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Testing the Drought and Heat Risk Assessment (DHR) Framework for Urban Green Infrastructure: The Case of Plauen, Germany

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Abstract.

Urban green infrastructure (UGI) and their ecosystem services (ES) strengthen urban biodiversity and resilience—but are threatened by increasing drought and heat risks. This study applies the Drought and Heat Risk (DHR) Assessment Framework in an urban park in Plauen, Germany, using an indicator-based approach to assess multi-risks for selected ES. The risk system is first delineated by considering hazards, exposure, and vulnerability to define key endpoints and derive descriptors. Local stakeholders—experts in urban planning, UGI management, biodiversity conservation, water management, climate, meteorology, soil, and environmental science—then validate the system, select appropriate indicators, and define evaluation criteria with weights and thresholds. Risk indicators are calculated using station measurements, remote sensing, microclimate modeling, and GIS analysis. Multi-risks are evaluated with the TOPSIS method, aggregating risks for the provisioning, regulating, and cultural dimensions of ES. Empirical testing confirms that the framework is able to capture system complexity through interconnected multi-risk indicators with attributes from diverse tiers, while underscoring the need for flexible, multi-method approaches in the face of data limitations. The results, presented as sub-city spatial maps, offer decision makers valuable insights into the spatiotemporal risks affecting UGI's ES and support efforts to safeguard their benefits for both society and the environment.

Keywords: Multi-risk, Drought, Heat, Ecosystem Services, Indicators, Decision-making

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

1 Introduction

1.1 Background

Urban communities worldwide are already affected by drought and heat hazards where anthropogenic conditions such as impervious cover and exothermal activities exacerbate the situation (Cremades et al., 2021; Tuholske et al., 2021). According to the IPCC (2021), the intensity and frequency of droughts and heat events is expected to increase in many cities across the globe, adding uncertainty to the potential consequences. These effects propagate from larger regions down to cities, affecting streamflow, reservoir levels, and the urban micro climate.

Urban green infrastructure (UGI), defined as a network of natural or seminatural green (vegetation) and blue (water) features, are being optimized and utilized to support urban communities in mitigating and adapting to hydrometeorological risks (e.g., droughts, heat waves, floods). Additionally, UGI provide multiple ecosystem services (ES) and contribute to the sustainability of urban areas (e.g., Cheshmehzangi et al., 2021). Studies indicate that UGI are affected by drought and heat hazards (e.g., Brune, 2016; Allen et al., 2021), and the cascading effect results in the vulnerability of UGI's ES (Shehayeb et al., 2024). Hence, under drought and heat conditions, the expected benefits from the UGI might be lost without adequate measures. These measures could be within the planning and management of UGI to protect and utilize them through informed decision-making.

Deciding on the suitable measures with multiple criteria involved related to environmental, social, and economic aspects could prove to be challenging for decision makers. Risk assessments contribute in supporting decision-making through analyzing and evaluating the probability of negative consequences from hazards (National Research Council, 2009). Therefore, to address these challenges, research is required to provide means for decision makers to develop a comprehensive understanding of the drought and heat risks for the context-specific UGI including their functions and ecosystem services.

1.2 State of the Art

Researchers applied diverse methodologies to study the effects of droughts and heat on ecosystems such as vegetation and water bodies across various spatial scales and contexts. For instance, at an urban level, Juntakut (2020) and Kabano et al. (2021) investigated the impacts of individual drought and heat hazards on the biophysical features of urban green and blue spaces, whereas Bhuiyan et al. (2017) focused on the health consequences, and Allen et al. (2021) studied the effects on the cooling potential of vegetation. Shen et al. (2016) identified water-related, demographic, and air quality stressors on urban ecosystems to calculate their vulnerability. Zooming out to a regional or global scale, numerous researches investigated the physiological effects on forest and water ecosystems subjected to drought and heat hazards (e.g., Zhang et al., 2016; Duan et al., 2017; Jiang et al., 2020).

The concept of Ecosystem Services (ES) has been adopted in a few studies in combination with drought and heat stressors or more broadly, anthropogenic stressors. For instance, Al-Qubati et al. (2023) assessed the drought and heat impacts on ES

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

such as carbon sequestration, whereas Raheem et al. (2019) interviewed experts to determine the potential vulnerability of ES to droughts within a basin. To understand how certain regulating and cultural ES of urban parks are impacted during drought and heat conditions, Kabisch et al. (2021) presented a framework and implemented a set of mixed methods. On the other hand, Heremans and De Blust (2020) address the issue by developing a methodology to assess the vulnerability of green infrastructure landscapes to human-related stressors such as agriculture and urbanization.

In their research, Shah et al. (2020) aimed to maximize the effectiveness of nature-based solutions for disaster risk reduction and developed a risk assessment framework for socio-ecological systems (SES). This research followed a broad approach without considering the cascading risks for the ES nor accounting for the specific of urban conditions. A literature review by Walz et al. (2021) highlighted the evidence of disaster-related impacts on ES and what implications this could have on the risks, and the disaster risk reduction efforts. While this work does not provide a framework or methodology on how to assess the risks for UGI and their ES, it concludes that ecosystems and their services should be included in the risk assessments and they play a significant (reciprocal) role in hazards, exposure, and vulnerability.

Peng et al. (2023) worked on applying a risk concept for SES including the ES of river deltas, and considering a cascading model to general natural hazards. The study proposes indicators for ecosystems and their services related to vulnerability and exposure, and was applied by Peng et al. (2024). A limitation to this approach, is that the methodology lacks a systemic procedure showing the propagation of hazards to the exposed and vulnerable elements (endpoints) within the cascading model, and additionally, not integrating these interlinkages in the derivation of the information system and indicators. Moreover, a framework for the risk assessment based on analysis and evaluation was not explicitly presented. At an urban scale, Shehayeb et al. (2024) developed the Drought and Heat Risk (DHR) Assessment Framework incorporating the cascading risks for UGI ecosystems, functions, and their ES, and this was supplemented by an indicator-based methodology operationalizing the framework for application (Shehayeb et al., 2025). The methodology follows a systemic approach to translate the biophysical system into an information system with descriptors and attributes, followed by assigning and interconnecting indicators.

Considering the reviewed literature, research focusing on the drought and heat risks for ecosystems and their services are limited, and often the studies study individual impacts of droughts and heat on ES, without adopting a risk assessment perspective. Within the limited studies that follow a risk perspective, they tend to have a broader spatial scale and without considering the risk assessment for ES of urban ecosystems (e.g., UGI). The DHR Assessment Framework and its methodology are yet to be tested for their adaptability to specific case studies, and their effectiveness in assessing the aforementioned risks.

1.3 Aim and Approach

In response to the increasing risks posed by hydrometeorological hazards such as droughts and heat, and the significance of UGI and ES towards urban resilience and biodiversity, the DHR Assessment Framework has been proposed by Shehayeb et al., (2024). From the existing state of the art, there is a need for adapting and testing the framework in a real-life case study.

Therefore, this work aims to contextualize and test the DHR Assessment Framework and methodology to assess the risks in "Hammer Park" located in the town of Plauen, Germany. The challenges lying within the implementation such as data availability, spatiotemporal coverage, adapting to the local context, and delivering assessed risk results that support decision-making will be addressed. The major outputs of this work are: (1) a defined situation and delineated risk system for the Hammer Park, (2) a drought and heat risk analysis for Hammer Park with its ES, (3) an evaluation of the risks with the participation of local experts, and (4) a reflection on the tested framework. The expected outcome is risk information for decision-making support on the management of Hammer Park resources and protecting its ES.

The testing of the framework constitutes of contextualizing, implementing and reflecting on the DHR Framework in Hammer Park, Plauen. According to Shehayeb et al. (2025), assessing the risk is done over the following procedures: risk system delineation (analysis), translation into an information system (analysis), calculation of attributes and indicators (analysis), setting the criteria for evaluation, and evaluating the risk. For contextualizing and reflecting on the results, a close involvement from the local decision makers is required in the risk analysis and evaluation. Hence, a prerequisite step of stakeholder network analysis, and a subsequent step of disseminating the assessment results and receiving feedback are added to the core assessment procedures. Thereafter, the reflection is based on the degree to which the framework addresses the multi-risks, the spatiotemporal aspects, and the usability for local stakeholders.

2 DHR Assessment Framework

The DHR Assessment Framework is contextualized and implemented based on the analysis and evaluation, as well as the involvement of decision makers in both procedures as presented in Fig. 1. The multi-risk assessment outputs aim to support decision makers in selecting and implementing risk reduction alternatives. The conceptual and methodological levels for testing the framework are introduced in the current section.

https://doi.org/10.5194/egusphere-2025-2060
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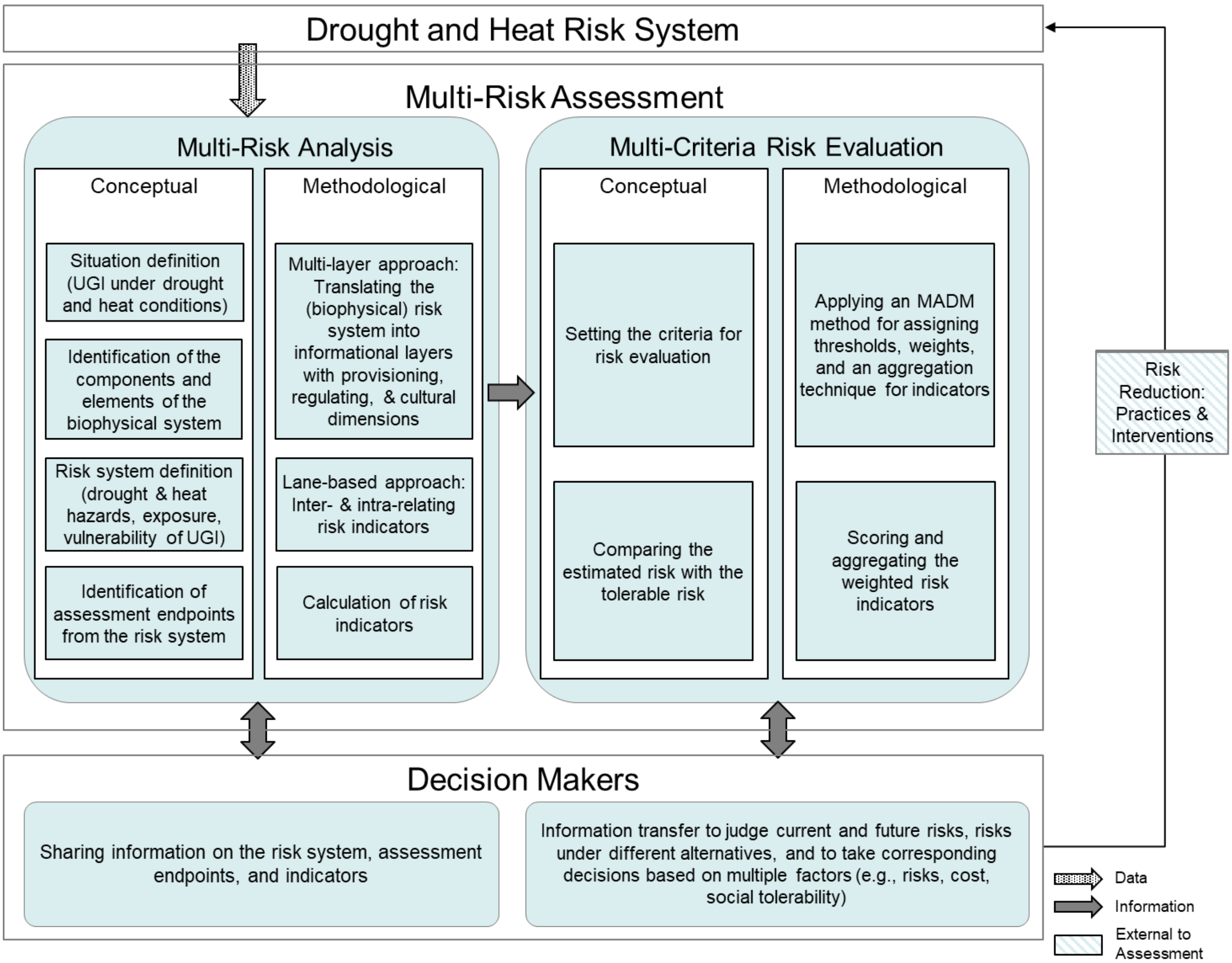

Figure 1. The DHR Assessment Framework (Shehayeb et al., 2024)

2.1 Analysis and Evaluation Concepts

The conceptual aspects of the multi-risk analysis include defining the situation and the biophysical risk system, and identifying endpoints for the risk assessment. The drought and heat risk situation for UGI was defined by Shehayeb et al. (2024) as a Coupled Human and Natural System (CHANS) including the decision makers, who receive information from the system and decide on interventions. The risk system was delineated by Shehayeb et al. (2025) considering the UGI example of Parks and (semi-)natural urban green areas, including urban forests in addition to blue areas. Endpoints were identified from the drought and heat hazards, as well as the three tiers of vulnerability: UGI entities, ecosystem functions, and ecosystem services. Endpoints denote the entities or characteristics of the biophysical system, present at multiple organizational levels, which could be prone to external disturbances such as droughts and heat (USEPA, 2003; Wolt et al., 2010). The present study adapts the risk system and its endpoints to Hammer Park in Plauen, and focuses on the endpoints

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

from the ES tier to represent the vulnerability component of risks. The selection of endpoints was based on the existing potential ES of the Hammer Park determined with the local decision makers.

