Deliverable Phase 2 – Climate risk assessment

CliMAaXImal COntribution to building the resilience of the ZilinA region (MAXICONZA)

Slovakia, Žilina Region

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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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Abbreviations and acronyms

Abbreviation / acronym	Description
CDS	Climate Data Store
CINEA	European Climate, Infrastructure and Environment Executive Agency
CRA	Climate Risk Assessment
CRM	Climate Risk Management
EMS	Emergency Medical Services
ESIF	European Structural and Investment Funds
GCM	Global Climate Model
GKÚ	Geodetický a kartografický ústav Bratislava (Geodetic and Cartographic Institute, Bratislava)
GIS	Geographic Information System
HE	Horizon Europe
IDF	Intensity Duration Frequency
KPI	Key Performance Indicator
KRA	Key Risk Assessment
LST	Land Surface Temperature
MIP4Adapt	Mission Implementation Platform for Adaptation
NDBI	Normalized Difference Built-Up Index
NDS	Národná diaľničná spoločnosť (National Highway Company)
NGO	Non-Governmental Organisation
NLC	Národné lesnícke centrum (National Forest Centre)
P2R	Pathways2Resilience
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RP	Return Period
SHMÚ	Slovenský hydrometeorologický ústav (Slovak Hydrometeorological Institute)
SVP	Slovenský vodohospodársky podnik (Slovak Water Management Enterprise)
UHI	Urban Heat Island
ŽSK	Žilinský samosprávny kraj (Žilina Self-Governing Region)

Executive summary

This deliverable presents the results of Phase 2 of the CLIMAAX project in the Žilina Region and provides an overview of the region's first Climate Risk Assessment (CRA). Beyond the results, it offers insight into the process of developing a CRA in the Slovak context, where obtaining, processing and harmonising data from multiple institutions remains a significant challenge. The deliverable demonstrates how local datasets, expert knowledge and cooperation with external partners contributed to improving the assessment, including collaboration with the Austrian Research Centre for Forests and the use of data from the Seed4Forest application. It also highlights synergies with Horizon Europe JUSTAFE and Pathways2resilience (P2R) projects.

The CRA initially focused on heatwaves and heavy rainfall and was later expanded to include river floods, climate impacts on forests and agriculture, and a multi-hazard assessment of tourism destinations. A major effort was devoted to data acquisition and harmonisation. As a result, the hazard-impact database increased from 20 records in Phase 1 to 863 events, substantially strengthening the evidence base for risk evaluation. Given its importance for future assessments, the database should be maintained as a living system and regularly updated, including within ŽSK-managed facilities where impacts are not yet recorded systematically.

The assessment confirmed increasing intensity of all analysed hazards. Heavy rainfall and flash floods emerged as the most critical risk. Both SHMÚ (Slovak Hydrometeorological Institute) and Euro-CORDEX scenarios project a strong increase in extreme precipitation, while the impact database demonstrated that serious damage already occurs below the 40 mm/24 h threshold used by SHMÚ to define extreme precipitation events. The analysis further confirmed that most high-impact flash flood events occur in areas naturally susceptible to flash flooding, highlighting the adaptation challenge in locations where increasing rainfall extremes coincide with naturally vulnerable environmental conditions.

Heatwaves were assessed as a moderate but highly urgent risk. The Key Risk Assessment (KRA) highlighted the region's limited preparedness for this relatively new hazard, despite projections indicating a substantial increase in future exposure. The mean annual number of tropical days is projected to increase from 7.5 to almost 25 days by the end of the century under RCP 8.5, representing an increase of more than 230% and exposing the population to heat-related stress for almost an entire month each year.

Additional analyses revealed that climate change would significantly reduce the future suitability of Norway spruce, the region's dominant tree species. The river flood analysis showed that river floods currently occur more frequently than flash floods, while also identifying discrepancies between observed flood occurrence and official flood-risk maps. The multi-hazard assessment of tourism destinations further demonstrated that climate risks extend beyond urban centres and affect important tourism areas across the region.

In conclusion, Phase 2 significantly improved the understanding of climate risks in the region through integration of local impact data, climate scenarios and expert knowledge. It also highlighted the importance of systematically collecting and maintaining impact data as a long-term resource and strengthening institutional knowledge on data availability and use.

In Phase 3, results will be refined and validated through stakeholder engagement and translated into recommendations for adaptation planning, investment prioritization and regional resilience building.

1. Introduction

1.1. Background

Žilina Self-Governing Region (ŽSK) is a regional public administration body which, according to Act No. 539/2008 Coll., is responsible for the region's sustainable economic development and the preparation of regional strategies and policies. ŽSK manages 114 organizations (57 secondary schools, 5 hospitals, 22 cultural facilities, 24 social services, and a road network). The Žilina Region is characterized by the highest annual rainfall in the Slovak Republic. As the unevenness of rainfall distribution during the year increases, so does the number of extreme rainfall events that negatively affect the Žilina Region, whether we are talking about flash floods, landslides, or intense water erosion activity. The Žilina Region is a mountainous, predominantly rural area. The rugged mountain relief significantly affects the road network. Villages in mountain valleys are often connected to larger urban settlements by only one road, and detours often cause long delays. This greatly impacts emergency response and access to health care. Road damage is one of the most significant impacts of extreme rainfall in the Žilina Region. This issue affects not only residents but also the region's visitors. Tourism is a crucial pillar of the local economy, with nearly 60% the Žilina Region designated as a protected area, making it one of Slovakia's most attractive tourist destinations. Famous spots such as Demänovská, Vrátna and Gaderská Valley are among the most visited in the country, drawing thousands of visitors annually. Extreme rainfall can severely disrupt tourism activities, leading to a decrease in visitor numbers.

1.2. Main objectives of the project

The main objective of the project is to enhance the resilience of the Žilina Region to selected climate hazards (extreme rainfall and heatwaves) by applying the Climaax methodology to identify the most critical climate risks. Based on these findings, recommendations for adjusting regional investment and development policies, as well as recommendations for regional stakeholders on preparing adaptation solutions, will be developed through a participatory process.

Phase 2 focuses on refining the assessment of selected climate hazards already evaluated in Phase 1 through the use of local data and models, while also assessing additional climate hazards. Phase 2 also includes the mapping of the adaptation potential of properties managed by the ŽSK.

From a regional perspective, the integration of local data is a key prerequisite for accurately identifying the areas most at risk from selected climate hazards. Compared to Phase 1, where only a single indicator for the entire region was available in the case of heavy rainfall, the outputs of Phase 2 represent a significant improvement in understanding the spatial distribution of risk. This information is essential for regional planning. ŽSK intends to use these findings to direct investments towards the most vulnerable locations and thereby strengthen regional resilience.

At the same time, ŽSK is responsible for preparing the regional spatial plan, which defines land-use parameters and restrictions and serves as a framework for local spatial planning. Improved knowledge of the spatial distribution of climate risks enables the region to design and implement more appropriate interventions within the territory.

In the case of heatwaves, the incorporation of local data is important for prioritising the urban heat islands (UHIs) identified in Phase 1, particularly with regard to the presence of vulnerable population groups. This information is especially valuable for planning at the local level and contributes to building resilience in the region's urban environments.

The refined CRA will also support the management of approximately 800 properties owned or administered by ŽSK throughout the region. Improved knowledge of the spatial distribution of climate hazards will be combined with the mapping of the adaptation potential of these properties. This assessment identifies their potential for water retention, thereby reducing risks associated with extreme rainfall events, as well as their potential for the implementation of blue-green infrastructure. In addition to other benefits, blue-green infrastructure can help reduce the impacts of summer heat and its adverse effects on human health.

The CLIMAAX Handbook was particularly helpful in the case of heavy rainfall when developing the impact database. The process of building the database not only enabled the region to identify critical locations more accurately but also highlighted the need for a systematic approach to collecting and maintaining impact data, both at the regional level and specifically for facilities managed by ŽSK. The Handbook was also valuable in defining thresholds, which are particularly important for the development of early warning systems related to intense rainfall events. However, obtaining the data required to establish these thresholds proved challenging. Despite charging for access to these datasets, the SHMÚ responded only sporadically to data requests. Initially, we intended to use radar data for threshold definition, but after several months without a meaningful response from the department responsible for these datasets, we were forced to rely on data from precipitation gauge stations instead, as that department was willing to provide the necessary information. To date, we have also been unable to obtain drought-related data. Following guidance from SHMÚ, which develops these datasets in cooperation with CzechGlobe, an official data request was submitted directly to CzechGlobe. However, despite repeated attempts to follow up, the requested data have not yet been provided. As a result, the drought assessment could not be supported by this dataset within this phase. More broadly, both SHMÚ and CzechGlobe are publicly established institutions in their respective countries. This raises the question of whether data produced using public resources should be subject to fees. More importantly, it highlights the need for mechanisms that ensure data requests are processed within a reasonable timeframe, particularly when applicants are willing to pay for access.

Despite these challenges, the delays in obtaining certain datasets provided an opportunity to advance the assessment of other climate hazards included in Phase 2, such as river floods, drought impacts on agriculture and forests. Although these hazards were not analysed in the same level of detail as heavy rainfall and heatwaves, their assessment contributed to a more comprehensive understanding of climate risks across the region.

The CLIMAAX Handbook also provided valuable guidance for the KRA. The methodology helped us contextualise the results of the hazard-specific risk analyses and systematically prioritise risks according to their severity, urgency, and the region's capacity to cope with and adapt to them. This was particularly useful for identifying priority risks that should inform future adaptation planning and resilience-building measures.

1.3. Project team

The project team is led by members of the ŽSK team, responsible for project coordination, planning, administration, and the application of knowledge gained through previous ŽSK activities in this field.

Key team members are Dana Gavalierová and Dávid Bače from the Department of Regional Development.

Technical and methodological support is provided by Straton Technologies, a technology startup originating from the University of Žilina that specializes in unmanned aerial systems, environmental monitoring, climate data collection, and related innovative solutions.

To ensure the quality of project outputs, an external expert group has been established, bringing together representatives from academia (hydrology and forestry), regional and local authorities, NGOs, tourism organizations, spatial planning professionals, and climate change adaptation experts.

1.4. Outline of the document's structure

This document is composed of the following parts. An introduction describes project background, main objectives, team included as well as regional context. The core of the deliverable is focused on respective CRA, depicting scoping, analyses, and preliminary findings of extreme rainfall and heatwave workflows. The final parts of the document provide conclusions of the entire process, progress evaluation and outline further steps to be done in the last stage of the project.

2. Climate risk assessment – phase 2

2.1. Scoping

Scoping in Phase 2 was conducted in largely the same way as in Phase 1. This section therefore focuses primarily on the progress achieved during Phase 2 in meeting the CRA objectives, on how this progress has contributed to an enhanced understanding of climate risks in a broader context, and on the additional stakeholders that have been involved in the process, as well as those identified as relevant for subsequent phases of the project.

2.1.1. Objectives

The objectives remained unchanged compared to Phase 1, with continued focus on extreme precipitation and heatwaves. For extreme precipitation, the aim remained to assess the vulnerability of the road network and tourism sector, while identifying areas most susceptible to landslides and flash floods. For heatwaves, the objective continued to be the identification of UHI in relation to vulnerable populations and critical infrastructure. As in Phase 1, the results are intended to support regional planning, investment decisions, and adaptation policies.

In Phase 2, the scope was expanded to include drought impacts on agricultural crops and forests, as well as river flood risks. Drought was added because it has become increasingly evident in the region in recent years. Given the predominantly rural character of the region, the analysis initially focused on agricultural crops, with the intention of extending the approach to forests. Collaboration with an expert from the National Forest Centre (NLC) led to the identification of the Seed4Forest application, developed through a Horizon Europe project, which supports the assessment of climate change impacts on forest species. River floods were added during the development of the impact database, when it became apparent that civil protection statistics do not distinguish between flash floods and river floods. The development of the impact database proved particularly challenging in the Slovak context. Data are fragmented across multiple sources, formats, and levels of detail, often requiring extraction from narrative reports, removal of duplicates, and extensive harmonisation. Despite these challenges, a comprehensive database containing 863 hazard events recorded over the last 13 years was created. Although originally developed for flash flood analysis, the database also captured information on other hazards, including windstorms, landslides, water scarcity, and snow-related events. The results indicate that snow-related emergencies are currently among the most frequent weather-related extreme events in some parts of the region, highlighting the need for greater attention to this hazard in future assessments.

2.1.2. Context

Decision-makers in ŽSK recognise the need to adapt to climate change and have anchored this commitment in key regional strategies. However, the CRA developed through the project represents the first attempt to systematically assess climate hazards, vulnerabilities and risks at the regional scale and provide an evidence base for future adaptation planning.

The assessment focused on hazards that are already affecting the region and are expected to become more relevant under future climate conditions. Heatwaves have become increasingly visible in recent years, with Žilina Region recording the highest number of emergency interventions related to heat-related collapses and hospital transports among Slovak regions (zilina.sp21.sk, 2025). This is notable given that ŽSK is not among the regions most exposed to extreme heat. The assessment therefore sought to identify the most vulnerable areas and better understand how heat-related risks may evolve in the future. The findings highlight the importance of strengthening public awareness and preparedness, particularly in the context of an ageing population.

Floods remain the most significant weather-related hazard in the region, causing recurrent damage and requiring substantial public investment for recovery. While flood protection on major rivers falls under the responsibility of national authorities, the assessment can help identify areas where improved land management and nature-based solutions focused on water retention may contribute to risk reduction. Water retention in the landscape is already recognised as a regional priority and forms part of ŽSK’s climate adaptation framework (ŽSK, 2024).

The project has also contributed to a broader understanding of the regional climate risk profile. In addition to floods and heatwaves, the assessment highlighted the growing relevance of drought and confirmed the importance of other hazards, particularly snow-related emergencies in the northernmost parts of the region. Together, these findings provide a basis for prioritising future climate adaptation efforts and identifying areas where more detailed assessments will be needed.

2.1.3. Participation and risk ownership

The key stakeholders involved in Phase 2 were the members of the Expert group. Two expert group meetings were held during the reporting period, complemented by individual consultations. The sectors represented by the experts are described in Section 1.3 Project team. The experts supported the CRA by identifying relevant data sources, facilitating data access, reviewing intermediate results, and providing methodological feedback.

The most relevant stakeholder groups were already identified and described in Phase 1 deliverable. During Phase 2, engagement focused primarily on data collection. Approximately 20 organisations under the authority of ŽSK contributed information on past climate-related events and impacts through a structured questionnaire. In addition, supplementary datasets and information were obtained from 22 organisations and institutions (see also Annex 2 – Collected Datasets). Data collection was carried out through direct requests, bilateral consultations, questionnaires, and the exchange of existing datasets.

Particular attention was given to older people as a priority vulnerable group, reflecting the demographic characteristics of the region. This focus was further strengthened by the launch of the HE JustSafe project, which works with elderly people living in remote rural areas and will test "What If" scenarios for floods and heatwaves. To maximise synergies between the two projects, the CRA places particular emphasis on climate risks affecting older people.

Risk ownership varies by hazard, as illustrated in Figure 2-1. There is currently no formally defined acceptable or tolerable level of climate risk at the regional level.

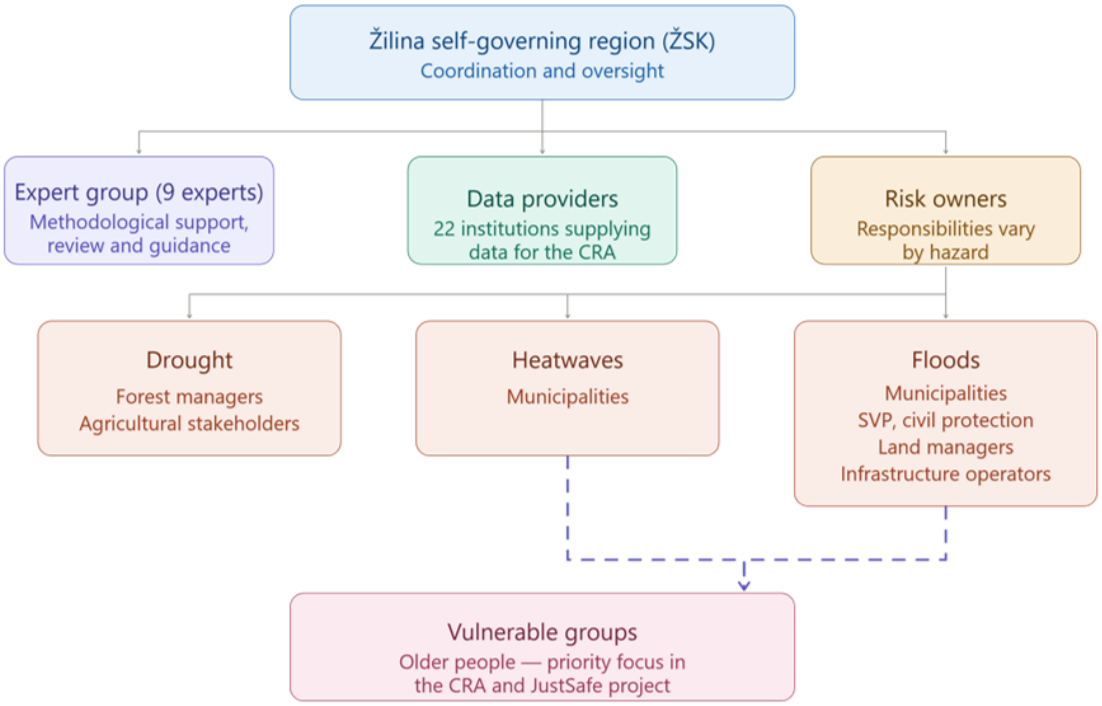

Figure 2-1 Organigram illustrating risks ownership

2.1.4. Application of principles

As Phase 2 was primarily focused on data collection, considerations of justice, equity, and inclusivity in stakeholder engagement could not be fully addressed at this stage. These aspects are instead being built into the design of Phase 3 activities.

The five planned sub-regional workshops are designed to reduce transport-related barriers to participation. Due to the region's mountainous terrain, travel time and transfers — rather than distance alone — often discourage attendance at events held only in the regional capital. The workshops will therefore take place in accessible local hubs across different parts of the region.

These workshops will primarily target risk owners who can act on the assessment findings, while outputs will also be made publicly available through online channels and the regional newspaper, distributed to every household.

Vulnerable groups remain a key consideration within the assessment itself rather than as direct workshop participants. Based on expert feedback, the vulnerable groups considered in Phase 3 will be expanded beyond older people to also include children under five and economically disadvantaged populations. It is also worth noting that the expert group maintains a gender-balanced composition.

