CLIMAAX
climate ready regions

Deliverable Phase 2 – Climate risk assessment

MARCAdapt

Hungary, Municipality of 12th District of Budapest

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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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Document Information

Deliverable Title	Phase 2 – Climate risk assessment
Brief Description	The document is the second deliverable submitted by the Municipality of 12th District of Budapest (Hegyvidék Municipality), participating as a pilot region in the Horizon Europe CLIMAAX project. The deliverable summarizes the work completed in Phase 2 and presents the regionalized risk analysis and key risk assessment applied to this pilot territory.
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Country	Hungary
Region/Municipality	Municipality of 12th District of Budapest (Hegyvidék Municipality)
Leading Institution	Municipality of 12th District of Budapest (Hegyvidék Municipality)
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Abbreviations and acronyms

Abbreviation / acronym	Description
Hegyvidék Municipality	Municipality of 12th District of Budapest – meaning the physical area of the city or the institution of the local government
CRA	Climate Risk Assessment developed in the CLIMAAX project
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
WASP	Weighted Anomaly of Standardized Precipitation
NDVI	Normalized Difference Vegetation Index
Ibid	*ibidem*. When a reference is the same as indicated in a previous footnote, the page and the corresponding footnote number are mentioned. E.g. *Ibid 3, 1* = same as indicated in the footnote nº1 on page 3.

Executive summary

This document is the second deliverable submitted by Hegyvidék Municipality (project MARCAdapt) in the framework of the CLIMAAX project. The deliverable presents the tasks and results accomplished during the second phase of the project between April 2025 and January 2026. The document elaborates how Hegyvidék Municipality applied the climate risk assessment (CRA) methodology presented in the CLIMAAX Handbook, following the guideline of the toolbox: scoping, risk exploration, risk analysis, and key risk assessment.

The primary objective of Phase 2 was the adaptation of the CLIMAAX methodology on a local level, resulting in comprehensive and meaningful outputs. Three assessments were accomplished, including heatwaves, heavy rainfall, and relative drought – the latter specifically focused on urban green spaces. Due to the territorial scale of Hegyvidék Municipality, the spatial resolution of urban blocks and streets was targeted for each CRA.

The fine-tuning of the workflows based on the local context required the identification of the most influential factors of the studied climate risks. In addition to the municipal officers and the external experts involved the project, various local stakeholders were engaged, representing the vulnerable population groups and the most affected infrastructures and organizations. About 20 hazard, exposure and vulnerability indicators were identified in total, which allowed capturing the local conditions on the urban block and street level. Then, the collection of various high-spatial-resolution data sources allowed to translate the local indicators in a quantitative way, and downscale the CLIMAAX workflows from regional to local scale. This deliverable offers short descriptions of the technical background of the CRA, while emphasizing the interpretation of the results. The technical documentation, the datasets and the code files are submitted in supporting documentation on the Zenodo platform. The quantitative approach of the CRA workflows was followed by a qualitative analysis in the framework of the key risk assessment. The final outcomes are heatwave, heavy rainfall and relative drought risk maps presenting different climate change scenarios. In all cases, increasing risks are observed in future climate conditions, affecting most intensively the high-density urban areas. Heatwaves are projected to be more frequent and longer, heavy rainfall tends to concentrate in short and intense events, while drought is expected to become prolonged with more expanded impacts. An interesting finding is that several high-risk areas overlap in the three CRA, meaning that climate risks are connected and may intensify the impacts of each other, demanding interconnected adaptation actions, too.

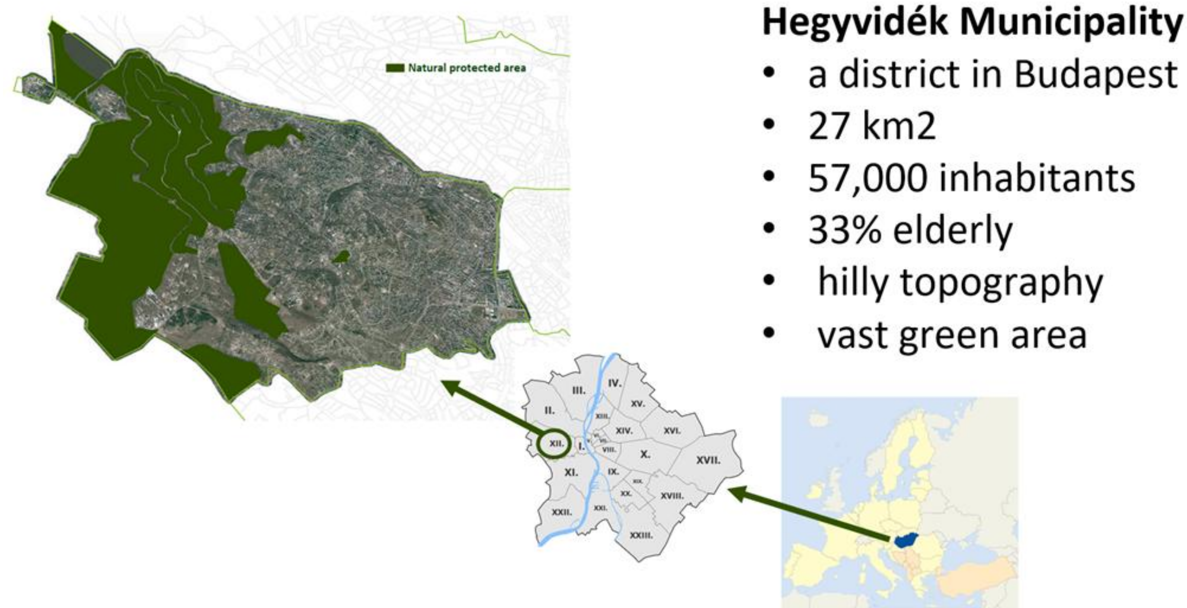
In Phase 3, the work will continue by evaluating the current risk management practices and designing action territories and sectors. Local decision makers, concerned municipal departments and stakeholders will be involved in the framework of workshops. This participatory process allows stakeholders to fine-tune the key risk assessment aspects (severity, urgency, resilience capacity) and risk prioritization, suggest realistic actions and good practices, identify the time range of each action, take responsibilities to carry out actions, and propose pragmatic public engagement for risk management.

From the perspective of the overall CLIMAAX project, the experiences of this pilot can be used for understanding how a city is able to interpret the general framework originally developed on a higher geographical scale. To conclude, the work accomplished in Phase 2 offers the main directions for preparing a climate risk management action plan in Phase 3.

1. Introduction

1.1. Background

The 12th District of Budapest (Hegyvidék Municipality) is located on the western side of the city of Budapest, Hungary. It has a specific microclimate caused by the hilly features of its topography (up to 400 m difference in level between the highest and the lowest points) and its west-to-east prevailing wind direction. Extreme weather conditions (e.g. heavy rain, heatwaves, drought) caused by climate change have increased in the last 10-20 years, negatively affecting the vulnerability of the local ecosystem, infrastructure, and residents. Furthermore, 33% of the local population are elderly (above 60), therefore a large proportion of the residents is significantly vulnerable to climate change. In terms of land cover, the Eastern part of the municipality is a mixed-use high-density downtown area with few green spaces and high traffic. The topography gradually elevates from East to West, and the neighborhoods, dominated by residential buildings, are characterized by larger and larger green areas. The western part of the municipality is a natural protected area, including forests that many residents and tourists visit for recreation, resulting in overcrowded areas similar to city parks.



1. Figure Location and main characteristics of Hegyvidék Municipality

1.2. Main objectives of the project

The MARCAdapt project aims to understand the risks caused by extreme climate phenomena in the area of the Hegyvidék Municipality in order to establish a comprehensive risk management strategy and action plan. The main impact of the project is the addition of a data-based, systemic view to the Municipality's approach to climate hazards and their impacts.

In Phase 1 Hegyvidék Municipality familiarized with the Climate Risk Assessment (CRA) methodology[1] and launched consultations with the local stakeholders. Nevertheless, using the data suggested in the CLIMAAX Handbook, the first results were inadequate for detailed local analysis due to the too large territorial scale. The main objective of Phase 2 was the collection of high-

[1] As presented in the CLIMAAX Handbook: https://handbook.climaax.eu/intro.html

resolution local data and the adaptation of the CRA on a small territorial scale, on urban block and street level. Furthermore, the expansion of the participatory processes, involving residents, professional and community stakeholders was also targeted.

Considering the benefits of Phase 2, Hegyvidék Municipality acquired and processed new high-resolution local data-sets, tailored the CRA methodology of the CLIMAAX Handbook on urban block level and, thus, obtained comprehensive results relevant for local analysis. The outputs help Hegyvidék Municipality to assess and compare the impacts of climate hazards within the administrative boundaries and build a well prioritized action plan for improved climate adaptation. Phase 2 also benefited organizations and professionals most concerned by climate risks in Budapest. The stakeholder meetings and newsletters communicating the evolution of the CRA adaptation contribute to the local platforms for sharing knowledge and resources among the concerned actors. Finally, the actions of Phase 2 served the residents of Hegyvidék Municipality too, allowing them to share their experiences considering climate risks in the city. Also, the residents learnt about how the CLIMAAX project supported their interests in urban adaptation to climate change in their neighborhood. As a result, the achievements in Phase 2 found a proper basis to proceed with the action planning in Phase 3.

1.3. Project team

The Green Office and the International Projects Office of Hegyvidék Municipality are in charge of the general project management, the coordination of the involved experts, and the communication with other municipal departments, the Mayor and the City Council. In addition, three Budapest-based external experts are involved in the implementation of the project:

- External data scientist - Milán Janosov phd.
- External climate change expert - EnviAdapt Kft. (Lilian Fejes)
- External communication and participation expert - Urbavis Kft. (Dorottya Teveli-Horváth phd., Anita Szőllőssy)

1.4. Outline of the document's structure

After the executive summary and the introduction, this document elaborates the sub-results achieved in the CRA during the second phase (16 months) of the project. The document follows the CLIMAAX Handbook's structure and develops the findings accordingly in this order: Scoping, Risk Exploration, Regionalized Risk Assessment, Key Risk Assessment Findings, Monitoring and Evaluation. Then, a work plan for the third phase of the project and a conclusion is elaborated, followed by progress evaluation. Finally, the list of supporting documentation uploaded to the Zenodo platform and the collection of references close this deliverable.

2. Climate risk assessment – phase 2

2.1. Scoping

2.1.1. Objectives

The objective, purpose, and expected outcome of the CRA are detailed in Deliverable 1, and some new aspects are presented in this document in section 1.2. Hence, this section focuses only on the encountered limitations and boundaries in Phase 2.

The local adaptation of the CRA on urban block and street levels demanded the use of various local datasets in diverse formats and geospatial geometries which had to be processed in a more complex way than expected. Also, when descending on the local scale, the MARCAdapt team and the stakeholders identified many exposure and vulnerability aspects to incorporate in addition to the metrics presented in the CLIMAAX Handbook. To address these challenges, the computing had to alter the codes of the original notebooks. Consequently, the adapted local CRA differs almost completely from those presented in the CLIMAAX Handbook. As the objective of CLIMAAX is to develop a common framework of CRA for all regions and communities in Europe, the limitations encountered by Hegyvidék Municipality with local level adaptation may be important takeaways from the general perspective of the CLIMAAX methodology as well.

Some further challenges were encountered regarding data collection (especially in the drought workflow), stakeholder motivation, and the reach-out to the citizens. These topics are addressed in the following sections.

2.1.2. Context

The contextual background is elaborated in Deliverable 1 that this section doesn't repeat but complete with newly discovered context aspects and outside influences during Phase 2.

First, Hegyvidék Municipality started exchanges concerning the management of climate risks with the Ministry of Public Administration and Regional Development, lead partner of several EU-funded regional projects related to this topic. The Interreg Centrale Europe LOCALIENCE project[2] developed several tools for municipalities to better prepare for and manage climate hazards. Some of these methods can complement the CLIMAAX framework, especially in risk management planning (Phase 3). This dialogue with the Ministry is helpful for Hegyvidék Municipality to represent its interests and share knowledge on a higher administrative level, as well as to better incorporate in the national context of risk management.

Second, several Budapest-based organizations and project partnerships carry out climate risk-related projects and expressed their interests in further knowledge sharing with Hegyvidék Municipality. Furthermore, international events are also organized in Budapest, such as the Pathways2Resilience[3] Summit 2026 organized in Budapest in February[4] (the Municipality of the City of Budapest is a pilot region). Therefore, climate risk assessment, management, and climate adaptation emerged as a trending theme among public institutions and relating organizations in the region. As a result, there is a huge potential to catch the general interest of the crucial stakeholders for fine-tuning the local CRA and the risk management plan of Hegyvidék Municipality. These

[2] https://www.interreg-central.eu/projects/localience/
[3] https://www.pathways2resilience.eu/
[4] https://www.pathways2resilience.eu/news-P2R-Summit-2026

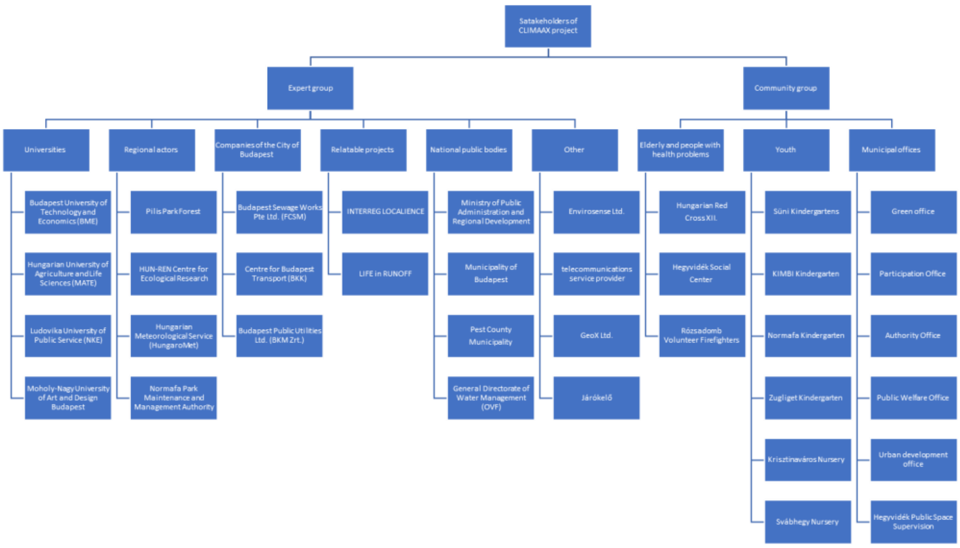
favorable conditions also help to share knowledge with others and, after the CLIMAAX project, to implement in practice climate management and adaptation actions in a harmonized and organized way on several levels (local, national, regional).

