between 30–42% for maize and 30–42% for wheat under RCP 4.5 by 2036–2065. This translates to substantial economic impacts for local farmers, with estimated revenue losses of 160 000 – 320 000€ for maize and 50 000 – 120 000€ for wheat per growing season per grid cell 12x12 km (the range of the % and € depends on selected GCM and RCM)
- ***Enhanced stakeholder awareness:*** The results were presented to local stakeholders, including municipal departments, NGOs, and academic partners. The spatial nature of the outputs helped raise awareness about critical heat and drought risks affecting Trnava's infrastructure, public health, agriculture, and green spaces.

Challenges Addressed and Remaining:

- ***Data harmonization and technical execution:*** Thanks to collaboration with external experts from STU and the use of standardized workflows, no major technical barriers were encountered. Pan-European datasets enabled consistent assessments across hazards and regions.
- ***Stakeholder engagement and interpretation gaps:*** While the initial engagement was successful, stakeholders highlighted the need for clearer interpretation of results. Some outputs, especially from the drought workflow require further simplification and localization to be fully usable in municipal decision-making.
- ***Limited local data integration in Phase 1:*** The initial CRA relied heavily on pan-European datasets. While this allowed for consistent baseline risk screening, key local layers such as building-level thermal data, local vegetation health indicators, or detailed social vulnerability profiles were not yet integrated. This limits the precision of current results and their operational value for targeted adaptation planning.

Lessons Learned:

The Phase 1 CRA process demonstrated that even a first-pass application of the CLIMAAX methodology can yield valuable insights and generate momentum for adaptation planning. However, effective communication of results, stakeholder-tailored outputs, and the incorporation of local knowledge and datasets are critical next steps.

Outlook:

Phase 2 will address these gaps by integrating:

- High-resolution climate projections from SHMU (1 km resolution).
- Locally validated population vulnerability data.
- Spatial data on heat-sensitive locations and green infrastructure stress.
- Feedback from local farmers and municipal departments.

Additionally, methodologies will be developed for mapping urban greenery vulnerability and for presenting CRA findings in formats useable for both strategic planning and public engagement.

The conclusions of Phase 1 affirm that Trnava is exposed to high and urgent climate risks, particularly from extreme heat and drought, and that a more localized, stakeholder-informed approach is essential for the next stages of climate resilience building.

4 Progress evaluation and contribution to future phases

This section outlines the connection between the outputs of Phase 1 and the planned activities for Phases 2 and 3 of the CLIMAAX project in Trnava. It evaluates the extent to which the project met its objectives and key performance indicators (KPIs) and summarizes milestones achieved. The section also describes how these results contribute to the advancement and refinement of the Climate Risk Assessment (CRA) process.

Progress Overview

The first project phase successfully delivered initial CRA outputs for Trnava, with a strong focus on heatwaves and droughts. Both workflows from the CLIMAAX Toolbox were implemented, providing spatially explicit maps and risk indicators that form the evidence base for strategy revision and stakeholder engagement.

Collaboration between the City of Trnava and the Slovak University of Technology (STU) ensured a technically sound and locally relevant application of the CRA methodology. External data processing was minimized due to the STU team's involvement, streamlining implementation and strengthening local ownership of the process.

The following key performance indicators were addressed (see Table 4-1 and 4-2):

Table 4-1 Overview key performance indicators

Key performance indicators	***Progress***
2 CLIMAAX toolboxes successfully applied due M6 of the project (Heatwave, Drought) - Phase 1	**Done –** During Phase One, the Heatwave and Drought workflows were successfully applied, and initial results were prepared and visualized using QGIS software to meet the needs of the City of Trnava.
At least 6 stakeholders groups involved in the activities of the project (Municipality, NGOs, first responders, representatives of the vulnerable population, healthcare system representatives, water management institutions). Phase 1, Phase 2 and Phase 3	**Done** – A group of stakeholders were created, informed and invited to the project workshops. In total, people from more than 10 different initiatives were involved in the First phase. (Trnava self-governing region, SVP, SHMU, SRZ Trnava, TAVOS, Ministry of Interior, 15 Mayors of surrounding cities and villages, ZZS SR, Local environmental initiatives Baterkaren and Youth for reality)
2 workshops (First in Phase1 and second in Phase3) executed throughout the project (presenting planned activities upon the start of the project, presenting achieved outcomes of the project). Phase 1 and Phase 3	**Done -** An online workshop held for stakeholders; the invitation,and proof of online meeting have been uploaded to Zenodo.
Disseminate the project results on Trnava city webpage, facebook or instagram. Phase 1, Phase 2 and Phase 3	**Done** - Information (press release) about the project was published on the City of Trnava's website, the city's social media, and the municipal radio – the recordings were uploaded to Zenodo. A project poster was created to inform the public and stakeholders about the project's implementation – it was published on the city's website and displayed in the premises of the City Hall accessible to the public and others.