The multi-criteria evaluation consists of setting the criteria for risk evaluation comparing the calculated risk with the tolerable risk to base the judgement on, and to decide on risk reduction alternatives (Shehayeb et al., 2024). The aim of the evaluation is to determine subjectively and according to local goals and values, which aspects of the risks are of importance and which levels are tolerable.

2.2 Analysis and Evaluation Methodology

The methodological steps of the analysis constitute the translation of the endpoints of risk system into an information system provisioning, regulating, and cultural dimensions of ES. Shehayeb et al., (2025) followed the multi-layer approach developed by Müller et al. (2022), which translated the assessment endpoints into layers of descriptors, attributes and indicators. Descriptors express which endpoint aspects are assessed, and can be calculated with different attributes and indicators providing a degree of flexibility (Müller et al., 2022). Each descriptor includes multiple qualities and parameters for its measurements referred to as attributes. Subsequently, indicators were assigned to the set of descriptors and attributes to represent the risks by combining hazard exposure and vulnerability information.

The indicator set provided by Shehayeb et al. (2025), includes a generic list of indicators for urban parks and blue spaces, and covers the three vulnerability tiers. In this study, the focus is on the risk for UGI's ES (3rd order risk), as they are what the community receives from the UGI and includes information (attributes) from the two other orders of risk, UGI entities and ecosystem functions. Hence, this list requires contextualization by selecting which ES endpoints are relevant for the study area, then following the translation by Shehayeb et al. (2025) into information (descriptors), and determining which risk indicators are feasible to calculate and represent the descriptors of the selected endpoints.

Subsequently, the case-specific indicators are further analyzed through the lane-based (LB) approach by identifying the interlinkages between indicators based on common indicator attributes. The LB approach had been applied to the full indicators list (Shehayeb et al., 2025), however, the interlinkages of the selected indicators will be further investigated in the current study. According to Müller et al. (2022), the LB approach helps determine key indicators that other indicators depend on, as well as creating an understanding on how the information system is interconnected.

For the methodological procedures of the evaluation, a multi-criteria evaluation (MCE) method is applied to set the thresholds of the selected indicators, assign the respective weights, and the aggregation of indicators into indices if required. Based on the requirements of the DHR Assessment Framework, Shehayeb et al. (2025) suggested methods such as the Analytical Hierarchy Process (AHP), Simple Additive Weighting (SAW), Weighted Product (WP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR). Due to its simplicity to apply, especially by decision makers unexperienced in MCE methods, and its ability to adapt to different considered alternatives (Chakrabarty, 2012; Müller et al., 2023), the TOPSIS method is adopted in the present study.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

3 Methods and Data

3.1 Study Area

As an exemplary study area for implementing and testing the framework, the Hammer park in the town of Plauen was selected. The town is located in a region where drought and heat events have recently increased (e.g., Franke et al., 2004), and the town council aims to address these emerging challenges through the department of urban planning and environment including climate change adaptation. The park was found suitable as a study area since it comprises diverse UGI elements and allows the framework to be tested under limited data availability compared to major German cities. As Fig. 2 illustrates, Plauen is located in the Vogtland district of Saxony, Germany. The average annual temperature in Plauen is 8.65 °C and annual precipitation averages at 643 mm and considered a temperate oceanic climate zone (Deutscher Wetterdienst (DWD), no date). The time series of the annual precipitation can be observed in Fig. 3 indicating a slightly decreasing trend. The park is located in the southern part of Plauen, which is home to 63,372 inhabitants (Statistisches Landesamt des Freistaates Sachsen, 2021).

Figure 2. Location and MMUs of Hammer park, Plauen (Base-maps: GADM; © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.; © Google Earth).

https://doi.org/10.5194/egusphere-2025-2060
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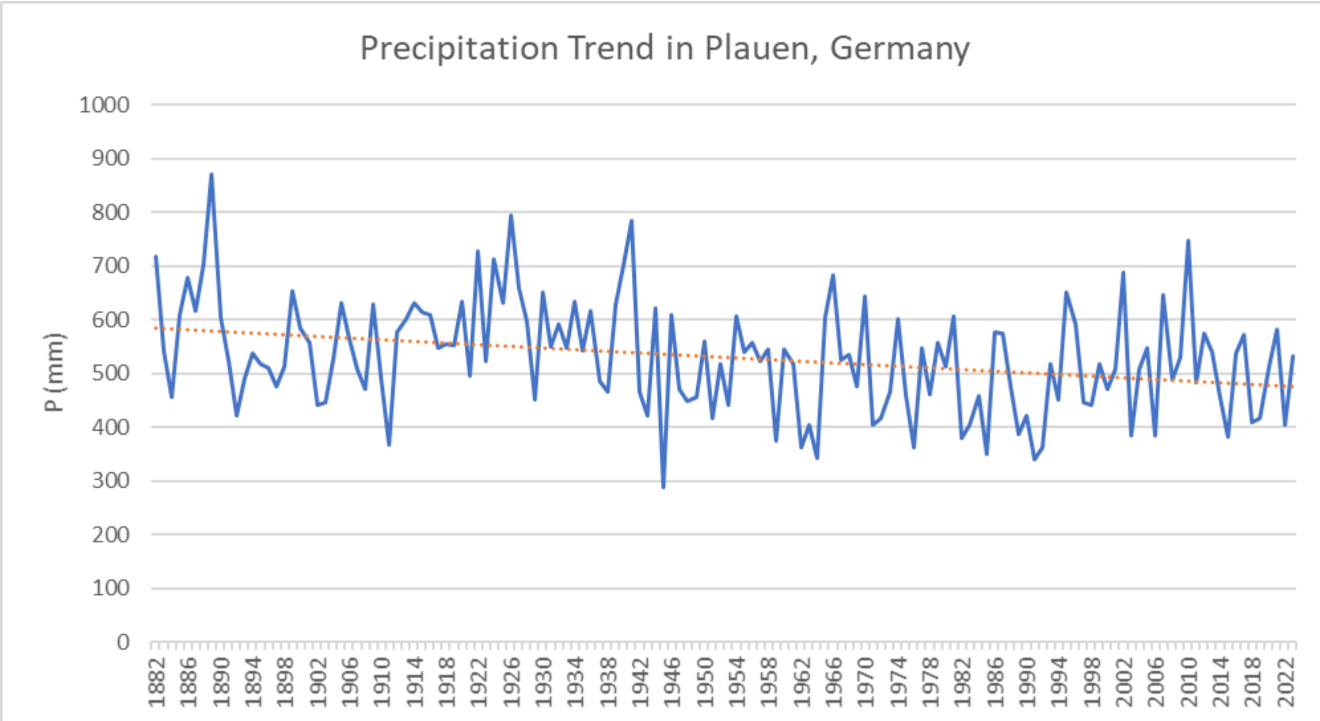

Figure 3. Average annual precipitation (P) in Plauen, Germany (DWD, Nd).

Ranging from 333 m to 372 m above sea level, Hammer park is sided by a slope from the west side, and covers an area of 84,962 m². The vegetation is diverse but dominated by Norwegian Maple (Acer platanoides) and a strong presence of European Ash (Fraxinus excelsior), Small- and Large-leaved Lindens (Tilia cordata and Tilia platyphyllos), Silver Birtch (Betula pendula), and Horse Chestnut (Aesculus hippocastanum). Some tree species such as English Oak (Quercus robur), Large-leaved Linden, and Horse Chestnut are sensitive to droughts, whereas Silver Birch and Horse Chestnut are sensitive to both droughts and heat (Vogt et al., 2017). The park was transferred from a forest to an urban park in 2013-2014 and includes a creek (Milmesbach) and a pond (Hammerteich).

The outer boundary of the study area is delineated based on the street surroundings from OpenStreetMap®. Additionally, the inner part of the study area is divided into six minimum mapping units (MMUs) with the division based on natural barriers (e.g. creek, slope), artificial barrier (e.g., fence), accessibility, or land cover/land use type. This helps provide spatial distribution for certain risk indicators within the park. The MMU specifications are presented in Table 1.

Table 1. MMU Specifications in Hammer Park Plauen

MMU	Area (m²)	Average slope (%)	Land use/ land cover	Accessibility
A1	9,876.53	13.75	Dense tree cover	Yes

A2	17,909.46	10.01	Roughly half of the area is built-up including gardens, other half is sparsely covered by trees	Yes
A3	12,015.41	14.74	Dense tree cover with minor built-up area	Yes
A4	3,270.32	-	Lake	Yes
A5	19,986.42	14.95	Roughly half of the area is built-up, other half is densely covered by trees	Limited/private
A6	21,903.73	15.98	Dense tree cover with minor built-up areas	Limited/private

3.2 Stakeholder Involvement

3.2.1 Stakeholder Network Analysis

Given the study's objective, the focus is not on the decision-making process itself but on leveraging the experience and local knowledge of expert practitioners to contextualize the framework. As a result, analyzing power dynamics, agency, and interrelationships through a stakeholder analysis is not required. Instead, a network analysis focusing on identifying stakeholders is conducted. According to Prell et al. (2009) and Reed et al. (2009), there are two key steps that precede the identification of stakeholders: defining the situation and boundary conditions, as well as defining the criteria for limiting the number of stakeholders. In the present study, the stakeholders are involved in the risk analysis and evaluation. They contribute by confirming the delineated system and selecting relevant risk indicators as part of the analysis procedure. Additionally, stakeholders assign indicator thresholds and weights for the multi-risk evaluation.

A large group of stakeholders are affected or related to the drought and heat risk for UGI, but based on the required involvement, specific selection criteria can be set. Experts are needed in the fields of urban planning, UGI management, nature and biodiversity protection, water management, climate and meteorology, soil protection, environmental engineering, and cultural activities. Stakeholders are required to have strong knowledge in the local context, and hence, stakeholders were selected from the city level (Plauen) and if not available from the district (Vogtland) level. Both, the public and private sectors are considered. Finally, snowball sampling was followed to identify additional stakeholders based on preliminary meetings with some of the identified stakeholders.

3.2.2 Workshop

To involve the experts (stakeholders) tailoring the risk assessment to the local context, a workshop was planned and coordinated in prior with some of the stakeholders through preliminary meetings. The workshop was divided into four core parts:

i. Discussion of the main concepts, situation, risk system, DHR Assessment Framework, and the indicator-based methods (information system).

ii. Selecting the relevant indicators, examining data availability, and feasibility of calculation.

iii. Setting the thresholds for indicators.

iv. Assigning weights by applying the budget allocation method. In this method, a fixed budget of points is distributed over a number of indicators within each dimension, with more points indicating higher importance (Gan et al., 2017).

As a core outcome of the workshop, the results can contribute to more resilient and sustainable UGI planning and management through contextualizing the assessment to local needs and priorities. Additionally, stakeholders are expected to gain a better understanding of the benefits of the DHR Assessment Framework, leading to informed decision-making.

3.2.3 Feedback questions

Following the workshop and the calculation of the risk indicators, the results were shared with the identified stakeholders for transferring the knowledge on the risks and gaining feedback to improve the assessment. Feedback was requested on the clarity of the background information, the usefulness of graphics, the understanding of the procedure and results of the risk assessment, as well as the degree to which this can support decision making. Additionally, an open space for questions and comments was provided. Stakeholders were given the option for their feedback through either a short survey or a virtual meeting based on their preference.