2.1.5. Stakeholder engagement

Stakeholder engagement during Phase 2 focused on expert consultations, data collection, and dissemination of intermediate results. 2 expert meetings were organized during phase 2 where outputs were always presented on a large screen, with space for discussion and feedback. Outputs were also shared via SharePoint, allowing experts to provide feedback afterwards. Intermediate results were presented at an online meeting with the Slovak Insurance Association, as well as at the

InDays innovation conference, internal training programme organized through the P2R, and a trilateral exchange with representatives of the Moravian-Silesian Region and the Silesian Voivodeship. Feedback showed that stakeholders were particularly interested in the spatial distribution and frequency of hazards across the region. Outputs on agricultural drought, framed through crop yield losses, did not generate much interest among the audience. Visual outputs illustrating the effects of drought on forests attracted considerably more attention. More broadly, participants mainly focused on the spatial distribution of hazards, with much less attention to vulnerability. The term “risk” was used in a narrower sense, referring to hazard, or hazard combined with exposure rather than full climate risk. The final outputs will primarily support the integration of climate adaptation considerations into regional planning and project preparation. They also provide a basis for future discussions with sectoral stakeholders and municipalities. 2 additional expert meetings and 5 sub-regional workshops are planned for Phase 3. These activities will be used to present final results, collect feedback, and support the co-creation of the KRA. The main challenge encountered during Phase 2 was related to data availability and processing.

2.2. Risk Exploration

2.2.1. Screen risks (selection of main hazards)

Compared to the first deliverable, the selection of hazards for the CRA remained largely unchanged, with the only addition of drought and river flooding. The rationale for including these hazards has been described above. The publication of the new national adaptation strategy in spring 2026 further confirmed the relevance of the selected hazards. The strategy identifies extreme precipitation as the most significant climate hazard for the Žilina Region at present and projects the largest increase in its impacts among all Slovak regions in the future (MŽP, 2026). Since Phase 1, the knowledge available from public sources regarding where hazards occur and whom they affect has not substantially changed. However, the CRA carried out within this project has significantly improved the regional evidence base. In particular, knowledge of where hazards occur and how severe their impacts have been greatly enhanced through the development of a comprehensive impact database containing 863 records collected over a 13-year period. The creation of this database represents one of the key outcomes of the project. Its systematic maintenance and further expansion beyond the project's completion will be essential for supporting future CRA and evidence-based adaptation planning in the region.

2.2.2. Choose Scenario

Compared to Phase 1, the scenario selection was revised. The CRA focused primarily on the RCP 8.5 scenario for the period 2071–2100. This decision was influenced by the Žilina Region’s participation in the P2R project supporting the development of a regional adaptation strategy, action plan, and investment plan. The project promotes a long-term perspective on climate resilience and encourages regions to prepare for more severe future conditions. Designing adaptation measures for high-impact scenarios is considered more effective than repeatedly adjusting measures over time as climate impacts intensify. The assessment therefore combined a long-term climate scenario (RCP 8.5, 2071–2100) with relevant socio-economic trends. For the Žilina Region, the most significant socio-economic factor is population ageing. While demographic projections are available at the regional level, reliable municipality-level projections for the end of the century are not available. To account for the expected increase in the share of older residents, municipalities with more than 20% of the population aged 65 and over were considered particularly vulnerable, based on the assumption that many of these municipalities are likely to exceed 25% in the future. This is also supported by demographic projections indicating a stronger ageing trend by 2080 (Šprocha, 2024). The chosen time horizon reflects the long lead times required for adaptation planning and implementation. It also coincides with broader socio-economic pressures, including population ageing, rising energy costs, and increasing demands on infrastructure and social services.

2.3. Regionalized Risk Analysis

Phase 2 refined the CLIMAAX workflows through the integration of higher-resolution climate datasets, locally collected information, and several new datasets developed specifically for the Žilina Region. Compared to Phase 1, the assessment benefited from improved spatial resolution, a substantially expanded hazard-impact database, and additional sector-specific analyses covering agriculture, forests, river floods and tourism.

For heatwaves and heavy rainfall, hazard assessment was based on high-resolution (1 × 1 km) climate scenario data provided by SHMÚ. For variables requiring daily time-series data, Euro-CORDEX datasets were used, with the most suitable GCM–RCM combination selected using the CLIMAAX bias uncertainty tool. The heavy rainfall workflow was further refined through the integration of measured rainfall intensities corresponding to 163 flash flood events recorded in the hazard-impact database, compared with only 20 events used in Phase 1. Combined with an existing flash flood susceptibility map based on soil permeability (Solin, 2004), this enabled a more robust assessment of both current and future flash flood risk.

The heatwave assessment incorporated locally collected datasets from municipalities describing the spatial distribution of vulnerable population groups and locations that may experience high concentrations of people during hot summer days. The assessment also included facilities managed by ŽSK, as these assets are directly under regional control and can therefore be prioritised for future adaptation measures and investments.

A key element of both the heatwave and heavy rainfall workflows was the identification of municipalities, excluding cities, where residents aged 65 and over account for more than 20% of the population. Cities were excluded as the assessment focused on smaller municipalities, which generally have more limited budgets, weaker service provision, and lower accessibility to healthcare due to greater distance from regional centres, and are therefore considered comparatively more vulnerable. This threshold was selected to reflect expected demographic ageing over the coming decades, as municipality-level projections for the end of the century were not available.

Phase 2 also introduced several additional assessments. The agricultural drought assessment combined Euro-CORDEX-based yield-loss estimates with information on the dominant crops cultivated in the region. The forest assessment used tree suitability data from Seed4forest together with forest-type maps. River flood assessment used flood maps provided by SVP.

The tourism assessment used municipalities with supra-regional tourism importance, defined on the basis of visitor numbers. It combined the hazard datasets described above with records from the hazard-impact database and additional information on landslide-prone road sections and bridges in poor technical condition, reflecting potential impacts on the accessibility of tourist destinations.

Indirect impacts were not explicitly modelled as a separate analytical layer within the CRA. The assessment primarily focuses on hazard, exposure and vulnerability dimensions, with indirect consequences considered only implicitly through selected datasets and risk outputs.

2.3.1. Hazard #Heatwaves - fine-tuning to local context

Table 2-1 Data overview workflow #1

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
LST from LANDSAT 8-9 Summer months 2013-2024 (**RSLab**)	Exposed kindergartens, hospitals and social care buildings for 4 biggest cities with UHI potential (data from the local municipalities)	ŽSK-managed buildings by adaptation potential assessment status	Heat risk to vulnerable population based on the combination of the LST and local vulnerability for 4 biggest cities with the potential of the heat island effect occurrence (depends on the city)
National Climate scenarios – Tropical day and nights occurrence. (**SHMU**)	Vulnerable municipalities with a population aged 65+ exceeding 20% (**Statistical office of the Slovak republic**)		Heat risk to vulnerable population based on the occurrence of the tropical days and municipalities with the share of the vulnerable population over 20% (past and projection)

2.3.1.1. Hazard assessment

The phase two hazard assessment was based on two approaches:

1. The national SHMÚ climate scenarios for the occurrence of tropical days.
2. The LST images from RSLab for the summer months.

The SHMÚ climate scenarios for the occurrence of tropical days:

For the second phase, national climate scenarios from SHMÚ were selected to show the possible projected changes in heat-related variables, namely tropical days and tropical nights. SHMÚ does not provide daily data from which heatwave occurrence can be estimated, as was done using Euro-CORDEX data in the first phase. Therefore, from the variables provided by SHMÚ through Klima-adapt (2026), the occurrence of tropical days and tropical nights was selected as the most relevant threat to the vulnerable population.

The provided variables are available in a downscaled 1 km grid for the climate normal periods 1991–2020, 2021–2050, and 2071–2100, and for the RCP 4.5 and RCP 8.5 scenarios. The results presented in Tables 2-2 and 2-3 were estimated as the statistical mean and maximum values for the provided time periods and RCP scenarios. The results are also presented in Figures 2-1 and 2-2 to support better visual interpretation and the localization of the most problematic areas in relation to the spatial distribution of the vulnerable population.

According to SHMÚ, a tropical day is defined as a day when the daily maximum air temperature reaches 30 °C or more. The temperature of 30 °C A tropical night is defined as a night during which the air temperature does not fall below 20 °C. In practice, this means that the minimum night-time temperature remains 20 °C or higher.

Table 2-2 Projected Annual Number of Tropical Days in the Žilina region based on the SHMÚ climate scenarios

time period		*scenario*	*mean*	*max*	*relative change in mean value to reference period (%)*
ref. period	1991-2020		7,5	16,6	
near future	2021-2050	RCP 4.5	10,6	21,3	41%
		RCP 8.5	10,6	21,1	41%
far future	2071-2100	RCP 4.5	13,0	25,3	73%
		RCP 8.5	24,9	41,8	232%

Table 2-3 Projected Annual Number of Tropical Nights in the Žilina region based on the SHMÚ climate scenarios

time period		*scenario*	*mean*	*max*
ref. period	1991-2020		0,1	0,8
near future	2021-2050	RCP 4.5	0,4	1,8
		RCP 8.5	0,5	1,9
far future	2071-2100	RCP 4.5	0,8	3,3
		RCP 8.5	4,8	12,5

The results presented in Tables 2-2 and 2-3 show an increase in the occurrence of tropical days and tropical nights, which may cause problems for the vulnerable population. The highest potential increase is projected under the RCP 8.5 scenario for the period 2071–2100 when the mean annual number of tropical days is expected to increase from 7.5 to 24.9 days per year and the mean annual number of tropical nights from 0.1 to 4.8 nights per year compared to the reference period. This time period and scenario were also selected by ŽSK for the visual presentation of the results.

The LST images from RSLab for the summer months:

For the local-level hazard assessment, Land Surface Temperature (LST) data from the first phase were used for the four largest cities within the ŽSK. ŽSK is the most mountainous region in Slovakia and has one of the highest shares of forested areas, which generally limits the conditions for the development of urban heat island effects. Therefore, the four largest cities in terms of population were selected for the urban heat island analysis in the first phase. The second phase follows this workflow and further improves it by incorporating local vulnerability and exposure data. The five-point LST scale was selected to highlight the most overheated parts of the urban areas in the four largest cities of the Žilina Region. The threshold of 40 °C, used to separate high and very high surface heat classes, is supported by studies that apply or analyses LST thresholds around 35–40 °C and above 40 °C to identify strongly overheated built-up, commercial and industrial surfaces. Similar studies in Central and Eastern European urban areas show that LST values above 35, 38 and 40 °C are strongly associated with built-up areas (Ivan et al., 2017; Renc et al., 2022; Dimitriou et al., 2025).

2.3.1.2. Risk assessment

The heatwave risk and exposure assessment was divided into three steps:

1. A regional assessment based on SHMÚ climate scenarios and vulnerable municipalities.

2. An assessment of heat exposure of facilities under the management of ŽSK.
3. An assessment of heat risk to vulnerable people and heat exposure of vulnerable places.

A regional assessment based on SHMÚ climate scenarios and vulnerable municipalities

The higher spatial resolution of climate scenarios provided by SHMU 1x1km (against the first phase Euro-Cordex 12x12km) allows to also apply the risk approach on the level of the Žilina region. For this approach the variable of the tropical days was selected with the combination of the vulnerable municipalities where the share of the vulnerable population is more than 20% (which is used as high vulnerability). These results provided valuable information on the regional scale since the MAXICONZA project aims to focus on the small villages with the higher number of the vulnerable population (Figure 2-1 and 2-2). The results show that the projected occurrence in the period 2071-2100 should bring the significant change in the tropical days occurrence also in the vulnerable municipalities (vulnerable population above 20%) and also in the 4 biggest cities (by total population) inside the ZSK. The vulnerable municipalities in this the mean annual number of the tropical days should be higher than 30 were highlighted in the Figure 2-2.

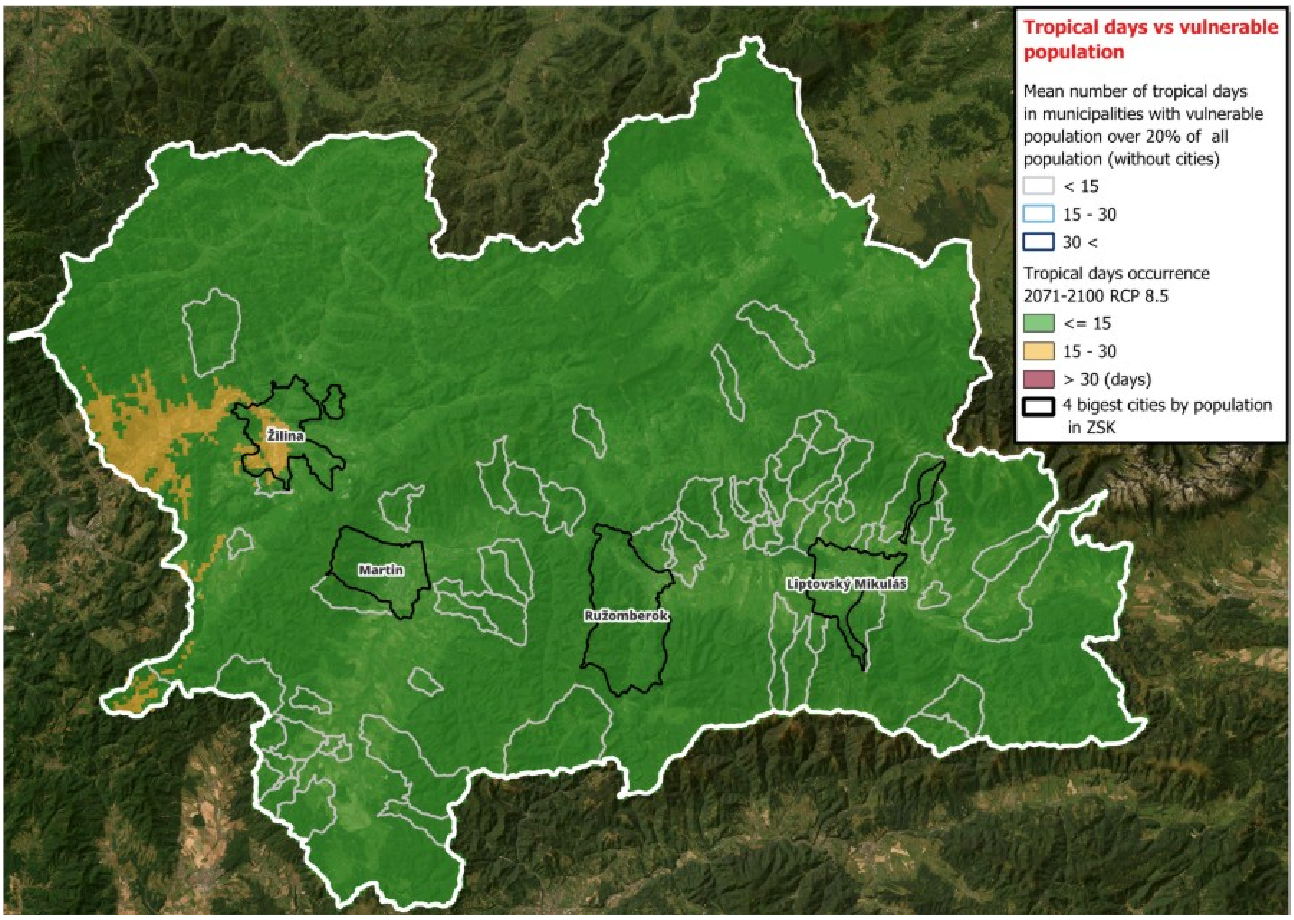

Figure 2-2 Occurrence of tropical days in 1991–2020 and spatial distribution of vulnerable municipalities

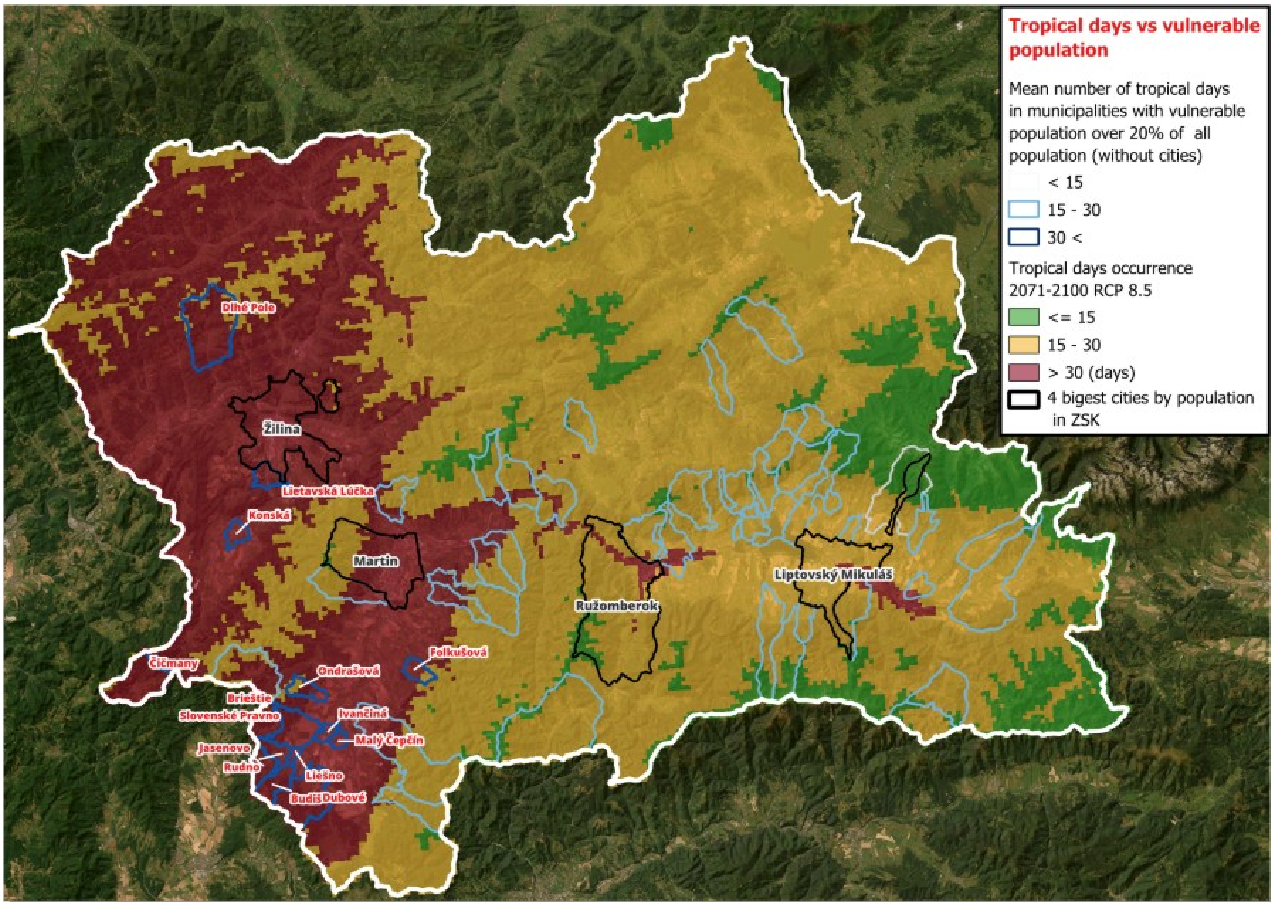

Figure 2-3 Projected occurrence of tropical days in 2071–2100 RCP 8.5 and spatial distribution of vulnerable municipalities

The heat exposure to the facilities under the management of the ŽSK:

In the next step, the analysis focused on the four largest cities by population within ŽSK: Žilina, Martin, Ružomberok, and Liptovský Mikuláš. The focus was placed on buildings under the administration of ŽSK, as possible adaptation measures can be implemented more easily in these buildings.