Finally, the crucial role of the local population in the interpretation of the CRA results, as well as in the climate risk management actions and adaptation must be highlighted in this section. The citizens' behavior and decisions influence a lot how the city, as a whole, reacts and prepares for climate risks. In order to involve the citizens, Hegyvidék Municipality must communicate the basics of the CRA and why it is useful. The difficulties regarding communicating complex and scientific topics to citizens are presented in the following sections in more detail.

2.1.3. Participation and risk ownership

The participatory processes were started with a local stakeholder analysis in Phase 1. The first step of the stakeholder analysis was to create a detailed excel spreadsheet, where contacts and requests were listed. Stakeholders relevant to the project were divided into two broad categories, according to whether cooperation and consultation with them would be more appropriate in professional and analytical tasks ("Expert stakeholder group"), or whether cooperation with them would be more relevant in community engagement and public participation ("Community stakeholder group").[5] Figure 2 presents the involved stakeholders on an organigramme.

Cooperation and consultation with members of the expert group is a good opportunity for analytical tasks. They are the ones who can validate the correctness of the risks identified as a result of the analysis and their assessment, as well as the relevance of the action plan steps in mitigating the risks. Members of the community group are those who can play a greater role in connecting with the residents, especially the local vulnerable groups, and engaging them. These are primarily representatives of locally based organizations, meaning they have knowledge of the area and can therefore help to identify local issues and strengthen connections with vulnerable groups.



2. Figure Stakeholders involved in the project

[5] All materials related to stakeholder involvement are presented in the „Stakeholder involvement" folder, uploaded on Zenodo.

2.1.4. Application of principles

The social justice, equity, and inclusivity principles are addressed with a careful selection of stakeholders representing the local vulnerable groups (especially the elderly) and several participatory actions with them to fully understand the most influential factors regarding the climate hazards. Furthermore, direct citizen involvement actions were carried out during Phase 2, including workshops, meetings, lectures, online questionnaires, printed newspapers etc. These actions are elaborated in section 2.1.5. and in the supporting documentation.[6]
The quality, rigour, and transparency principles are included by using several open data sources, national statistics, satellite imagery-based evaluations, which can be accessible by external parties. It must be highlighted though that the majority of the high-resolution data sources were purchased from specialized organizations because the municipality does not have knowledge to process the raw database. Furthermore, the project progress is presented and updated on Hegyvidék Municipality's webpage[7], as well as thematic newsletters, online and printed newspaper articles are published, several meetings are organized with the stakeholders and the residents.[8]
The precautionary approach is incorporated primarily by several rounds of proof reading of the results within the MARCAdapt team. The stakeholders were also involved in the confirmation of the local CRA metrics and the interpretation of the results. Moreover, external independent data sources were gathered to cross-check the CRA results, as explained in section 2.3.4.

2.1.5. Stakeholder engagement

Cooperation with stakeholders took two forms. Meetings and preliminary interviews were organized, which provided an opportunity for one-on-one conversations, gathering information, and answering questions. In addition, it was important to maintain contact between meetings, so when partial CRA results were available, a newsletter enclosing illustrations, maps, and explanations was sent out to maintain the stakeholders' interest.[9]

The first phase of stakeholder analysis focused on stakeholders in the "expert group" (detailed in Deliverable 1). In addition to the first stakeholder meeting with the "expert group", a separate session focusing on urban green areas were organized. Stakeholders involved in the management of green spaces[10] were invited to discuss issues related to the vulnerability of urban green areas (parks, trees, forests, etc.), primarily in relation to heatwaves and drought. The aim of the meeting was to identify aspects affecting urban green spaces and the available data, thereby helping to select and refine the indicators used in the CRA. The participants discussed the current and future status and situation of the forests and the urban green spaces they manage, based on available models, monitoring results, and practical experience. They also shared their thoughts on what could make forests and urban green spaces more resilient.

In Phase 2, the engagement activities also began with the "community stakeholder group". Preliminary interviews were conducted, followed by a separate meeting in a workshop setting. Through institutional cooperation and community meetings, the aim was to promote the interests

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[6] „Stakeholder involvement" and „Community involvement" folders, uploaded on Zenodo.
[7] https://zold.hegyvidek.hu/szakmai-munkank/horizon-europe-climaax
[8] All communication materials related to the CLIMAAX project are included in the „Stakeholder involvement" and „Community involvement" folders, uploaded on Zenodo.
[9] *Ibid. 12, 5*
[10] Pilisi Park Forest, Normafa Park Maintenance and Management Authority, Budapest Public Utilities Ltd., Green Office of the Hegyvidék Municipality

of the most vulnerable groups in the upcoming risk management plan. The workshop provided opportunity to identify specific locations, urban blocks, and street sections that should be considered priorities for development and renovation.

Among the 11 participants, a group was primarily concerned with the elderly: local health services, aid organizations, and volunteer firefighters. Another group consisted of representatives of local kindergartens, working with young people. The main outcome of the meeting was a detailed map that identified several problems in the municipality. The streets around the participating organizations were surveyed, as these areas are used extensively by vulnerable groups. This information (along with the information gathered during community involvement) can be used as inputs for the analysis of the CRA and for the action planning in Phase 3.

Approaching the end of Phase 2, the 3rd stakeholder meeting was held to present the final methodology and results of the adapted CRA. Though all stakeholders were invited, only the "expert group" participated because the analytical results of Phase 2 were mostly relevant to their work. The 14 participants of the 3rd stakeholder meeting gave feedback on how the results could be used by their organization, whether there were any surprising revealed information, and what else could be added to the work. A mutually beneficial knowledge-sharing process formed during and between the meetings with "expert group". Moreover, the stakeholder meetings provided a new professional platform for Hungarian experts to develop cooperation e.g. sharing data, methodology and contacts among themselves. Compared to typical conferences, these stakeholder meetings offered space to discuss concrete conceptional and methodological problems in practice.

Compared to this the research process and results of the CLIMAAX project seemed abstract and difficult to capture for the "community group". For future cooperation, innovative science communication tools can help to develop more active engagement. Based on the gathered experiences, more infographics, gamification and various modes of incentives could be implemented in the community involvement process.

The final stakeholder meeting will be scheduled for the beginning of Phase 3. The topic will be the targeted presentation of the areas with the most severe risk where intervention is crucial. Moreover, input will be gathered for the risk management action plan, including the identification of the responsibilities and useful tools too.

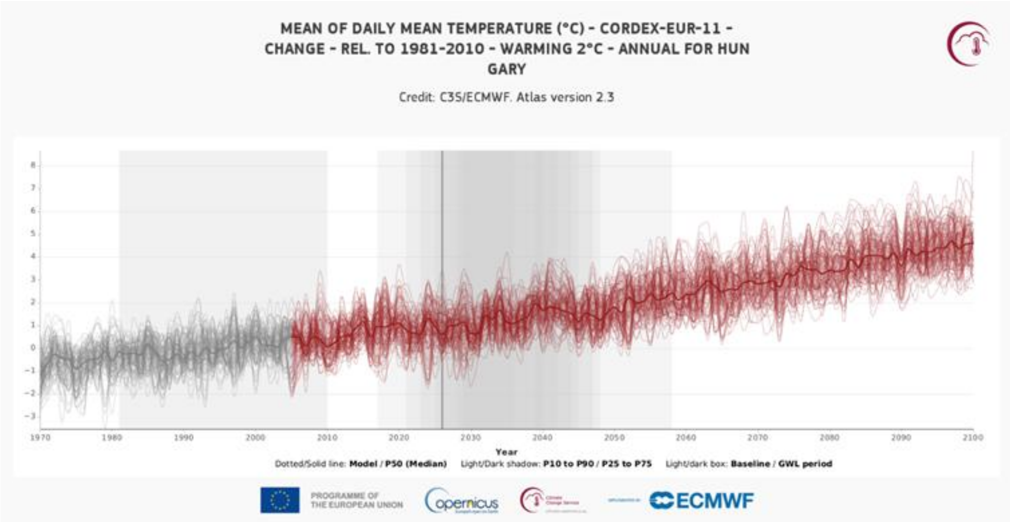
It is important to emphasize that Hegyvidék Municipality considers the local population to be a key partner, which means that they are also an important stakeholder group in the project. Therefore, residents actively participated in the process through questionnaires, community meetings, and informational lectures. The aim was to incorporate local knowledge, experiences, and observations into the analyses. During the data collection phase, Hegyvidék Municipality gathered information from residents about flood-prone areas, the effects of drought, and experiences during heatwaves.[11] During the action plan preparation in Phase 3, residents' opinions will be compared with the results CRA. This involvement also aims to familiarize residents with the cause and possible responses to climate risks, increasing the action plan's acceptance and raising awareness of the responsibilities and duties assigned to the local community.

[11] All materials related to community involvement are presented in the „Community involvement" folder, uploaded on Zenodo.

2.2. Risk Exploration

2.2.1. Screen risks (selection of main hazards)

The Copernicus Climate Atlas projections indicate that Hungary, including the area of the Hegyvidék Municipality, is facing significant and increasing climate hazards, mainly related to rising temperatures, heat extremes, and changing precipitation patterns. The projections of mean daily temperature show a clear and continuous warming trend throughout the 21st century. Compared to the 1981–2010 reference period. Warming becomes evident after 2000 and accelerates after 2020. Under the RCP8.5 emission scenario, temperatures are projected to increase substantially by mid- and late century. This warming affects all seasons, increasing baseline climate stress on ecosystems, agriculture, water resources, and human health.



3. Figure Projections of mean of daily main temperature (°C) in Hungary, based on EURO-CORDEX ensemble in 2°C global warming level (Source: Copernicus Climate Atlas)

The number of extreme hot days (maximum temperature above 35 °C) increases strongly in the summer period. In the near term (2021–2040), several hot days per year are expected and by mid-century (2041–2060), the median number roughly doubles. By the end of the century (2081–2100) projections show a dramatic rise, with over 14 extremely hot days per year on average, and much higher values in extreme cases.

The Copernicus Climate Atlas data indicate longer periods of high temperatures combined with reduced and more irregular precipitation, which increases the frequency and severity of droughts in Hungary. The rising number of hot days above 35 °C and longer consecutive dry periods enhance soil moisture deficits, especially during the summer period.

Urban green areas are particularly affected, as drought stress reduces vegetation vitality, increases tree mortality, and limits ecosystem services such as cooling, shading, and air quality improvement. Without sufficient water availability, urban parks and street trees become more vulnerable to pests and heat stress, reducing their capacity to mitigate urban heat island effects.

Extreme hot days (maximum temperature above 35 °C) (days) - Bias adjusted - CORDEX-EUR-11 - Change - rel. to 1981-2010 - RCP8.5 - Near Term (2021-2040) - Summer (JJA) HUNGARY

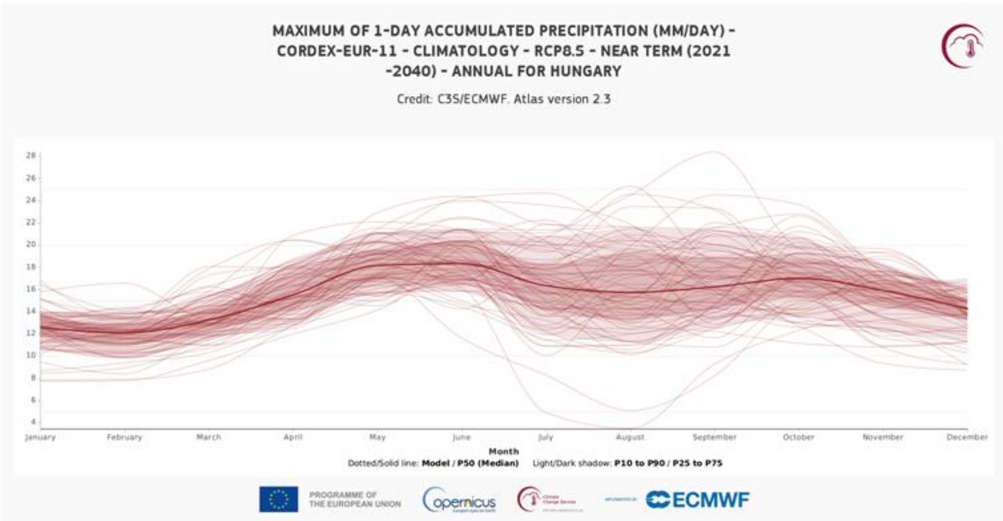
PERIOD	SCENARIO	MEDIAN (DAYS)	P25 | P75	P10 | P90	P5 | P95
Near Term (2021-2040)	RCP8.5	2.5	1.4 | 3.4	0.7 | 6.1	0.4 | 7.1
Medium Term (2041-2060)	RCP8.5	5.2	2.1 | 8.0	1.4 | 12.5	0.8 | 14.9
Long Term (2081-2100)	RCP8.5	14.4	11.3 | 19.1	8.5 | 33.0	6.9 | 38.2

Maximum consecutive dry days (days) - Bias adjusted - CORDEX-EUR-11 - Climatology - RCP8.5 - Near Term (2021-2040) - Annual HUNGARY

PERIOD	SCENARIO	MEDIAN (DAYS)	P25 | P75	P10 | P90	P5 | P95
Near Term (2021-2040)	RCP8.5	28.6	26.4 | 29.9	25.1 | 31.9	24.9 | 32.4
Medium Term (2041-2060)	RCP8.5	28.0	26.2 | 29.6	25.0 | 31.9	24.5 | 35.0
Long Term (2081-2100)	RCP8.5	28.8	26.9 | 30.9	25.4 | 33.1	24.4 | 34.3

4. Figure Projections of summer extreme hot days (maximum temperature above 35 °C) and annual maximum consecutive dry days in Hungary, based on EURO-CORDEX ensemble under RCP8.5 scenario (Source: Copernicus Climate Atlas)

The projections for maximum 1-day accumulated precipitation show higher intensity rainfall events, especially during late spring and summer. Increased variability, with stronger peaks during certain months. The projected increase in maximum 1-day precipitation intensity suggests a higher likelihood of short, intense rainfall events. Such heavy precipitation often exceeds urban drainage capacity, leading to surface runoff and flooding, while contributing little to long-term soil moisture recharge, thereby failing to offset drought impacts.



5. Figure Projections of annual distribution of maximum of 1-day accumulated precipitation (mm/day) in Hungary, based on EURO-CORDEX ensemble under RCP8.5 scenario in the period of 2021-2040 (Source: Copernicus Climate Atlas)

Hegyvidék Municipality chose to carry out 3 risk assessments in the project: heatwaves, heavy rainfall, and relative drought especially in the urban area. Heatwave and heavy rainfall CRA were carried out using the methodologies presented in the handbook, while for relative drought the analysis focused specifically on the risk aspects considering urban green spaces, using the highest-resolution data available.