3.3 Multi-Risk Analysis

Starting with the drought and heat hazards, two main parameters were required, intensity and frequency (return period). The spatially distributed intensity of the drought hazard was represented by plant available water (PAW) through a soil moisture sensor (Shehayeb, 2025a), whereas the historic data from soil moisture monitoring station was used to calculate the return period of a drought event with certain intensity (Shehayeb, 2025b). As for the heat hazard, an ENVI-met model v5.6 was used to calculate the spatial distribution of air temperature (Shehayeb, 2025c), while a monitoring station was used to calculate the return period of a heat event with certain intensity (Shehayeb, 2025d).

For reference, the initial PAW and air temperature values represent a return period of 70 months for the drought and 500 days for the heat hazards. These return periods are deduced from the values from the first simulated day (3rd of July, 2015), compared to the long-term data. Only for the correlation indicator, a return period of 19 months was used for the drought hazard due to statistical limitations of air quality data. The used ENVI-met model simulation was applied for the drought and heat period from the 3rd to the 5th of July 2015, and another simulation for the period from the 28th until the 30th of May 2023 was used to validate the model using a meteorological device for mobile climate monitoring (Gallacher and Boehnke, 2025). Two widely used statistical metrics were applied to validate the modeled results with the measured results, the mean absolute error (MAE) and the root mean squared error (RMSE). Resulting MAE and RMSE were 0.58 K and 0.71 K respectively. This compares well to the averages from other studies where MAE ranged between 0.72 K and 2.46 K and RMSE ranged between 0.76 K and 3.06 K, keeping in mind different site conditions, and model versions (Alsaad et al., 2022). Details on data used and validation process is also included in Shehayeb (2025c).

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

The selected set of indicators is diverse in nature, with qualitative and quantitative indicators. Some indicators (Groundwater protection area, Correlation of air quality with drought and heat, USDA textural soil classification, Access to forest (Park) resources, Access to water features, % shaded area) are originally vulnerability indicators, and were normalized and multiplied by the corresponding hazard attributes to convert into risk indicators (Shehayeb, 2025e). Other indicators were directly calculated as risk indicators (Leaf net CO2 assimilation (A_n), Net leaf-air temperature (T_v - T_a), Universal Thermal Climate Index (UTCI)).

To process and calculate the data, ENVI-met model v5.6 was built and ran for the indicators Leaf net CO2 assimilation (A_n), Net leaf-air temperature (T_v - T_a), and Shaded area (Shehayeb, 2025c). R-studio (build 764) and R-script (4.4.1) were used to calculate the indicators correlation of air quality with drought and heat, and UTCI (Shehayeb, 2025f, 2025g). The rest of the indicators were processed directly with QGIS (3.28.6). QGIS was also used to spatially represent the indicators (Shehayeb, 2025h). An overview of the data sources and data flow used for the risk assessment are included in (Shehayeb, 2025i).

3.4 Multi-Risk Evaluation

The TOPSIS method, firstly introduced by Hwang and Yoon (1981), is based on defining positive ideal (best) and negative ideal (worst) situations and evaluating the considered alternatives based on their distances from those two ideal situations. In the current case study in Hammer Park Plauen, only one alternative is considered (A_1), which is the current risk situation (no action), in addition to the maximum tolerable situation for comparative reasons (A_2). As a prerequisite, the thresholds of the indicators, their weights, and their aggregation scheme should be defined. This is done with the contribution of local decision makers and described in Section 3.2. The data was processed through R-studio and Excel, and spatially presented through QGIS (Shehayeb, 2025e, 2025j).

The main steps of the TOPSIS methods are as follows (Chakrabarty, 2012; Madanchian and Taherdoost, 2023):

i. Defining the evaluation Matrix (X)

In this step, the alternative A_1 is assessed through the indicators x_{i1} (i =1, 2, …, I), and defined in a Matrix X. "I" is the number of indicators. Note that in the present study, most indicators are spatial, and even temporal, therefore, indicators x_{i1} are spatially distributed vectors and not point values. In contrast, the alternative A_2 is a single value for each indicator and can be calculated within a spreadsheet (Shehayeb, 2025j). Aj (j= 1, 2, …, J) represents the number of alternatives (j).

$$\mathbf{X} = \begin{vmatrix} x_{11} & x_{12} & x_{1J} \\ x_{21} & & \\ x_{I1} & & x_{IJ} \end{vmatrix}$$

ii. Normalizing the Matrix (R)

The indicators considered for the multi-criteria evaluation have different units. Thus, unitless scores are needed to compare and aggregate the performance of these indicators, and this is done through normalization. Multiple methods are available for normalizing indicators such as the vector, linear, and non-monotonic normalization techniques (Shih *et al.*, 2007). Since alternative solutions are not considered in this study, and to keep the normalization dissociated from the potential alternative

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

solutions, a min-max scaling (linear normalization) is suitable for converting the indicator results into a score between 1 (minimum risk) – 5 (maximum risk). The result is Matrix R.

$$\mathbf{R} = \begin{vmatrix} r_{11} & r_{12} & r_{1J} \\ r_{21} & & \\ r_{I1} & & r_{IJ} \end{vmatrix}$$

$r_{ij} = \frac{x_{ij} - x_i^-}{x_i^+ - x_i^-}$ (for benefit indicators) Eq. (1)

$r_{ij} = \frac{x_i^- - x_{ij}}{x_i^+ - x_i^-}$ (for cost indicators) Eq. (2)

where $x_i^+ = max_i$ and $x_i^+ = min_i$

iii. Calculating the weighted normalized Matrix (V)

The normalized risk indicators from Matrix R are then multiplied by the assigned weights to get the weighted score of each indicator formulating Matrix V.

$$\mathbf{V} = \begin{vmatrix} r_{11} & r_{12} & r_{1J} \\ r_{21} & & \\ r_{I1} & & r_{IJ} \end{vmatrix}$$

$v_{ij} = w_i \times r_{ij}$ Eq. (3)

where v_{ij} is the weighted value, and w_i is the weight for indicator i.

iv. Determining the positive ideal (best) and negative ideal (worst) solutions

A^+ and A^- are denoted as the positive and negative ideal solution sets respectively, which can be detected from Matrix V as:

$A^+ = [\, v_1^+, v_2^+, \ldots, v_i^+]$ Eq. (4)

$A^- = [\, v_1^-, v_2^-, \ldots, v_i^-]$ Eq. (5)

where v_i^+ = { max v_{ij}, if i is a benefit indicator; min v_{ij}, if i is a cost indicator }

and v_i^- = { min v_{ij}, if i is a benefit indicator; max v_{ij}, if i is a cost indicator }

v. Calculating the separation (distance) values

The separation values indicate the distance between each alternative or situation from the positive and negative ideal solutions. This is calculated through the following equations:

$S_j^+ = \sqrt{\sum_{i=1}^{I} (v_{ij} - v_i^+)^2}$, j = 1, 2, …, J Eq. (6)

$S_j^- = \sqrt{\sum_{i=1}^{I} (v_{ij} - v_i^-)^2}$, j = 1, 2, …, J Eq. (7)

where S_j^+ and S_j^- are the distances of the j th alternative to the positive-ideal solution and the negative-ideal solution respectively.

vi. Calculating the relative closeness (overall score)

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

The relative closeness of each alternative from the positive ideal solutions is the final overall score obtained from the TOPSIS, which is calculated through the following equation:

$$P_j^+ = \frac{s_j^-}{s_j^+ + s_j^-}, \text{j} = 1, 2, \ldots, \text{J} \qquad \text{Eq. (8)}$$

where P_j^+ as an overall score represents the relative closeness of the j th alternative to the positive-ideal solution. The value of P_j^+ is between 0 (ideal negative solution) and 1 (ideal positive solution).

vii. Ranking the alternatives

In the present work, if the relative closeness of the current situation (A1) is higher than the maximum tolerable risk situation (A2), then the risk at a specific area or point is considered tolerable. The lower the relative closeness value of A1 compared to A2, the higher the urgency to take risk reduction measures. If more alternatives were considered, they can be ranked according to their P_j^+ value.

4 Results

4.1 Stakeholder Network Analysis

In accordance with the required fields of expertise and the need to have a solid local knowledge, 13 key stakeholders are identified. These are either organizations or departments (e.g., within the city administration). The stakeholders are categorized using three main criteria: spatial level, sector, and expertise as shown in Fig. 4. Connections between the different departments at the city level helped discover additional stakeholders (e.g., forestry) and facilitated the coordination of the workshop.

Within preparatory meetings, the “tourism and culture” department decided that the discussed topic is not directly related to their expertise, and the department of “land use planning” indicated that the “green & environmental planning” department could represent the planning perspective better in this study. Therefore, the two aforementioned departments were not contacted for the workshop. The remaining 11 stakeholders were invited for a workshop on the 16th of April 2024 hosted by the city of Plauen in the town hall. The concept note of the workshop was shared with the invitees and discussed beforehand. Nine representatives of eight departments/organizations participated in the workshop and contributed to the results in selecting indicators (Section 4.2.1.), and setting the evaluation criteria and weights (Section 4.3.1). The departments of “water management” and “soil protection” from the district level, as well as the BUND Vogtland did not take part in the workshop.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

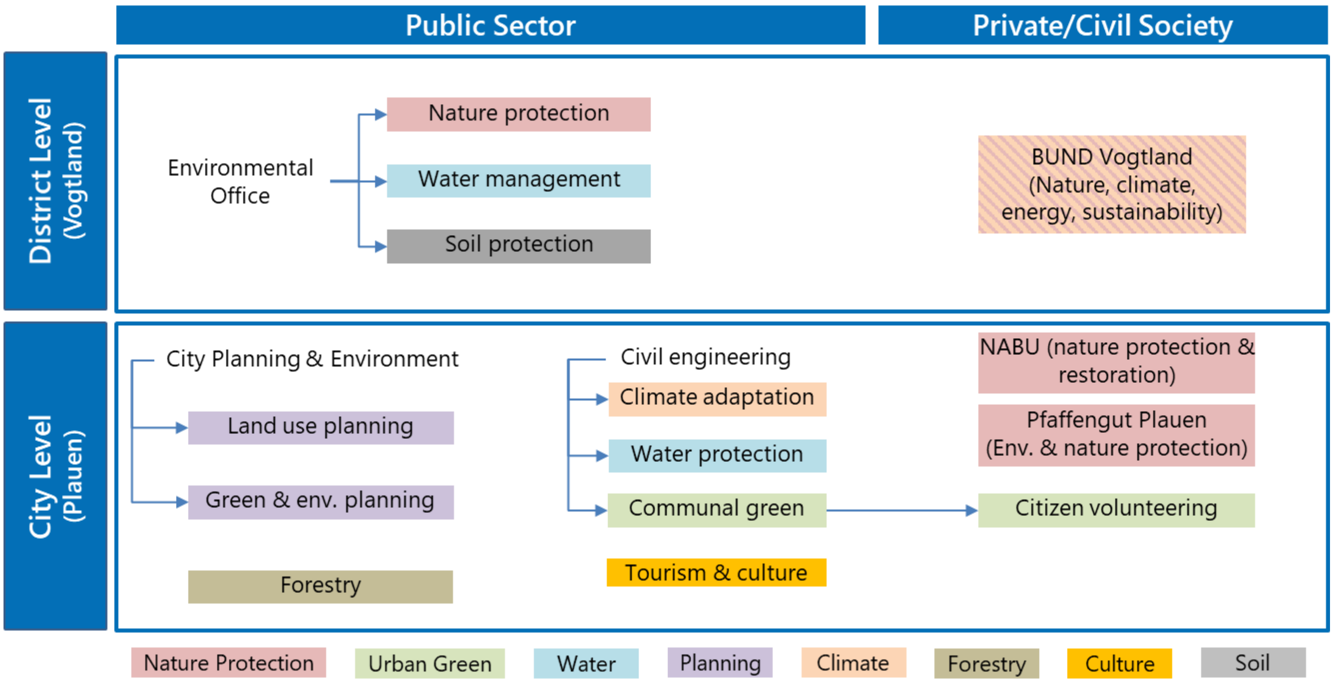

Figure 4. The mapping and analysis of stakeholders. The mashed color represents both, nature protection and climate.

4.2 Risk Analysis

4.2.1 Delineation of the system – Workshop Output

In the present study, endpoints from the drought and heat hazards, as well as the ES are identified form the risk system presented by Shehayeb et al. (2025). Moreover, the endpoints “Hydrological drought” and “The use of plant and animals” are not relevant as no surface water is extracted and plants and animals are not harvested in the Hammer park. Similarly, the descriptors “Viable extraction of surface water resources”, “Treatment if used water resources”, and “Soil sedimentation” are not considered for the assessment. The selected endpoints and descriptors are presented in Table 2.