Based on LST data from the summer months and the spatial distribution of ŽSK objects, buildings located in areas with the highest LST values were identified. The results also include a list of buildings and information on whether ŽSK has already validated their adaptation potential or whether further validation is needed. ŽSK objects located in areas with the highest LST values will be prioritized in the next validation process. The result for the city of Žilina is presented in Figure 2-3, the other results are uploaded to Zenodo.

Objects under management of ZSK

ID	Object	Validated adpatation potential
1	BD Žilina Kuzmányho	NO
2	BD Žilina Pri Rajčianke	NO
4	CSS Harmónia Republiky	YES
5	CSS Harmónia útulok	YES
7	CSS Letokruhy 6,7	YES
8	CSS Letokruhy 8,9	YES
9	CSS Lúč Strážov	YES
10	CSS Lúč Žilina	YES
13	CSS Straník Horizont	NO
14	CSS Straník Zástranie	NO
15	CSS Synnómia Moyzesova	YES
16	CSS Synnómia Sv. Gorazda	YES
20	Gymnázium Hlinská Žilina	YES
24	Gymnázium V. Okružná Žilina	YES
26	Gymnázium Varšavská Žilina	YES
29	Hotelová akadémia Žilina	YES
30	Hvezdáreň Žilina Malý diel	NO
31	Jazyková škola Žilina	NO
32	Konzervatórium Žilina A	NO
33	Konzervatórium Žilina B a D	YES
34	Krajská knižnica Žilina	NO
35	Krajské KS Makovického	NO
46	Obchodná akadémia Žilina	NO
47	Považská galéria	NO
52	SOŠ dopravná Žilina Košická	NO
53	SOŠ dopravná Žilina Rosinská	YES
54	SOŠ elektrotechnická Žilina	YES
57	SOŠ podnikania a služieb Bytčica	YES
58	SOŠ poľnohospodárstva a služieb Žilina	YES
60	SOŠ stavebná dielne Bánová	NO
63	SOŠ stavebná Žilina Tulipánová	YES
68	SPŠ stavebná Žilina	YES
70	Športová škola Žilina	YES
73	Vnútorná správa Hollého	NO
74	Vnútorná správa Komenského	YES
75	Vnútorná správa Sasinkova	NO
77	Zdravotnícka škola Žilina	YES

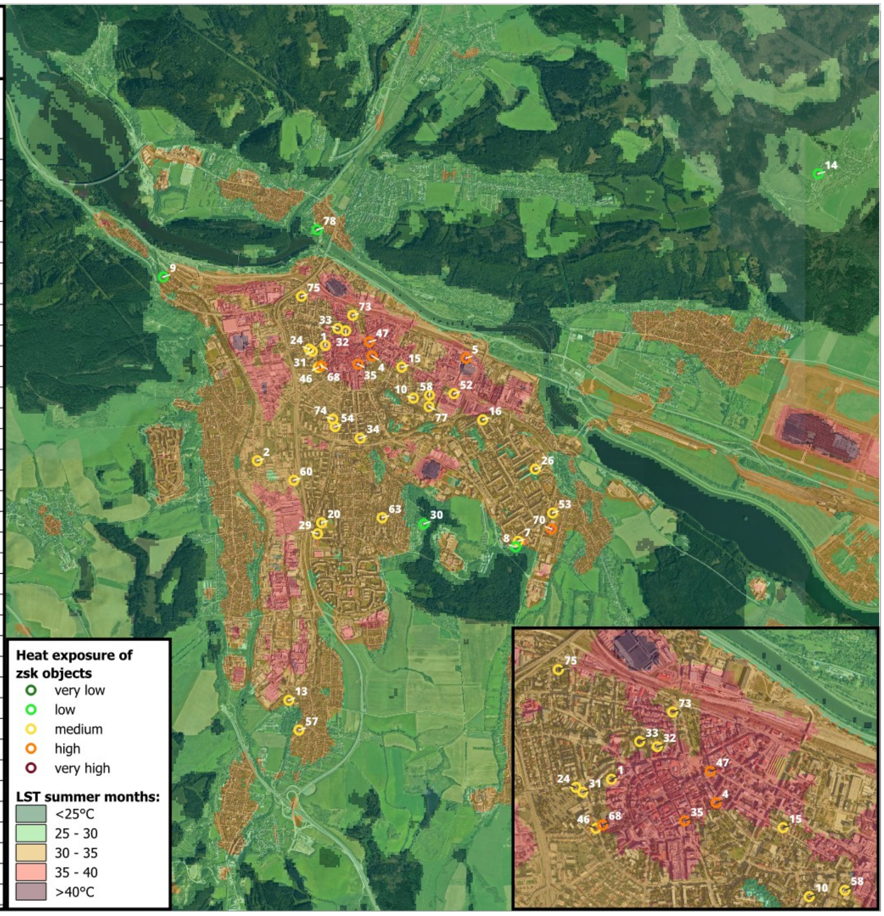

Figure 2-4 Heat exposure to the facilities under the management of the ŽSK, in Žilina city.

The heat risk and exposure to vulnerable people (risk) and places (exposure):

Subsequently the representatives of the 4 biggest cities by population were asked to provide the data about the most vulnerable buildings, infrastructure, and population inside their city. The data provided varied between cities. Žilina supplied maps of critical infrastructure, areas with high concentrations of vulnerable groups (older people and young children), and locations that experience high population densities during hot summer periods. Martin provided data on the spatial distribution of children under four years of age, residents aged 75 and over, economically disadvantaged populations, kindergartens, and social care facilities. (Figure 2-5). The Liptovský Mikuláš provided the spatial distribution of the kindergartens and social care facilities, and Ružomberok city provides the spatial distribution of the social care centres. The examples of the results for the Martin city are displayed on the Figure 2-4.

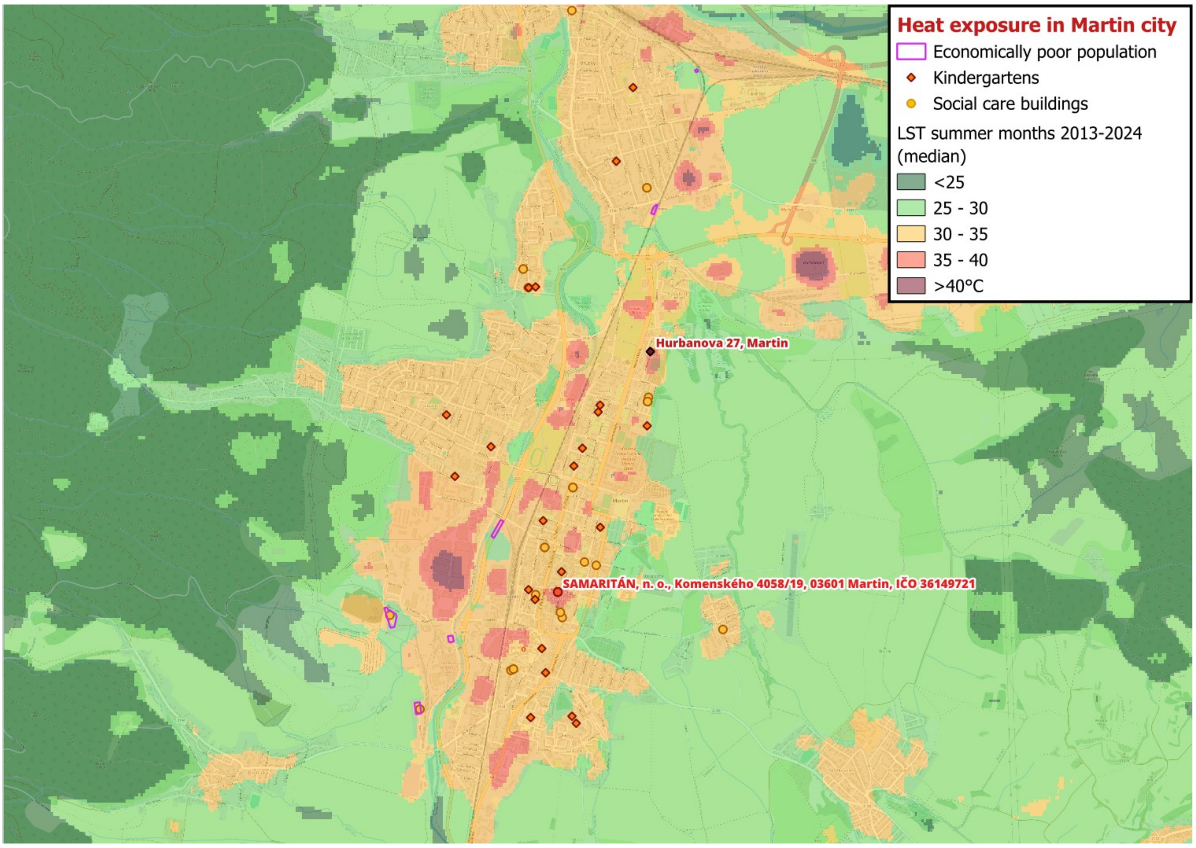

Figure 2-5 Heat (LST summer days) exposure to the economically poor population, kindergartens and social care buildings (data provided by Martin city office)

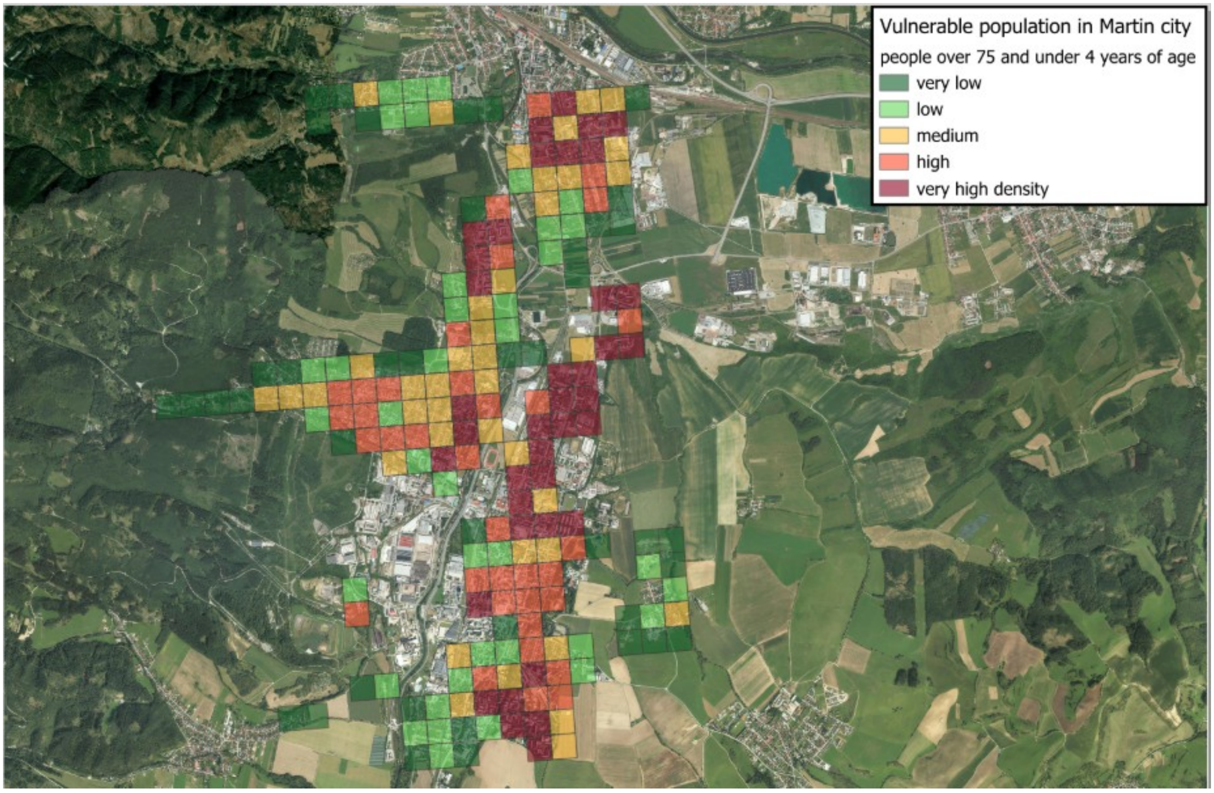

Figure 2-6 Spatial distribution of the vulnerable population over the city of Martin

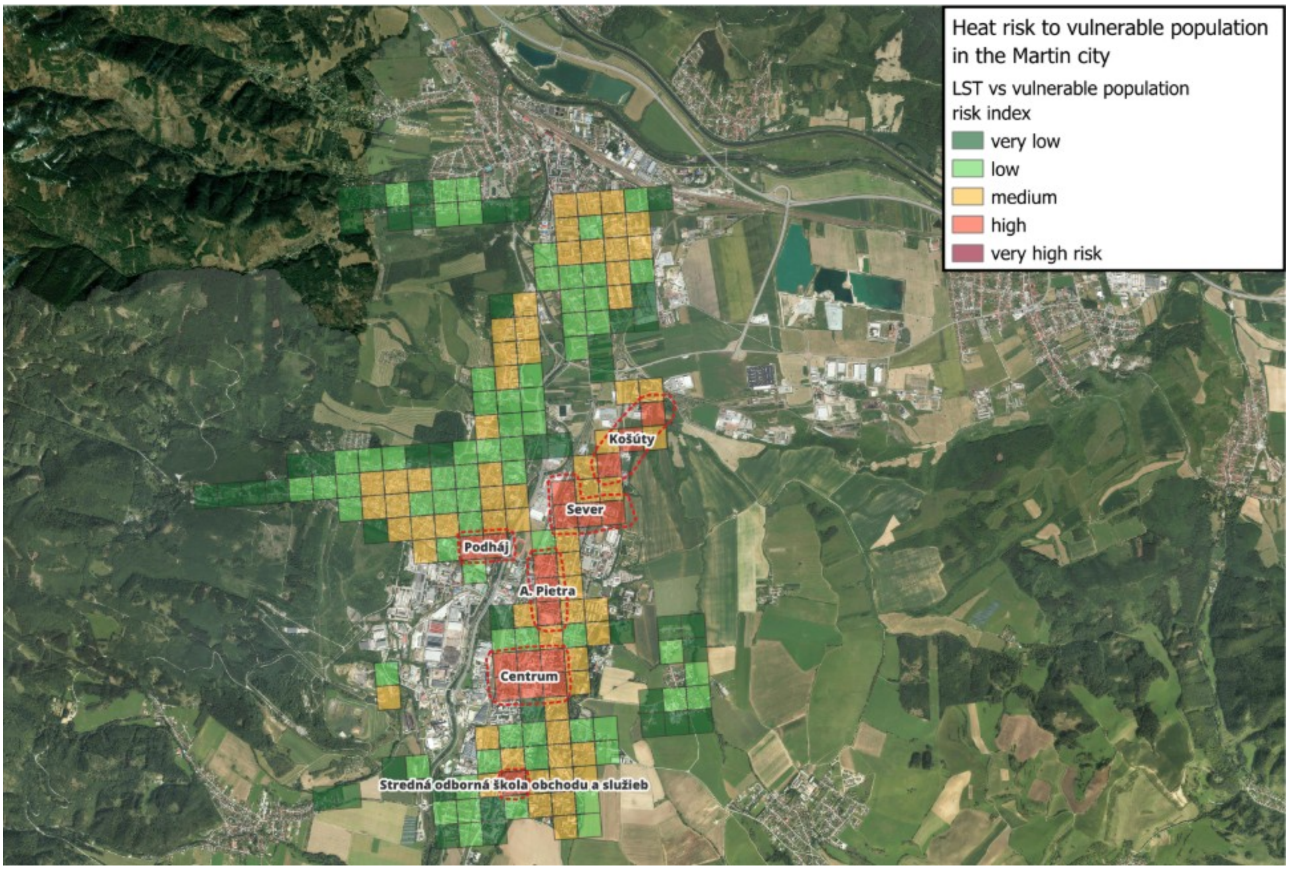

Figure 2-7 The heat risk to vulnerable population (locally estimated by the Martin city office), with the highlighted areas with high and very high heat (not occurred) risk.

Since each of the cities provided slightly different local vulnerability data, the datasets had to be adapted for use in the heat risk matrix where possible (CLIMAAX handbook, heatwaves). In the city of Martin, the local vulnerable population dataset was provided as the number of vulnerable people per 250 m grid cell. These cells were divided into five groups according to the number of vulnerable people, using five equal intervals. As a final step, a 5 × 5 risk matrix combining vulnerable population and LST was used to estimate areas exposed to heat risk.

The areas with high heat risk are highlighted in Figure 2-6. No areas with very high heat risk were identified. The highlighted high-risk areas are mainly densely built-up residential areas in the city of Martin. Based on this analysis, these areas, together with the kindergarten on Hurbanova 27 Street and social care building Samaritán (Figure 2-4) should be prioritized for the implementation of adaptation and monitoring measures.

From the selected 4 biggest cities inside the ŽSK, the LST reaches the highest numbers inside the Žilina and Martin cities. The Žilina city was also selected as a pilot city inside the CLIMAAX heatwave workflow. In this study the buildings which are under the management of the ŽSK

2.3.2. Hazard Heavy rainfall - finetuning to local context

Table 2-4 Data overview workflow Heavy rainfall

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
SHMÚ climate scenario of the occurrence of days with	Vulnerable municipalities with a	Municipality, district, affected buildings, affected transport,	Vulnerable municipalities at risk of the heavy rainfall

Hazard data	*Vulnerability data*	*Exposure data*	*Impact metrics/Risk output*
precipitation over 40mm 2021-2050 and 2071-2100 RCP 4.5 and 8.5 (SHMU)	population aged 65+ exceeding 20% (Statistical office of the Slovak republic)	affected people, roads/bridges recorded in hazard impact database (MAXICONZA)	occurrence historical 1991-2020 and future occurrence 2071-2100 and flood susceptibility by soil permeability (MAXICONZA)
EuroCordex daily precipitation 1975-2099 (CDS)		Catchments contributing to the vulnerable municipalities (MAXICONZA)	Estimated impact based on the hazard impact database (MAXICONZA)
Floods susceptibility map based on the soil permeability (GKU)			
163 registered heavy rainfall events with the measured intensities mm/24 hours (MAXICONZA + SHMU)			
Estimated return periods for the measured intensities in ŽSK (CLIMAAX workflow)			

2.3.2.1. Hazard assessment

The Phase 2 hazard assessment was based on 4 approaches:

1. SHMÚ climate scenarios for the average annual number of days with precipitation > 40 mm.
2. Euro-CORDEX climate scenarios from CDS, used to estimate IDF curves.
3. Measured rainfall intensities from SHMÚ for registered heavy rainfall events within ŽSK.
4. Flood susceptibility maps based on the soil permeability

SHMÚ climate scenarios for the average annual number of days with precipitation > 40 mm:

For the hazard assessment in the first phase, the heavy rainfall workflow based on Euro-CORDEX data was used. The Euro-CORDEX data had a relatively coarse spatial resolution of 12 × 12 km. In the second phase, higher-spatial-resolution 1 × 1 km climate scenarios from SHMÚ were used for the average annual number of days with precipitation totals above 40 mm.