Considering the available data and knowledge, Hegyvidék Municipality conducts a climate vulnerability assessment in the framework of the LIFE in RUNOFF project[12]. The assessment's methodology is based on the SIVAs model, adapted to the city of Budapest. Though the main topic is similar to the CLIMAAX project, there are considerable differences in terms of the objectives, the theoretical background, and the computational framework. Nevertheless, Hegyvidék Municipality reused some data sources and sub-results in the CLIMAAX CRA as well, including land cover and tree canopy database, mobility data, statistical data, sewer-related assessments, and heatwave hazard data (see section 2.3.). Further necessary data sources were identified in Phase 2, such as detailed maps of shadow coverage and drought impact, which were procured within the CLIMAAX budget. Other data needs were defined, but could not be collected, including high-resolution plant register and green space maintenance information, as well as high-resolution rainfall and drought hazard data. Section 2.3. details the eventually selected data sources in the three CRA, as well as indicates additional datasets that could not be incorporated in the workflows, but the MARCAdapt team used them for interpretation and cross-validation of the results.

2.2.2. Choose Scenario

In the framework of the three climate risk assessments—heatwaves, heavy rainfall, and relative drought—a set of future climate and socio-economic scenarios was applied to capture a range of plausible future conditions for the region, including the area of the Hegyvidék Municipality. The selected scenarios reflect both moderate and high climate change pathways, allowing for a robust assessment of climate-related risks under different levels of global mitigation and development trajectories.

Across the three climate risk assessments, different scenario frameworks were applied depending on data availability and methodological suitability, as presented in section 2.3. For some hazards, future climate conditions were assessed using RCP (Representative Concentration Pathways) based climate projections, while for others SSP (Shared Socioeconomic Pathways) based scenarios were applied. RCPs primarily describe future greenhouse gas concentration pathways and resulting climate outcomes and therefore provide limited information on socio-economic development. SSP scenarios offer a more comprehensive framework, combining emissions trajectories with globally consistent socio-economic narratives covering population growth, economic development, consumption patterns, land use, and adaptive capacity. Local assumptions were applied only in a qualitative manner and were not included in the quantitative risk calculations, as reliable, long-term local projections were not available.

For the heatwave risk assessment, climate projections based on RCP4.5 and RCP8.5 were applied for the 2031–2060 period. RCP4.5 represents a stabilization scenario assuming effective mitigation measures, while RCP8.5 reflects a high-emission pathway with limited mitigation. This combination allows for assessing heat-related risks under both policy-relevant and worst-case conditions within a medium-term planning horizon, which is particularly relevant for urban adaptation and public health measures.

The heavy rainfall risk assessment also used RCP4.5 and RCP8.5, focusing on a slightly later time window (2041–2070). This period was selected to better capture projected changes in precipitation

[12] LIFE20 CCA/HU/001774 https://varosieso.hu/en/ The uploading of the project deliverables is in progress on the Document repository sub-page of the project website. All deliverables will be available by the project closure, April 30, 2026.

intensity, which tend to become more pronounced toward mid-century. Using both scenarios enables the evaluation of uncertainty ranges in extreme rainfall projections and their implications for urban drainage systems and flood risk management.

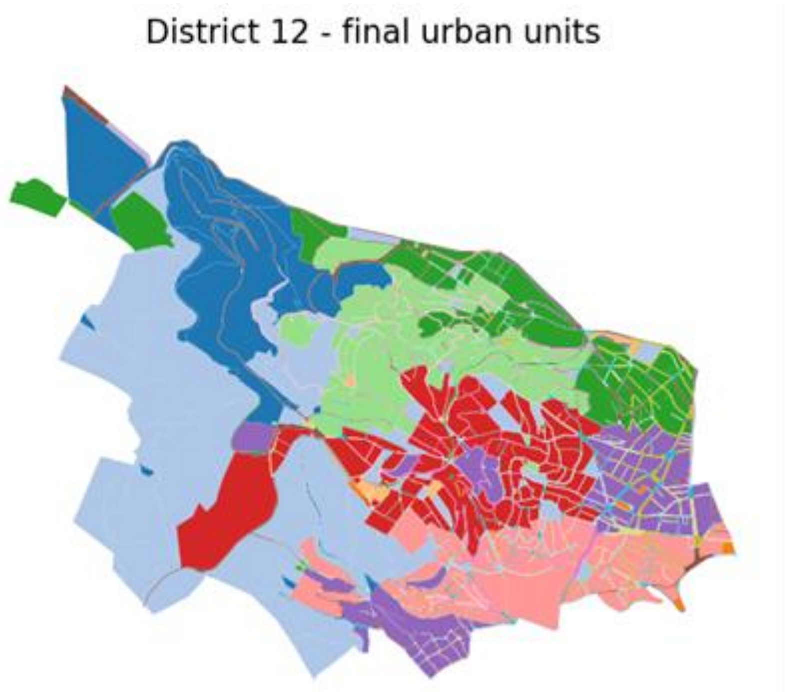
For the relative drought risk assessment, future climate conditions were analyzed using SSP3-7.0 and SSP5-8.5, with a specific focus on urban green spaces. These scenarios were selected because they combine climatic forcing with socio-economic development pathways that strongly influence land use, water demand, and the management of urban vegetation. SSP3-7.0 represents a future with limited institutional capacity and increasing pressure on natural resources, which can exacerbate drought stress on urban green infrastructure. In contrast, SSP5-8.5 reflects a high-emission, resource-intensive development pathway, leading to intensified warming and higher evapotranspiration rates, significantly increasing drought risk for urban trees, parks, and other green areas. This approach allows for assessing how prolonged water deficits and heat stress may reduce the resilience and ecosystem services of urban green spaces under different socio-economic and climate futures.

2.3. Regionalized Risk Analysis

The first step of the regionalized risk assessment was to identify the appropriate spatial scale allowing meaningful local analysis. Local urban planning addresses the scale of neighborhoods, and intervention planning is based on streets and blocks of houses. To support future local decision-making and planning, Hegyvidék Municipality decided to conduct the CRA on the spatial scale of urban blocks (areas delimited by streets) and streets (sections bordered by junctions), presented on Figure 6.

The primary objective of this approach was to construct logically segmented, small-scale urban units that can serve as consistent spatial scale for downstream analysis and modelling. The approach ensures complete spatial coverage while maintaining a level of geometric granularity appropriate for urban-scale applications. The technical details and quality control process can be found in the supporting documentation.[13]

[13] „Technical documentation” folder uploaded on Zenodo, including the „Climaax tech summary_MARCAdapt” document with detailed explanations, as well as the notebooks and outputs organized in a logical folder structure.



6. Figure Illustration of the urban blocks and streets in random coloring. This geometry is the basis of the adapted CRA

2.3.1. Heatwave - fine-tuning to local context

1. Table Data overview workflow #1 Heatwaves

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
SURFEX land surface model: number of tier-1 heatwaves (HWDI1), tier-2 heatwaves (HWDI2), and the number of tropical nights (TR), 1 x 1 km resolution	Demographics census statistics on urban block-level: the number of residents aged under 15, the number of residents aged 65 and above, the number of people with mobility impairments, and the presence of air conditioning	Surface temperature based on LANDSAT	Heatwave Risk assessment RCP 4.5 on urban block level
	Public transport data of bus and tram stops: accessibility	Tree canopy data based on 5 cm resolution orthophotography LiDAR survey: canopy area data represents the total ground area covered by tree crowns; canopy area ratio expresses green canopy coverage density	Heatwave Risk assessment RCP 8.5 on urban block level
	Type of bus and tram stop	Land-cover data based on 5 cm spatial resolution orthophotography survey	

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
	Building characteristics on urban block level: time of construction	Shade coverage based on satellite data 1 m resolution based on LiDAR	
	Coverage of public institutions and basic services on urban block and street level	Aggregated GPS mobility data from apps describing the average distribution of users in summer between 2022 and 2024, 50 x 50 m spatial resolution	
		Aggregated telecommunication mobility data (cell-tower based) describing the average distribution of users during heatwave days and the percentage difference between heatwave and reference-day traffic, between 2022 and 2024, 50 x 50 m spatial resolution	

2.3.1.1. Hazard assessment #1 Heatwaves

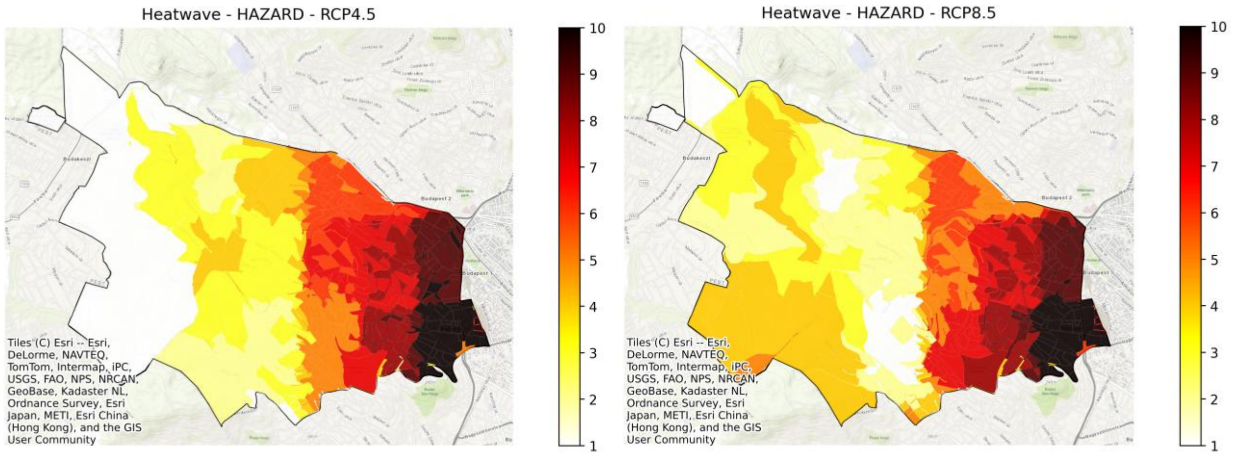
For the heatwave hazard assessment, the CLIMAAX workflow was significantly refined by integrating very high-resolution local climate model outputs, allowing for a detailed representation of urban-scale processes. The hazard analysis was based on results from the SURFEX land surface model, available at a 1 × 1 km spatial resolution[14], which represents the highest-resolution dataset used across the three risk assessments.

To capture the expected urban-specific impacts of climate change, SURFEX simulations were performed for a future period (2031–2060), with projected changes assessed relative to the defined baseline reference period, driven by atmospheric forcings from regional climate model simulations under RCP4.5 and RCP8.5 emission scenarios. Urban processes within SURFEX are represented by the Town Energy Balance (TEB) sub-model (Masson, 2000), which describes cities as street canyon

[14] The data was acquired in the framework of the LIFE in RUNOFF project. LIFE20 CCA/HU/001774 https://varosieso.hu/en/ The uploading of the project deliverables is in progress on the Document repository sub-page of the project website. All deliverables will be available by the project closure, April 30, 2026.

systems and explicitly accounts for heat conduction through roofs and walls, as well as anthropogenic heat and moisture emissions from traffic and industrial activities. This approach allows for a realistic representation of the urban heat island effect and heat stress conditions.

The hazard component of the heatwave risk assessment was quantified using three locally relevant indicators derived from the model outputs: number of first-level heat alert days, number of second-level heat alert days, and number of tropical nights. Technical information of the hazard assessment, the data processing and the output is presented in the supporting documentation[15].



7. Figure Heatwave hazard derived from SURFEX model simulations for the RCP4.5 (left) and RCP8.5 (right) scenarios for the period of 2031–2060

Hazard maps present the spatial distribution of heatwave hazard derived from SURFEX model simulations for the RCP4.5 (left) and RCP8.5 (right) scenarios. These maps illustrate the modeled intensity and frequency of heat-related conditions based on high-resolution simulations.

Under RCP4.5, elevated heatwave hazard values are concentrated mainly in the eastern and south-eastern parts of Hegyvidék Municipality, corresponding to areas with higher building density and more intensive urban land use. Lower hazard levels dominate the western and north-western zones, which are characterized by higher elevation, more vegetation, and lower built-up density. This spatial pattern highlights the role of urban morphology and land cover in shaping heat stress, even under a moderate climate change scenario.

Under RCP8.5, the overall spatial pattern remains broadly similar; however, heatwave hazard levels increase in several parts of the area. Higher hazard classes become more widespread, and a noticeable increase is also observed in areas that previously exhibited lower hazard levels, including the less densely built-up zones. This reflects the stronger warming signal associated with the high-emission pathway, leading to more frequent and intense heat stress conditions simulated by SURFEX.

2.3.1.2. Risk assessment #1 Heatwaves

In the heatwave risk assessment, local data was used for both vulnerability and exposure indices to improve resolution and capture urban block and street level characteristics, as presented in Table 2 The general approach of the CLIMAAX Handbook was followed: vulnerability indices are related to the vulnerable population, while exposure indices capture the characteristics of the urban

[15] ibid, 18, 13

environment. The identification of the datasets was carried out with stakeholder input representing the vulnerable groups, especially the elderly, as detailed in sections 2.1.3 and 2.1.5.

While a short summary is provided in this section as follows, the technical information of the risk assessment, the data processing and the output is presented in the supporting documentation[16].

Vulnerability indices

- The **demographic indicators** describe population vulnerability. These variables capture the number of residents aged under 15, the number of residents aged 65 and above, the number of people with mobility impairments, and the presence of air conditioning in residential apartments. This data enrich each spatial unit with socio-demographic and structural attributes that are directly relevant for climate exposure and resilience assessment.
- The indicators of accessibility, walkability of the **public transport** stops and the quality of the bus and tram stops (the presence of shading elements and seating opportunities) reflect their usability and comfort during extreme heat conditions. These indicators were selected because vulnerable groups (elderly) use public transport on a daily basis even in heatwaves. In addition, the mere use of public transportation forces people to walk distances and wait longer times outside regardless the climatic conditions.
- **Building characteristics** on urban block level includes the time of the construction, capturing the relative climate resilience of the built environment within each urban unit. Newer buildings are more likely to be well insulated, and thus their residents are less vulnerable to heatwaves.
- The coverage of **public institutions and basic services** on urban block and street level indicator captures essential services (nurseries, kindergartens, care centers, grocery stores, pharmacies, etc.) whose accessibility is especially critical for vulnerable groups (elderly, children) during extreme heat conditions.