Table 2. The selected endpoints and descriptors for Hammer park, Plauen. (D: Dimension; N/A: Not applicable; P: Provisioning; R: Regulating; C: Cultural)

Category	Endpoint	Code	Descriptor
Drought Hazard	Ecological drought	N/A	Soil Moisture
Heat Hazard	Urban heat wave	N/A	Extreme heat
Ecosystem Services	The use of plants and animals	P-3.1	Viable harvesting of plant and animal resources
	The use (& treatment) of surface and ground water	P-3.3	Viable extraction of groundwater resources

	Regulation of atmospheric composition & conditions	R-3.5	Vegetation ability to maintain air quality regulating capacity
		R-3.6	Ability to maintain cooling capacity
	Regulation of soil quality and fertility	R-3.7	Soil texture
		R-3.9	Vegetation decomposition & fixation
		R.3.10	Soil microbial composition
	UGI landscape's cultural uses	C-3.11	Attractive features of UGI
		C-3.12	Community's usage under D&H conditions

Thereafter, the selected descriptors are assigned a preliminary number of indicators from the set of indicators of Shehayeb et al. (2025). These indicators are then analyzed following a lane-based approach to indicating the interlinkages (Fig. 4). From the full list of indicators from Shehayeb et al. (2025), "Leaf net CO2 assimilation (An)" and the "Net leaf-air temperature (T_v - T_a)" have the most interlinkages with 10 each. When considering only the indicators for the selected descriptors in the present study, clusters of interlinkages can be recognized such as the accessibility-related indicators as well as the interlinked indicator pairs. The total 11 interlinkages show that there are common attributes between these indicators, and changing one could lead to changes in another.

The preliminary list of indicators (Fig. 5) was presented to the stakeholders in the workshop and further reduced to indicators relevant to the study area (Table 3). Additional indicators were suggested, but were found to be in the tier of biophysical entities and not of ES. Some attributes of these indicators were considered in the simulated model. For example, "Vegetation canopy area" and "Density" (health of vegetation), as well as the "Slope" and "Soil cover" (area conditions) were inputs for the ENVI-met model. "Leaf breakdown rates" and the "Microbial Shannon diversity" indicators were not calculated due to the current unavailability of data or the lack of feasibility to measure within this study's timeframe.

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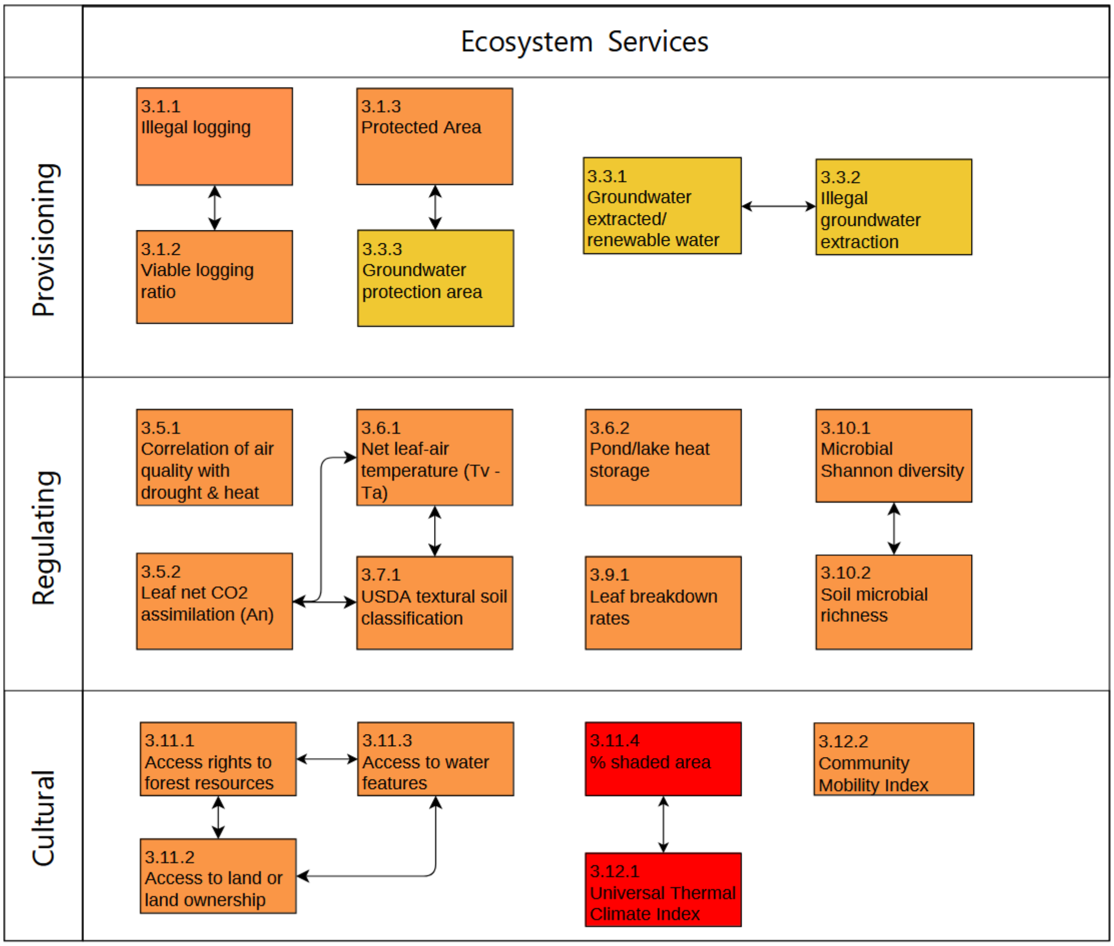
Preprint. Discussion started: 20 May 2025



350 **Figure 5. Interlinkages of ES risk indicators through a lane-based approach (Yellow: Drought related; Red: Heat related; Orange: Drought & heat related)**

Table 3. Selected ES indicators for the risk assessment of Hammer park, Plauen

Descriptor	Code	Indicator	Notes
Viable harvesting of plant and animal resources	P-3.1.3	Protected area	Only water protection zone was used as provisioning ES indicator; Source: Stadt Plauen
Viable extraction of groundwater resources	P-3.3.3	Groundwater protection area	
N/A	N/A	Health of vegetation (from workshop)	It is part of the UGI entities which effects the ES, but not directly an ES indicator: Not Calculated → weight discarded

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

N/A	N/A	Area conditions (from workshop)	It is part of the UGI entities which effects the ES, but not directly an ES indicator: Not Calculated → weight discarded
N/A	N/A	Water levels/discharge (from workshop)	It is part of the UGI entities which effects the ES, but not directly an ES indicator: Not Calculated → weight discarded
Vegetation ability to maintain air quality regulating capacity	R-3.5.1	Correlation of air quality with drought and heat	Calculation through R; Data from DWD stations
	R-3.5.2	Leaf net CO2 assimilation (An) - risk	Calculation through ENVI-met; Data from DWD stations and multiple other sources
Ability to maintain cooling capacity	R-3.6.1	Net leaf-air temperature (Tv - Ta) - risk	Calculation through ENVI-met; Data from DWD stations and multiple other sources
Soil texture	R-3.7.1	USDA textural soil classification	Based on data from www.boden.sachsen.de and workshop
Vegetation decomposition & fixation	R-3.9.1	Leaf breakdown rates	Not calculated due to lack of data → weight discarded
	R-3.10.1	Microbial Shannon diversity	Not calculated due to lack of data → weight discarded
Attractive features of UGI	C-3.11.1	Access to forest (Park) resources	Based on site observations/ workshop
	C-3.11.3	Access to water features	Based on site observations/ workshop
	C-3.11.4	% shaded area	Data from Google Satellite, digital elevation models
Community's usage under D&H conditions	C-3.12.1	Universal Thermal Climate Index (UTCI) - risk	Calculation through ENVI-met; Data from DWD stations and multiple other sources

4.2.2 Calculation of Indicators

355 The risk indicators represent attributes from the hazards and vulnerability. Risks indicators that were directly modeled were left in their initial units, whereas risk indicators that had to be manually calculated through hazard and vulnerability attributes are normalized to a scale from 1 to 5, where 1 characterizes the lowest risk and 5 the highest risk. The return period for heat risk is 500 days (30.8 °C), and for soil moisture 70 months (monthly avg. = 36.6%), except for the correlation indicator (R-3.5.1), where the return period of 19 months (46.04%) was used.

360 **Groundwater protection area - P-3.3.3**

Although no groundwater is extracted from within the Hammer park, wells are located in other regions of the city and the park is categorized as a groundwater resource area. That being said, the park is not situated within a water protection zone.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

Hence, the score of the "Groundwater Protection Area" indicator in Fig. 6 is the drought hazard multiplied by 5 (for unprotected) and normalized. It is observable that parts of A2, A3 and east of A6 are under very high risk (>4.5). Since the protection zone is common within the park, the variation of risk relates to the variation of the soil moisture (PAW) within the park. However, the mean risk across the park (2.93) being just below the scale's median (3), is due to the high value of the vulnerability component (no protection zone).

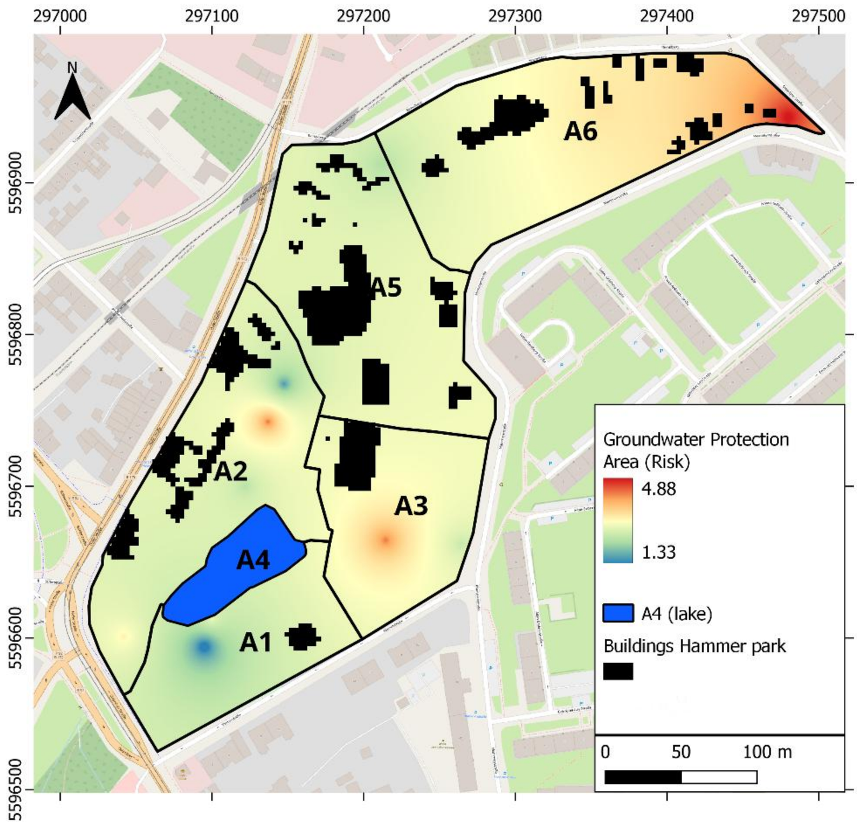


Figure 6. Groundwater protection area risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Correlation of air quality with drought and heat - R-3.5.1

Air purification is one of the regulating ES provided by UGI, and holds special significance for the health of urban dwellers. Therefore, finding whether the air purification is affected under drought and heat conditions is considered as one of the risk indicators. With a non-linear relationship between the air temperature and the air quality (PM10), Spearman correlation is applied considering days where PAW was less than 46.04% (19-month drought return period). The resulting coefficient "Rho" was 0.635 with p-value <0.002. The result is categorized as a strong correlation with a value of 4/5. To calculate the risk result, the value is multiplied with the drought and heat hazards and normalized as presented in Fig. 7. Since the air quality data were acquired from one station, the correlation value is uniform along the park, but the drought and heat hazards

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

result in the risk variation. Hotspots can be detected in the western parts of A2 and A5, in addition to the eastern part of A6 where the risk values can exceed 3.5. The mean value of 2.36 is on the lower side of the risk scale.