Table 4-2 Overview milestones

Milestones	***Progress***
M1: Reviewing the original adaptation strategy. Hire a team of experts, selecting from scientific partners involved in previous projects. Phase 1	**Done –** The Trnava adaptation strategy were studied by the Trnava city office and STU, the findings (mainly about vulnerability mapping) were applied in the phase 1 or will be applied in the Phase2 or 3
M2: Utilize the CLIMAAX toolboxes, focusing on droughts and heatwaves, and generate initial Climate Risk Assessment (CRA) results based on European data. Phase 1	**Done -** The Trnava adaptation strategy was studied by the Trnava City Office and STU. The findings (mainly concerning vulnerability mapping) will be applied in Phases 2 or 3.
M3: Participate in the CLIMAAX workshop in Barcelona. Phase 1	**Done –** One representative of the Trnava City Office and one representative of STU actively participated in the CLIMAAX workshop in Barcelona.
M4: Select and purchase high-resolution local data to enhance the performance of the toolboxes and	**In progress –** The initial discussion with SHMU regarding the package of climate-related data has already started.

Milestones	Progress
improve the quality of CRA results. Phase 1 and Phase 2.	

Contribution to Future Phases

Phase 1 has laid a strong technical and strategic foundation for subsequent activities. However, some limitations remain:

- The Phase 1 CRA was based primarily on harmonized European datasets. While these offer a consistent framework, they lack granularity in capturing local exposure and vulnerability.
- Stakeholder feedback highlighted the need for clearer, localized interpretation of results and more direct support for decision-making (e.g., priority areas for interventions).
- Urban drought and green infrastructure vulnerability were only partially addressed and will be prioritized in future phases.

In **Phase 2**, the focus will shift to:

- Incorporating locally sourced data on vulnerable populations, critical hotspots, and urban vegetation,
- Acquiring high-resolution, bias-corrected climate scenarios (2036–2065) from SHMU,
- Improving the usability and communication of risk results for municipal departments and stakeholders.

Phase 3 will concentrate on:

- Integrating CRA findings into Trnava’s updated adaptation strategy,
- Ensuring long-term sustainability of the CRA approach within city planning processes,
- Disseminating final results through public workshops and city communication channels.

5 Supporting documentation

The list of outputs:

1. CLIMAAX_M6_Deliverable_template_FSTP_Trnava_Slovakia
2. Trnava_workshop_for_stake_holders.doc
3. Trnava_climaax_workshop_invitation.doc
4. Trnava_climaax_press_release_1phase.doc
5. Trnava_climaax_poster_A3_2025.pdf
6. Trnava_climaax_fb.png
7. Trnava_climaax_ig.png
8. Trnava_munipolis1.png
9. Trnava_munipolis2.png
10. Trnava_adaptation_strategy_2015.pdf
11. Low_emmision_strategy_for_Trnava_region.pdf

Heatwave workflow outputs:

12. HW_hazard_EuroHEAT_heatdays_occurrence_rcp45_85
13. HW_hazard_EuroHEAT_rel_change_rcp45
14. HW_hazard_EuroHEAT_rel_change_rcp85
15. HW_Trnava_median_LST.png
16. HW_Trnava_possible_heat_risk_to_vulnerable_pop_zones.png
17. HW_Trnava_vulnerable_pop_raw.tif
18. HW_Trnava_heat_risk_raw.tif
19. HW_Trnava_heat_risk_to_vulnerable_pop_raw.tif
20. HW_Trnava_LST_medianTempSummer_2013_2024_raw.tif
21. tx-CMIP6_timeseries.png

Drought workflow outputs:

22. cdd-CMIP6_timeseries.png
23. mrsos-CMIP6_timeseries.png
24. pr-CMIP6_timeseries.png
25. Západné Slovensko_AWC .png

Drought workflow visual outputs cnrm + aladin:

26. Západné Slovensko_ET0_cnrm_aladin.png
27. Západné Slovensko_MAIZ_revenue_loss_EUR_cnrm_aladin .png
28. Západné Slovensko_maize_yield_loss_cnrm_aladin .png
29. Západné Slovensko_Precipitation_cnrm_aladin .png
30. Západné Slovensko_WHEA_revenue_loss_EUR_cnrm_aladin .png
31. Západné Slovensko_wheat_yield_loss_cnrm_aladin .png
32. Západné Slovensko_yield_loss_SPREADSHEET_cnrm_aladin .csv

Drought workflow visual outputs cnrm + racmo:

33. Západné Slovensko_ET0_cnrm_racmo.png
34. Západné Slovensko_MAIZ_revenue_loss_EUR_cnrm_racmo.png
35. Západné Slovensko_maize_yield_loss_cnrm_racmo.png
36. Západné Slovensko_Precipitation_cnrm_racmo.png
37. Západné Slovensko_WHEA_revenue_loss_EUR_cnrm_racmo.png
38. Západné Slovensko_wheat_yield_loss_cnrm_racmo.png

39. Západné Slovensko_yield_loss_SPREADSHEET_cnrm_racmo.csv

Drought workflow visual outputs mpi + smhi:

40. Západné Slovensko_ET0_cnrm_racmo.png
41. Západné Slovensko_MAIZ_revenue_loss_EUR_cnrm_racmo.png
42. Západné Slovensko_maize_yield_loss_cnrm_racmo.png
43. Západné Slovensko_Precipitation_cnrm_racmo.png
44. Západné Slovensko_WHEA_revenue_loss_EUR_cnrm_racmo.png
45. Západné Slovensko_wheat_yield_loss_cnrm_racmo.png
46. Západné Slovensko_yield_loss_SPREADSHEET_cnrm_racmo.csv

6 References

Agricultural Cooperative Trnava: History of the Cooperative, https://www.pdtrnava.sk/historia-druzstva, (available online: 20.7.2025)

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation and Drainage Paper 56, FAO, Rome, 1998

Baterkaren – Local environmental initiative, https://www.baterkaren.sk (available online: 25 August 2025)

CEZAAR award for architecture in Slovakia, https://cezaar.sk/ , 2025(available online: available online: 20.7.2025)

City of Trnava – Official website of the City of Trnava, https://www.trnava.sk (available online: 25 August 2025)

CLIMAAX, GitHub: https://github.com/CLIMAAX, 2025 (available online: 14.7.2025)

CLIMAAX, handbook: https://handbook.climaax.eu/intro.html, 2025 (available online: 14.7.2025)

CDS (Copernicus Climate Change Service, Climate Data Store): Heat waves and cold spells in Europe derived from climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.9e7ca677, 2019 (available online: 14.7.2025)

CDS (Copernicus Climate Change Service, Climate Data Store): CORDEX regional climate model data on single levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.bc91edc3, 2019 (Accessed on DD-MMM-YYYY)

CCA (Copernicus Interactive Climate Atlas): https://atlas.climate.copernicus.eu/atlas, 2024 (available online: 14.7.2025)

Covenant of mayors for climate and energy Europe, https://www.globalcovenantofmayors.org/cities/european-union-and-western-europe/slovakia/trnava/, 2016, (available online: 14.7.2025)

Danielson, J.J., Gesch, D.B.: Global multi-resolution terrain elevation data (GMTED2010), U.S. Geological Survey Open-File Report 2011–1073, p.26, 2011

Department of Land and Water Resources Management of Slovak University of Technology: https://www.kvhk.sk/, 2025 (available online: 14.7.2025)

Difference between Trnava city budget revenues and expenditures by year, 2025:https://egov.trnava.sk/default.aspx?NavigationState=440:0: (available online: 14.7.2025)

Doorenbos, J. & Kassam, A.H.: Yield response to water. FAO Irrigation and Drainage Paper 33, 257, 1979

EPRS (European Parliament): Slovakia's climate action strategy, https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/769539/EPRS_BRI(2025)769539_EN.pdf, 2025

GAEZ (Global Agro-Ecological Zones), FAO and IIASA: https://gaez.fao.org/, available online: 20.8.2025

Hengl, T., Gupta, S.: Soil available water capacity (250 m resolution), https://doi.org/10.5281/zenodo.2629149, 2019

Holec, J., Feranec, J., Stastný, P., Szatmári, D., Kopecka, M., Garaj, M.: Evolution and assessment of urban heat island between the years 1998 and 2016: case study of the cities Bratislava and Trnava in western Slovakia. Theoretical and Applied Climatology. 141. 10.1007/s00704-020-03197-1. 2020

IFPRI (International Food Policy Research Institute): "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0", https://doi.org/10.7910/DVN/PRFF8V, Harvard Dataverse, V4, 2019

Intersucho: Monitoring of Drought and Soil Moisture in Slovakia, https://www.intersucho.sk/sk/?mapcountry=sk&from=2025-07-04&to=2025-08-01&current=2025-07-27, 2025

IROP (Integrated Regional Operational Programme), 2014–2020. Ministry of Investments, Regional Development and Informatization of the Slovak Republic. Available online: https://mirri.gov.sk/projekty/projekty-esif/integrovany-regionalny-operacny-program/ (accessed: 21 August 2025).