However, SHMÚ does not provide daily time-step datasets that would allow the estimation of selected historical and future heavy rainfall intensities or return periods. Instead, SHMÚ provides data estimating the mean annual occurrence of days with precipitation totals above 40 mm/24 h for the climate normal periods 1991–2020, 2021–2050, and 2071–2100. In addition, SHMÚ defined the 40 mm/24 h threshold as a heavy rainfall event that can potentially affect local infrastructure and people and provides results only for this precipitation intensity. The estimated results for the area of the ŽSK based on the SHMÚ climate scenarios are displayed in Table 2-5.

Table 2-5 Projected Annual Number of Heavy Rain Days (>40 mm/day) (SHMU, climate scenarios)

time period		*scenario*	*mean*	*max*	*relative change in mean value to reference period (%)*
ref. period	1991-2020		0,9	3,3	

time period		*scenario*	*mean*	*max*	*relative change in mean value to reference period (%)*
near future	2021-2050	RCP 4.5	1,6	3,3	78%
		RCP 8.5	1,8	4,0	100%
far future	2071-2100	RCP 4.5	1,8	3,9	100%
		RCP 8.5	2,1	4,1	133%

Euro-CORDEX climate scenarios from CDS, used to estimate IDF curves:

Since SHMÚ does not provide daily climate datasets required for the estimation of rainfall intensities and related return periods, the Euro-CORDEX data from CDS were used following the CLIMAAX heavy rainfall hazard workflow. As in Phase 1, Euro-CORDEX data were applied; however, for Phase 2, the combination of the GCM and RCM was selected based on the CLIMAAX Bias and Uncertainty Tool (CLIMAAX, handbook) (Table 2-6). In line with the justification provided above for selecting the 2071–2100 period, the closest available Euro-CORDEX timeframe (2070–2099) was used in combination with the RCP 8.5 scenario, due to data availability constraints.

Table 2-6 Selection of the GCM and RCM based on the CLIMAAX bias uncertainty tool (CLIMAAX, handbook)

Global Climate Model	*Regional Climate Model*	*Precipitation*	*Temperature*
MOHC-HadGEM2-ES	KNMI-RACMO22E	-0.77	-1.35

Following the heavy rainfall hazard workflow the intensities and return period for the selected time periods and RCP was estimated. The results are displayed in the Figure 2-7 and Table 2-7; the results show a significant increase of the intensities for the projected 2070-2099 RCP 8.5 period or shortened Return period for the same intensities.

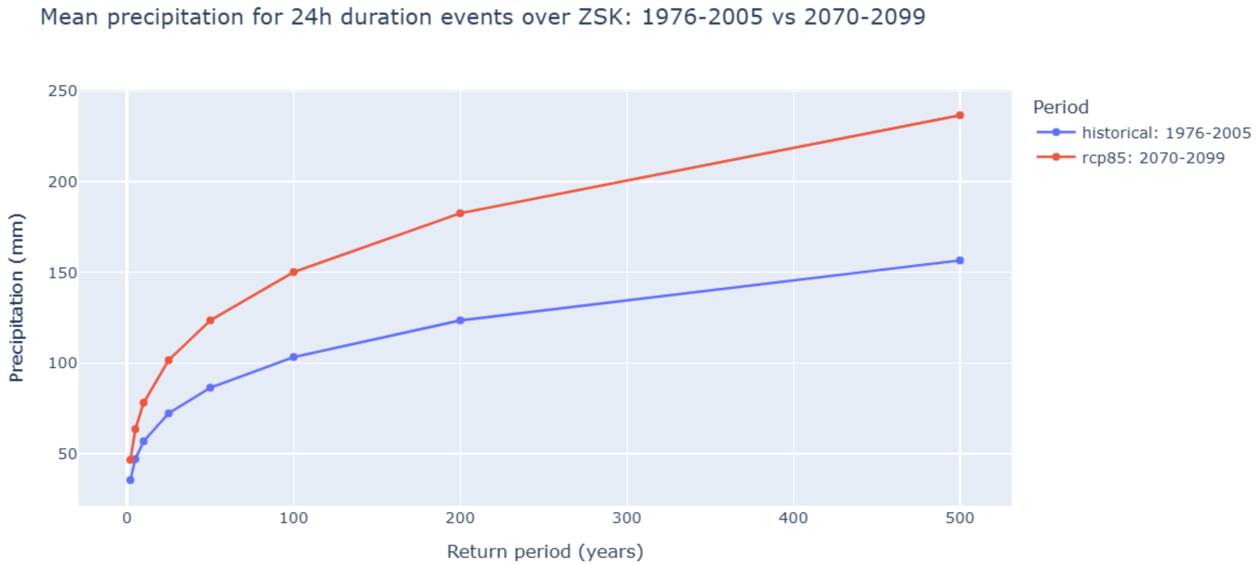

Figure 2-8 Mean precipitation for the 24h duration events over ŽSK based on Euro-CORDEX climate scenarios, using the GCM MOHC-HadGEM2-ES and the RCM KNMI-RACMO22E, for the historical period 1976–2005 and the future period 2070–2099 under the RCP8.5 scenario

Table 2-7 Estimated rainfall intensities (mm/24 h) and return periods (years) based on Euro-CORDEX climate scenarios, using the GCM MOHC-HadGEM2-ES and the RCM KNMI-RACMO22E, for the historical period 1976–2005 and the future period 2070–2099 under the RCP8.5 scenario

Return period, RP (years)	*Historical 1976–2005 intensity (mm/24 h)*	*RCP8.5 2070–2099 intensity (mm/24 h)*
2	36	48
5	48	64
10	57	79
25	72	101
50	86	123
100	103	150

The estimated mean return period (RP) for the intensity of 40 mm/24 h, corresponding to the SHMÚ heavy rainfall threshold, was close to 3 years for the ŽSK area in the historical period 1976–2005, based on Euro-CORDEX data. More specifically, the extrapolated value was approximately 2.7 years. For the future period 2070–2099, the same intensity is projected to correspond to a return period close to 1 year, with an extrapolated value of approximately 1.3 years. These estimates were derived by extrapolation from the displayed IDF curves (Table 2-8).

The Euro-CORDEX-derived results are compared with the higher-resolution results based on SHMÚ scenarios for the period 2071–2100, or 2070–2099 in the case of Euro-CORDEX, in Table 2-8. The SHMÚ-derived results predict a much more frequent occurrence of heavy rainfall events. These differences may be caused by several factors, such as spatial resolution, more precise bias correction in the SHMÚ scenarios, and differences in the underlying climate models and methodological assumptions. Results were also displayed in the Figures 2-8 and 2-9 (Euro-Cordex) and Figures 2-11 and 2-12 (SHMU) to better understand the resolution differences. However, based on these results, it can be assumed that the SHMÚ scenarios predict a much more frequent occurrence of heavy rainfall events. This information should therefore be considered when planning future flash flood mitigation measures in ŽSK.

Table 2-8 Estimated return periods for the 40mm/24h intensity based on the Euro-Cordex and SHMU climate scenarios for the 2071-2100 time period RCP 8.5

40mm/24h in 2071-2100 RCP 8.5	*Return period (RP)*
Euro-Cordex (12x12km)	1.3 (0.77 per year)
SHMU (1x1km)	0.48 (2.1 per year)

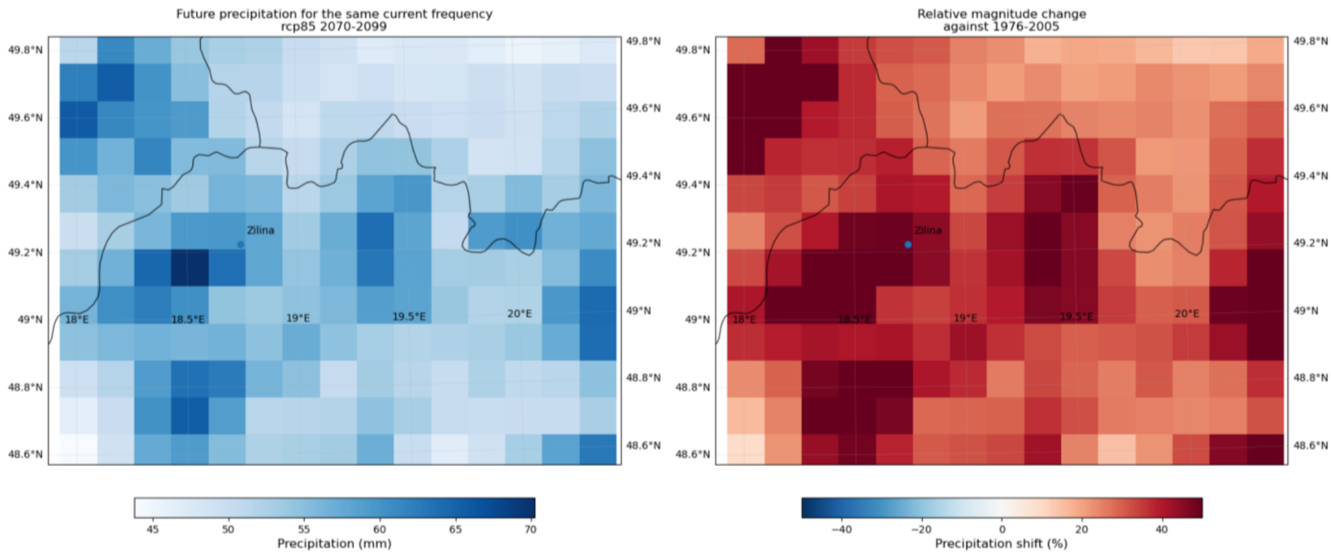

Figure 2-9 Magnitude shift for the current (1976-2005) frequency of 40mm/24h threshold over ŽSK based on Euro-CORDEX climate scenarios, using the GCM MOHC-HadGEM2-ES and the RCM KNMI-RACMO22E, for the historical period 1976–2005 and the future period 2070–2099 under the RCP8.5 scenario

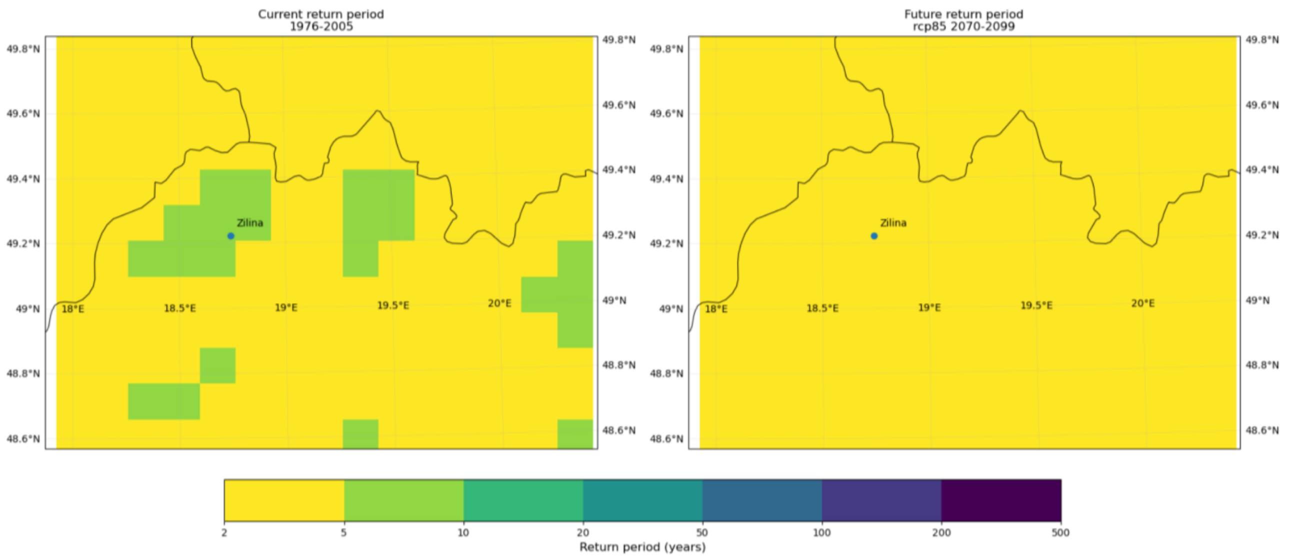

Figure 2-10 Return period shift for 40mm/24h threshold over ŽSK based on Euro-CORDEX climate scenarios, using the GCM MOHC-HadGEM2-ES and the RCM KNMI-RACMO22E, for the historical period 1976–2005 and the future period 2070–2099 under the RCP8.5 scenario

Measured rainfall intensities from SHMÚ for registered heavy rainfall events within ŽSK:

In the first phase, the hazard-impact database was based only on publicly available content, such as scientific papers and news reports. In the second phase, the database was extended using measured rainfall intensities from SHMÚ (paid data), together with information on registered heavy rainfall events from local administration statistics, flood reports, the Slovak Ministry of the Environment, and the Ministry of the Interior.

In total, 163 registered heavy rainfall events within ŽSK were collected for the period 2012–2025, as the databases started publishing flood reports data from 2012. However, flood reports and local administration statistics do not contain information on measured rainfall intensities. They mainly include information on damage, timing, and event duration. For this reason, the rainfall intensity datasets need to be purchased additionally from SHMÚ. The registered heavy rainfall events with measured intensities are displayed in Figure 2-10.

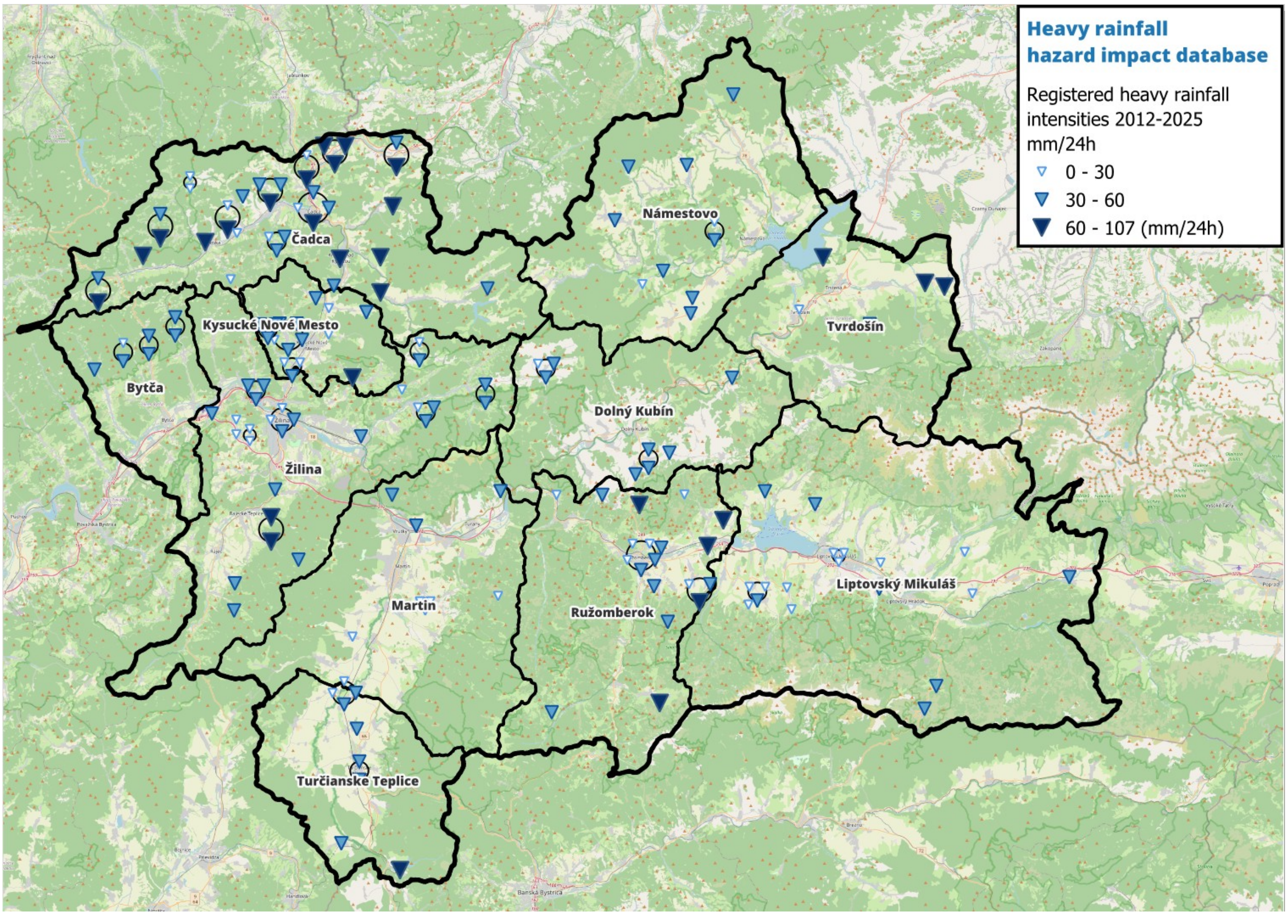

Figure 2-11 Registered heavy rainfall intensities inside the ŽSK for the years 2012-2025

Flood susceptibility maps based on the soil permeability:

Because the ŽSK region is characterized by hilly terrain and steep slopes, soil permeability is an important factor that can contribute to flooding during heavy rainfall events. Within the cooperation of the CLIMAAX SK group, a flood susceptibility map based on soil permeability in small basins was obtained from GKÚ (Solin, 2004). This map, presented in Figure 2-15 in the risk section, shows the potential for flood occurrence caused by soil properties, mainly soil texture and structure.

Figure 2-15 also shows the spatial distribution of registered heavy rainfall impacts in relation to flood susceptibility. The results indicate a strong relationship between the flood susceptibility map and registered flood occurrences. After excluding points that did not intersect with the susceptibility catchment layer, 79.7% of the registered heavy rainfall events occurred in catchments with high flood susceptibility. This result supports the importance of the hazard-impact database and increases the relevance and credibility of the assessment results.

2.3.2.2. Risk assessment

Comparison of the Phase1 and Phase 2:

In Phase 1, the heavy rainfall risk assessment was based only on a hazard-impact database containing 20 registered events identified from news and other online sources. Changes in rainfall intensity and return periods were assessed using Euro-CORDEX data with a test combination of GCM and RCM.