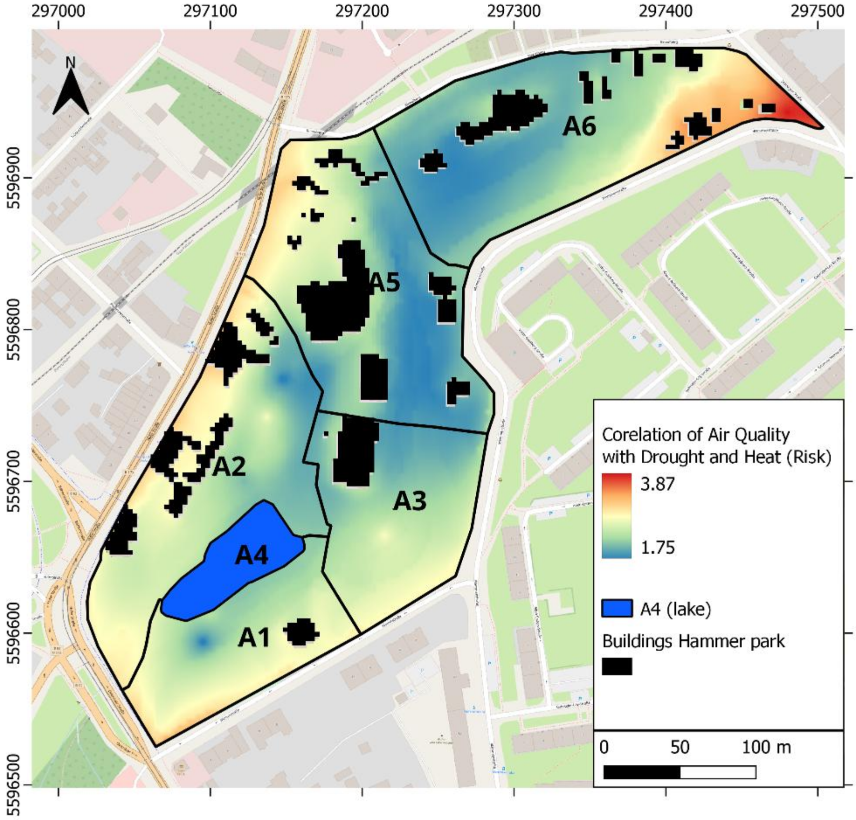


Figure 7. Correlation of air quality with drought and heat risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Leaf net CO2 assimilation (An) - R-3.5.2

The leaf net CO2 assimilation measures how much carbon dioxide is absorbed by the vegetation leaves while subtracting the amount released from respiration (Tcherkez and Limami, 2019). Figure 8 (left) displays the variation of the A_n within Hammer park at a selected height of 5.12 m as an output of the ENVI-met model. The lower negative numbers indicate higher carbon sequestration rates while posive numbers indicate that the leaves are releasing CO2. Studies indicate that initially in heat conditions, vegetation tend to open their stomata for transpirative cooling, but close their stomata in case of water stress (low PAW) (Duan et al., 2017). In addition to stomatal closure, other extreme heat and water stress effects also lead to reducing the CO2 assimilation. Observing the average A_n levels in Fig. 8 (right), A1 and A3, which have high tree density and leaf area index, have the highest average An (lowest carbon intake). For reference, the value of -0.497 mg *m-2 *s-1 is considered a high carbon intake for maple trees on a sunny day (Schindler and Lichtenthaler, 1996). Competition between vegetation on water resources can cause additional water stress and reduced CO2 intake (Bottero et al., 2016). Additionally, an important factor affecting the A_n is the photosynthesis rate which is highly dependent on available sunlight.

Hence, leaves located in shaded area can show lower rates if An. Although the dominant tree species, Norwegian Maple, is considered drought tolerant and with medium heat tolerance, this could help in post-stress recovery of the trees but still cause temporary disturbances in A_n for example.

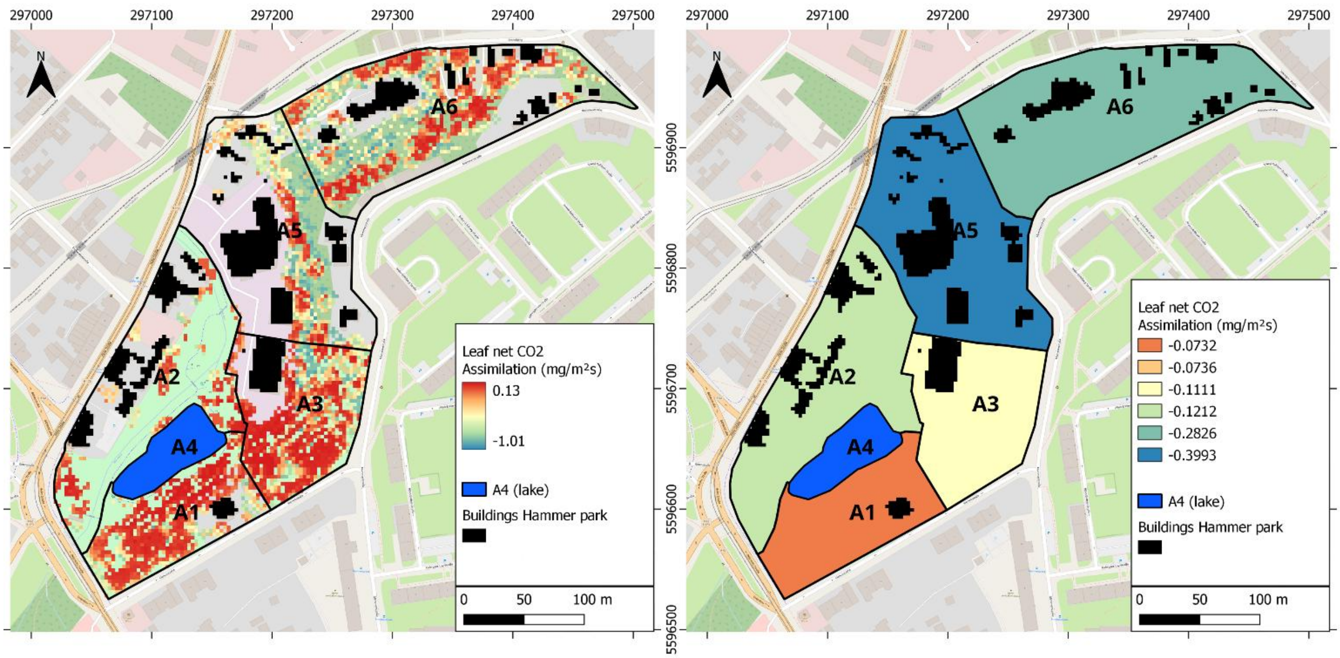


Figure 8. Leaf net-CO2 assimilation risk indicator ENVI-met output (left) and MMU average (right) (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Net leaf-air temperature (T_v - T_a) - R-3.6.1

The cooling capacity of the vegetation is measured through the temperature difference between the leaves and the air, with transpiration being the main agent for cooling. At high temperatures, if the difference is close to zero or negative, this indicates that the leaves are warming up and not maintaining their cooling function (Still et al., 2022). Figure 9 (left) displays the variation of the T_v-T_a within Hammer park at a selected height of 5.12 m as an output of the ENVI-met model. The MMU averages from Fig. 9 (right) indicate that T_v-T_a were the highest for A2 and A5 with -2.75 and -3.14 °C respectively. A2 and A5 have relatively many areas with sealed soil, several built-up areas and sparse vegetation. These factors play a role in higher air temperatures and lower soil infiltration rates. When a compound drought and heat stress exceeds a certain threshold, stomata closure occurs and the leaves cannot maintain their cool temperature.

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Preprint. Discussion started: 20 May 2025

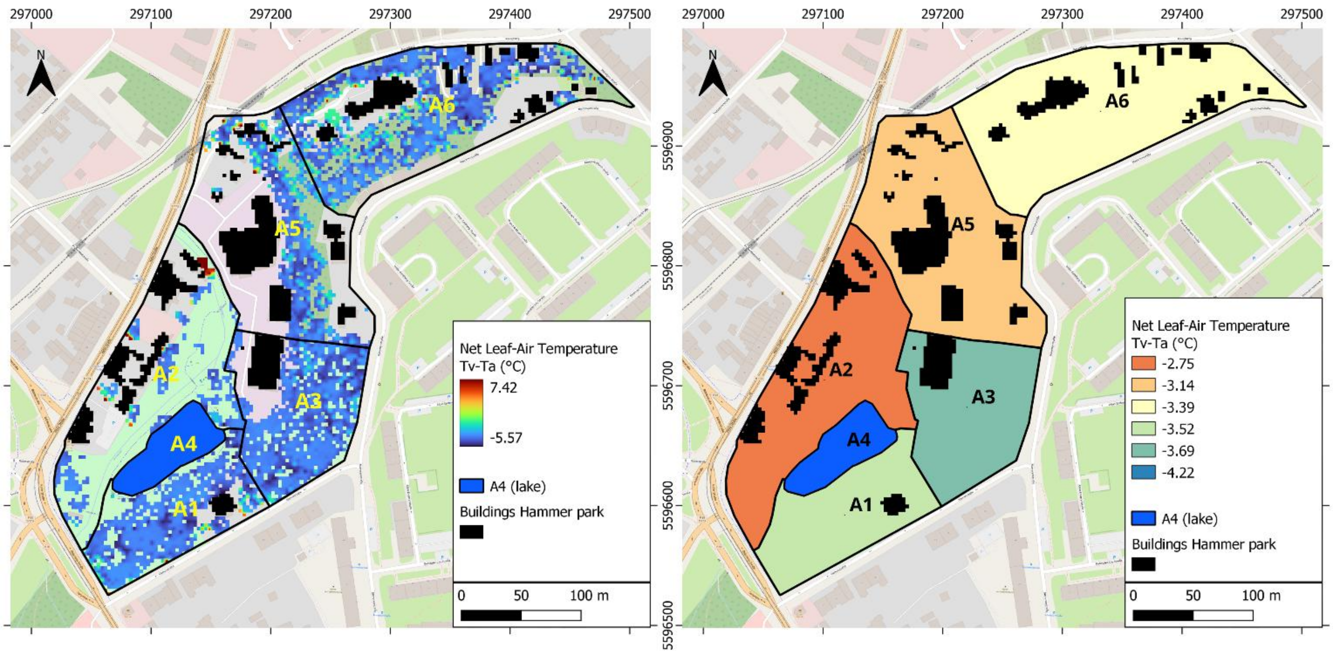

Figure 9. Net leaf-air temperature risk indicator: ENVI-met output (left) and MMU average (right) (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

USDA textural soil classification - R-3.7.1

415 In addition to determining the water holding capacity of soil, the soil texture affects the quality and regulation of soil. To consider this as a risk indicator, the drought and heat hazards are mutiplied by the soil texture value (1 for loamy soil) and normalized to a scale from 1-5. In this case, the hazards imply spatial variations within the park as illustrated in Fig. 10. The low value of risk ranging between 1.17 and 1.72 relates to the low vulnerability of loamy soils. Sealed areas are not modeled in this indicator showing only the background map.