Exposure indices

- **Surface temperature** based on LANDSAT, similar to the CLIMAAX Handbook. The aggregated land surface temperature (LST) indicator includes the mean summer LST and the median summer LST over the last ten-year period. These metrics provide a robust summary of long-term thermal exposure, and serve as key inputs for assessing heat-island effect.
- The **tree canopy** dataset allows to consider the total canopy area (representing the total ground area covered by tree crowns) and canopy area ratio (expressing green canopy coverage density). These indicators form a key component of the exposure by showing where trees are able to provide shade and moderate temperature with evapotranspiration.
- The **land cover** data helps to improve the resolution of surface temperature (LANDSAT), and contribute with a new aspect - the effects of the different surface types on the surface temperature. For example, vegetation surfaces can decrease temperature, artificial surfaces can increase temperature.
- The **shade coverage** dataset captures the spatial extent of shadows cast by buildings and trees under specific solar conditions and provides a detailed representation of shade

[16] ibid 18,13

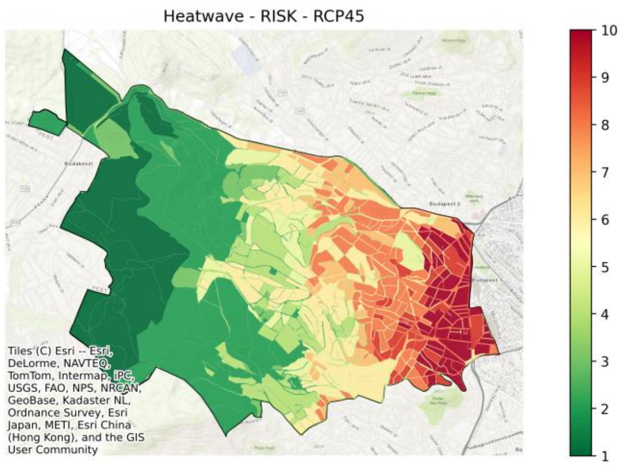
availability in the street environment. This indicator forms another important component of the exposure by showing where buildings are able to provide shade and reduce surface temperature by several degrees, thus moderating the effect of heatwaves.

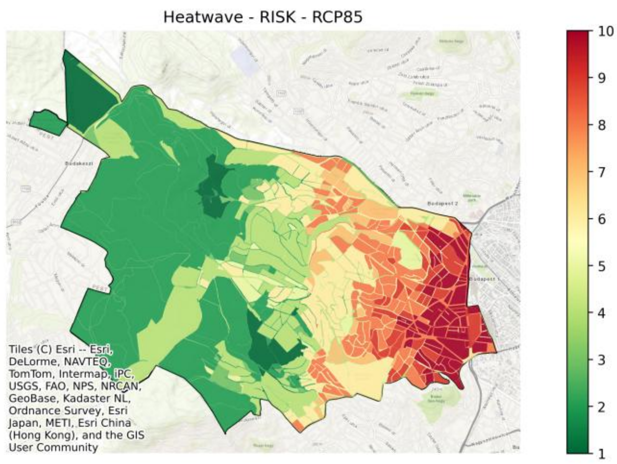
- The aggregated **GPS mobility** indicator represents the average number of detected GPS devices per urban unit over the selected summer period between 2022 and 2024. The data shows the general distribution of people in the city, highlighting the streets with the highest traffic (high car traffic can intensify the temperature). The indicator also provides an additional behavioral dimension to the environmental and demographic indicators.
- Aggregated **telco mobility** indicator represents network traffic intensity as a proxy for population presence and activity during ten days classified as heatwave days between 2022 and 2024. Compared to the GPS mobility, telco data is much more accurate and allows the comparisons between heatwave days and reference days. The indicator captures how population presence and activity respond to extreme heat conditions relative to normal periods, providing a complementary behavioral signal to the GPS mobility data.

The above introduced vulnerability and exposure indicators were derived from diverse data sources with different formats and scales (POIs, rasters grids, polygons, etc.). The raw datasets were processed and fitted to the urban block geometry described in the introduction of section 2.3. The technical details of the data processing is presented in the supporting documentation[17]

Since the exposure and vulnerability indicators originate from heterogeneous data sources and are expressed in different units and ranges, direct comparison or aggregation would not be meaningful without normalization. To address this, each indicator is rescaled into a discrete 1-10 vulnerability/exposure score, where 1 represents low vulnerability/exposure and 10 represents high vulnerability/exposure.[18]

Then, the MARCAdapt team determined weights for each vulnerability and exposure indicator, thus refining how strongly they should influence the final heatwave risk map. The final heatwave risk scores were calculated by combining vulnerability, exposure, and hazard components for RCP 4.5 and RCP 8.5 scenarios.[19]





[17] *Ibid. 18,13* Folder „01_data processing"
[18] *Ibid. 18,13* Folder „02_scoring"
[19] *Ibid 18,13* Folders „03_climate risk assessment" and „04_output"

8. Figure Heatwave Risk maps of Hegyvidék Municipality for the RCP4.5 (left) and RCP8.5 (right) scenarios for the period of 2031–2060. 10 indicates high risk (red), 1 indicates low risk (green)

As Figure 8 shows, heatwave risk is highest in the Eastern areas of the municipality with higher building density and more intensive urban land use. In these neighborhoods green spaces are scarce, and the vulnerable groups, especially elderly people, and crucial public services are concentrated. On the contrary, the lowest heatwave risk scores are in the forests and the neighboring residential areas with gardens. These neighborhoods are located in the Western and North-Western areas which are characterized by higher elevation, more vegetation, and lower built-up density.

When comparing the two scenarios, the highest risk scores are almost identical in RCP4.5 and RCP8.5. The differences appear in the mid -and low risk scored urban blocks (1-5) - green residential areas and even forests reach higher risk scores under the pessimistic RCP8.5 scenario.

An interesting discovery is that urban parks located in the downtown are characterized by very different heatwave risk scores. The dissimilarities can be caused not only by the size of the parks, but also by the built-up area and traffic volume of their surroundings - heatwave risk is lower in larger parks surrounded by less urban density and lower traffic. All of these factors can also influence the extent to which a given park can have an impact (e.g. a temperature-reducing effect) on the surrounding streets.

In some localized instances RCP8.5 results in lower heatwave hazard indicators than RCP4.5. This can be attributed to the threshold-based nature of the indicators, internal climate variability, and non-linear urban surface–atmosphere interactions represented in the SURFEX –TEB model. The model explicitly accounts for urban radiation balance, heat conduction through walls and roofs, and turbulent heat fluxes, which can lead to scenario-dependent and non-monotonic responses of near-surface air temperature, particularly at high spatial resolution and for near- to mid-term future periods.

In Phase 3, the MARCAdapt team will choose target areas for heatwave-related adaptation actions based on the final risk maps, while also pondering the input indicators, the severity, urgency, resilience aspects, as well as the opinions and roles of the stakeholders.

2.3.2. Heavy rainfall - finetuning to local context

2. Table Data overview workflow #2 Heavy rainfall

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
EURO-CORDEX climate projections at 12 km spatial resolution	Sewer vulnerability indicator at sewer section-level	Land cover data based on 5 cm spatial resolution orthophotography survey.	Heavy Rain Risk assessment RCP 4.5 on urban block level (2041–2070 period)
	Flood points of the sewage system	Aggregated telecommunication mobility data (cell-tower based) describing the average distribution of users on selected days with heavy rainfall events	Heavy Rain Risk assessment RCP 8.5 on urban block level (2041–2070 period)

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
		between 2022 and 2024, 50 x 50 m spatial resolution	
	Building characteristics on urban block level: Time of construction	Aggregated GPS mobility data from apps describing the average distribution of users between 2022 and 2024, 50 x 50 m spatial resolution	
	Public transport accessibility on urban block and street level		
	Type of bus stop		
	Coverage of public institutions and basic services on urban block and street level		

2.3.2.1. Hazard assessment #2 Heavy rainfall

For the heavy rainfall hazard assessment, the CLIMAAX workflow was adapted through a two-step approach combining historical observations with climate projections.

First, past extreme precipitation events were analyzed using daily and hourly precipitation data from local meteorological stations, enabling the identification of recent critical events in terms of both frequency and intensity. This analysis provided a strong empirical basis for understanding local vulnerabilities and validating the relevance of projected future changes. This data is further explained in section 2.3.4.

For future hazard assessment, EURO-CORDEX climate projections were employed, using precipitation flux data at a 12 km spatial resolution. The analysis relied on the EC-Earth / RACMO22E model combination under RCP4.5 and RCP8.5 scenarios, focusing on the 2041–2070 period, with changes assessed relative to a reference period. Where available, bias-corrected 24-hour precipitation datasets were applied to improve the reliability of extreme precipitation estimates. Due to the spatial resolution of the available climate projections, dedicated rainfall hazard maps are not presented in this section, differences between the climate scenarios and their implications are illustrated in the risk assessment chapter, where scenario-specific impacts are more clearly expressed through the heavy rainfall risk maps in section 2.3.2.2.

2.3.2.2. Risk assessment #2 Heavy rainfall

In the heavy rainfall CRA, local data was used for both vulnerability and exposure indices to provide accurate spatial resolution and capture urban block and street-level characteristics, as presented in Table 3 The chosen vulnerability indicators describe the vulnerable infrastructures (streets, sewage system, buildings, public infrastructure, basic services) responsible for the general functioning of the city. When heavy rainfall causes significant disturbances and damage to these infrastructures, a large proportion of the population is affected. The selected exposure indicators feature the urban environment (pavement, traffic) influencing the occurrence of floods and the range of the damage. The local datasets were first identified based on the experiences and knowledge of Hegyvidék Municipality, then completed and approved by the stakeholders, as detailed in sections 2.1.3 and 2.1.5. The most important input for the heavy rainfall CRA was provided by city operation companies (sewer works, public transportation operator), universities and the LIFE in RUNOFF[20].

While a short summary is provided in this section as follows, the technical information of the risk assessment, the data processing and the output is presented in the supporting documentation[21].

Vulnerability indices

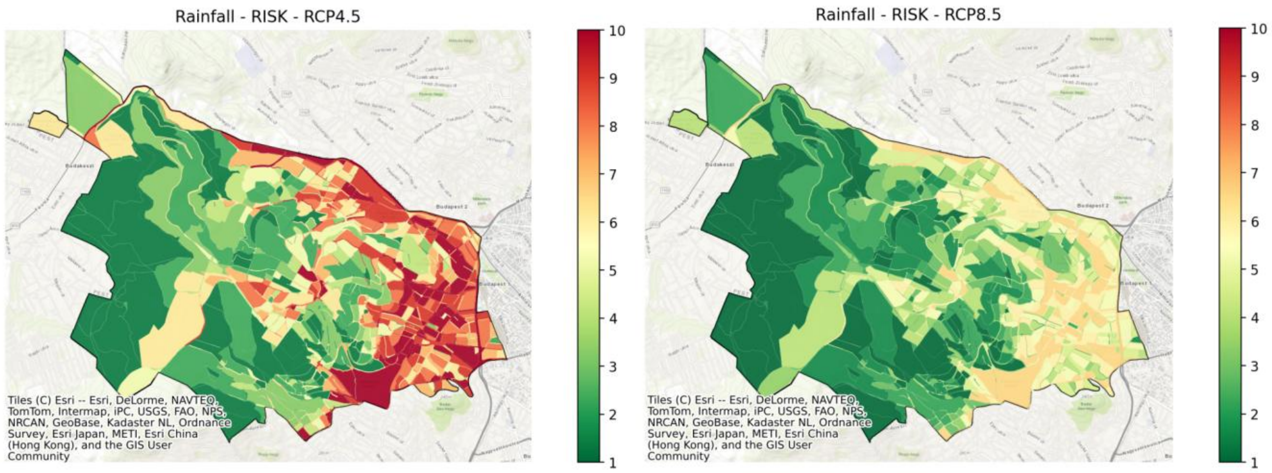
- **Sewer vulnerability** indicator at sewer section-level (approximately corresponding to street sections), based on the characteristics of each section (time of construction, diameter, slope, etc.). The indicator was developed by the Technical University of Budapest in the LIFE in RUNOFF project and Hegyvidék Municipality decided to include it in the heavy rainfall assessment.
- **Flood points of the sewage sections**, derived from the Stormwater Management Model (SWMM)[22] applied to the territory of Hegyvidék Municipality. The model was adapted by the Technical University of Budapest in the framework of the LIFE in RUNOFF project. The SWMM estimates how much rainwater is likely to spill off from the underground drainage network to the surface at different sewer sections, flooding the roads and the neighboring buildings. The model operates on a dual level, taking into consideration rainwater runoff both on the surface and in the underground drainage network. The model also includes the topography: lower areas are more likely to be flooded because the runoff accumulates from the higher areas.
- **Building characteristics** (time of construction) are also included, taking into account that the basis, the roof, and the drainage of older buildings are less adapted to the extreme rain events caused by climate change.
- **Public transport** accessibility describes how easily people access transport, and the type of bus and tram stop shows the conditions in which passengers must wait at the stops in heavy rain. Public transportation is a critical and highly vulnerable infrastructure because it serves a large portion of the population who are unable to use private transport. Furthermore, rainwater accumulates mostly in public spaces where public transportation operates, thus blocking entire bus lanes or stops.
- Coverage of **public institutions and basic services** is also considered because there are daily destinations (kindergartens, schools, healthcare services, social care, groceries, etc.) that are necessarily visited even in heavy rain events by the population. When a neighborhood has a good coverage of these services, the daily routes are short and less likely to be blocked in heavy rainfall events.

[20] *Ibid. 17, 12*
[21] *Ibid. 18, 13*
[22] https://www.epa.gov/water-research/storm-water-management-model-swmm

Exposure indices

- **Land cover** data helps to identify the share of the permeable surfaces enabling rainwater infiltration (vegetation, grass, open soil, green roof), and the impermeable surfaces where rainwater runs off, surcharging the drainage networks and causing floods (roads, paved surfaces, traditional roofs, etc.)
- **Aggregated telecommunication and GPS mobility** data describes the average distribution of people in given intervals. Crowded areas are the most exposed to the floods because the damages directly affect a large number of people.

The data processing of the raw datasets to compute the final risk maps on urban block level followed the logic already presented in the heatwave assessment (section 2.3.1.2), including the common urban block geometry transformation, the 1-10 scoring, and the weighting processes. The technical details are presented in the supporting documentation.[23]



9. Figure Heavy Rainfall Risk maps of Hegyvidék Municipality for the RCP4.5 (left) and RCP8.5 (right) scenarios for the period of 2031–2060. 10 indicates high risk (red), 1 indicates low risk (green)

Indicators used in the heavy rainfall hazard analyses reflect projected changes in short-duration (3-hour) and daily (24-hour) maximum precipitation for the mid-century period compared to the reference climate. The results indicate an overall increase in extreme precipitation intensity under both scenarios, with a stronger increase under the intermediate emission pathway for short-duration extremes, while longer-duration extremes show a more moderate but consistent increase across scenarios.

The heavy rainfall risk maps for the 2031–2060 period (Figure 9) illustrate clear differences in both the spatial pattern and overall intensity of risk between the two scenarios. Under RCP4.5, areas classified as higher risk are more widespread and spatially coherent, particularly in zones where increases in both short-duration and daily precipitation extremes contribute to elevated hazard levels. RCP8.5 scenario also indicates an intensification of heavy rainfall risk, but with a generally more moderate and fragmented spatial distribution. These patterns are consistent with the underlying hazard indicators, which point to an increase in extreme precipitation at multiple temporal scales in the mid-term future, although with differing relative magnitudes across scenarios.