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., et al.: EURO-CORDEX regional climate model simulations for Europe: evaluation and future climate projections, https://doi.org/10.1007/s10584-013-0831-3, 2013

Local Government Structure, Trnava city: https://www.trnava.sk/stranka/struktura-samospravy, (available oniline: 18.07.2025)

Low emission strategy for Trnava self governing region till the year 2030, https://trnava-vuc.sk/dokumenty/nizkouhlikova-strategia-trnavskej-zupy/

Mancosu, N., Spano, D., Orang, M., Sarreshteh, S. & Snyder, R.L.: SIMETAW# – A model for agricultural water demand planning, Water Resources Management, 30(2), 541–557, doi:10.1007/s11269-015-1176-7, 2016

Ministry of Interior – Official website of the Ministry of Interior of the Slovak Republic, https://www.minv.sk (available online: 25 August 2025)

MTT, Mestská televízia Trnava, (Trnava local televison), https://www.mtt.sk/, (available oniline: 18.07.2025)

Novinky z radnice, (News from Town hall), https://www.trnava.sk/stranka/novinky-z-radnice, (available oniline: 18.07.2025)

Revision and update of the national strategy on adaptation to climate change in Slovakia, Ministry of Environment of the Slovak Republic (Smith, Janoska, Cuervo Blanco, Leimane & Schvalb): Revision and update of the national strategy on adaptation to climate change in Slovakia: Deliverable 2.2 – Final Report, https://www.klima-adapt.sk/cms/documents/2024/state-of-play_67330086d1201.pdf, 2024

NATURANCE project: https://www.naturanceproject.eu/, (available online: 14.7.2025)

OECD: Adaptation measurement: Assessing municipal climate risks to inform adaptation policy in the Slovak Republic, https://www.oecd.org/environment/adaptation-measurement-assessing-municipal-climate-risks-to-inform-adaptation-policy-in-the-slovak-frepublic_93169e79.pdf, 2023

Parastatidis, D.; Mitraka, Z.; Chrysoulakis, N.; Abrams, M. Online Global Land Surface Temperature Estimation from Landsat. Remote Sens. 9, 1208. https://doi.org/10.3390/rs9121208, 2017

Pecho, J.: Zmena klímy a ako ďalej, Košice, 17.5.2023 *https://www.sazp.sk/dokument/f/2-scenare-zmeny-klimy-sr-pecho.pdf (available online: 1.8.2025)*

Steduto, P., Hsiao, T.C., Fereres, E. & Raes, D.: Crop yield response to water, FAO, Rome, 2012

Strom do domu project: https://www.trnava.sk/stranka/zmena-klimy, 2021 (available online: 14.7.2025)

SHMU, Slovak Hydrometeorological Institute https://www.shmu.sk/sk/?page=1&id=meteo_num_mgram&nwp_mesto=32331 *(available online: 25 August 2025)*

SRZ Trnava, Slovak Anglers' Association – Trnava Local Organization (SRZ MsO Trnava) – Official website, https://www.srztrnava.sk (available online: 25 August 2025)

SVP, Slovak Water Management Enterprise – Official website of SVP, https://www.svp.sk/en/uvodna-stranka-en/ (available online: 25 August 2025)

TAVOS, Trnavská vodárenská spoločnosť – Official website of the regional water company, https://tavos.sk *(available online: 25 August 2025)*

Trnava adaptation strategy, 2015: https://www.trnava.sk/userfiles/download/attachment/Strategia_adaptacie_Trnava%20schv%C3%A1len%C3%A1.pdf, 2018 (available online: 14.7.2025)

Trnava description: https://www.trnava.sk/aktualita/13117/pocet-obyvatelov-trnavy-narasta, 2023 (available online: 14.7.2025)

Trnava Self-Governing Region – Official website of the Trnava Region, https://www.trnava-vuc.sk (available online: 25 August 2025)

Trnka, M., et al. 2015: Drought monitoring system for the Czech Republic and Slovakia: The Intersucho project, Meteorologický časopis, 18(1), 1–7, 2015.

Van Velthuizen, H., Huddleston, B., Fischer, G., Salvatore, M., Ataman, E., et al.: Mapping biophysical factors that influence agricultural production and rural vulnerability (Issue 11), Food & Agriculture Org., 2007

WHO, 2009: Improving public health responses to extreme weather/heat-waves-EuroHEAT, Technical summary, Editors: B. Menne and F. Matthies, 2009

WorldPop (World population data), Humdata: – Distribution of critical population groups, 11.6.2024 [https://data.humdata.org/dataset/worldpop-population-counts-for-world] (available online: 14.7.2025)

Youth for Reality – Environmental initiative, https://www.youthforreality.sk (available online: 25 August 2025)

Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W. & Morgan, K.T.: Step-by-step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method), 2009

ZZS SR, Emergency Medical Operations Centre: https://155.sk/, (available online: 14.7.2025)