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Preprint. Discussion started: 20 May 2025

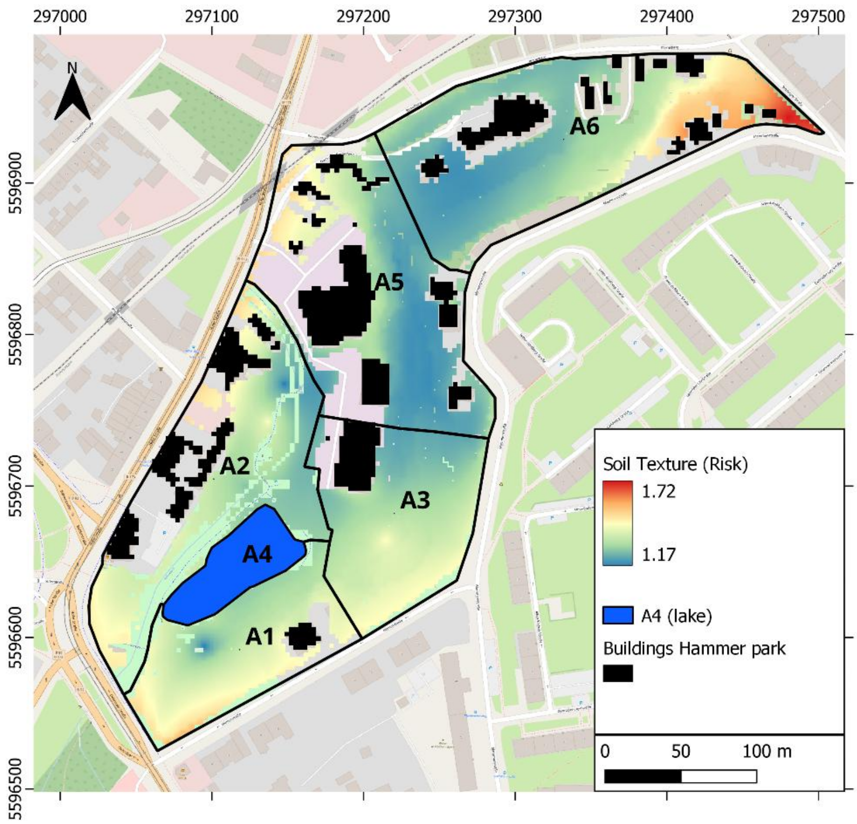

Figure 10. Soil texture risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Access to forest (park) resources - C-3.11.1

Having the park divided into MMUs, we find that A1, A2, and A3 are publically accessible whereas A5 and A6 are private areas. The park accessibility is a key indicator for cultural ES. The resulting risk indicator in Fig. 11 is a normalized combination of the drought and heat hazards with the vulnerability attribute of accessibility value on a scale from 1 to 5. The high-risk values exceeding 3.5 are mainly located within the west of A5 and east of A6 where both hazard and vulnerability attributes are at their highest levels.

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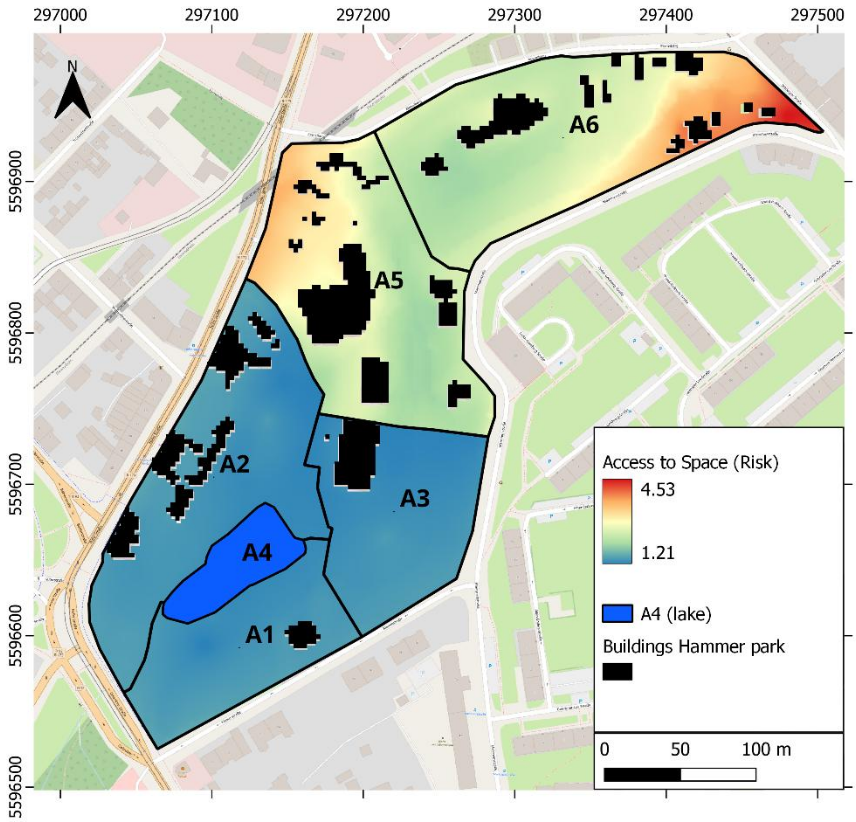
Preprint. Discussion started: 20 May 2025



430 **Figure 11. Access to space risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).**

Access to water features - C-3.11.3

Similar to the park accessibility, access to water features is a key indicator for the cultural ES. Here, the options are fully accessible (1), partially accessible (3), and not accessible (5). Full accessibility means direct contact with water is possible (e.g., bathing), whereas partial accessibility is being in close proximity with water. After multiplying and normalizing the drought and heat hazards with the water accessibility values, we get the risk indicator results in Fig. 12. A1 and A2 are in close proximity with the small lake (Hammerteich), and the creek (Milmesbach) passes through A2. Therefore, A1 and A2 have lower risk compared to A3, A5 and A6. The high-risk areas (exceeding 3.5) can be noticed in the south of A3, north-west of A5, and east of A6.

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Preprint. Discussion started: 20 May 2025

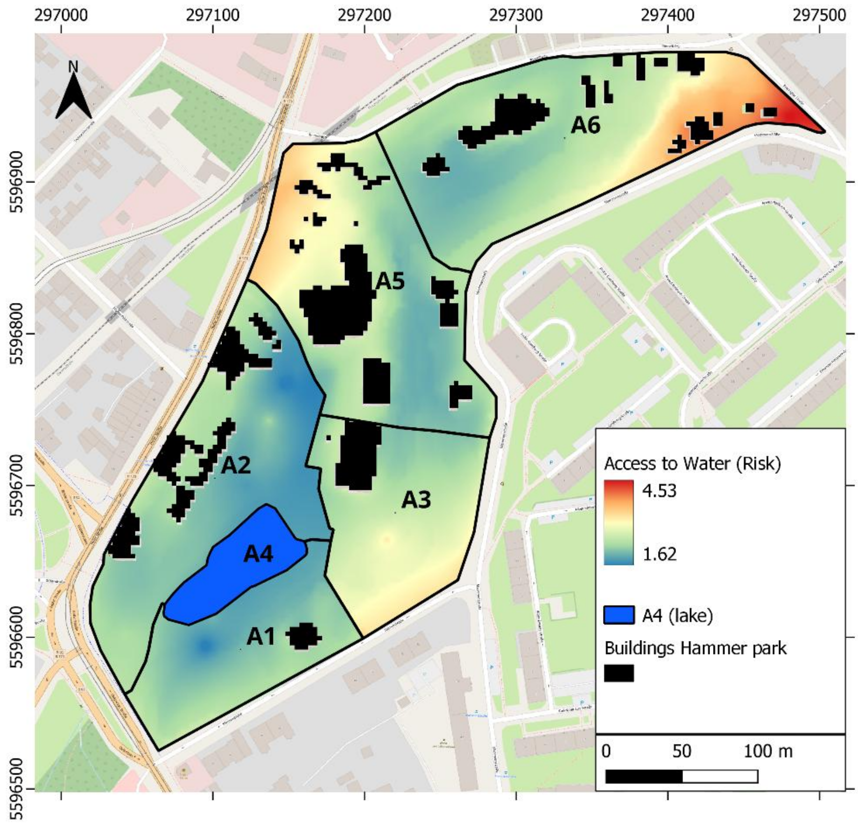

Figure 12. Water access risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Shaded area - C-3.11.4

Shade is an attractive feature for users of the park during heat conditions, and hence an indicator of cultural ES. Figure 13 displays the heat hazard multiplied by the shade value (1 or 5) and then normalized. With plenty of shaded areas in A1 an A3, the risk indicator reaches very high values (exceeding 4.5) in the western sections of A2 and A5 and the eastern section of A6. The shade considered for this indicator was approximately at 1 p.m. (solar noon in May).

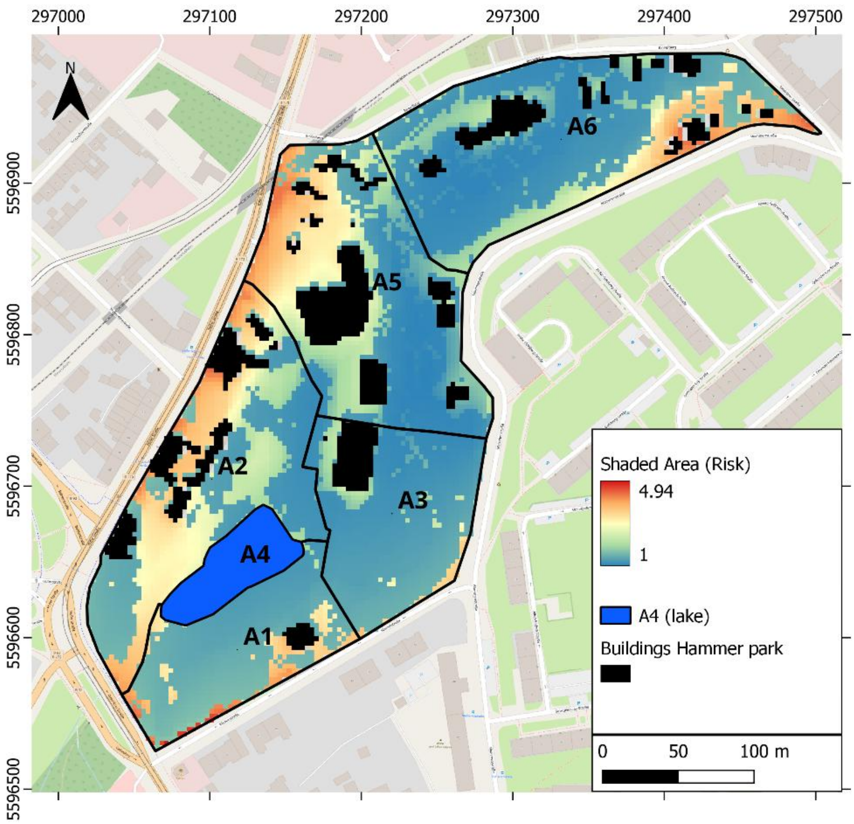

Figure 13. Shaded area risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Universal Thermal Climate Index (UTCI) - C-3.12.1

Using the air temperature, relative humidity, wind speed, and mean radiant temperature outputs from ENVI-met model, an R-script was applied to calculate the UTCI are the grids of the park. Results in Fig. 14 show that points of high temperature are located around buildings, sealed soil, and sparce vegetation areas. Most of the A5 and A2 MMUs had UTCI values exceeding 38 °C. Since A2 is publically accessible, having high UTCI values can hinder the potential of cultural activites in this area.

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Preprint. Discussion started: 20 May 2025

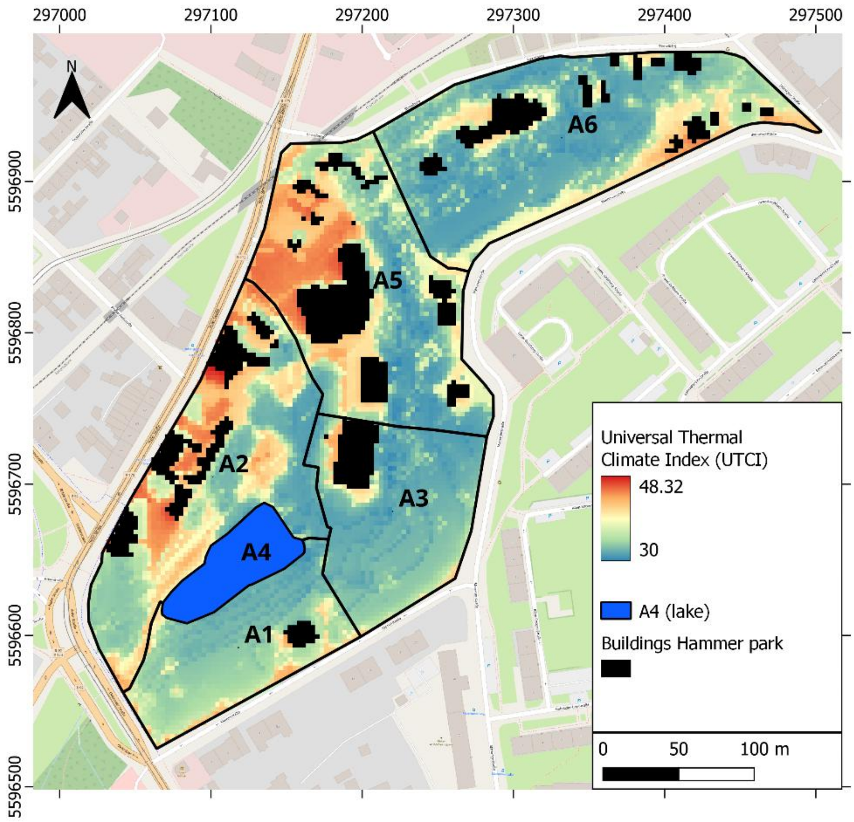

Figure 14. Universal Thermal Climate Index risk indicator (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

4.3 Risk Evaluation

4.3.1 Evaluation Criteria – Workshop Output

The thresholds of the selected risk indicators were adopted from the literature when available, and proposed to the stakeholders in the workshop to decide on. Thresholds helped determine the criteria for TOPSIS evaluation by defining the ideal worst, ideal best, and maximum tolerable values of the indicators (Shehayeb, 2025e). Thereafter, the weights of the indicators within each dimension were assigned. The weight $w*_i$ represents the original weight and w_i represents the weight after factoring out the discarded indicators. Since only one indicator within the provisioning dimension is calculated, the assigned weight is 1. The indicators A_n and UTCI are assigned the highest weight of (8/12) and (5/12) in the regulating and cultural dimensions respectively. The thresholds and weights of the selected indicators are provided in Table 4.