[23] *Ibid 18, 13*, Folders "01_data processing", "02_scoring", „03_climate risk assessment" and „04_output"

RCP4.5 shows a stronger increase in heavy rainfall–related risk in some locations does not represent an inconsistency but rather reflects the inherently non-linear response of precipitation extremes to climate warming. Extreme rainfall does not scale linearly with increasing temperature; it is strongly influenced by changes in atmospheric circulation, convective processes, and moisture dynamics, which may favour enhanced extremes within certain temperature ranges. In addition, the mid-term time horizon considered here, together with internal climate variability, can amplify scenario-specific differences at the regional scale. Together, these factors highlight that heavy rainfall risk is highly dependent on regional dynamics and temporal context and cannot be reasoned only from the relative strength of the emission pathway.

In terms of the spatial patterns of the heavy rainfall risk, RCP4.5 and RCP8.5 scenarios show a similar layout, though with different amplitudes. Hegyvidék Municipality decided to consider the scenario projecting higher risks (RCP4.5) as a reference for strategy building and action planning in Phase 3.

Considering the intra-territorial differences, Figure 9 shows that the risk scores are the highest at the topographical low points and at the bottom of the rainwater sub-catchment areas. The forests and the urban neighbourhoods with more green spaces further up on the hillside are lower scored. This pattern synchronizes with the general affirmation that rainwater runoff is minimal on green spaces due to the direct infiltration into the soil.

Furthermore, heavy rainfall risk affects most severely the dense urban areas on the Eastern side of the municipality, where the population concentrates, and the share of the elderly is higher in the population. The largest roads and transportation axes are also highly scored. Hegyvidék Municipality already experiences serious damage at these high-risk areas during heavy rainfall events. However, the results also emphasize some territories with high scores where Hegyvidék Municipality has no direct experience yet of extreme impacts.

In Phase 3, the MARCAdapt team will choose target areas for heavy rainfall-related adaptation actions based on the final risk maps, while also pondering the input indicators, the severity, urgency, resilience aspects, as well as the opinions and roles of the stakeholders.

2.3.3. Relative drought - fine-tuning to local context

3. Table Data overview workflow #3 Relative drought

Hazard data	*Vulnerability data*	*Exposure data*	*Risk output*
CMIP6 global climate models - Weighted Anomaly Standardized Precipitation (WASP) index	Land cover data based on 5 cm resolution orthophoto	LANDSAT surface temperature	Relative Drought Risk assessment on urban block level (SSP3-7.0 and SSP5-8.5)
NDVI-WASP combined indicator	Tree density data based on 5 cm resolution orthophoto	Aggregated telecommunication mobility data (cell-tower based) describing the average distribution of users between	

		2022 and 2024, 50 x 50 m spatial resolution	
Heatwave days and tropical nights		Aggregated GPS mobility data from apps describing the average distribution of users between 2022 and 2024, 50 x 50 m spatial resolution	

2.3.3.1. Hazard assessment #3 Relative drought

For the relative drought risk assessment, the CLIMAAX Handbook workflow was adapted specifically to evaluate drought impacts on urban green areas, rather than on agricultural or natural ecosystems. This fine-tuning was necessary to reflect the distinct water balance characteristics, soil sealing effects, and management dependencies of urban vegetation.

The hazard component was based on the Weighted Anomaly Standardized Precipitation (WASP) index, as recommended in the CLIMAAX Handbook, ensuring methodological consistency while being specifically tailored to the assessment of drought risk for urban green areas. The WASP index was selected because it effectively captures precipitation anomalies relevant to vegetation water stress, which is a key driver of drought impacts on urban trees, parks, and other green areas.

The hazard assessment used an average of five CMIP6 global climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL). The analysis was performed for SSP3-7.0 and SSP5-8.5, which represent futures with elevated drought risk due to increasing temperatures, higher evapotranspiration, and intensified pressure on water resources. This multi-model, multi-scenario approach allowed for a more reliable assessment of drought hazard trends affecting urban green infrastructure under different socio-economic and climate development pathways. Due to the spatial resolution of the available climate projections, dedicated drought hazard maps for the analysed future period are not presented in this section, differences between the climate scenarios and their implications are illustrated in the risk assessment chapter, where scenario-specific impacts are more clearly expressed through the drought risk maps in section 2.3.3.2.

For drought assessment, a combined indicator integrating past NDVI (Normalized Difference Vegetation Index) and WASP values was developed to capture both meteorological drought conditions and vegetation response. The WASP component was calculated using precipitation data from two local meteorological stations operated by the Hungarian national meteorological agency (HungaroMet), following the CLIMAAX workflow methodology. WASP indices were derived for August 2022, 2023, and 2024, with each year assigned a weighting score in order to represent recent drought conditions across the assessment period. In parallel, changes in NDVI were calculated for August 2022, 2023, and 2024 relative to the 2014–2024 reference period, allowing the identification of areas experiencing persistent or recurrent vegetation stress. Each urban block was assigned an aggregated score based on the magnitude and direction of NDVI change across these years. The final NDVI-WASP combined indicator was obtained by integrating the NDVI-based scores with the WASP-derived weights. This combined approach enhances the interpretation of drought risk by linking atmospheric water deficits directly with observed ecosystem response, providing a more impact-oriented representation of past drought conditions at the local scale.

Furthermore, the relative drought hazard assessment was completed with certain aspects of the hazard assessment elaborated for heatwaves (number of tropical nights and heatwave days), because extreme heat events intensifies the impact of precipitation loss on the vegetation and soil.

2.3.3.2. Risk assessment #3 Relative drought

As Hegyvidék Municipality adapted the CLIMAAX relative drought workflow specifically on urban green areas, new indicators had to be defined on the highest spatial resolution possible. Therefore, the vulnerability and exposure indices were selected characterizing the urban green spaces – trees, flower beds, shrubs, lawns, bee pastures, forests, etc. - and the urban environment influencing the impact of drought.

The main vulnerability and exposure aspects were identified with the help of expert stakeholders, especially the green space maintenance companies and forest maintenance companies operating on the territory of Hegyvidék Municipality, as detailet in sections 2.1.3. and 2.1.5. Nevertheless, some of these aspects couldn't be transformed into sufficiently detailed dataset for inclusion in the workflow. Such features are namely maintenance related information which influence the resistance of the vegetation to drought: irrigation practices, mowing frequency, mulching, etc. Furthermore, different plant species are more or less resistant to drought, but data on this aspect was also too limited for integration in the workflow.

While a short summary is provided in this section as follows, the technical information of the risk assessment, the data processing and the output is presented in the supporting documentation[24].

Vulnerability indices

- **Land cover** data was used to incorporate the spatial expanse and intensity of the vegetation, as well as the density of green spaces versus the paved and built-up surfaces.
- **Tree density** describes how vulnerable each area is to drought in relation to others. The higher the tree density in an area, the more vulnerable it is to drought. The struggle for water is the most significant factor.

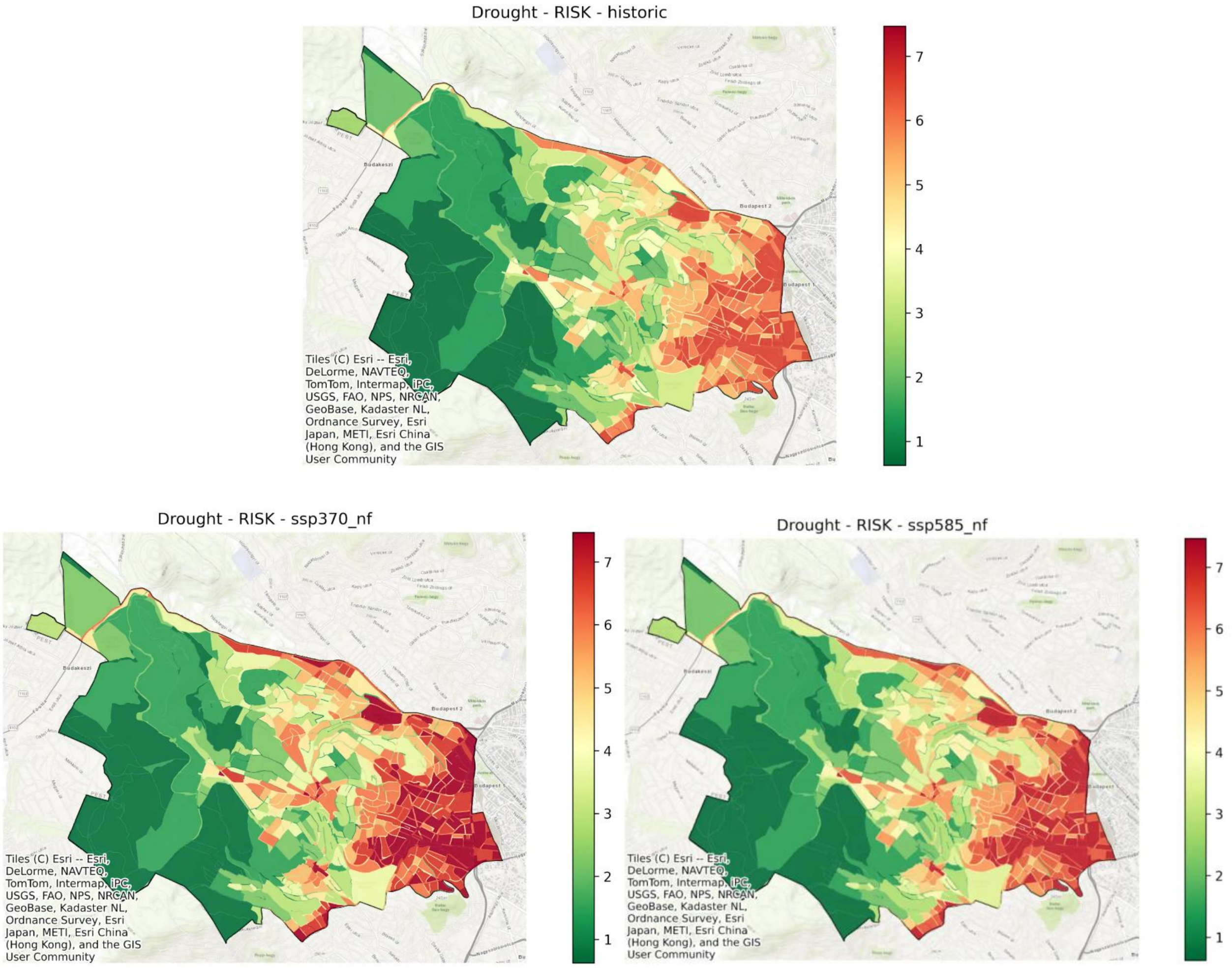
Exposure indices

- LANDSAT **surface temperature** allows to include the effect of urban heat islands, a phenomenon crucially increasing the effect of drought on urban green spaces and the surrounding forests.
- **Mobility data** describes the intensity of the use of the urban green spaces by the inhabitants. In the most visited green areas, the soil is compressed and plants are damaged, thus making them less resistant to drought.

The data processing of the raw datasets to compute the final risk maps on urban block level followed the logic already presented in the heatwave assessment (section 2.3.1.2), including the common urban block geometry transformation, the 1-10 scoring and the weighting processes. The technical details are presented in the supporting documentation.[25]

[24] *Ibid. 18, 13.*

[25] *Ibid 18, 13*, Folders "01_data processing", "02_scoring", „03_climate risk assessment" and „04_output"



10. Figure Relative Drought Risk maps of Hegyvidék Municipality for the historic conditions (top), SSP3-7.0 near future (left) and SSP5-8.5 near future (right) scenarios. 10 indicates high risk (red), 1 indicates low risk (green)

Drought risk maps (Figure 10), interpreted together with the WASP-based hazard methodology, provide a coherent picture of both the spatial patterns and the scenario-dependent evolution of drought hazard across the municipality. The historical map shows a clear West–East gradient, with lower drought risk prevailing in the Western part of the municipality, where larger and more contiguous green areas are present, and higher risk concentrated in the more densely built Eastern zones. This contrast reflects the combined effect of precipitation deficits and land-cover characteristics, as vegetated areas are better able to buffer short-term rainfall anomalies, while impervious surfaces amplify drought-related stress. WASP indicator explicitly accounts for the seasonal distribution of precipitation deficits, which enhances the sensitivity of the hazard assessment to periods when water shortages are most critical.

Under future climate scenarios, both SSP3-7.0 and SSP5-8.5 indicate an overall intensification of drought risk relative to historical conditions, while largely preserving the existing spatial structure. The maps on the left and right of Figure 10 show that areas currently experiencing moderate drought risk increasingly shift toward higher risk categories, particularly in the Eastern parts of the municipality. Differences between the two scenarios emerge in the magnitude and spatial coherence of the projected changes, differences are not uniform across the area, reflecting the non-linear response of the WASP indicator to changes in precipitation seasonality, threshold exceedances, and cumulative deficits. Internal climate variability and the mid-term time horizon further contribute to scenario-specific deviations, underscoring that drought risk evolution is driven not only by the strength of the emission pathway but also by how precipitation deficits accumulate across seasons and interact with local land-surface characteristics.

Considering the overall spatial patterns of both historic conditions and future scenarios, Figure 10 shows that drought risk affects mostly the areas with a low ratio of green spaces and a high density of buildings and paved surfaces. On the other hand, drought risk is the lowest at more extensive green areas, especially the natural protected forests on the West. This resilience to drought makes them extremely valuable parts of the municipality, so it is paramount to preserve both the ratio and the quality of these green areas. Nevertheless, the risk increases in densely visited forested areas regardless the high proportion of green space, accentuating the harmful effect of overcharging tourism.

An interesting conclusion is that the risk maps of all three studied climate risks can be linked to each other. For example, comparing the results of the heavy rainfall CRA (Figure 9) to that of relative drought (Figure 10), high risk scores overlap in many neighborhoods in both assessments. As a result, augmenting the urban greenery and directing rainfall to green spaces for in-site infiltration might propose a solution to both risks. Furthermore, similarities in the spatial patterns of the heatwave risk (Figure 8) can be observed as well. While green spaces are able to reduce temperature with evapotranspiration and shading, the vegetation damaged by drought isn’t able to perform these ecosystem services. In addition, the green areas most exposed to urban heat islands are most affected by the negative impact of drought as well.

As mentioned previously in this section, a dataset about the species of the plants isn’t available presently for the entire territory of Hegyvidék Municipality, however, tree registers of the public spaces are under development. In addition to the species of the trees, the registers include detailed information about the height, diameter, age, and canopy of the trees. Naturally, the dataset is limited because only the trees maintained by public authorities are included (not the trees located in private gardens). Moreover, the data is currently available only in a few streets of Hegyvidék Municipality, operated by the City of Budapest (Budapest Public Utilities Ltd.). To complete this limited tree register, Hegyvidék Municipality scheduled the procurement of a similar database for the remaining streets as well in Spring 2026.