In Phase 2, an improved version of the hazard-impact database was used, containing 163 registered events. The GCM and RCM combination used for estimating changes in heavy rainfall intensity and return periods was selected based on the CLIMAAX Bias and Uncertainty Tool. Based on the improved hazard-impact database, vulnerable municipalities were highlighted according to impacts on people, infrastructure, and transport. In addition, pre-calculated high-resolution national SHMÚ climate scenarios with a spatial resolution of 1 × 1 km were used in combination with the distribution of the vulnerable population and flood susceptibility maps from GKÚ (Solin, 2004).

The heavy rainfall risk assessment consists of the 2 parts:

1. Annual mean number of days over 40 mm/24h vs vulnerable municipalities vs flood susceptibility
2. Hazard impact database (163 registered events) for whole ZSK area

Annual mean number of days over 40 mm/24h vs vulnerable municipalities vs flood susceptibility:

The Phase 2 risk assessment compares the occurrence of the annual mean number of days with precipitation above 40 mm/24 h, which is the SHMÚ threshold for heavy rainfall events with potential destructive impacts, with the spatial distribution of municipalities where the share of the vulnerable population over 65 years of age is high and flood susceptibility based on the soil permeability.

The comparison of the vulnerable municipalities with the SHMU scenarios was carried out for the historical period, 1991–2020, and the future climate period, 2071–2100 under RCP 8.5 Figures 2-11 and 2-12 (below).

The selected municipalities, based on the share of vulnerable population, represent pilot vulnerable municipalities. The main goal of the project is to focus primarily on these municipalities, assess how they were affected by climate risks in the past, and prepare them for possible future climate-related challenges.

Based on the results presented in Figures 2-11 and 2-12 (below), it is evident that the total number of heavy rainfall days is expected to increase across almost the entire ŽSK region. The increase is particularly pronounced in areas with higher altitude, where the mean annual occurrence of heavy rainfall days is expected to almost triple.

Since cadastral areas can differ from hydrological catchment boundaries, this aspect was also considered. Based on the comparison of catchment and municipality boundaries, most municipality boundaries follow the shape of the catchments. This is because ŽSK is a mountainous region, where catchments and municipalities are often separated by mountain ridges.

Therefore, the annual mean number of heavy rainfall days for vulnerable municipalities was estimated based on the occurrence of these days in the catchments that contribute to each vulnerable municipality.

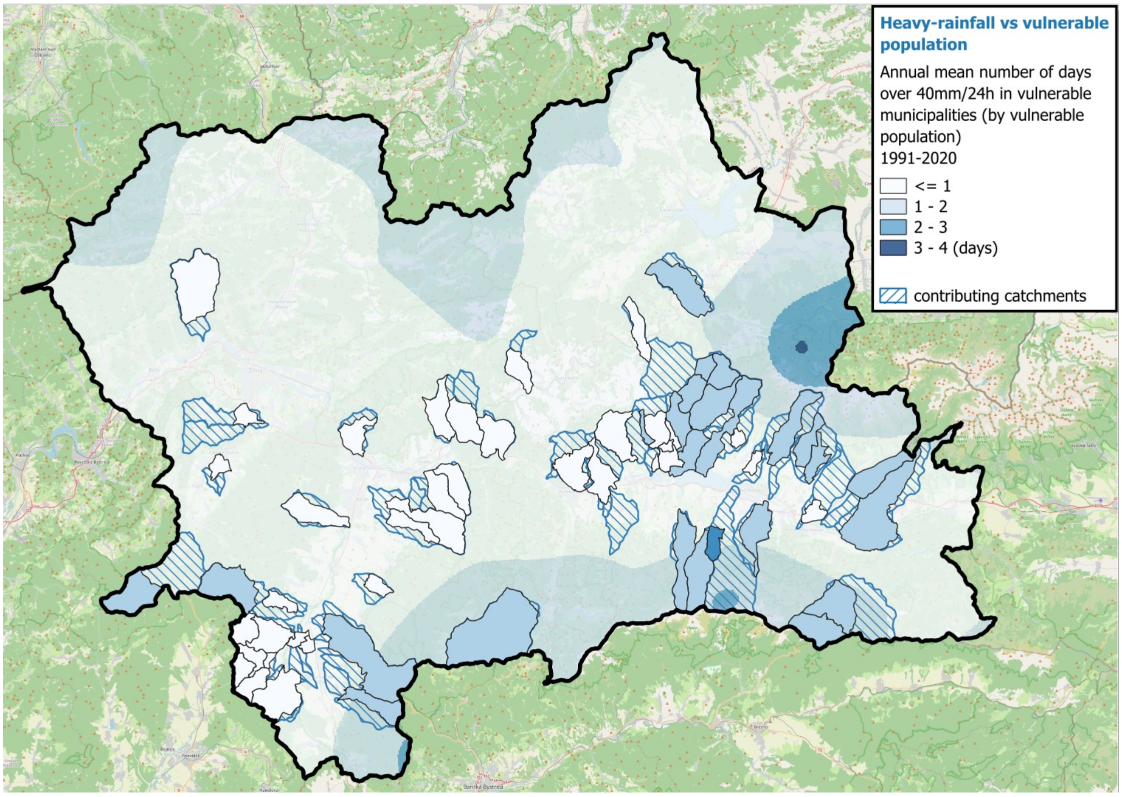

Figure 2-12 Mean annual number of days above 40mm/24h in the ŽSK vs vulnerable municipalities (with contributing catchments) for the historical period 1991-2020 based on the SHMU climate scenarios.

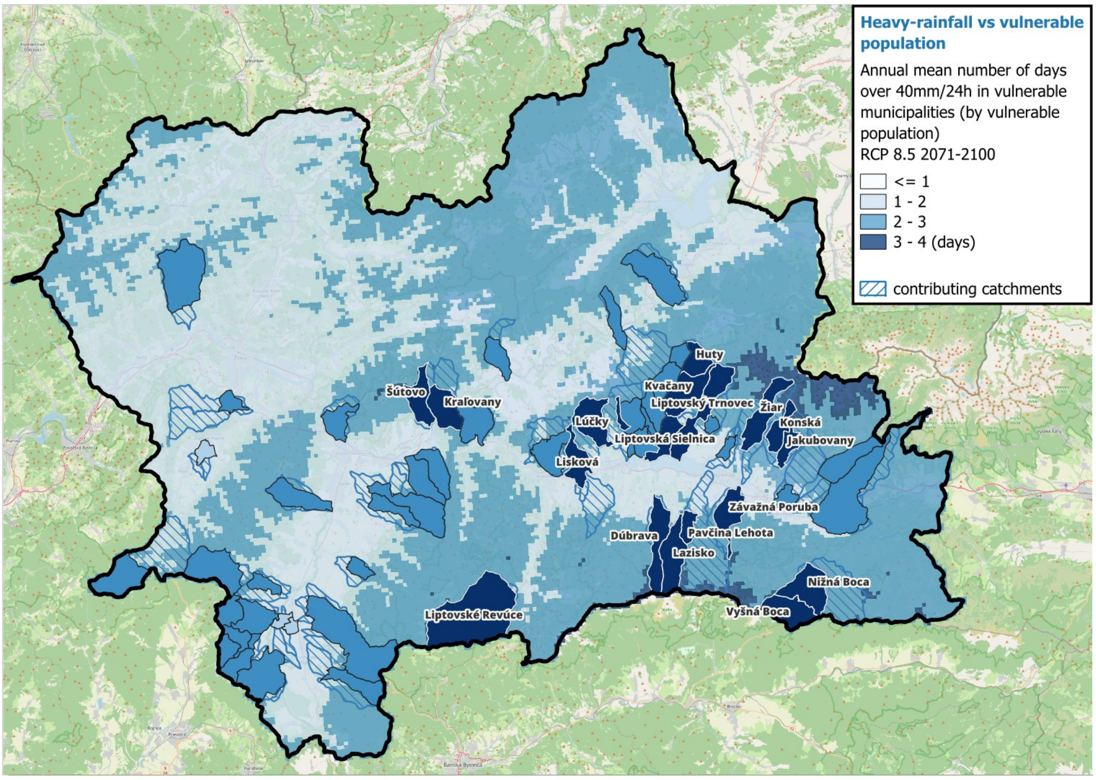

Figure 2-13 Mean annual number of days above 40mm/24h in the ŽSK vs vulnerable municipalities (with contributing catchments) for the period 2071-2100 RCP 8.5 based on the SHMU climate scenarios.

From the perspective of SHMÚ heavy rainfall climate occurrence scenarios, the most affected vulnerable municipalities are expected to be located near the Low Tatras and Western Tatras, mainly in the Liptovský Mikuláš, Ružomberok, and Dolný Kubín districts. These districts are characterized by high mountain relief, with peaks above 2,000 meters, which may influence the occurrence of heavy rainfall events in the future according to the provided scenarios.

From the vulnerable municipalities with the highest number of projected heavy rainfall days was selected those which also have the high susceptibility to floods based on the soil permeability. From total of 60 vulnerable municipalities were selected 12 vulnerable municipalities which are highest danger from projected heavy rainfall occurrence for the period 2071-2100 RCP 8.5 (SHMU) and with highest flood susceptibility form the soil permeability (GKU), the results are displayed on the Figure 2-14 (below).

For better visual interpretation the schematic description of the workflow was created Figure 2-13.

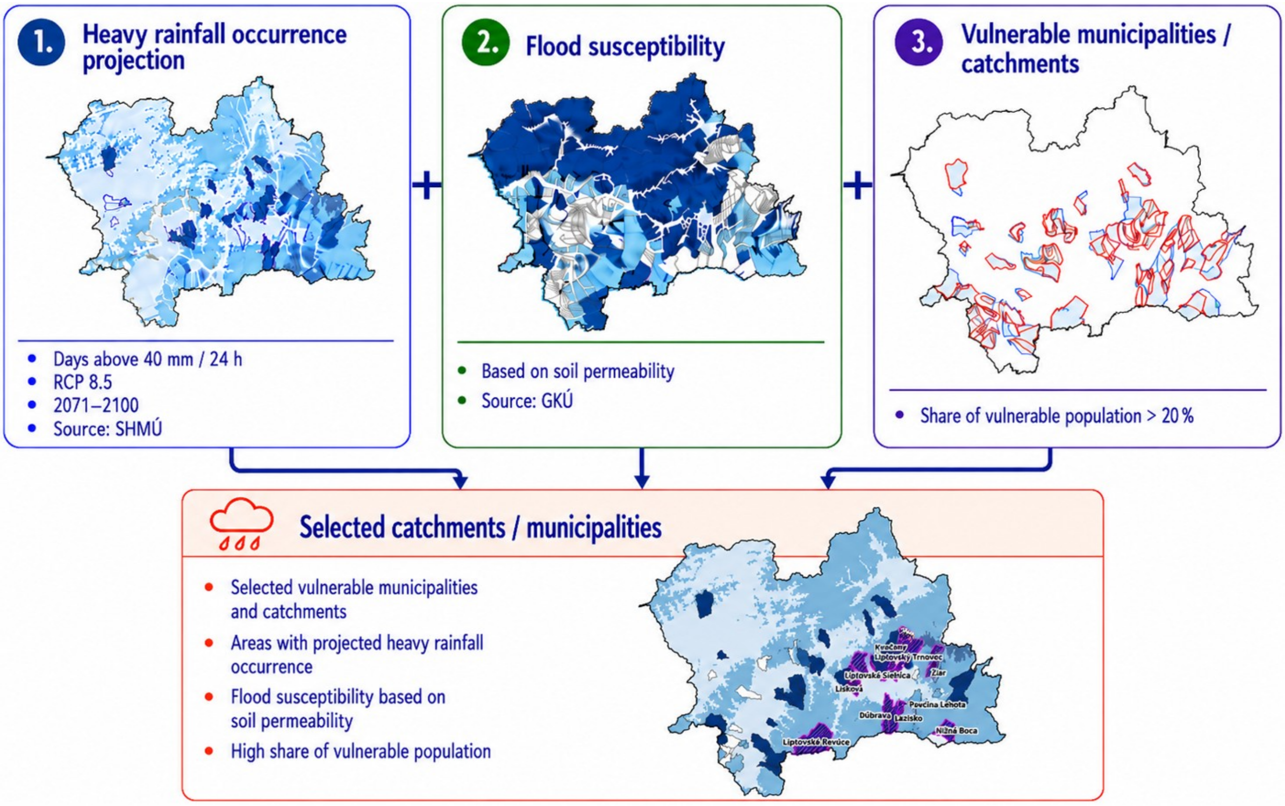

Figure 2-14 Heavy rainfall risk schematic description of catchments selection based on flood susceptibility (GKÚ), projected heavy rainfall occurrence 2071-2100 RCP 8.5 (SHMU, climate scenarios) and share of the vulnerable population above 20%

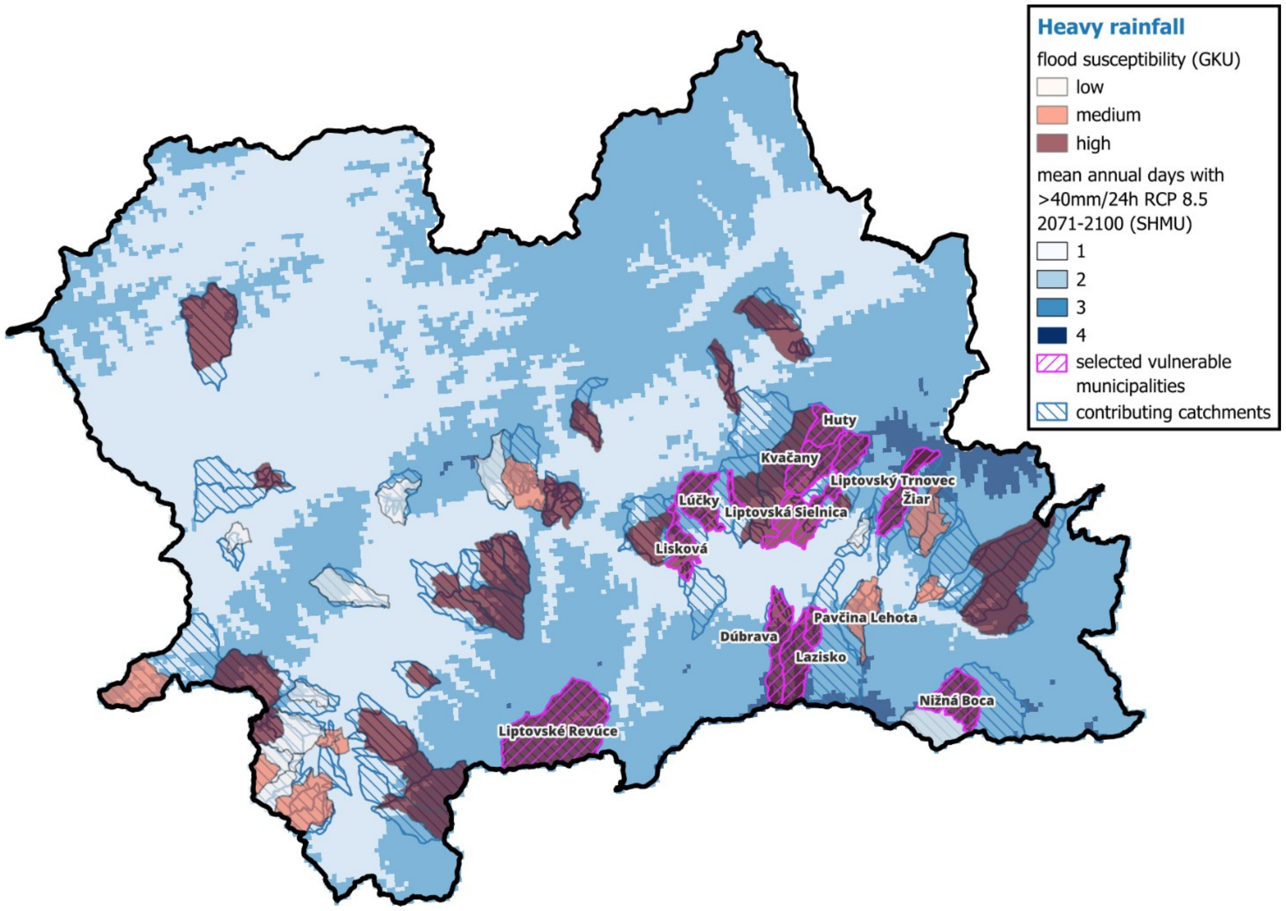

Figure 2-15 Heavy rainfall risk, selected catchments based on flood susceptibility (GKÚ), projected heavy rainfall occurrence 2071-2100 RCP 8.5 (SHMU, climate scenarios) and share of the vulnerable population above 20%

Hazard impact database:

In the second phase the hazard impact database was renewed with the addition of the 163 registered events the (against 20 in first phase). For achieving this the massive data gathering was initiated with the goal of the explore every possible database (local and national) with mentions about registered heavy rainfall events, unfortunately these databases in Slovakia contain only dataset newer than 2012, but the total number of 163 registered events for the period 2012-2025 was enough for the solid hazard impact analysis in the area of ŽSK. The mentions about the registered events contain mostly the information about place (municipality), time and estimated damages (only briefly described not with monetary losses). On these events the CLIMAAX heavy rainfall hazard impact methodology was applied to estimate the level of impact based on the potential risk to people, buildings and transport. The results were displayed in the Figure 2-15 (below). To be able to analyse the areas with the highest concentration of the heavy rainfall impact events the resolution of ŽSK regions was selected. From the results it was evident that the area of Čadca region suffered the most heavy rainfall events and also high impact events. To be able to quantify it the results were also displayed in the table below (Table 2-9).