Table 4. Assigned indicator weights and thresholds ($w*_i$ represents the original weight and w_i represents the weight after factoring out the discarded indicators).

Code	Indicator	$w*_i$	w_i	Thresholds

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

P-3.1.3	Protected area			
P-3.3.3	Groundwater protection area	1/12	1/1	Drought Hazard * Vulnerability: High protection e.g., Zone I – "Wasserschutzgebiete" (1), medium protection e.g., Zone II (2.33), low protection e.g., Zone III, (3.67), no protection (5) (BMUV, no date)
N/A	Health of vegetation (from workshop)	5/12	-	N/A
N/A	Area conditions (from workshop)	3/12	-	N/A
N/A	Water levels/discharge (from workshop)	3/12	-	N/A
R-3.5.1	Correlation of air quality with drought and heat	2/18	2/12	Drought & Heat Hazard * Vulnerability: Spearman Correlation Coef. Rho= 0-0.19 (1); 0.2-0.39 (2); 0.4-0.59 (3); 0.6-0.79 (4); 0.8-1.0 (5); with p-value < 0.02 (Yan *et al.*, 2019)
R-3.5.2	Leaf net CO2 assimilation (An) - risk	8/18	8/12	Risk indicator: min-max scaling
R-3.6.1	Net leaf-air temperature (Tv - Ta) - risk	2/18	2/12	Risk indicator: min (- 5.5 °C) - max (12.06 °C) scaling (Crous *et al.*, 2023)
R-3.7.1	USDA textural soil classification	2/18	2/12	Drought & Heat Hazard * Vulnerability: loam, clay loam, silt loam, silty clay loam, sandy loam, sandy clay loam (1); sandy clay, silty clay, loamy sand (3); silt, sand, clay (5) (Hamarashid et al., 2010)
R-3.9.1	Leaf breakdown rates	2/18	-	N/A
R-3.10.1	Microbial Shannon diversity	2/18	-	N/A
C-3.11.1	Access to forest (Park) resources	2/12	2/12	Drought & Heat Hazard * Vulnerability: yes (1); no (5)
C-3.11.3	Access to water features	2/12	2/12	Drought & Heat Hazard * Vulnerability: yes (1); partially (3); no (5)
C-3.11.4	% shaded area	3/12	3/12	Drought & Heat Hazard * Vulnerability: yes (1); no (5)
C-3.12.1	Universal Thermal Climate Index (UTCI) - risk	5/12	5/12	Risk indicator: above +46: extreme heat stress; +38 to +46: very strong heat stress; +32 to +38: strong heat stress; +26 to +32: moderate heat stress; +9 to +26: no thermal stress (Bröde *et al.*, 2012)

4.3.2 Evaluation Results (TOPSIS)

Following the TOPSIS method, the indicators are evaluated based on the differences to the ideal best and worst values, in addition to the tolerable value. The final results (Fig. 15-17) are aggregated into the dimensions of provisioning, regulating, and cultural ES showing the relative closeness of each dimension to the ideal solution.

Risk for Provisioning Ecosystem Services

The risk evaluation for provisioning dimension in the present study area is based only on the "Groundwater protection area" indicator. The relative closeness values below the min desirable (0.67) are considered of intolerable risk. As Fig. 15

https://doi.org/10.5194/egusphere-2025-2060
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demonstrates, most of the park is exceeding the tolerable risk and particularly A3 and A6 are found to be with high risk. These areas are exposed to a relatively higher drought hazards causing the higher risks.

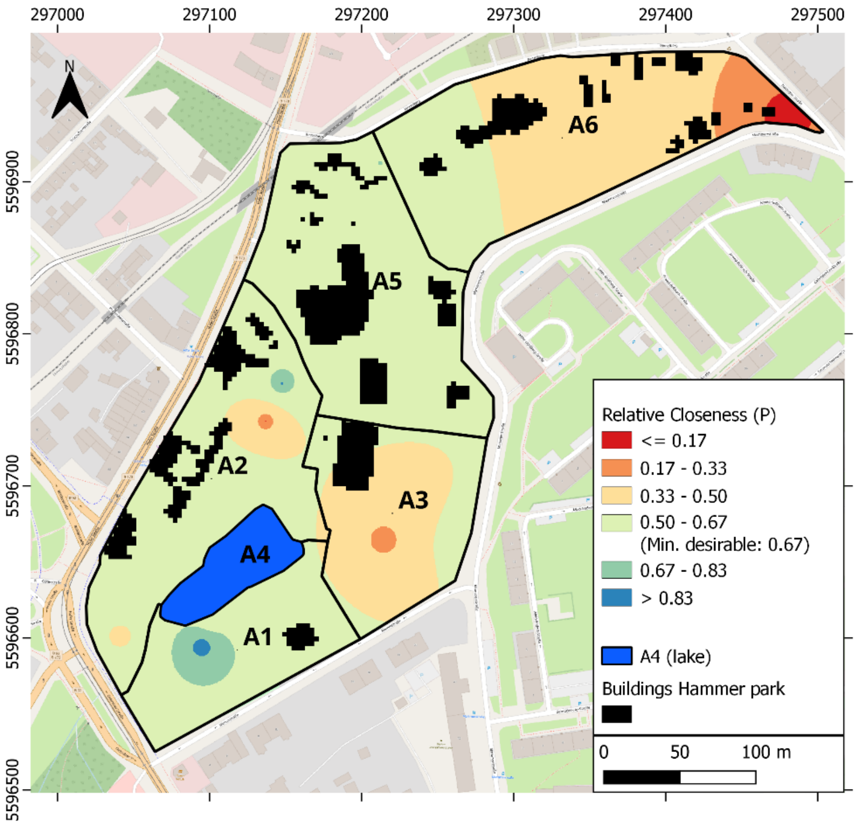

Figure 15. Relative closeness for the provisioning ES (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

Risk for Regulating Ecosystem Services

The risk evaluation for the regulating ES is based on the four indicators, “Correlation of air quality with drought and heat”, “Leaf net CO2 assimilation (A_n)”, “Net leaf-air temperature (T_v - T_a)”, and “USDA textural soil classification”. The highest weight was assigned to the indicator An, making it the most influencing indicator on this dimension. Moreover, the indicators are diverse in terms of spatial distribution and thus, the overlapping cells were considered. According to the relative closeness values in Fig. 16 (left), minor areas of A5 and A6 are above the minimum desirable values, i.e. below the max tolerable risk. On the contrary, almost all areas of A1 and A2 are below the minimum desirable relative closeness, hence, exceeding the tolerable risk. Figure 16 (right) displays the average relative closeness in each MMU, and indicates that all MMus are below the minimum desirable relative closeness, with A1 and A2 well exceeding the tolerable risk values.

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Preprint. Discussion started: 20 May 2025

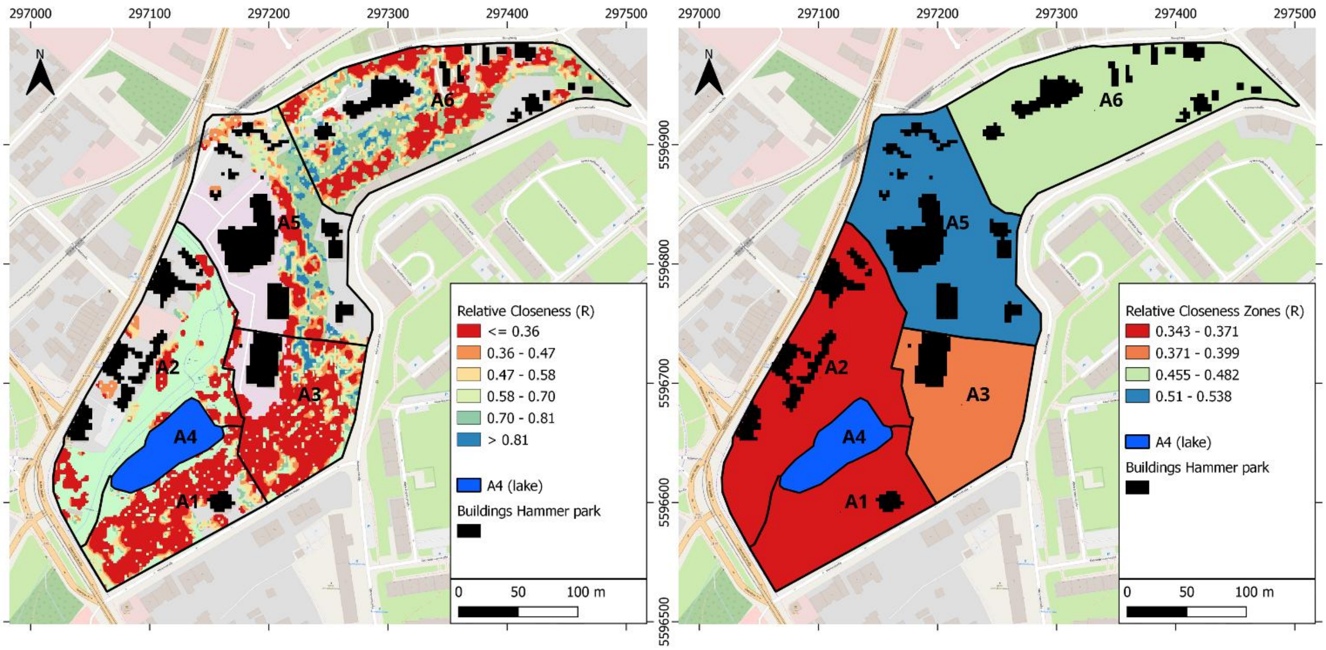

Figure 16. Relative closeness for the regulating ES 0.5mx0.5m resolution (left) and MMU average (right) (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.)

Risk for Cultural Ecosystem Services

Four indicators contribute to the risks for cultural ES, “Access to forest (Park) resources”, “Access to water features”, “Percentage shaded area”, and the “Universal Thermal Climate Index (UTCI)”, with the latter carrying the highest weight (5/12). The results presented in Fig. 19 indicate that most of the areas with intolerable risk, which have relative closeness below 0.692, are located west of the park (A2 and A5) as well as a small area north-east of the park in A6. The highest risk areas (e.g. in A5) are a combination of high UTCI, lack of shaded area, and lacking accessibility.