The MARCAdapt team decided to implement a complementary demo of a fine-tuned relative drought assessment only for the trees located in public spaces in Phase 3, using precise tree register data. This demo will support future development of the drought CRA of urban green spaces, supposing that precise data will be available of trees in private areas as well (e.g. with the help of a tree census programme or remote sensing).

Based on the available Tree Register database of the City of Budapest, the theoretical background of a tailored vulnerability indicator is compiled based on the trees’ different features. The indicator is composed of four different data points:

- Branch volume: The trunk height is divided by the height of the branch system, which can be determined as the difference between the total tree height and the trunk height. This shows the approximate height of the “branch volume” carried by the tree canopy. If the tree dries out, the larger the volume of branch, the more easily it will be damaged in extreme climate conditions.

- Trunk diameter: the smaller the diameter, the more vulnerable the tree is, because the diameter usually indicates the approximate age of the tree and the state of development of tree root system.
- Age: the youngest and the eldest trees are both more vulnerable to long drought periods.
- Vulnerable species: certain species (e.g. Aesculus hippocastanum, Pinus nigra) are more resilient to drought than others (e.g. Koelreuteria paniculate, Celtis occidentalis).[26]

In Phase 3, the MARCAdapt team will complete the CRA with a fine-tuned tree register database, continue monitoring other green spaces (e.g. soil moisture measurement, botanical analysis), and choose target areas for drought-related adaptation actions. The input indicators, the severity, urgency, resilience aspects, as well as the opinions and roles of the stakeholders will be pondered too.

2.3.4. Additional assessments based on local models and data

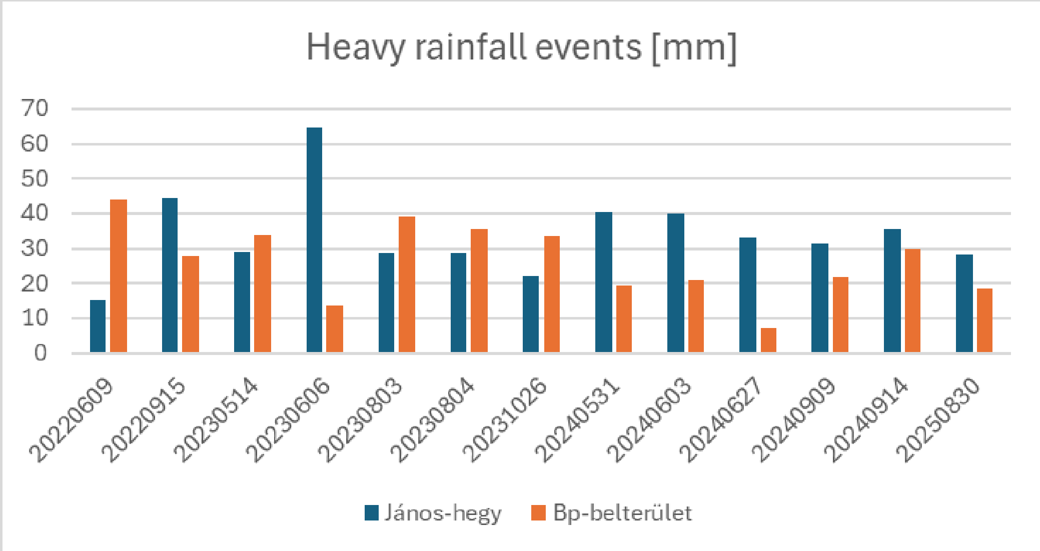
2.3.4.1. Additional hazard assessments

The analysis of past heavy rainfall events was carried out within the hazard and impact data collection framework, focusing on the identification of recent critical precipitation events based on observed daily and hourly station data. Several data sources were analyzed, but due to lack of data, the work continued with data from two local meteorological stations. Precipitation records from two meteorological stations located in and around Hegyvidék Municipality were analyzed for the 2014–2024 period to characterize the frequency and intensity of heavy rainfall[27]. The assessment identified a substantial number of days exceeding commonly used intensity thresholds, indicating that short-duration and high-intensity precipitation events are recurrent features of the local climate. For days exceeding higher thresholds, additional local information was sought to better understand potential impacts and the relevance of these events for emergency situations.

Due to limited availability of consistent and comparable data on event-related damages and recovery times, a more detailed impact assessment could not be carried out for all identified events. However, the availability of complementary risk-relevant datasets was higher for the 2022–2025 period, which motivated a focused analysis of ten selected days during which daily precipitation totals were likely to trigger emergency or disruption scenarios. Figure 11 illustrates these events, highlighting both the temporal variability and the differences in recorded precipitation between the studied stations.

[26] https://fokert.budapestikozmuvek.hu/a-bp-fatar-alkalmazas

[27] The data recorded by the meteorological stations of HungaroMet are publicly available online: https://www.met.hu/rolunk/tevekenysegek/adattar/index.php, https://odp.met.hu/ . The two considered stations are called „János-hegy" (located on a peak of the Western forest area of Hegyvidék Municipality), and „Budapest Belterület", (located near the Eastern downtown neighborhoods of the Municipality).



11. Figure Selected heavy rainfall events, recorded by two meteorological stations in and around Hegyvidék Municipality (Source: HungaroMet)

Several events show markedly higher totals at the station called “János-hegy” (situated on the hillside and forest area), underscoring the influence of local topography on extreme rainfall intensity, while other events exhibit comparable or higher values in the other station (“Budapest Belterület”, located in the downtown urban area), pointing to the potential for intense rainfall directly affecting densely built areas. Together, these observations support the relevance of using multiple stations to capture spatial variability in heavy rainfall and to inform subsequent risk and impact assessments.

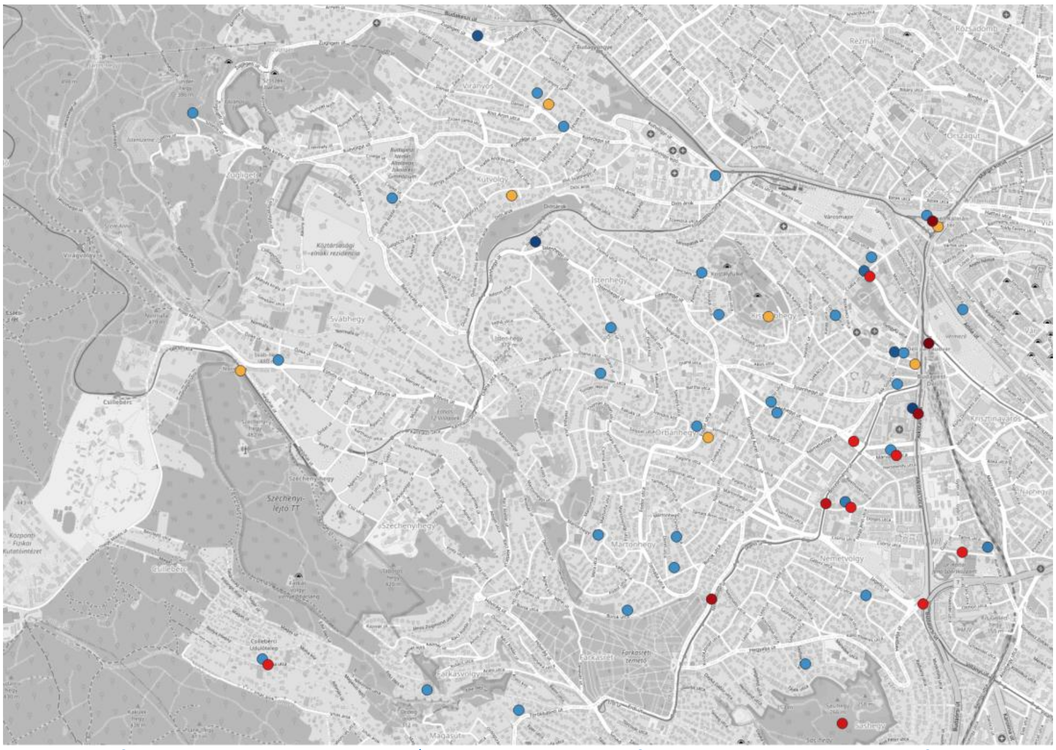
2.3.4.2. Additional risk assessments

In addition to the datasets incorporated in the CRA, other climate risk-related datasets were reviewed and compared to the results. For instance, the Hungarian city app "Járókelő"[28] is a platform through which citizens can send any kind of damage reports experienced in public spaces. The reports from 2012 to 2025 located in the territory of Hegyvidék Municipality concerning damage caused by heavy rainfall, drought, and heatwaves were gathered and assessed. In addition, traffic problems registered by the itinerary planning app “Waze”[29] on selected dates with heavy rainfall were also gathered for the territory of the Municipality. Studying these data bases is useful for better understanding what kind of impact extreme climate events can cause, especially where the CRA resulted high risk scores. Moreover, reports published by disaster recovery organizations[30] were also consulted, though these datasets couldn't be directly linked to the CLIMAAX CRA due to temporal and spatial resolution issues.

During the public involvement process, numerous inputs considering the perception of climate risks were received from local residents as well. These contributions were collected on maps at community events and through a series of questionnaires. In addition, information was gathered

[28] https://jarokelo.hu/
[29] https://www.waze.com/hu/live-map/
[30] National Directorate General for Disaster Management https://www.katasztrofavedelem.hu/modules/vesz/esemenyterkep , Volunteer Firefighters https://www.rozsadombote.hu/

using a mentimeter during an educational event organized for the residents.[31] Figure 12 shows the locations where residents attested to experience the harmful effects of heatwaves, heavy rainfall events and drought. This data set helps to compare local experiences and perceptions with the results of the CRA, and prioritize interventions in the action planning process in Phase 3.



12. Figure Locations of perceived high climate risk (red=heatwave, blue=floods caused by heavy rainfall, orange=drought affecting green areas) mentioned during public involvement. The darker the dot, the more people mentioned that same location

In Phase 3, at the beginning of the action planning process, these independent data sources will be thoroughly contrasted with the CRA results for a more accurate and holistic understanding of the risk impacts.

2.4. Key Risk Assessment Findings

2.4.1. Mode of engagement for participation

Through the adaptation process of the CRA stakeholders were actively engaged in a workshop setting[32]. The experts were asked about the methodology and the first CRA results from the following aspects:

- *What are the most applicable elements of the presented HORIZON CLIMAAX methodology?* Participants fully validated the presented methodology and expressed their support and interest in following the steps of analysis. Final version and conclusions of the analysis will be shared with them via newsletters.
- *What are the possibly useful data sources that are owned by the stakeholders / available for the stakeholders?* Several stakeholders have relevant quantitative databases that contributed

[31] All materials related to public involvement are presented in the „Community involvement" folder, uploaded on Zenodo.
[32] *Ibid. 12, 15*

to the complexity of the analysis (e.g. cooperation with the public transport company). These databases are useful for localizing the epicenter of the main problems connected to heavy rainfalls, heatwaves or droughts.

- *What are the most surprising methodological elements and results in the adapted CRA on local conditions*? Participants were mostly unfamiliar with the mobility data sources provided by telecommunication companies. The use of these datasets by public bodies is a recent evolution and can open new perspectives about the use od public spaces in different climate conditions.

Regarding the risk evaluation process, the main spatial patterns of the results were approved by the stakeholders. However, an in-depth, more targeted analysis will be necessary in Phase 3 to help the stakeholder understand the connections between the hazard and risk indicators and interpret the outcomes in terms of risk management. Therefore, the next stakeholder workshop will focus on outlining the risk management action plan and formulating concrete, local actions, including all responsible parties. So, the workshop will provide an opportunity for the following:

- Reviewing the location with highest risk priority
    - Reasons of high risk, study of the vulnerability, exposure, and hazard indicators,
    - Comparisons with independent external data sources,
    - Identification of the responsible stakeholders,
    - Possible modes of intervention, good practices,
- Mapping available human, financial and knowledge resources
- Formulating concrete steps of systemic intervention, and specific actions targeting the locations with highest risk priority,
- Discovering modes of cooperation with the institutions of the participant stakeholders,
    - Joint communication action,
    - Common intervention as a pilot action.

2.4.2. Gather output from Risk Analysis step

For heatwave risk, hazard outputs used in the risk evaluation are derived from high-resolution SURFEX model simulations at a 1 × 1 km spatial resolution. Number of first-level heat alert days, number of second-level heat alert days and number of tropical nights were selected as hazard outputs. These indicators were calculated for the 2031–2060 period under RCP4.5 and RCP8.5 scenarios and provide spatially explicit information on the frequency and severity of heat stress conditions in urban areas.

For heavy rainfall, hazard outputs consist of extreme precipitation metrics derived from EC-Earth / RACMO22E climate model projections using RCP4.5 and RCP8.5 scenarios for the 2041–2070 period. The key outputs include the projected changes in the intensity and frequency of extreme 3-hour and 24-hour precipitation events. These hazard outputs characterize future rainfall extremes relevant for urban flooding and surface runoff risk.

For relative drought, hazard outputs used for risk evaluation are based on the Weighted Anomaly Standardized Precipitation (WASP) index, which quantifies precipitation anomalies linked to drought conditions affecting vegetation. WASP index was calculated using an ensemble mean of five CMIP6 global climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) across on SSP3-7.0 and SSP5-8.5. These outputs provide information on future drought conditions relevant to urban green areas, forming the basis for assessing drought risk to urban vegetation.

2.4.3. Assess Severity

Heatwave

Under current climate conditions, heatwave risk is assessed as **moderate severity (2).** Observed trends show an increasing number of hot days and tropical nights, leading to measurable impacts on public health, primarily affecting vulnerable population groups. **Under future climate conditions** (2031–2060, RCP4.5 and RCP8.5), heatwave severity increases to **substantial (3).** The projected high frequency, duration, and intensity of heatwaves may lead to sever impacts, mainly in the inner city and densely built-up areas, including increased heat-related mortality and systemic stress on urban infrastructure and health services. Furthermore, intensified heatwaves are expected to affect directly even more neighborhoods comparing to the present conditions. In addition, some characteristics of the most affected neighborhoods are rigid and hard to change for better adaptation. Such features are namely the high-density urban infrastructures (e.g. utilities networks, roads, public transportation, parking lots, buildings etc.) consuming all available space, and the concentration of the elderly residents and key public services in areas with highest heatwave risk. Reducing heatwave risk also involves a significant financial burden. Furthermore, the neighborhoods currently at lower heatwave risk levels are expected to become more urbanized, and thus more exposed at heatwave risk too.

Heavy Rainfall

For current conditions, heavy rainfall risk remains **moderate (2)**. Observed extreme rainfall events cause localized flooding and infrastructure disruption, but impacts are typically spatially limited and short-lived. Public transportation, sewer works, and public space maintenance are the currently concerned sectors, but the usual damages are repaired within some hours or days. Citizens are mostly affected when their property is connected to flooded public spaces, and their buildings are damaged.