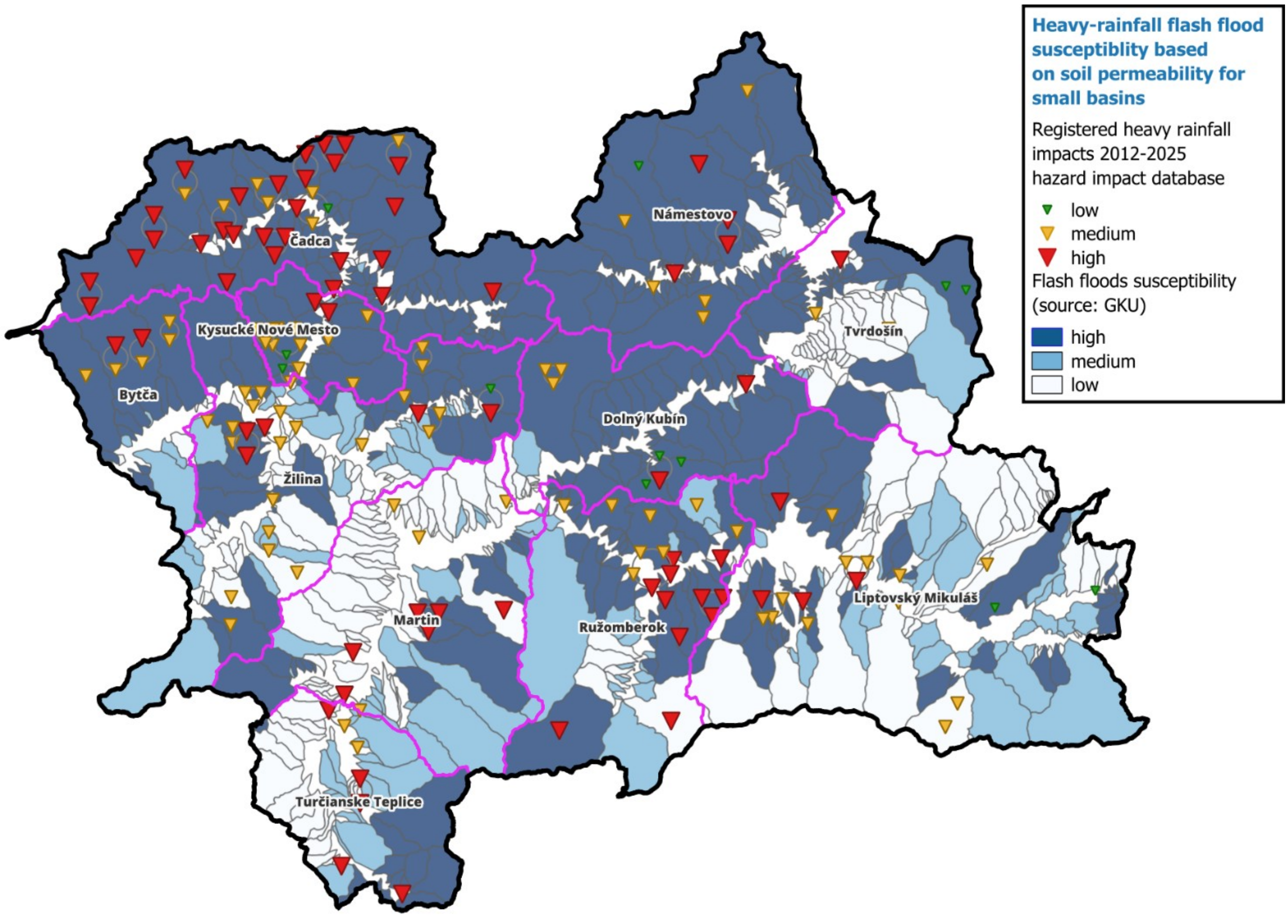

Figure 2-16 Registered heavy rainfall events 2012-2025 with the estimated impact and flood susceptibility reclassed to 3 classes

The results in Table 2-9 indicate that heavy rainfall events in ŽSK most commonly caused material damage to buildings and infrastructure, followed by disruption of transport systems. Direct risk to people was less frequent, but it still occurred in several districts, especially in Čadca, where 12 of the 17 cases of risk to people were recorded.

From the spatial point of view, the highest number of total events was recorded in Čadca district with 36 events, followed by Žilina with 33 events and Ružomberok with 18 events. These districts also show the highest number of impacts on buildings and transport. Čadca was the most affected district overall, with 33 events causing damage to buildings and 24 events causing transport disruption. Žilina also showed strong impacts, with 26 building damage events and 23 transport disruption events.

In terms of impact severity, most events were classified as medium or high impact. Low-impact events represented only 12 events, or 7.4% of all records. Medium-impact events accounted for 81 events, or 49.7%, while high-impact events represented 70 events, or 42.9%. This means that more than 92% of the recorded events were classified as either medium or high impact.

Table 2-9 Results of the hazard impact database divided to districts of ŽSK

District	*Total events*	*Low impact*	*Medium impact*	*High impact*	*Risk to people*	*Damage to buildings*	*Disruption of transport*
Čadca	36	1	7	28	12	33	24
Ružomberok	18	0	8	10	0	15	9
Žilina	33	1	23	9	2	26	23
Turčianske Teplice	9	0	3	6	0	9	4
Liptovský Mikuláš	17	2	11	4	1	9	12
Martin	6	0	3	3	1	5	5
Námestovo	8	1	4	3	0	7	5
Bytča	7	0	5	2	0	7	6
Dolný Kubín	8	3	3	2	0	4	3
Kysucké Nové Mesto	16	2	12	2	0	12	6
Tvrdošín	5	2	2	1	1	3	2
ZSK all	163	12	81	70	17	130	99

The next step was the estimation of critical heavy rainfall intensity thresholds for the ŽSK region. For this purpose, the CLIMAAX heavy rainfall methodology was applied together with the results of the hazard-impact database. The aim was to estimate district-level rainfall intensity thresholds from which potential negative impacts may start to occur, based on registered heavy rainfall events and measured precipitation intensities.

The analysis also considered the SHMÚ critical threshold of 40 mm/24 h, which represents a nationally used heavy rainfall threshold based on long-term observational experience and indicates rainfall events with potential destructive impacts. However, since local impacts can also occur below or above this value depending on local conditions, the hazard-impact database was used to derive more locally specific empirical thresholds for individual districts.

For each district, the 25% quantile of measured 24-hour rainfall intensities from registered impact events was calculated. This value was used as a robust lower empirical threshold indicating the rainfall intensity from which negative impacts have already been observed. The use of the 25% quantile is preferable to the absolute minimum value, because it reduces the influence of potentially uncertain, exceptional, or incorrectly assigned low-intensity events. In addition, the mean intensity of events below the 25% quantile was calculated as supporting information describing the average intensity of the lowest 25% of documented damaging events.

The estimated district-level thresholds were then compared with the historical and future IDF curves in order to interpret the corresponding return periods under the historical climate period 1976–2005 and the future climate period 2070–2099 under RCP 8.5. This allowed the assessment of whether rainfall intensities that have already caused negative impacts in the past may become more frequent under future climate conditions.

The measured rainfall intensities used in the hazard-impact database were provided from representative rainfall measurement stations selected by SHMÚ for each of the 163 registered events. Therefore, the results provide a solid empirical basis for estimating impact-related rainfall thresholds. However, due to the complex mountainous topography of the ŽSK region, local rainfall maxima may not always be fully captured by measurement stations. This means that some observed impacts may have been caused by local precipitation intensities higher than those recorded at the selected representative stations. For this reason, the estimated thresholds should be interpreted as empirical and indicative values rather than exact physical limits.

It is important to note that heavy rainfall events in mountainous regions such as ŽSK are difficult to measure and estimate precisely due to the strong spatial variability of precipitation, complex topography, and the limited ability of individual measurement stations to capture local rainfall maxima. Therefore, the Phase 2 results should be interpreted as indicative empirical estimates based on the best available data. In Phase 3, these results will be further consulted and validated with the MAXICONZA expert group and SHMÚ in order to improve the interpretation of critical rainfall thresholds and their relevance for local risk assessment. At the same time, these findings highlight the importance of building a denser measurement station network, especially around locations with the highest occurrence of heavy rainfall events with documented negative impacts.

Table 2-10 Results from the hazard impact database sorted by the occurrence of the high impact events with provided mean intensity (for all events) and 25% quantile for the estimation of the robust lower threshold

District	*Critical threshold Q25 (mm/24h)*	*Mean 24h intensity (mm)*	*Mean historical RP (years)*	*Mean future RP RCP8.5 (years)*	*Relative change in RP (%)*	*Times more frequent (×)*
Čadca	30,3	55,1	8,8	3,2	63,6	2,75
Ružomberok	27,1	44,7	4,4	1,8	59,1	2,44
Žilina	26,7	34,3	1,8	1,0	44,4	1,80
Turčianske Teplice	37,5	42,4	3,6	1,5	58,3	2,40
Liptovský Mikuláš	18,2	29,5	1,2	1,0	16,7	1,20
Martin	20,1	28,3	1,1	1,0	9,1	1,10
Námestovo	32,7	36,1	2,1	1,1	47,6	1,91
Bytča	32,9	36,9	2,2	1,1	50,0	2,00
Dolný Kubín	31,3	35,4	2,0	1,1	45,0	1,82
Kysucké Nové Mesto	29,5	36,9	2,2	1,1	50,0	2,00
Tvrdošín	33,9	64,7	16,0	5,3	66,9	3,02
ŽSK all	28,4	41,2	3,2	1,4	56,3	2,29

Based on the measured intensities presented in Table 2-10 above, impacts can occur even at relatively low rainfall intensities. The 25% quantile threshold was estimated at 28.4 mm/24h, while the mean measured intensity was 41.2 mm/24h. This naturally depends on the initial catchment conditions; however, the database of 163 registered heavy rainfall events provides a solid reference for estimating this threshold as a first warning level for the area.

However, the number of registered events was not sufficient to estimate reliable thresholds for all three impact categories. This is mainly due to the highly diverse geological and morphological conditions across ŽSK. Based on the spatial distribution of high-impact events, the highest measured rainfall intensities, and the flood susceptibility (Figure 2-15) above the most dominant affected area was identified the Čadca region.

2.3.3. Additional assessments based on local models and data

Within the MAXICONZA project, multiple forms of cooperation were initiated. The CLIMAAX SK group initiative and consultations within the MAXICONZA expert groups helped with the collection of additional CRA datasets suitable for the ŽSK. The results from the additional assessments will be used in the Phase 3 as additional information for the stakeholders and decision-makers. In case these will be interesting for them, they will be used for the further analysis. The additional assessment results were provided for:

1. Trees suitability under the effect of climate change
2. Agriculture drought
3. River floods
4. Severe weather and tourism

Trees suitability under the effect of climate change:

The ŽSK region is densely forested, and forests are a crucial part of the local ecosystem, landscape stability, biodiversity, and regional climate resilience. Therefore, the assessment of future tree species suitability is highly relevant for understanding potential climate change impacts in the region. The first dataset was obtained from the Seed4Forest web application, which shows tree suitability not only for the current climate but also under the influence of climate change projections. Since the web application provides only a visual display, which cannot be quantified for selected zones but only for selected points, the Seed4Forest team was contacted with the help of the NLC. After the meeting, the Seed4Forest team provided georeferenced datasets, which were used in GIS software to calculate zonal statistics for the ŽSK area for the most dominant tree species recommended by the NLC. The results for the most dominant tree species, *Picea abies*, displayed in Figures 2-16 and 2-17, show tree suitability for the historical period 1981–2010 and the future period 2071–2100. The zonal statistics presented in Table 2-11 below show that areas with high suitability are expected to decrease by 19%, while areas with medium and low suitability will increase. The Seed4Forest tool can also be shared with the whole CLIMAAX community, which the Seed4Forest team would highly appreciate.

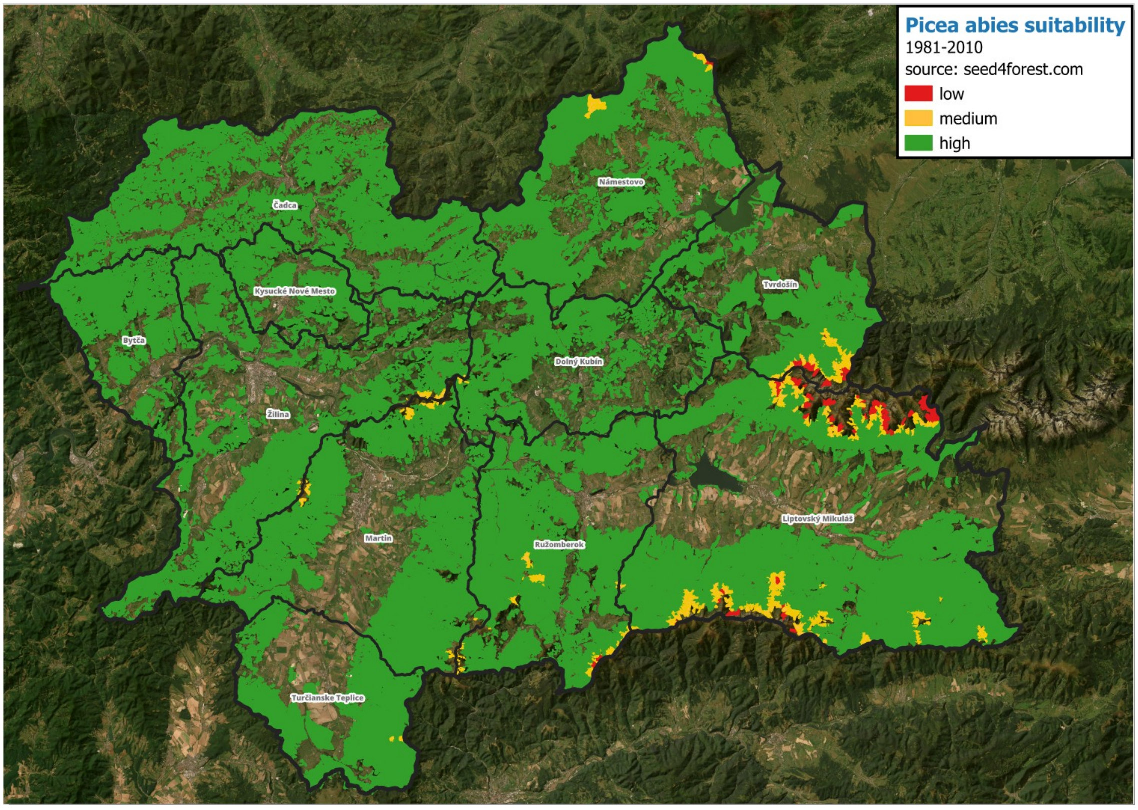

Figure 2-17 Picea abies suitability 1981-2010 (Seed4forest)

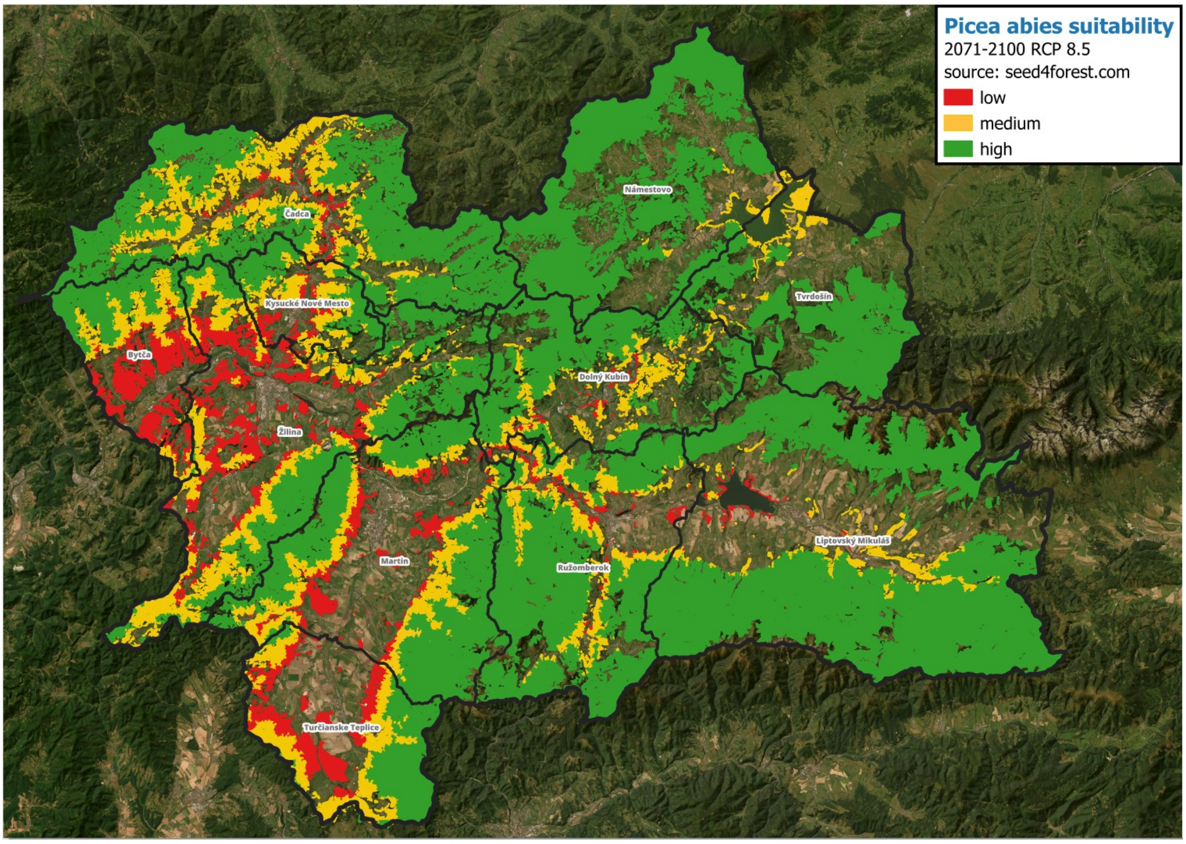

Figure 2-18 Picea abies suitability 2071-2100 (Seed4forest)

Table 2-11 Zonal statistics of the Picea abies suitability within the ŽSK

Period	*Suitability*	*Area (ha)*	*%*
1981_2010_ref	low	2404	1
1981_2010_ref	medium	10886	2
1981_2010_ref	high	444453	97
2071_2100_rcp85	low	28809	6
2071_2100_rcp85	medium	73144	16
2071_2100_rcp85	high	355790	78

Agriculture drought:

The CLIMAAX agricultural drought hazard assessment, based on yield loss, and risk assessment, based on revenue loss, were carried out using the selected GCM–RCM combination GCM = ncc_noresm1_m and RCM = smhi_rca4, selected with the CLIMAAX bias uncertainty tool.

The results were estimated for the most important crops in the ŽSK region, based on data from the Agricultural Payment Agency. The results are presented in Table 2-12. The highest yield loss was estimated for maize, while the highest revenue loss was estimated for wheat. Since these two crops are among the most important in terms of yield and agricultural production in the region, this information may be relevant for stakeholders and policymakers in the ŽSK.

Table 2-12 yield and revenue loss 2021-2050 rcp4.5, GCM–RCM combination GCM = ncc_noresm1_m and RCM = smhi_rca4, selected with the CLIMAAX bias uncertainty tool

Crop	*Area (ha) 2023*	*Yield (t) 2023*	*Area (ha) 2024*	*Yield (t) 2024*	*Yield loss (2021-2050) (%)*	*Revenue loss (EUR) 12x12km / growing season (2021-2050)*
Maize	5761.1	173505.4	5741.3	171471.6	44	35 000
Wheat	12822.7	63470.9	10846.0	47322.6	19	82 000
Barley	3522.4	15349.0	4357.0	18447.8	13	50 000
Sugar beet	235.3	14431.2	381.1	18898.7	19	45 000
Rapeseed	3759.7	12788.0	3634.2	9155.2	26	32 000
Potatoes	600.6	8333.6	587.8	8410.0	35	65 000

River floods:

River floods represent a workflow that naturally follows the heavy rainfall assessment. A database of almost 900 severe weather events was collected, in which river floods represent the most dominant share. Therefore, this workflow cannot be skipped.