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Preprint. Discussion started: 20 May 2025

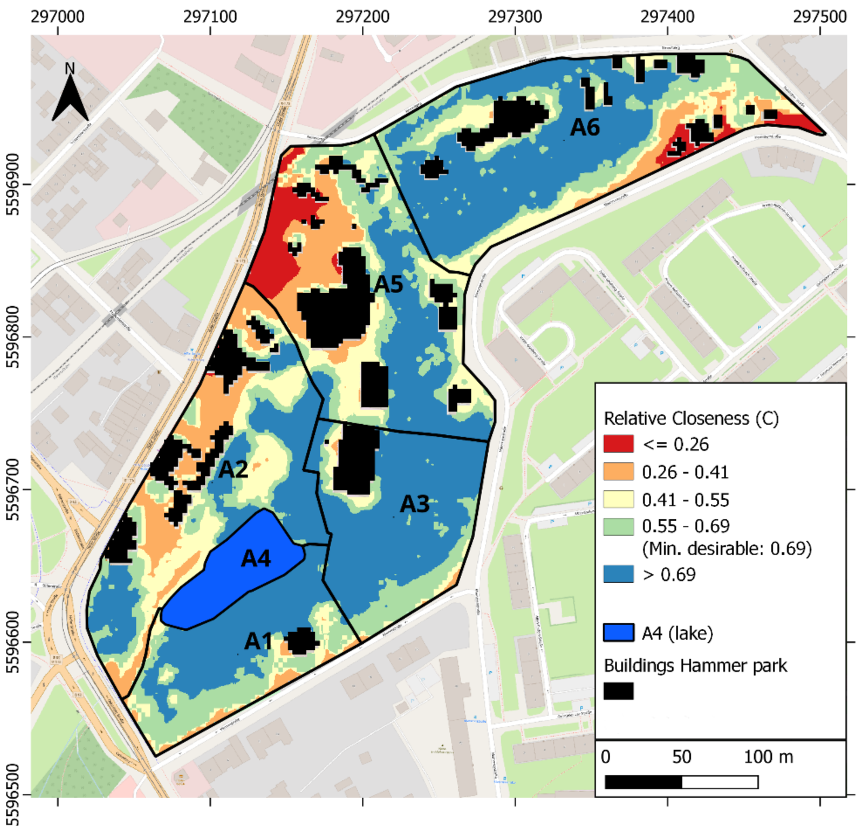

Figure 17. Relative closeness for cultural ES (Base-map: © OpenStreetMap contributors 2025. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.).

4.4 Interpretation of Results and Feedback

4.4.1 Interpretation of Results

The assessment results highlight the areas with intolerable risks within each ES dimension, which can direct decision makers to planning and management actions from the reduction of these risks. These results are based on many factors, including the hazard and vulnerability attributes of the individual indicators, the combination of multiple indicators, as well as the evaluation criteria (thresholds and weights). Therefore, applying reverse investigation from the assessment results to the attributes can help identify what type of interventions are needed. In this section, potential interventions are mentioned not as final recommendations but as alternatives. These alternatives need to be further assessed from the risk perspective, as well as other considerations such as the social acceptance and economic feasibility.

Beginning with the provisioning ES, areas A3 and A6 are identified as high-risk areas. In this dimension, only the groundwater protection indicator contributes to the assessment. Since the vulnerability attribute is constant across the MMUs, the high risk is due to the hazard attribute represented by the soil moisture (plant available water). In A3 and A6, the area is a densely vegetated area, which further increases the competition for available water resources in drought periods.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

Therefore, for this dimension, alternatives could include short-period irrigation, preferably using reclaimed water or harvested rainwater, and investigate, if a groundwater protection zone is required.

The risk assessment for the regulating ES shows that on average all the MMUs are over the tolerable risk. However, A1 and A2 are particularly high-risk areas. The indicator with the highest weight within this dimension is the "Leaf net CO2 assimilation (An)". This indicator has shared attributes and interlinked with two other indicators, "Net leaf-air temperature (T_v - T_a)", and "USDA textural soil classification". A1 scores poorly in the "Leaf net CO2 assimilation (A_n)", and the relevant attributes are related to the vegetation type and characteristics, soil characteristics, plant available water, and the air temperature. On the other hand, the high risk in A2 relates mainly to the "Correlation of air quality with drought and heat" and "Net leaf-air temperature (T_v - T_a)". A1 has high vegetation density increasing the competition of the available water, and placing the trees under water stress. In A2, the water and heat stress are due to the direct hazards. This raises the question of what is the ideal density of vegetation in such areas to be resilient to droughts (Bottero et al., 2016). Moreover, drought and heat resilient tree species, and short-period irrigation preferably using reclaimed water or harvested rainwater can be explored as risk reduction alternatives.

Lastly, the risk assessment results for the cultural ES show higher risks in areas with high UTCI, high heat and drought hazards, and low accessibility. Comparing the MMUs, most of A1 and A3 are exposed to tolerable risk, due to their shaded areas, accessibility and lower drought and heat risks. On the contrary, A2 has less shaded areas due to sparse canopy cover, and high UTCI, which depends on attributes of air temperature, humidity, radiation, and wind. Although A2 is meant to be an accessible space for the public users to benefit from cultural activities, high risks to cultural ES can hinder that. In parts of A5 and A6, the combination of high drought and heat hazards with high UTCI and no accessibility cause the risk hotspots. Looking at the contributing attributes, alternatives such as increasing the canopy cover (resilient trees), providing more accessibility (e.g., walking trails), and water elements (e.g., fountains) could be further investigated. Attention should be paid to synergies and tradeoffs with other ES dimensions, for example, increasing the canopy cover should not be excessive to avoid high competition on soil and water.

4.4.2 Stakeholder Feedback

After sharing a report on the results with the stakeholders who participated in the workshop, feedback was requested to determine which aspects of the risk assessment meet the specified objectives and which still require further development. The first aspect considered is the clarity of the background information provided on the drought and heat risks for UGI and their ES. Stakeholders considered the situation addressed understandable and relevant for the study area. The use of graphics and the spatial dimension of risk was determined equally helpful in identifying high risk areas that require action. On the contrary, the risk assessment process of analysis and evaluation was not fully understood by all stakeholders. Particularly, some indicators have different nature and scales within the analysis, and the TOPSIS steps were not presented in details in the risk assessment report, which obscured the connection between the evaluation criteria and the TOPSIS results. The results themselves, however, were well recognized by the stakeholders in terms of the high-risk areas and their consequences

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

for the ES. The stakeholders' feedback on the potential of the risk assessment to support decisions on risk reduction measures varied from low to high potential. This could be associated to the department and decision-making position of the stakeholders, but would require further research and deeper stakeholder analysis to determine.

5 Discussion

There are several advances that emerged from testing the DHR Assessment Framework using an indicator-based approach. The study area for the empirical work was an urban park with a diverse vegetation cover, water elements, and built-up areas. In a field where most studies on ecosystems (e.g., UGI) and their services are impact based (e.g., Al-Qubati et al., 2023), the assessment focuses on the multi-risks for ES with indicators from the provisioning, regulating, and cultural dimensions. However, the risks for the ES is a result of the hazard propagating to the exposed and vulnerable ecosystem entities, then functions, and to reach the services. The ML and LB approaches enabled the representation of the cascading risk system by an information system from the different orders of risk and denoted by descriptors, attributes and indicators, as well as analyzing the interlinkages of these indicators.

In contrast to prior studies focusing on risk indicators for UGI or NbS (e.g., Shah et al., 2020), this research expands the scope to evaluate risks for EF and ES. Given that the primary benefits of UGI are delivered to society through ES, this study underscores the importance of assessing risks for ES. Compared to the few studies on the risks for ES at larger spatial scales (e.g., Peng et al., 2024), the assessment is guided by a framework with multi-risk analysis and multi-criterial risk evaluation procedures allowing the participation of stakeholders at both stages. Moreover, the risk indicators in the current work are a result of the interrelation of specific hazards (drought and heat) to vulnerability (to these hazards) at an attribute level. This helps determine which specific attributes are contributing to the high risks and suggesting relevant risk reduction alternatives to be examined.

With the complexity of the human-nature system studied, challenges arise in the different nature of indicators to represent the system from both, hazard and vulnerability aspects. Qualitative and quantitative indicators were used with different combinations of hazards and vulnerabilities. For example, qualitative indicators such as "Accessibility" and "Protection areas" do not inherently include hazard attributes, those attributes were normalized and multiplied with the vulnerability. On the other hand, the quantitative indicator "Leaf net CO2 assimilation" comprised both drought and heat attributes and had to be modeled for its calculation. Furthermore, despite the limited data availability for certain indicators (e.g., "Microbial diversity" and "Leaf breakdown rates"), most of the selected descriptors could be calculated. This can be further improved with site sampling and testing, but would require resources exceeding the scope of this study.

Spatial and temporal aspects were a core part of the study aiming to provide micro-scale (sub-city) high resolution spatial assessment with the possibility of changing temporal conditions. Spatial variability was possible through remote sensing, satellite imagery and modeling software, in addition to field measurements (e.g., soil moisture). The temporal aspect was included with the analysis of return periods of droughts and heat limited to the years 1991-2022 due to data availability.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

Additionally, the methodology allows testing of drought and heat risks with long-term impacts to vegetation, or with a variable seasonality by changing the model's vegetation characteristics. The same applies for evaluating the risks for different alternatives such as irrigation or changing land cover. A limitation to the vegetation characteristics used in the present study is the consideration of the actual vegetation structure (e.g., canopy density and height), but setting the other species-specific characteristics similar to that of the dominant tree species in the study area (Norwegian Maple).

Overall, the testing indicated that the framework can be applied by researchers or practitioners through a series of methods and tools within the analysis and the evaluation processes. The development of the conceptual and methodological background and their operationalization are based on a generic drought and heat risk system for UGI. The methodology allows the adaptation of the indicators with their selection and criteria to the specific contexts through the involvement of local stakeholders, and the use of other available tools to assess the risk. Therefore, transferability can be further tested in additional study areas.

6 Conclusions and Outlook

The present research tested the DHR Assessment Framework with its proposed methods for practical application. This includes the objectives of contextualizing the methods, analyzing and evaluating the risks, and examining its suitability for decision makers to understand the risks, and if needed, to explore risk reduction alternatives. Several conclusions can be drawn from the empirical work based on the final results, and the reflection of the results with the involvement of the local stakeholders.

Overall, the topic is of interest for the stakeholders of the study area and was visible by their commitment to participate in the discussions, workshops, and follow up activities indicating the significance of the challenges caused by droughts and heat. Delineating the risk system with the local stakeholders helps focus the assessment and understand the interlinkages between the different system elements and reflected by attributes of indicators. Despite the limited data availability, the calculation of risk indicators representing the relevant descriptors was possible to a high degree, with the exception of two out of seven descriptors due to resource limitations. The provided options of multiple indicators per descriptor to measure each relevant risk aspect facilitates the risk analysis process by only including indicators that are feasible to measure. The involvement of the stakeholders in the risk assessment provides a greater contextual understanding of the study area by the researcher, and a better scientific understanding of the risks by the stakeholders, and the assessment is considered by some local experts as relevant for decision making.

The evaluation of the risks based on the criteria set by the local stakeholders offers a spatially distributed risk for each dimension and compared to the tolerable risk values, best situation, and worst situation. The study advances the vulnerability and risk assessments for ecosystems in general at the services tier, and applies diverse models and tools to deliver high resolution hyperlocal distribution of risk, with the possibility of the assessment at different temporal points.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

Furthermore, the systemic approach to assess the risks allows detailed investigation of the sources of the risks through examining the attributes of each indicator, which is valuable for decision makers to identify different risk reduction alternatives. Testing the DHR Assessment Framework demonstrated that the risk on different orders (tiers) can be spatiotemporally assessed considering attributes from the tiers of UGI entities, functions and services. Moreover, the results were well understood by the local stakeholders with potential for simplifying the calculation process behind it.

For future perspectives, identified alternatives can be further studied for their impacts on the risks by simulating different models. This also applies to future scenarios related to climate change or other anthropogenic developments. Upcoming research direction can include additional case studies in other climatic or socio-economic contexts. Monetary valuation of the risks (through valuation of ES) can be studied and can act as an incentive for decision makers to take actions. Finally, with the ever-growing role of UGI and their ES in sustainable transformations and biodiversity protection for urban areas, practitioners can apply the DHR assessment to support planning and managing of UGI and their ES under continuous changes.

Code Availability

The used code is made available in an open repository as follows:

Arduino Code for Soil Moisture Sensor: https://doi.org/10.5281/zenodo.14732100

Air Quality Correlation Code: https://doi.org/10.5281/zenodo.14725805

Multi- criteria Risk Evaluation Code: https://doi.org/10.5281/zenodo.14726281

Data Availability

Data sources are cited in the text and processed data are published in an open repository as follows:

Overview and Data Sources: https://doi.org/10.5281/zenodo.14719567

Drought Return Period: https://doi.org/10.5281/zenodo.14724218

Envi-met Model: https://doi.org/10.5281/zenodo.14724374

Heat Hazard Return Period: https://doi.org/10.5281/zenodo.14724849

Multi- criteria risk evaluation geodata: https://doi.org/10.5281/zenodo.14726396

Universal Thermal Climate Index: https://doi.org/10.5281/zenodo.14726047

Risk analysis geodata indicators: https://doi.org/10.5281/zenodo.14726084

Competing Interests

The authors declare that they have no conflict of interest.

https://doi.org/10.5194/egusphere-2025-2060
Preprint. Discussion started: 20 May 2025

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