Under future climate conditions (2041–2070, RCP4.5 and RCP8.5), the severity of heavy precipitation risk increases to **substantial (3)**. While precipitation-related projections are subject to higher model uncertainty compared to temperature-based hazards, available evidence consistently indicates an increase in the intensity of short-duration, high-impact rainfall events (flash floods). A growing share of winter precipitation is expected to occur as rain rather than snow, increasing runoff and flood potential. In addition, interactions with other climate extremes—such as vegetation loss following drought periods—may further exacerbate the severity of heavy precipitation impacts by reducing infiltration capacity and increasing surface runoff.

Furthermore, the combined sewage system of Budapest is an old and static infrastructure that was designed for a much smaller city, but physically cannot be expanded further due to a lack of space in the dense urban tissue. The network is already overcharged in the currently experienced flash floods, and rainwater mixed with wastewater spills onto the surface at low points. Under future increased risk conditions, these spills are likely to increase in volume and spatial distribution, potentially causing serious public sanitation issues, too. The public health sector is further affected because several national hospitals are located in areas where heavy rainfall risk is expected to increase. If flash floods make these hospitals inaccessible, patients from all over the country may be delayed from medical treatment.

The future scenarios also imply wider effects on the transportation sector as well, because several primary transportation axes (e.g. main roads, main railway station) linking Budapest (capital city) and the countryside are located alongside the Northern and Eastern borders of Hegyvidék Municipality, where heavy rainfall risk is high. If these transportation axes are disturbed, supply chains of national importance are also jeopardized. In terms of economic burden, the repairs of wider and more frequent damage demand more resources, too. Adaptation actions are also necessary to moderate rainwater runoff, like new rainwater retention infrastructures (e.g. underground water tanks, raingardens, green roofs, ponds, etc.). Pilot projects are already in progress in Hegyvidék Municipality with the help of European funding (LIFE in RUNOFF project[33], Interreg HU-SK MountGreenfra project[34]). However, to prepare for future substantial heavy rainfall risk, supplementary resources are necessary to cover more expanded and systemic interventions both in public and private spaces.

Relative drought

Under current conditions, drought risk affecting urban green spaces is assessed as **moderate (2).** Periodic dry spells already lead to water stress, increased maintenance costs, and reduced ecosystem service provision, but impacts remain largely manageable with existing measures. **Under future climate conditions**, drought severity increases to **substantial (3).** The projected rise in summer heatwaves, combined with further changes in the temporal distribution of precipitation, is expected to significantly intensify drought impacts. Precipitation is projected to occur less frequently and increasingly in the form of short, intense convective events, which contribute limited effective soil moisture recharge. On an annual scale, the occurrence of extremely dry years, coupled with more frequent and prolonged summer drought periods, may lead to substantial damage to urban vegetation.

These conditions increase plant stress and vulnerability, favor the spread of pests and diseases, and can result in lasting degradation of urban green spaces. As plants and soil dry out, the natural habitat is reduced, and food and water become less available. As a result, both plants and animals may lack suitable environment to reproduce. This directly causes a decline in biodiversity and the destruction of ecosystems. Furthermore, searching for new habitat, animals (e.g. boars, foxes) spread to urban areas where conflicts between humans and animals would escalate. This phenomenon already started and is expected to upsurge in more severe climate conditions.

Another relating aspect of substantial drought severity is that a significant part of the municipality to the West is a nature conservation area. Considering that Budapest is the capital city, this comes with enormous responsibility. The forests, being popular recreational destinations, are exponentially exposed to human use and deterioration. As a result, invasive species can gain ground, reducing resilience and the natural balance of the ecosystem. When a natural area loses its ecological value, regulation can more easily retrieve the legal protection and allow urbanization. These are all irreversible processes and can be characterized by a cascade effect.

The drastic decline of groundwater levels due to more severe drought is an irreversible process to which societies must adapt. Water consumption habits will change, and the water supply problems currently affecting the surrounding settlements will appear in Budapest too. It is likely that intensively maintained and highly irrigated parks and gardens will not be sustainable anymore.

[33] *Ibid. 17, 12*

[34] HUSK/2302/1.2/060 https://interreghusk.eu/projects/mountgreenfra-2/

Drought risk increasing in severity has also significant financial implications in both short and long term. Maintaining green spaces becomes more and more expensive, water supply gains uncertainty, and planting new, climate-adaptive species to replace dried-up plants is very costly. The energy- and cost-intensive green space maintenance will thus demand more financial resources as well.

In terms of the stakeholders' points of view, the perceptions about the severity of the three studied climate risks is similar to the assessment presented above. Local stakeholders observed substantial or critical severity for both current and future risks at similar areas of Hegyvidék Municipality. Also, the stakeholders noted that the neighborhoods facing the highest risk of heavy rainfall are more prone to face heatwaves or droughts, too. It was also confirmed that the most vulnerable population groups of Hegyvidék Municipality are located in these high-risk areas, too.

2.4.4. Assess Urgency

Heatwave

The severity of heatwave risk shows an increase from current to future conditions (2031–2060), based on the climate scenarios, indicating a significant but continuing increase rather than an immediate change. Heatwaves are expected to worsen in the near future, with an increasing frequency of heat alert days and tropical nights, a trend that is already observable in recent decades.

Heatwaves are associated with both sudden-onset events and persistent conditions, as extreme heat episodes can develop rapidly while also lasting for extended periods. This combination increases stress on urban populations and infrastructure but does not yet justify an immediate-action classification, as adaptation measures can still be implemented progressively.

Although heatwave impacts are likely to persist and intensify, many adaptation options—such as urban greening, shading, heat warning systems, and building-level interventions—can be introduced within short to medium timeframes. However, given the projected continuation and acceleration of heat-related hazards, additional and timely action is required, supporting an overall **"more action needed" (3)** urgency classification. Some elements or neighborhoods, however, require higher priority and specific developments and activities must be targeted in the action plan in Phase 3.

On the other hand, heatwave risk is a topic addressed at a national level, thus helping wider adaptation options. People are experiencing heatwave risk the most directly and intensively, and this is where intervention is most urgently needed. The public awareness helps the population to better accept the developments carried out by the municipality (for example, they accept that by eliminating parking lots there will be more green space), and it is also easier to actively involve residents in actions. There are also technical solutions to reduce the heatwave risk (air conditioning, insulation, air circulation), widening the adaptation options on the citizens' level.

Heavy Rainfall

The urgency level for heavy precipitation risk is assessed as **immediate action needed (4)**. Although the rate of change of extreme precipitation is difficult to quantify due to the higher uncertainty associated with precipitation projections, there is strong evidence that short-duration, high-intensity rainfall events pose an increasing threat. In addition, the short-term, local-scale forecasting of extreme rainfall remains highly challenging, which significantly limits the ability to prevent or mitigate impacts in real time.

Both short- and long-term climate outlooks indicate the possibility of extremely adverse years, during which the frequency of sudden, intense precipitation events may be higher across the municipality. These events are associated with rapid-onset flooding, infrastructure disruption, and cascading impacts on urban systems.

As explained in section 2.4.3., future heavy rainfall risk is likely to affect several sectors, crucial public services, and the population not only locally, but also on the scales of Budapest and the entire country as well. The main challenges of managing and adapting to heavy rainfall events are, firstly, the necessity for several sectors to tightly cooperate, and secondly, the identification of the optimal location for efficient interventions[35]. Furthermore, stormwater management improvements are often impeded by the rigid legal environment, making the status quo unchangeable. In all cases, the involved sectors (e.g. sewage system, road network, transportation network, buildings, legal system, etc.) are extremely inflexible, and significant alterations for better adaptation would require several years. Another difficulty is that people are less aware that stormwater management is a common cause, and their own actions and decisions influence floods and damage in other areas[36]. However, to reach significant behavior changes, long and wide awareness-raising and education campaigns are necessary.

To sum up, adaptation measures—such as renovating sewers, implementing rainwater-retention solutions, improving stormwater management, initiating early warning systems, launching damage control plans, improving regulations, and changing citizen behavior, etc. — require long planning and implementation periods, often exceeding a decade. Given the high potential for severe impacts, limited predictability, and long adaptation processes, immediate action is required to reduce current and future heavy precipitation risks. Specific developments and activities will be defined in the action plan in Phase 3.

Relative drought

Drought risk shows an increase from current to future conditions, driven by rising temperatures, increased evapotranspiration, and more frequent precipitation deficits. While drought is a slow-onset hazard, its impacts are persistent and cumulative, making them particularly challenging to reverse once established.

Urban green spaces are exposed to long-term water stress, and recovery from severe drought may take multiple years or may not be possible without active intervention. The hazard is expected to persist and intensify, especially during critical summer periods, reducing the resilience of urban ecosystems.

Adapting urban green infrastructure—through species selection, irrigation strategies, and redesign of green spaces—typically requires long-term planning and investment, often exceeding a decade. As the capacity to respond quickly is limited and impacts accumulate over time, more **immediate and sustained action (4)** is required to prevent irreversible degradation.

[35] To prevent floods, rainwater retention must be started at topographically higher points of the same rainwater subcatchment area to prevent the accumulation of runoff

[36] For example, if citizens retained and reused rainwater within their property, the combined sewage system would be less overcharged during heavy rainfall, so spills and floods wouldn't occur, and transportation wouldn't be blocked either.

2.4.5. Understand Resilience Capacity

Heatwave

The resilience capacity level for heatwave risk is assessed as **substantial (3).** At district, city, regional and national levels, several institutions are working to combat the impact of heatwaves. For example, a heat warning system operates at a national level. Hegyvidék Municipality designates cooling points (public institutions with air conditioning) in the municipality during heatwave periods, where any residents can find refuge and access drinking water for free.

Furthermore, a public space development program of Hegyvidék Municipality is designated to reduce the heat island effect in dense downtown neighborhoods by creating livable, inclusive, and pleasant public spaces. Such improvements include, for example, new green spaces and trees, shading infrastructures, as well as outdoor leisure and community spaces with shaded seating and greenery. Hegyvidék Municipality allocates funds from its own budget each year for the implementation of this program.

Furthermore, the municipality operates a grant program for residents, supporting the greening of the courtyards of apartment buildings in the densely built-up downtown. One of the goals of the grant program is to reduce the risk of heatwaves by increasing the proportion of green space through the connecting private properties.

Heavy rainfall

As for heavy rainfall risk, the resilience capacity level is evaluated as **substantial (3).** Several water-related European projects[37] launched discussions, pilot projects, strategy building, policy initiatives, and awareness-raising actions not only in Hegyvidék Municipality, but also in the City of Budapest, other district municipalities, the Ministry of Public Administration and Regional Development, other Hungarian cities, and national institutions. For example, in the framework of the LIFE in RUNOFF project, the elaboration of a Budapest-level Rainwater Management Strategy and three district-level Rainwater Management Action Plans is in progress, including Hegyvidék Municipality. These documents provide a groundwork for short, mid, and long-term rainwater management actions based on integrated assessments of the current and projected conditions. Furthermore, various already implemented pilot rainwater retention projects help to test several methods and discover their potential deficiencies and necessary alterations for more efficient future interventions. Furthermore, due to the more frequent and serious damage related to flash floods, many stakeholders experience supplementary financial charges - thus they become more and more interested in the topic and forced to cooperate. In terms of the legal environment, certain progressive local regulations[38] are already in place in Hegyvidék Municipality, though supervision and law enforcement measures are still insufficient. Finally, awareness-raising campaigns[39] targeting the residents started, though with still limited reach-out.

Relative drought

[37] LIFE in RUNOFF, LIFE LOGOS4WATERS, Interreg Centrale Europe LOCALIENCE, Horizon Europe Pathways2Resilience, Interreg Europe NBS4LOCAL, Interreg Danube Region SAFETY4TMF, Horizon Europe SoS2LearnDBS, etc.

[38] E.g. compulsory green roofs on new flat roof buildings, mandatory underground water tanks or infiltration blocks for new constructions

[39] E.g. educational materials, free thematic lectures, gamification, site visits, subventions for private green space development, and rainwater retention equipment

Considering drought risk, the resilience capacity level is determined as **medium (2).** Hegyvidék Municipality, urban green space and forest management organizations have already recognized the problems and risks caused by drought, though practical solutions are still in the testing phase. For example, changes in irrigation practices, planting climate-adaptive plants that are yet uncommon in the current practice, reusing green waste for extensive mulching in public parks have been introduced. There is no comprehensive, detailed program yet, but data collection, research, and surveys have already begun. Hegyvidék Municipality also launched public awareness raising initiatives addressing this issue, such as grants for composting equipment, educational activities for reusing green waste in private gardens and grants for improving green spaces in courtyards. The goal is not only to shape the public's attitude towards protecting and enriching the soil, but also to achieve behavioral change in private gardening practices. Such extensive transformation, however, requires time and more intensive communication and education from the municipality.

2.4.6. Decide on Risk Priority

4. Table Key Risk Assessment dashboard of Hegyvidék Municipality

Risk Workflow	*Severity*		*Urgency*	*Capacity*	*Risk Priority*
	C	F		Resilience/ CRM	
Heavy rainfall					Very high
Heatwaves					High
Drought					Very high

Table 4 summarizes the current and future severity, urgency, and resilience capacity levels based on the CRA of heatwave, heavy rainfall, and drought. Risk priority reflects a qualitative interpretation of the key risk assessment results. Based on the reasons outlined in sections 2.4.3-2.4.5, heavy rainfall and drought are assessed as "Very high" risk priority and heatwave as "High" risk priority. To summarize, the results of the key risk assessment provide a general direction for the action planning in phase 3, highlighting the different sectors and aspects that must be targeted.

2.5. Monitoring and Evaluation

Through the climate risk assessment process in Phase 2, the MARCAdapt team learnt a holistic approach to reveal the main factors, impacts and interactions influencing three selected climate risks (heatwave, heavy rainfall, relative drought). The quantitative results of the CRA are well balanced with the qualitative approach of the key risk assessment process. Therefore, Phase 2 prepared a solid ground for integrated strategy building and targeted risk management action planning.

The main challenge of Phase 2 was the adaptation of the originally region-scaled CLIMAAX workflows to a local, urban-block, and street-level. The formulation of new vulnerability and exposure indicators with the stakeholders helped to capture local specificities and discover the differences between the neighborhoods. Nevertheless, the work with local data demanded an in-depth reformulation of the initial CLIMAAX notebooks.

New data sources were collected, including public transportation-related datasets, shade maps, NDVI-based drought maps, damage reports from city apps, traffic problems, etc., as presented in section 2.3. To fine-tune the relative drought assessment, high-resolution data is further necessary to identify plant species for an advanced relative drought workflow. This issue will be addressed by procuring a state-of-the-art tree register database in Phase 3, allowing a final update of the relative drought CRA of urban green spaces.