The ŽSK region is, and historically has been, one of the regions most susceptible to river flood events. At the same time, the most dominant rivers, the Váh and Orava, are covered by a complex system of water management structures, including major water reservoirs such as Oravská priehrada and Liptovská Mara, each with a storage capacity exceeding 300 million m³. These are followed by several other dams and reservoirs, such as Bešeňová, Krpeľany, Hričov, Žilina, and others, which, through their retention capacity, provide flood protection for a large part of the catchments within the ŽSK region. However, local river flood events are still being recorded.

The Slovak Water Management Enterprise, state enterprise (SVP), prepares flood risk maps for catchments where potential flood risk to people and housing has been identified. These flood risk maps show the number of potentially affected people in the case of flood discharge with a 100-year return period.

Within MAXICONZA, the SVP flood risk maps were supported by the database of registered river flood events in the ŽSK region. The main aim was to highlight catchments where high flood risk was identified by SVP and where river flood events have also occurred in reality. The results presented in Figure 2-18 show the selected municipalities.

These results mainly highlighted the same districts, especially **Čadca** and **Liptovský Mikuláš**, as those identified in the heavy rainfall workflow. This further supports the importance of implementing mitigation measures in these areas.

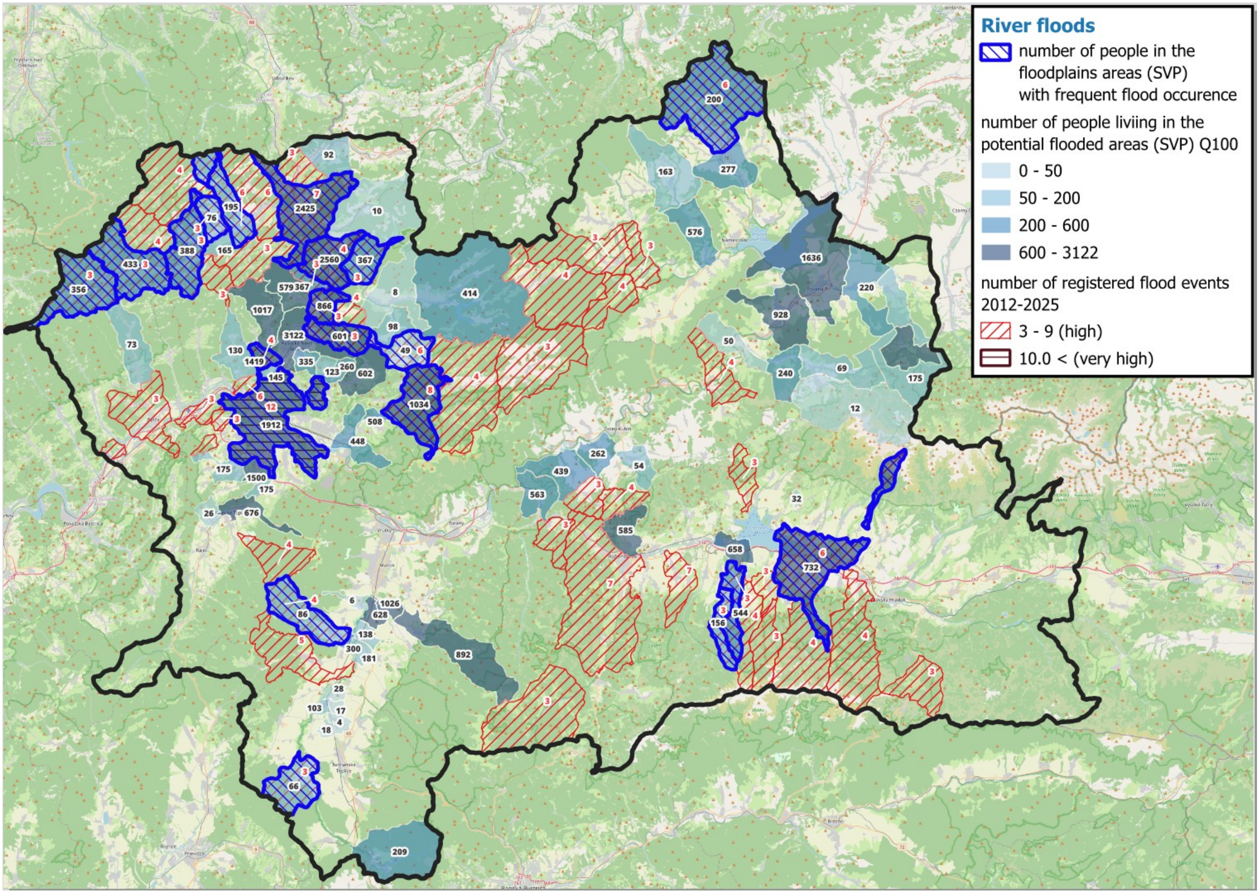

Figure 2-19 Number of people in the areas with high flood risk (SVP) with the frequent river flood occurrence areas.

Severe weather and tourism:

A part of Phase 2 also focused on the CRA in the tourism sector. Tourism is one of the most important sectors of the ŽSK economy. Based on the results from the selected workflows, climate change is also expected to influence this sector.

The mission of the MAXICONZA project is therefore clear: to inform stakeholders in the tourism sector about potential climate-related problems that may affect this sector. The main goal of Phase 2 was to estimate the potential changes and impacts on vulnerable sectors.

The map of the most important tourism areas, represented by municipalities of supra-regional tourism importance within the ŽSK, was combined with the database of registered severe weather events.

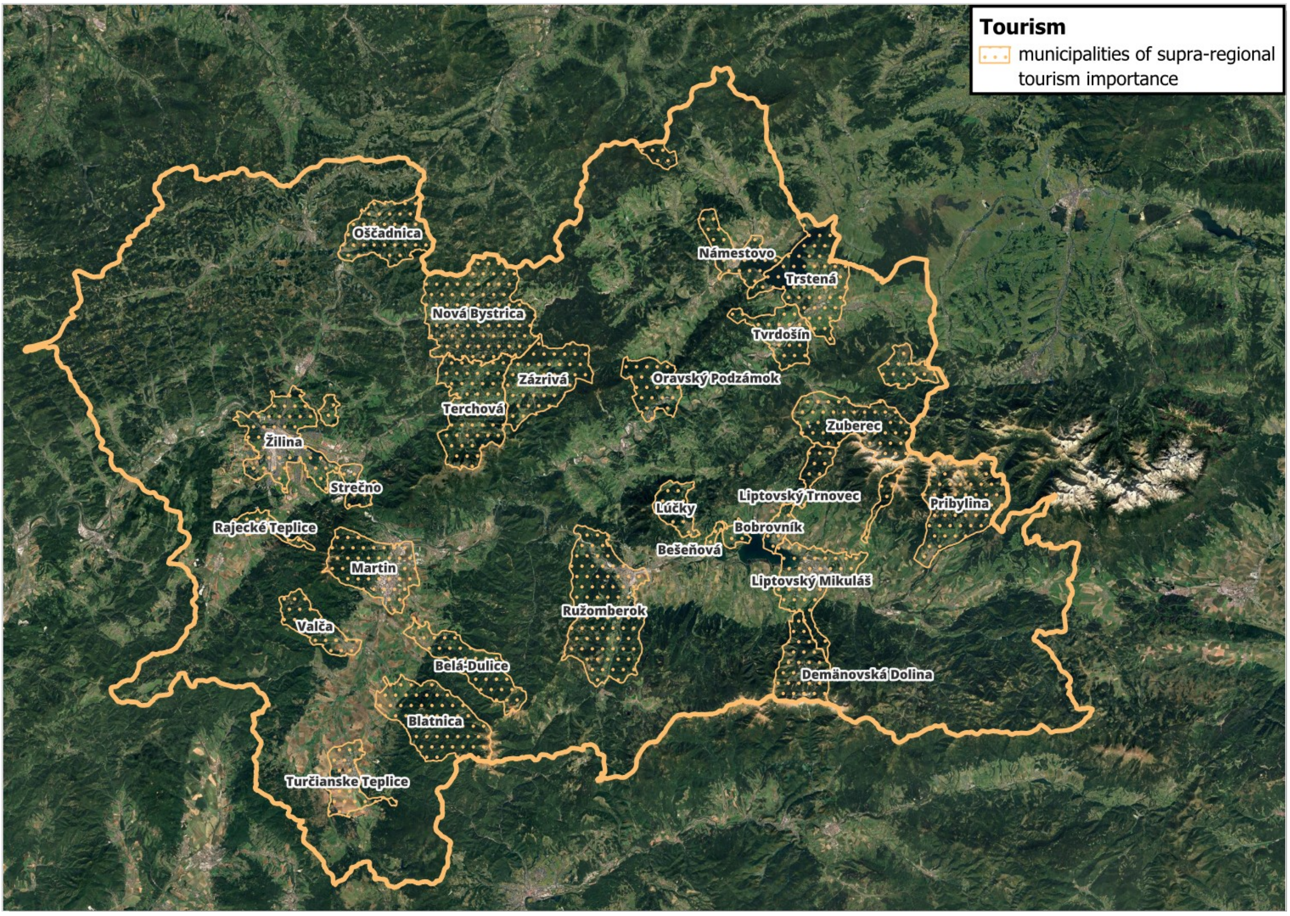

Figure 2-20 Municipalities of supra-regional tourism importance

A preliminary multi-hazard screening score (Table 2-13) was calculated using equal-weight min–max normalization of six selected indicators: poor-condition bridges, landslide-related road exposure, registered extreme weather events, projected heavy rainfall occurrence, flood susceptibility, and projected tropical days. The resulting score was used only as a relative prioritisation tool to identify municipalities of supra-regional tourism importance where several climate-related hazard, exposure, and vulnerability indicators overlap. The “number of high indicators” means the number of indicators where the municipality reached at least the 75th percentile among the selected municipalities.

Table 2-13 The multi-hazard screening score

Rank	*Municipality*	*Multi-hazard score*	*Number of high indicators*
1	Žilina	69.31	5
2	Liptovský Mikuláš	67.52	6
3	Terchová	57.09	4
4	Ružomberok	52.95	2
5	Zázrivá	48.46	4
6	Turčianske Teplice	46.23	4
7	Demänovská Dolina	40.36	2
8	Martin	38.02	2
9	Valča	38.02	3
10	Blatnica	37.67	3

Table 2-14 Most endangered municipalities by hazard type

Hazard / exposure indicator	*Most endangered municipalities*
Poor-condition bridges (NDS)	Liptovský Mikuláš and Zázrivá have the highest number of bridges in poor, very poor, or emergency technical conditions, both with 4 bridges. They are followed by Terchová, Turčianske Teplice, and Lúčky, each with 3 bridges.
Landslide exposure of roads (KAJO)	Oravský Podzámok has the highest landslide-related road exposure, with 12,923.67 m of roads in landslide classes Active and Possible. It is followed by Žilina, Tvrdošín, Nová Bystrica, and Liptovský Mikuláš.
Registered extreme weather events (MAXICONZA)	Žilina has the highest number of registered extreme weather events, with 19 events. It is followed by Terchová with 16 events and Ružomberok with 13 events.
Projected heavy rainfall occurrence >40 mm/24h (SHMÚ)	Pribylina has the highest projected maximum value under RCP8.5 for 2071–2100, followed by Zuberec, Liptovský Mikuláš, Demänovská Dolina, and Liptovský Trnovec.
Flood susceptibility (GKU)	The maximum susceptibility class 7 occurs in several municipalities, including Námestovo, Trstená, Liptovský Mikuláš, Martin, Blatnica, Turčianske Teplice, Valča, Žilina, and Strečno.
Tropical days / heat hazard (SHMÚ)	Žilina has the highest projected maximum number of tropical days under RCP8.5 for 2071–2100, followed by Rajecké Teplice, Strečno, Valča, and Turčianske Teplice.
Heavy rainfall impact events	Ružomberok and Žilina have the highest number of registered heavy rainfall impact events, both with 4 events. They are followed by Liptovský Mikuláš and Zázrivá, both with 3 events.

Based on the results (Table 2-14), Žilina and Liptovský Mikuláš can be considered the most important multi-hazard municipalities with supra-regional importance for tourism among the selected municipalities. Žilina shows the highest number of registered extreme weather events and the highest projected number of tropical days, together with high flood susceptibility, significant landslide-related road exposure, and the highest number of registered heavy rainfall impact events. Liptovský Mikuláš combines high values across several indicators, including poor-condition bridges, flood susceptibility, projected heavy rainfall occurrence, heat exposure, registered extreme weather events, and heavy rainfall impact events.

Terchová also represents an important priority municipality, mainly due to the high number of registered extreme weather events, poor-condition bridges, elevated heavy rainfall hazard, and registered impact events. Ružomberok becomes more important after including the impact-event database, as it has a high number of registered extreme weather events and the highest number of heavy rainfall impact events. Zázrivá and Turčianske Teplice also show multi-hazard importance, especially due to the combination of poor-condition bridges, flood or rainfall-related indicators, heat exposure, and registered impacts.

Overall, the results confirm that several municipalities with supra-regional importance for tourism combine multiple climate-related hazards, exposure factors, vulnerability indicators, and registered impacts. These municipalities should therefore be considered as priority areas for stakeholder discussion, targeted mitigation planning, and more detailed follow-up analysis in Phase 3.

2.4. Key Risk Assessment Findings

2.4.1. Mode of engagement for participation

Stakeholder engagement is described in Section 2.1.5, together with their feedback on the presented results. The KRA for this phase was conducted with experts, while the engagement of priority groups and broader stakeholders is planned for Phase 3. This sequencing follows the project's original work plan, which has, since the beginning of the project, foreseen five stakeholder workshops in Phase 3. In the months leading up to the summer vacation, numerous stakeholder engagement activities were already carried out within several adaptation-focused projects involving ŽSK. Organising an additional dedicated KRA workshop during this period would therefore have increased the risk of stakeholder fatigue and potentially reduced the quality and usefulness of the feedback received. For this reason, the KRA was carried out by a group of sectoral experts, while stakeholders will be engaged during the workshops already planned for Phase 3. Their role will not be to repeat the assessment process, but rather to review and validate the expert-based KRA results, discuss their practical implications, and support the identification of priorities and climate risk management measures. The experts involved in the KRA represented the different sectors listed in Section 1.3. They were engaged through a facilitated discussion process: CRA outputs were first presented, followed by a structured assessment of the different KRA elements until consensus was reached.

2.4.2. Gather output from Risk Analysis step

Maps showing the current and future occurrence of tropical days in the region were used to assess the risk of heatwaves. However, maps showing the UHI effect for the four largest cities were not useful as they apply to a local context and do not allow for an assessment of this hazard from a regional perspective. To assess the current severity of river and flash floods, maps showing the occurrence of individual hazards and events, and the susceptibility to flash floods were crucial, as were maps showing the risk of river floods from the SVP. Tables showing thresholds with the change in return period combined with a map of the future mean annual number of days above 40mm/24h, based on SHMU climate scenarios, were also used. To assess drought, all outputs generated for forests and agricultural crops were used.

The main limitation identified during the KRA was the lack of comparative information from other Slovak or neighbouring regions. Although the available outputs enabled an assessment of risks within the Žilina region, experts often lacked a broader reference context that would allow them to benchmark the results and better evaluate the relative importance of individual risks.

2.4.3. Assess Severity

The severity of all four assessed hazards was rated on a scale from 1 to 3. **Higher severity** values were assigned to **water-related hazards**, namely river floods and heavy rainfall, with river floods receiving a higher score than heavy rainfall due to their higher frequency of occurrence in recent years. Experts noted that information on insurance coverage related to flood risks would be useful to support more informed decision-making in the assessment of flood severity. Drought and heatwaves were assigned the lowest severity level (1). Although both hazards have been increasing in frequency in recent years, they remain less frequent than water-related hazards and are observed less frequently compared to other regions of Slovakia. Future severity was assessed as critical for both water-related hazards. The CRA results indicate a systematic shift in precipitation extremes, with changes varying across return periods. In particular, higher-return-period rainfall events (rarer extremes) exhibit a more pronounced reduction in return periods over time compared to more frequent events, indicating a non-linear response of extreme precipitation behaviour under future climate conditions. In addition, the region is projected to record the highest number of days with precipitation exceeding 40 mm/24 h among Slovak regions, and is the only region expected to reach the highest change category (>10 days) already in the near future period (2021–2050) under the RCP 4.5 scenario (MŽP SR, 2026). Regarding **temperature-related hazards**, heatwaves were assessed as less severe in the future than drought. This reflects the fact that drought is considered to have broader cascading effects within the landscape and may exacerbate other hazards such as heatwaves and flash floods. With approximately 60% forest cover in the region, drought impacts on forest ecosystems are already observable in some areas, where forest decline is occurring. If this trend continues, forest degradation may reduce groundwater recharge and subsequently impact drinking water resources, of which approximately 80% is derived from groundwater sources (Kotrikova, K. and Slivova, V., 2025). In addition, landscape degradation would increase susceptibility to flash floods and reduce the capacity of the territory to mitigate heatwave impacts.

2.4.4. Assess Urgency

Experts had a consistent perception of urgency across all hazards. While all hazards were assessed as requiring at least a “more action needed” level of response, heavy rainfall was identified as the most urgent hazard (level 4 out of 4), reflecting the most pronounced change in future severity. Both river floods and heavy rainfall are projected to reach severity level 4 in the future, with heavy rainfall showing a larger increase in severity due to a lower baseline level. All hazards are expected to persist and worsen over time, with more rapid deterioration projected for extreme precipitation compared to a more gradual intensification of heatwaves. Given their sudden and localised nature, these events require immediate preparedness measures. Heatwaves were also identified as highly urgent due to their increasing relevance as a relatively new hazard in the regional context and the limited availability of established adaptive responses. In contrast to short-duration, spatially concentrated floods, heatwaves are spatially extensive, longer-lasting, and associated with notable socio-economic impacts, including reduced productivity in outdoor sectors. Proactive preparedness and adaptation are therefore considered necessary.

2.4.5. Understand Resilience Capacity

All hazards scored 3 (substantial capacity) except heavy rain/flash floods, which scored 1 (low). Experts repeatedly noted they lacked sufficient data to score this parameter reliably and called for better comparative indicators in future iterations (e.g. regional economic and capacity benchmarks).

The region's natural capital was seen as the single most important asset for building resilience, particularly given that fiscal capacity is weak and the outlook is poor — Slovakia is widely described as being "on the Greek path" (source). Awareness of adaptation needs is strong among municipal executive staff but weak among elected leadership, where adaptation routinely loses out in decision-making. **Heatwaves** benefit from the region's forested, mountainous terrain and dispersed smaller settlements in foothill areas, which supports night-time cooling, alongside strong external funding availability for urban blue-green infrastructure. **Droughts**: capacity here rests on the availability of drought- and heat-resilient tree and crop varieties, strong sectoral awareness of adaptation needs, and supporting Common Agricultural Policy and national forestry funding instruments. The natural environment is also regarded as an asset here, as the region's substantial groundwater reserves can help mitigate drought impacts. **River floods** scored highly because flood risk has long been managed systematically at the state level. Effective protection exists against the most destructive floods, forecasting and warning systems are well established, and response protocols clearly define responsibilities. Although smaller watercourses have less flood-protection infrastructure, external funding is available and the state is currently mapping flood occurrence to identify priority areas for future investment. **Heavy rain** scored lowest, for several compounding reasons. A flash flood susceptibility map shows that most of the region is exposed to this hazard, making the natural environment more of a constraint than an asset in this case. Flash floods are also far less predictable than river floods, and no dedicated forecasting or early-warning system currently exists in the region. Flash floods are not tracked as a distinct hazard, and existing flood-management protocols largely reflect river flood conditions. Finally, mitigating measures require extensive coordination, as those responsible for implementing solutions are often not those exposed to the risk. Without legally defined responsibility for risk “originators”, ensuring that measures are implemented where they are needed remains difficult.

2.4.6. Decide on Risk Priority

The final prioritisation does not reflect a simple aggregation of scores but rather expert judgement balancing these three dimensions.

Heavy rainfall was identified as the highest-priority risk due to its critical future severity, highest urgency, and low adaptive capacity. While both heavy rainfall and river floods are expected to reach the same future severity level, the increase in severity is more pronounced for heavy rainfall. This is compounded by the widespread susceptibility of the region to the hazard and projections indicating further intensification of precipitation extremes. The lack of dedicated forecasting and management systems further reinforces the need for immediate action.

Both river floods and droughts were classified as high-priority risks, reflecting similar overall scores, but driven by different factors. **River floods** reach critical future severity and high urgency but benefit from substantial adaptive capacity due to long-established flood risk management systems, including infrastructure, forecasting, and clearly defined response mechanisms. The key challenge is therefore not a lack of systems, but rather the need to scale and adapt existing measures to future conditions (e.g. higher peak flows). **Droughts** also fall into the “high” priority category, with low current severity increasing significantly in the future, combined with high urgency and substantial adaptive capacity. Their prioritisation is strongly influenced by their system-wide cascading effects. Drought can drive forest degradation, reduce water retention capacity, and negatively affect groundwater recharge and drinking water availability. At the same time, it can exacerbate other hazards, including flash floods and heatwaves. **Heatwaves** were classified as a moderate-priority risk. While their future severity is lower than that of other hazards, their urgency is comparatively high due to increasing exposure and limited societal and institutional preparedness. As a relatively recent hazard in the region, adaptation measures are not yet well established. Nevertheless, heatwave intensity remains lower than in southern Slovakia and other parts of Europe, which moderates their overall priority.

Table 2-15 The prioritisation of different climate hazards according to their severity, urgency and adaptive capacity, and the final risk priority

Risk Workflow	*Severity*		*Urgency*	*Capacity*	*Risk Priority*
	C	*F*		*Resilience/ CRM*	*result*
River flooding	3	4	3	3	high
Heavy rainfall	2	4	4	1	very high
Heatwaves	1	2	3	3	moderate
Drought	1	3	3	3	high

2.5. Monitoring and Evaluation

The phase 2 significantly improved the region's understanding of climate risks and their spatial distribution. A key lesson learned was the importance of integrating local data and systematically recording climate-related impacts. The assessment demonstrated that reliable information on hazard occurrence, impacts, and losses is essential for a high-quality risk assessment. At the same time, the process highlighted important gaps in data availability and consistency, underlining the need for more systematic data collection and management in the future.

The expert group played a crucial role in improving the quality of the assessment. Experts supported methodological decisions, interpretation of results, and identification of relevant data sources. They also provided valuable recommendations for refining the analysis, in particular by expanding vulnerable groups to include young children and economically disadvantaged populations, especially in relation to flood impacts. Overall feedback on the CRA outcomes was positive, particularly with regard to the newly developed impact database. Experts recommended that these data be used in the ongoing national process of collecting flood-event information and prioritising investments in flood protection measures.

The project also contributed significantly to capacity building. CRA results have been incorporated into the P2R internal training programme involving representatives from all ZSK departments. Beyond the assessment itself, the project generated valuable knowledge on available data sources, their quality, availability, and limitations, creating a resource that can support future climate-related analyses.

Several areas requiring further investigation were identified. These include improved monitoring of heat-related health impacts, a better understanding of drought impacts on drinking water resources, and a more detailed assessment of landslide risks affecting transport infrastructure. Building on the knowledge generated through CLIMAAX, the region intends to continue developing these topics through future projects (e.g. MIP4Adapt technical assistance).

Overall, resources were used efficiently and generated outcomes extending beyond the CRA itself. The involvement of junior staff, primarily responsible for data collection and processing, significantly improved efficiency and allowed the core team to focus on the CRA. In addition to the CRA, this enabled the mapping of adaptation potential of selected regional properties, linking assessment outputs with practical adaptation options.

The results will be presented during Phase 3 through a series of regional workshops and internal meetings with regional decision-makers. At the same time, the findings are already being used within other adaptation projects involving a wide range of stakeholders, helping to further disseminate the knowledge generated through the assessment.

2.6. Work plan Phase 3

Phase 3 focuses on consolidating and operationalising the results of the CRA and the mapping of adaptation potential, with the aim of strengthening their uptake in regional planning and investment processes.

The CRA will be further refined through the following updates:

- extension of vulnerability assessment to additional at-risk groups (children under 4 years of age; economically disadvantaged populations)
- refinement of UHI analysis through classification of ŽSK-managed assets by vulnerability (high: hospitals and social care facilities; medium: secondary schools; low: cultural heritage sites and other buildings)
- enhancement of river flood analysis by adding impact-based information to complement frequency-based indicators
- inclusion of accessibility disruption indicators for heavy rainfall events (length of landslide-prone road segments; number of structurally deficient bridges)
- addition of accessibility to emergency medical services in heatwave analysis, including hospital travel times and EMS-identified critical road sections

Phase 3 will include five sub-regional workshops with relevant stakeholders. The workshops will focus on validation of CRA results, including verification of KRA outputs, and on their translation into practical climate risk management measures. They will also support dissemination of results from the adaptation potential mapping of ŽSK-managed assets, together with the methodological approach and AI-based assistant developed to support its application. A further focus will be placed on joint local planning of adaptation measures, particularly for water-related hazards requiring cross-level coordination.

Existing project platforms (notably P2R and GRACE) will be used to gather additional inputs and information required for the final Phase 3 deliverable, while avoiding duplication of consultation activities.

Based on CRA results and stakeholder input, recommendations will be developed for integrating climate risk and adaptation potential mapping into regional investment planning, strategic documents, project preparation, and the regional adaptation strategy.

3. Conclusions Phase 2 – Climate risk assessment

Phase 2 significantly improved the climate risk assessment for the Žilina Region by integrating local datasets, higher-resolution climate scenarios, and new analytical approaches.

A particularly important achievement was the expansion of the hazard-impact database from 20 records used in Phase 1 to 863 documented weather-related events. This substantially improved the evidence base for assessing the severity and risk level of individual hazards. Given its importance for future risk assessments, the database should be maintained as a living system and regularly updated with new events, both at the regional scale and within facilities managed by ŽSK, where climate-related impacts are currently not recorded in a systematic and consistent manner.

Obtaining both impact data and supplementary datasets proved to be one of the most challenging aspects of the assessment. Data were often fragmented across institutions, stored in inconsistent formats, provided at different levels of detail, and required substantial harmonisation before they could be analysed. Lengthy response times from some public institutions frequently delayed the analytical work, and in several cases, difficulties occurred even when data were available on a paid basis. The process also helped to build an institutional knowledge base regarding data availability, quality, and limitations, which will facilitate future updates of the regional adaptation strategy.

Another important lesson learned concerns the KRA methodology. Experts noted that assessments of severity, urgency, and resilience capacity would be more robust if supported by comparative indicators placing the region within a broader national or international context. From a methodological perspective, the use of high-resolution SHMÚ climate scenarios also proved particularly valuable. The 1 × 1 km scenarios enabled a more detailed identification of climate hotspots and vulnerable areas.

The assessment confirmed that both heat-related and precipitation-related hazards are expected to intensify considerably in the future. For heatwaves, the mean annual number of tropical days is projected to increase from 7.5 days during the reference period to almost 25 days by the end of the century under the RCP 8.5 scenario, exposing the population to heat-related stress for almost an entire month each year. Because heatwaves have historically not been perceived as a major hazard in the Žilina Region, the KRA assigned them a high level of urgency. Unlike floods, which typically affect limited areas for short periods, heatwaves affect large territories simultaneously and can persist for extended periods, creating pressure on public health, social care, and critical services.

The identification of municipalities with a high share of residents aged 65 and over is already being used within the HE JustSafe project, where workshops are being organised in the most vulnerable municipalities to improve preparedness and support the co-development of adaptation pathways for both heatwaves and heavy rainfall events.

The results for heavy rainfall indicate an even more significant challenge. Both SHMÚ and Euro-CORDEX climate scenarios project substantial increases in the frequency and intensity of extreme precipitation. While Euro-CORDEX projections suggest that rainfall events exceeding 40 mm/24 h may occur on average 0.77 times per year by the end of the century, the higher-resolution SHMÚ scenarios estimate approximately 2.1 such days per year, representing a 133% increase compared to the reference period. This difference suggests that future heavy rainfall intensities may be even higher than those estimated through the Euro-CORDEX-based IDF analysis. At the same time, the hazard-impact database demonstrated that serious impacts already occur at rainfall intensities below the nationally used threshold of 40 mm/24 h. Together, these findings strongly support the conclusion that heavy rainfall and associated flash floods represent the most critical climate risk for the Žilina Region.

In contrast to river floods, flash floods remain difficult to predict and are not adequately reflected in existing warning, monitoring, or civil protection procedures. The assessment also revealed that national flood records frequently do not distinguish between river floods and flash floods, complicating targeted risk management. Most documented high-impact flash flood events occurred in catchments already identified as highly susceptible to flash flooding, indicating a strong correspondence between observed impacts and the existing susceptibility maps. Events occurring outside these areas may point to land-use practices, landscape degradation, drainage deficiencies, or other human-induced factors that could potentially be addressed through targeted adaptation measures.

The spatial analysis of impacts identified Čadca District as the most vulnerable area to heavy rainfall and flash flood impacts, followed by Žilina and Ružomberok districts. Čadca recorded the highest number of high-impact flash flood events. The average observed rainfall event associated with these impacts reached 55.1 mm/24 h, while the empirically derived impact threshold was only 30.3 mm/24 h. Climate projections indicate that an event of this magnitude is expected to become approximately 2.75 times more frequent in the future. These findings suggest that Čadca is likely to experience the greatest increase in pressure from extreme precipitation and should therefore remain a priority area for adaptation and resilience-building measures.

The additional assessments highlighted the importance of considering climate impacts beyond the primary hazards. Forest suitability analysis showed a significant decline in the future climatic suitability of Norway spruce (Picea abies), currently one of the dominant tree species in the region. Given that forests cover approximately 56% of the Žilina Region, these findings are highly relevant for long-term regional resilience and future forest management.

The river flood assessment produced an additional important finding. While the impact database confirmed that river floods currently occur more frequently than flash floods in the region, it also revealed discrepancies between observed flood occurrence and official flood-risk maps. For example, Ružomberok recorded a frequency of flood events comparable to Čadca, despite not being identified as a significant flood-risk area in the current flood-risk maps. ŽSK therefore intends to share the results with national authorities to support future updates of flood-risk mapping and the prioritisation of flood-protection investments.

Finally, the tourism assessment demonstrated that climate risks are not limited to urban centres. While Žilina and Liptovský Mikuláš achieved the highest multi-hazard scores, the identification of Terchová as the third most exposed tourism destination was particularly noteworthy. As a gateway to the Malá Fatra National Park, Terchová faces challenges related to visitors being dispersed across a large natural area, making risk communication and emergency response more difficult during extreme weather events. These findings will be shared with tourism organisations and national park administrations to support adaptation planning in key tourism destinations across the region.

4. Progress evaluation

The outputs of Phase 2 provide the analytical foundation for all activities planned in Phase 3. The climate risk assessment identified the most significant climate hazards affecting the Žilina Region, their spatial distribution, vulnerable populations, and priority areas for intervention. At the same time, the adaptation potential assessment developed a methodological framework for evaluating the capacity of ŽSK-managed assets to adapt to future climate conditions.

Building on these results, Phase 3 will focus on further refining selected components of the climate risk assessment, particularly through the inclusion of additional vulnerability indicators and impact-related information. These refinements are intended to improve the practical relevance of the assessment and ensure that the identified risks are translated into decision-support information for regional planning and investment processes.

A key element of Phase 3 will be the validation and operationalisation of the results through stakeholder engagement. Five sub-regional workshops will provide an opportunity to discuss the findings with local authorities, sectoral experts, emergency services, infrastructure managers, and other relevant stakeholders. The workshops will support the verification of the identified risks, facilitate the exchange of local knowledge, and contribute to the development of adaptation pathways and risk management measures, particularly for hazards that require coordination across administrative levels and sectors.

The adaptation potential mapping has been completed for ŽSK-managed facilities and provides facility-level information on suitable adaptation measures, including nature-based solutions and blue-green infrastructure. In Phase 3, this output will be further developed through integration with the climate risk assessment in order to support investment prioritisation. This combined use of results will enable the identification of facilities where higher climate exposure coincides with higher vulnerability, thereby strengthening the basis for targeted adaptation planning and investment decisions.

The final outputs of Phase 3 will build directly on the evidence generated in Phase 2 and will translate analytical findings into actionable recommendations. These will include recommended steps for joint local planning of adaptation pathways, guidance for integrating climate risk and adaptation potential considerations into strategic, investment and project preparation processes, as well as inputs to the Regional Climate Adaptation Strategy, Action Plan and Investment Plan to be developed within the P2R project. In this way, Phase 3 will ensure that the knowledge generated through the project is not only assessed but also systematically incorporated into regional decision-making and long-term climate resilience planning.

In parallel, the project will continue its dissemination and stakeholder engagement activities through expert group meetings, public communication activities, and exchanges with regional and European partners, ensuring that the project results remain visible and accessible to both decision-makers and the wider public.

Table 4-1 Overview key performance indicators

Key performance indicators	*Progress*
Adjustment of at least 2 climate hazard assessments to local needs and conditions	The assessment of extreme precipitation and heat waves was adapted to local needs by incorporating local data or, where

Key performance indicators	*Progress*
	applicable, more accurate regional climate scenarios published by the Slovak Hydrometeorological Institute. The focus was on location-specific challenges, such as the road network and access to hospitals, as well as the vulnerability of facilities managed by the ŽSK that house vulnerable population groups.
1 report comparing the outputs of Phase 1 and Phase 2 of the project	A report comparing the results from Phases 1 and 2 and the possibilities for their use was prepared by the ŽSK on June 19, 2026, at the end of Phase 2.
6 meetings of the expert group	Four meetings have been held so far. The first meeting took place in person on July 17, 2025, at the ŽSK premises, attended by 12 people. The following meeting took place online on September 12, 2025 with 10 attendees in total. The subsequent two meetings took place on December 17, 2025 and May 29, 2026, respectively. The December meeting was held online and the May one took place in a hybrid format – online and in the ŽSK premises. In total, 13 people attended the most recent expert group meeting.
At least 6 social media posts	Four Facebook posts about the project's activities have been published to date. The first three posts announce Žilina Region's admission to the second cohort of the regions in the CLIMAAX project and the regional focus on investigating extreme rainfall and its impact on roads and tourism, as well as heatwaves (in cities) and their effects on human health. The latest Facebook post used the ongoing heatwave as an opportunity to communicate key CRA findings, including the projected increase in the frequency of heatwaves in the future.

Table 4-2 Overview milestones

Milestones	*Progress*
M6. Necessary data for phase 2 obtained (or reason for not obtaining some data evaluated)	We compiled a list of the data we sought to obtain in an Excel spreadsheet. This spreadsheet includes the data source and contact information, the data structure and format, and the validity period. Based on this information, we assess the usefulness of the data in evaluating climate risks.
M8. Comparison of the results of the first and second phases prepared	A report comparing the results from Phases 1 and 2 and the possibilities for their use was prepared by the ŽSK at the end of Phase 2.
M7. The successful tenderer for mapping the adaptation potential of real estate owned by ŽSK selected	In compliance with the applicable public procurement rules, a market survey was carried out and, on 18 November 2025, Energo-eko služby was selected as the successful tenderer for the adaptation potential mapping service.

5. Supporting documentation

- Main Report *Phase 2 - Climate risk* (in PDF form)
- Annex 1 on Communication outputs (in PDF form)
- Annex 2 on Collected datasets applicable in the ŽSK (in Excel form)
- Visual Outputs depicting the **heatwaves workflow**:
  - **Exposure:**

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    zsk_heatwaves_exposure_kindergartens_martin_city.gpkg
    zsk_heatwaves_exposure_municipalities_with_supra_regional_importance.gpkg
    zsk_heatwaves_exposure_municipalities_with_supra_regional_importance.sld
    zsk_heatwaves_exposure_objects_under_management_of_zsk.gpkg
    zsk_heatwaves_exposure_objects_under_management_of_zsk.sld
    zsk_heatwaves_exposure_social_care_4_biggest_cities.gpkg
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    zsk_heatwaves_exposure_social_care_4_biggest_cities_selected.gpkg
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    zsk_heatwaves_exposure_zsk_area_2025.sld

  - **Hazard:**

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    zsk_heatwaves_hazard_lst_summer_months_2013_2024_martin_city
    zsk_heatwaves_hazard_lst_summer_months_2013_2024_martin_city.tif.aux
    zsk_heatwaves_hazard_lst_summer_months_2013_2024_ruzomberok_city.sld
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    zsk_heatwaves_hazard_lst_summer_months_2023_2024.tif.aux
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    zsk_heatwaves_hazard_tropical_days_shmu_1991_2020.gpkg.aux
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    zsk_heatwaves_hazard_tropical_days_shmu_1991_2020
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zsk_heatwaves_hazard_tropical_days_shmu_rcp85_2071_2100.tif.aux

- **Risk (Martin City):**

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- **Risk (Liptovský Mikuláš City):**

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- **Risk (Ružomberok City):**

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- **Risk (Žilina city):**

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- **Risk (ŽSK):**

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- **Vulnerability:**

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  zsk_heatwaves_vulnerability_heat_vulnerable_places_zilina_city.gpkg

  zsk_heatwaves_vulnerability_heat_vulnerable_places_zilina_city.sld

  zsk_heatwaves_vulnerability_vulnerable_population_above75_under4_martin_city.gpkg

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- Visual Outputs depicting the **heavy rainfall workflow**:
  - **Exposure:**

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    zsk_heavy_rain_hazard_flood_susceptibility_gku_3classes.sld

    zsk_heavy_rain_hazard_impact_database_by_intensity.gpkg

    zsk_heavy_rain_hazard_impact_database_by_intensity.sld

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  - **Risk:**

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  - **Vulnerability:**

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