The interpretation of the CRA results caused some difficulties for the municipal officers of the MARCAdapt team due to the complex academic methodology, but the involved climate change researcher and data scientist external experts were equipped with the necessary knowledge to explain and clarify uncertainties. Weekly MARCAdapt team meetings ensured continuous dialogue, fast iterations, and steady teamwork. The external experts also participated in the stakeholder meetings and some of the public events, thus ensuring professional and clear explanations of the most technical parts of the project to the general audience.

Stakeholders were actively involved through the CRA process and some cooperations started, including sharing data and analytical tools. Though the results were presented to them as a general output, Phase 3 will include stakeholder meetings focusing on more localized analysis of the neighborhoods facing the higher risks.

Concerning the communication of the project results, the outcomes of Phase 2 will be presented to the stakeholders in dedicated newsletters. In parallel, a meeting will be scheduled with the municipality's decision makers and other municipal departments to walk through the takeaways and outline the objectives for the action planning in Phase 3. The communication targeting the residents continues in various forms, as presented in the community involvement plan in supporting documentation.[40]

In terms of direct risk monitoring, local meteorological stations are in operation and some ongoing European projects plans to publish disaster monitoring platforms, though on much higher territorial scales than Hegyvidék Municipality[41]. Nevertheless, the independent, continuously generating datasources mentioned in section 2.3.4. provide means to monitor certain damages linked to extreme climate events[42]. In addition, if the NDVI-based drought maps used in the relative drought CRA are regularly procured every year, long-term effects of summer drought can be detected.

Furthermore, Hegyvidéki Municipality successfully mapped and connected the CLIMAAX project with the LIFE in Runoff and HU-SK MountGreenfra projects, implemented in parallel by the municipality. Exploiting these synergies not only strengthen the results of each project, but also help to leverage the available resources. Further opportunities for cross-project activities will arise during the preparation of the risk management plan. Similarly, the CLIMAAX project was successfully linked to the municipality’s green space development program focusing on shading and tree planting in the high-density downtown neighborhoods. This connection effectively facilitated the involvement of residents in the CLIMAAX project too.

[40] *Ibid. 14, 11*
[41] E.g. Interreg Centrale Europe LOCALIENCE
[42] E.g. damage reports from the city app “Járókelő”, traffic problems registered in the app “Waze”

Finally, considering the work efficiency of the MARCAdapt team, the overall experience is positive, mainly due to rigorous planning, internal deadlines, dedicated workflow management methods, and regular team meetings. Some delays were experienced due to the slow procurement processes of new data sources, and when the work was suspended because of longer organization-level holidays. Overall, however, the MARCAdapt team achieved the objective of the CLIMAAX CRA adaptation at a local scale for all three targeted climate risks, involving stakeholders and residents as well. The understanding of the analyzed climate risks is generally improved in Hegyvidék Municipality, among the stakeholders and the residents as well. Phase 3 will focus not only on communicating the results, but also on motivating stakeholders and citizens to take charge of certain risk management actions.

2.6. Work plan Phase 3

The primary focus of Phase 3 is the development of an adaptation strategy and an enhanced risk management plan, based on the CRA results, the key risk assessment, and priorities identified in Phase 2. The work will start by evaluating the current risk management practices and designing action territories and sectors. In the preparatory phase of the action plan, local decision makers, several municipal departments and the stakeholders will be involved in the framework of workshops. This participatory process allows stakeholders to fine-tune the key risk assessment aspects (severity, urgency, resilience capacity) and risk prioritization, suggest realistic actions and good practices, identify the time range of each action, take responsibilities to carry out actions, and propose pragmatic public engagement for risk management.

While the heavy rainfall and heatwave CRA will not be modified in Phase 2, the relative drought workflow will be updated with a complete tree register database for public spaces, as explained in section 2.3.3. The finalized risk maps and each indicator will be incorporated into the municipal GIS system that any municipal officer can consult and use for their daily work.

Throughout Phase 3, several community involvement and dissemination actions will also take place including art workshops in partnership with Moholy-Nagy University of Art and Design Budapest, regular communications via social media, newsletters, and printed newspapers, as well as the publication of the project's Layman's report[43].

Phase 3 will conclude with the presentation of the project's overall results and the submission of final policy notes to the local decision makers. The MARCAdapt team will also participate in the closing CLIMAAX workshop in Brussels and prepare a poster presenting the outcomes and takeaways of the project.

Although the CLIMAAX project will end in July 2026, post-communication is also of paramount importance after the project implementation, targeting both professional and public audiences.

[43] *Ibid.14, 11*

3. Conclusions Phase 2- Climate risk assessment

The work in Phase 2 addressed the primary objective of adapting the climate risk assessment methodology of the CLIMAAX Handbook on a local level, resulting in comprehensive and meaningful results. Three CRA were accomplished, including heatwaves, heavy rainfall, and relative drought. Due to the territorial scale of Hegyvidék Municipality, the spatial resolution of urban blocks and streets was targeted.

The fine-tuning of the workflows on the local context required the identification of the most influential factors of the studied climate risks. In addition to the municipal officers and the external experts of the project, various local stakeholders were involved in this preparatory phase, representing the vulnerable population groups and the most affected infrastructures and organizations. About 20 exposure and vulnerability indicators were identified in total, which allowed capturing the local conditions on the urban block and street level. Then, the collection of various high-spatial-resolution data sources allowed to interpret the local indicators in a quantitative way, and downscale the CLIMAAX workflows from regional to local level. Though the general methodological approach and certain indicators of the CLIMAAX Handbook were incorporated, the initial CLIMAAX workflow notebooks were deeply transformed to process the local data sources, diverse in format, structure, and resolution. The CRA computing resulted in risk maps of several climate change scenarios, targeting mid-century conditions. All three climate risks tend to increase in the future, though with different amplitudes and spatial distribution.

Heatwaves risk tends to grow from currently moderate to substantial in the future due to the spatially extending high heatwave risk and the more frequent and intense heat stress conditions. The most affected area is the downtown with high urban density, concentrated vulnerable population, and paramount public health and social services. Although several adaptation actions are already in progress on the local and national levels too, more action is needed to efficiently manage risk related to heatwaves. Resilience capacity is substantial to target this area, providing a leverage for action planning and quickly improving risk management services.

For heavy rainfall, while the current risk conditions are still moderate due to mostly localized disaster events, more systemic impacts are expected in the future, and the risk is projected to become substantial. While the model uncertainty of precipitation climate projections doesn't allow to predict exact volumes of rainfall changes, a general increase in the intensity of short-duration, high-impact rainfall events (flash floods) can be expected, escalating the economic burden related to repairs and disaster recovery, too. The streets and neighborhoods at topographical low points are most concerned by high risk, but interventions must consider the entire rainwater sub-catchment areas and their interconnections. As the interventions require the cooperation of multiple sectors on multiple territorial scales and changes in everyday rainwater management practices, intermediate action is needed. Risk management actions can, however, benefit from the substantial resilience capacity ensured by ongoing progressive projects, expert platforms, and policy change initiatives.

In terms of the relative drought CRA, a new approach was developed focusing on urban green spaces. According to the results, risk escalates from currently moderate to substantial in the near future. On an annual scale, the occurrence of extremely dry years, coupled with more frequent and prolonged summer drought periods may lead to a decline in biodiversity, an imbalance in the ecological system, and a significantly wider spatial impact. The spatial patterns of the results emphasize high drought risk in the neighborhoods characterized by high urban density, high traffic, and smaller green areas among intensively paved surfaces. As the severity of the drought's impacts on urban green spaces has been only recently recognized, risk management and adaptation solutions are still in a research and testing phase. Immediate action is needed because the effect of any new green space maintenance and development intervention can be measured after several years, and the systemic change in the sector requires long negotiations and possibly new regulations. In addition, resilience capacity remains at a medium level due to the recent shift in awareness and the limited initiatives.

In addition to the technical work, participatory and engagement actions supported the evolution of the local CRA. Stakeholders were consulted to enrich the methodology and approve the results, while the residents were addressed to share experiences and perceptions. Several communication and educational materials were created targeting the general audience and explaining the causes and consequences of climate risks from the perspective of the citizens. Furthermore, synergies with other ongoing projects and development programs were mapped, strengthening resilience capacity and the efficient allocation of available resources.

To sum up, the MARCAdapt team achieved an improved and holistic understanding of the studied local climate risks and outlined the general directions for the risk management action planning process in Phase 3.

4. Progress evaluation

5. Table Overview key performance indicators

Key performance indicators	*Progress*
3 workflows (heavy rainfall, heatwaves, droughts) successfully applied on Deliverable 1	**Done** in Deliverable 1
3 workflows (heavy rainfall, heatwaves, droughts) successfully applied on Deliverable 2	**Done** in Deliverable 2
3 new layers (maps) added to the municipality's GIS system	To do in Phase 3
10 stakeholders (organizations) involved in the activities of the project	**Done**: 17 stakeholder interviews, 3 workshops with 24 participant stakeholder organizations (37 people) in total.
50 citizens (cases) involved in the Climate Risk Awareness Raising and Community Involvement Program	**Done**: 92 residents involved through community involvement actions in total
5 publications and dissemination actions	**Done**: 3 community meetings, 1 online survey, 3 educational posters exhibited at community events, 2 articles in the local newspaper, 3 Facebook posts
3 notes for policy makers	**In progress:** 2 policy notes submitted to the local policy makers about the project's progress

6. Table Overview milestones

Milestones	*Progress*
M1: Test of 3 workflows made	**Done**
M2: 3 workflows successfully applied	**Done**
M3: Climate Risk Awareness Raising and Community Involvement Program implemented	**Done**
M4: Attend the CLIMAAX workshop held in Barcelona	**Done**
M5: Stakeholder meetings done	3 / 4 meetings accomplished
M6: Presentation of the results to policy and decision makers	Due in Phase 3

Milestones	*Progress*
M7: Attend the CLIMAAX workshop held in Brussels	Due in Phase 3

5. Supporting documentation

To help readability, **the supporting documentation is organized in 5 main zipped folders**. The content of the zipped folders is presented bas follows. The technical documentation is elaborated in English. The materials related to communication, community and stakeholder involvement, and the policy notes are in Hungarian because of the language of the target audience.

"Communication" folder

Includes the documents related the communication during Phase 2, such as
- articles of the local newspaper (2025_03_11, Page2; 2025_09_23. Last page)
- Facebook posts
- print version of three educational posters targeting the residents and exhibited at community events
- call for participation in online survey in the local newspaper (2025_11_04, Page5)

"Community involvement" folder

Includes the documents related the citizens involvement process:
- *summary* - briefly describes Citizen participation, and the three folders about the *community meetings, posters, questioners*
- *Tippek klímaveszély esetén_CLIMAAX* – Climate adaptation ideas for population
    - To mobilize the population in taking climate adaptation actions, a collection of good practices was sent those who completed the questionnaire or participated in the relating community events.
- *Public involvement activities* – list of the tools and events implemented in accordance with the public involvement plan during Phase 2
- *Community_involvement_plan* – the documents covers the purpose, target group, and tools of the public involvement process related to the project. It also includes a brief communication plan.
- *communityinvolvement_problemmap* – locations of perceived high climate risk mentioned during public involvement.

"Stakeholder involvement" folder

Includes the documents related the stakeholder involvement process:
- *summary*–briefly describes the content of the *newsletter* document and the folders of the two stakeholder meetings
    - *2nd stakeholder meeting* – 16 May 2025
        - invitations and agenda,
        - list of participants,

        - presentations,
        - photos
    - *3rd stakeholder meeting* – 14 November 2025
        - invitations and agenda,
        - list of participants,
        - presentations,
        - photos
- *newsletter* –links to the newsletters which were sent to the stakeholders about the project's progress around the middle of Phase 2

"Policy note" folder

Includes notes submitted to the local policy makers to summarize the progress of the project.

Notes submitted in August 2025:
- *Newsletter_for_policy_makers_05082025*
- *Newsletter_for_policy_makers_community_05082025*

Note submitted in January 2026:
- *CLIMAAX_policy_note_16012026*

"Technical documentation" folder

Includes the documents and folders related to the technical implementation of the three CRA workflows and the methodology of local data processing:

- *Climaax tech summary_MARCAdapt* – step-by-step technical explanation of the computing process, the submitted notebooks, and the output files. The document's structure corresponds to the following folder structure organizing the relating files
- *0_preparation* folder
    - *building_blocks_clean* – GIS layer (geojson) consisting of 1827 polygon geometries of urban blocks and street sections of Hegyvidék Municipality. The local CRA computing was calibrated to this geometry.
    - *data_master-final* – working document used by the MARCAdapt team for gathering and organizing data sources and assessments
- *01_data processing* folder
    - notebooks in .html and .ipynb formats related to each data source and indicators explained in the *Climaax tech summary_MARCAdapt* document
- *02_scoring* folder
    - notebooks in .html and .ipynb formats related to scaling all indicators on a scale of 1-10, as explained in the *Climaax tech summary_MARCAdapt* document
    - the resulting indicators are harmonized and mapped to the common geometry of urban blocks, ensuring consistency and comparability across all derived indices
    - all indicators rated on a scale of 1-10 are included in the *scaled_features* folder, with .geojson extension
- *03_risk assessment* folder

  - notebooks in .html and .ipynb formats including the pipeline for the weighting the processed input indicators and the final risk assessment combining hazard, exposure, and vulnerability indices
- *04_output* folder
  - provide a structured set of the output files organized in sub-folders by hazard type (heatwave, heavy rain, relative drought)
  - each sub-folder includes the following documents:
    - *feature_list* in table format listing all input variables and the relating information: name, data source, description, weight, corresponding output file.
    - PNG-formatted visualizations of the scaled indicators and the output risk maps.
    - *output_summary* where all of the PNGs are presented, corresponding to the *feature_list* file's structure. The summary provides a quick visual overview of all processed indicators and the resulting risk maps in an organized way.
    - final risk maps in geojson format

6. References

Buskop, F., Sperna Weiland, F., and van den Hurk, B.: Amplifying Exploration of Regional Climate Risks: Clustering Future Projections on Regionally Relevant Impact Drivers Not Emission Scenarios, https://doi.org/10.1088/2752-5295/ad9f8f, 2024

Sources mentioned in footnotes:

- Hungarian city app "Járókelő" - Járókelő.hu. Ha megosztod, megoldod. - Jarokelo.hu
- Copernicus Climate Atlas - Climate Data Store
- Storm Water Management Model (SWMM) | US EPA
- Városi eső – A városi eső aranyat ér, de csak ha jól kezeljük! https://varosieso.hu/dokumentumtar/
- Joining forces against extreme weather events
- Meteorológiai Adattár - Tevékenységeink - met.hu
- https://www.waze.com/hu/live-map/
- National Directorate General for Disaster Management https://www.katasztrofavedelem.hu/modules/vesz/esemenyterkep , Volunteer Firefighters https://www.rozsadombote.hu/
- HUSK/2302/1.2/060 https://interreghusk.eu/projects/mountgreenfra-2/
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